A Risk Register for Energy Security: a UK Case Study

Colin J. Axon

Department of Mechanical and Aerospace Engineering,

Brunel University London

A thesis submitted to Brunel University London in accordance with the requirements of the degree of Doctor of Philosophy in the College of Engineering, Design and Physical Sciences.

April, 2019

Abstract

Energy policy in many countries, driven by concerns about resource scarcity and environmental damage, is promoting a shift from fossil fuels to a variety of renewable sources. This has consequences both for sustainability and energy security, concepts which share common features, some of which are poorly defined or lacking good data. Using the Process Analysis Method for systematically selecting (sustainability) indicators, we recognised the need to account for risks arising from resource discovery and processing, conversion, and the use of the final energy vector. We analyse the whole of the fuel supply chain in a six stage process for 25 renewable and non-renewable fuels, both current and potential sources. We find that causes of risks can be categorised into seven groups, namely: economic, environmental, innovation, manufacturing, political, skills, and technical. Furthermore, we identify 34 specific causes of risk which we assess to compare their relative importance for the different fuels. In both structuring the problem, and quantifying individual risks we use published information and consultation with experts to ensure that the analysis has a broad range of inputs. All of these impinge on a national or supra-national assessment of energy security, which are important for the formulation of energy policy. Using the UK as a case study, we have applied our method to both reference and low carbon future energy system scenarios to calculate the levels of risk as the system composition changes. Our method underlines the need for assessments and data relating to many issues which are commonly not considered as part of energy security.

Disclaimer

This thesis is submitted to Brunel University London in support of an application for admission to the degree of Doctor of Philosophy. The work described herein is that of the Author, except where indicated otherwise, and carried out (part-time) between September 2011 and April 2019. The views expressed in this thesis are entirely those of the Author and not the University. No part of this thesis has been submitted previously to this or any other university for the award of a degree.

Colin J. Axon,

April, 2019

For my colleagues and collaborators (past and present) who have helped me reach this stage of my academic journey.

In memoriam: Professor Malcolm Irving (1953-2019)

Acknowledgements

Firstly I wish to thank Professor Luiz Wrobel for acting as my supportive and very patient supervisor. I am grateful to many others at Brunel have been helpful in different ways. I should also like to thank my department for funding my trip to speak at the joint meeting of the World Congress of Chemical Engineering and the 6th International Congress on Sustainability Science and Engineering in Barcelona in October 2017.

I am indebted to the Energy Centre at the Institution of Chemical Engineers and its Director, Professor Stefaan Simmons (also of Brunel University), for hosting the expert workshop. I am grateful to all the participants for giving freely of their time and opinions, and to Dr Barry Rawn for being such a diligent rapporteur.

But there is one person I cannot thank sufficiently – Professor Richard Darton OBE FREng of the Department of Engineering Science at the University of Oxford. Our discussions about sustainability and energy security have been invaluable. Over the last 13 years I have learned so much from Richard as a collaborator and friend, and I trust that we will never run out of interesting topics to discuss.

Contents

List of Figures

List of Tables

List of Acronyms

AD	anaerobic digestion
ASHP	air-source heat pump
a.u.	arbitrary units
BEIS	[Department of] Business, Energy, and Industrial Strategy
BTES	borehole thermal energy storage
CBM	coal-bed methane
CCGT	combined cycle gas turbine
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CfD	contract for difference
CHP	combined heat and power
CO_2	carbon dioxide
CMA	Competition and Markets Authority
CTL	coal-to-liquid
DECC	Department of Energy and Climate Change
DH	district heating
DNO	distribution network operator
DR	demand reduction
EfW	energy from waste
EROEI	energy return on energy invested
ES	energy security
ESCO	energy service company
EV	electric vehicle
FIT	feed-in tariff
GHG	greenhouse gases
GSHP	ground-source heat pump
GW_e	giga Watt, electrical
GWHP	groundwater heat pump
HCCCC	House of Commons Climate Change Committee
HSE	Health and Safety Executive
IAEA	International Atomic Energy Agency
ICE	internal combustion engine
IEA	International Energy Agency
IPR	intellectual property rights
IRO	imported refined oil
LCA	life cycle assessment
LCOE	levelised cost of electricity

LCPD	large combustion plant directive
LFG	landfill gas
NG	National Grid
LNG	liquefied natural gas
MOSES	Model of Short-term Energy Security
NAO	National Audit Office
NEA	Nuclear Energy Agency
NORM	naturally occurring radioactive materials
NPV	net present value
MSW	municipal solid waste
MWh_e	mega Watt-hour, electrical
Ofgem	Office of Gas and Electricity Markets
OGA	Oil and Gas Association
OGUK	Oil and Gas UK
OPEC	Organisation of the Petroleum Exporting Countries
ORC	organic Rankine cycle
PAM	Process Analysis Method
PHEV	plug-in hybrid electric vehicle
PV	photovoltaic
R&D	research and development
RM	risk matrix (matrices)
SME	small or medium enterprise
SRC	short rotation coppicing
TRL	technology readiness level
TSO	transmission service operator
TTW	tank-to-wheel
TWh	tera Watt-hour
UCG	underground coal gasification
UKERC	UK Energy Research Centre
WEC	World Energy Council
WEF	World Economic Forum
WTT	well-to-tank
WTW	well-to-wheel

1 Introduction

Climate change was one of the most important international concerns for the last quarter of the 20th century, but will probably be the defining issue of the 21st century. There is a substantial and growing evidence base for the effects of greenhouse gas (GHG) emissions (IPCC, 2015) as the driving force for damage to the natural environment and the provision of ecosystem services. This is leading to calls for better understanding of, and tools to assess, the security of energy, water, and food (Keairns et al., 2016).

The most recent international accord to limit GHG emissions, the Paris Climate Change Agreement (UNFCCC, 2016), commits signatories to constraining global temperature increase using the mechanism of Nationally Determined Contributions (INDCs). An NDC describes the ambition and steps a nation will take to reduce its GHG emissions in five year accounting periods. Many nations have already created targets for using sustainable sources of energy (Jaccard et al., 2012) which Krewitt et al. (2007) suggest could amount to meeting half of global energy demand.

The UK contribution to climate change agreements is guided by the Climate Change Act (HM Government, 2008). This commits the Government to achieving an 80% reduction in GHG emissions compared with 1990 by 2050 using a series of five-yearly ‘carbon budgets’. The UK Government makes policy recommendations to meet these budgets, monitored by the Committee on Climate Change (CCC, 2013, 2017). Current planning is for the fifth carbon budget (CCC, 2015a). Principally, this to be achieved by a switch from using fossil fuels to renewables. However, there is discussion about the continued use of gas for electricity generation if coupled with carbon capture and storage (CCS) technologies.

The Government’s policy relating to, and views on, energy security are set out in the Clean Growth Strategy (BEIS, 2017a). Although this document does not explicitly reference the previous energy security strategy (DECC, 2012) there are common threads. The main difference is that the clean growth strategy is more focused on short-term security of supply regardless of the fuel mix emphasising flexibility, adequacy, and resilience. The 2012 strategy selected indicators for the supply of consumer fuels with respect to adequate capacity, diversity, reliability, and demand side responsiveness (including longer term demand reduction). The policy direction that remains common is the reliance on regulated competitive energy markets (Ofgem, 2017) to deliver diversity of supply and robust infrastructure. The return of the capacity market mechanism for electricity supply is charted by Grubb and Newbery (2018) in their review of electricity market reforms (EMR, introduced in 2013). Also part of the EMR is the support for deploying new renewable generation through the 'Contracts for Difference' mechanism (BEIS, 2019). Playing a role at the local level, the community energy strategy (DECC, 2014, 2015a) set out to support ES (and climate) policy objectives by reducing energy bills, developing skills, and reducing costs. There is a tension within Government over developing energy policy with Craig (2020) suggesting that "*... the Treasury doubts the necessity of rapid domestic decarbonisation, and instead orientates its policies towards a future in which such a transition occurs at a slower pace, if at all.*"; an example being the easing of the burdens on the UK oil and gas extractive industries (HM Treasury, 2014). The difficulties of translating energy policy into law is highlighted by Cairney et al. (2019). In his summary of recommendations for UK energy policy going forward, Jim Watson's message to the Government was that *"Policies to support renewable electricity generation should be more ambitious"*.

Commitments by the UK Government have inspired much work in pathway modelling for reaching the declared target (DECC, 2010a; Hughes and Strachan, 2010; Burt, 2011; Ekins et al., 2011; Skea et al., 2011a; Allen and Chatterton, 2013; Spataru et al., 2015; Trutnevyte et al., 2016; Demski et al., 2017). A well-considered overview of energy system scenarios relevant to the UK was conducted by Holland et al. (2016). The dominant UK energy systems models aim to find the least cost pathways (Ekins et al., 2011).

The UK Government expects to spend approximately £100 billion on energy infrastructure between 2010-2020 and a further £375 billion in the longer-term (HM Treasury, 2013). Turnover rates in long-lived energy infrastructure mean that investment costs remain sunk past the UK's policy focus of 2030 towards 2050 (Li and Trutnevyte, 2017). Many policy failure risks remain hidden including the lack of upstream emissions accounting for fuels, that CO_2 capture will claim 70% of emissions rather than the policy expectation of 90%, and that energy efficiency policies must be physically manifest at a much faster rate than current efforts are achieving (Barton et al., 2018). The key question is will the necessary decisions improve sustainability and security, or lock the nation into inflexible systems?

Any method for analysing scenarios for emissions reductions needs to account for the important physical, social, and economic characteristics; Narula and Reddy (2015) observe that individual indicators of energy security (ES) cannot give a complete picture, whilst Lefèvre (2010) claims that economic assessments alone of the welfare effects of energy [in]security typically do not give useful guidance for policymakers. The tensions between the physical, social, and economic characteristics stem from social-political risks, economic growth, planetary bio-physical capacity, ecosystem burdens, and the effects of climate change (Bithas and Kalimeris, 2013; Csereklyei and Stern, 2015; Lenzen et al., 2016). It was noted by Lesbirel (2004) that an *ex-ante* analysis of ES risks would be important to conduct because *"...subjective perceptions can and do play a crucial role in understanding risks."* Whilst Lesbirel made this comment in the context of pricing, we can extend the idea.

The rationale for our study is neatly summed up by Månsson et al. (2014) in their survey of methodologies of ES assessments, concluding that greater effort should be put into developing methods for:

1. evaluating sources of insecurity that can be dynamic and adaptable,
2. comparing energy carriers [vectors] and supply chains in the medium-term, and
3. assessing adaptive capacity and transformability.

We adapt and extend these to consider the long-term consequences of risks. Transformability is defined as *"the capacity to create a fundamentally new system when ecological, economic, or social structures makes the existing system untenable"* (Walker et al., 2004).

1.1 Energy Security and Sustainability: Two Sides of the Same Coin?

The 'long-term' can be described as inter-generational, so for long-term ES the energy supply and demand system must be sustainable. Therefore we suggest taking a sustainability approach to measuring ES; a short review of ES indicators and frameworks is given in chapter 2. The link between sustainability and ES has been made previously (Stirling, 2009) and adapted for the UK project 'Energy Security in a Multi-polar World' (Barrett et al., n.d.).

There are very large number of sustainability assessment frameworks from which to choose (Dalal-Clayton and Sadler, 2014). Frequently, broad-based sustainability appraisals are used in assessing sustainable development environmental impact, or human development. Less attention is paid to exploiting these approaches in more detailed process-oriented studies. An additional reason to attempt using an established method for generating indicator sets is that of the many ES indicators, aggregate indices, and frameworks few are being taken up by governments. In part this is because many of the proposed frameworks are hard to use, not transparent, not directly comparable with each other, or offer only an incomplete view i.e. environmental or economics biased.

Some appraisal methods only deal with a single aspect of sustainability, for example, land use, natural resources or ecosystems (WRI et al., 2005; UNEP, 2006; van Dijk et al., 2011), urban development (Moroke et al., 2019), or the circular economy (Hanumante et al., 2019). Some methods are designed specifically for a particular technology family e.g. hydropower (IHA, 2018), renewables as a class (LUC and Ecotec, 2001), or project development (Baxter et al., 2002; Arup, 2019). The IHA protocol is interesting as it asks the same questions at each stage of the lifecycle (except that decommissioning is ignored). Others offer insufficient flexibility in some other way. For example lifecycle assessment and its variants use extensive data inputs, but are unable to accommodate qualitative information. The ISO standard provides assurance of compliance with the method (Pryshlakivsky and Searcy, 2013), but this imposes constraints (Baumann and Tillman, 2004). Criticisms of LCA summarised by Lazarevic (2018) include the credibility and veracity of data, incompleteness of the aspects being analysed, and subject to creating hierarchies of worth or value (industrial, environmental, economic). Exergy analysis does not distinguish between renewables and non-renewables, nor the exo-toxicity of waste products (Hammond, 2004). The criticism in common is the inapplicability beyond their designed (narrow) boundaries of operation. We need a framework that is flexible and can be adapted for both quantitative and qualitative information.

Our requirements for selecting a method are that the key variables such as competing technologies, geographical sources of fuels, environmental constraints, technical limits, and societal factors, can be accounted for in a relatively disaggregated manner yet be able to cope with UK and non-UK issues. Furthermore, we need to be able to assess future portfolios of primary fuel supply and installed capacities of energy/power supply technologies. We can analyse the supply of primary fuels by examining their supply chains and treating the technologies which exploit these fuel as subsidiary.

The Process Analysis Method (PAM) for sustainability assessment fits these requirements (Darton, 2017). The PAM was developed whilst examining a palm oil production facility (Chee Tahir and Darton, 2010) and subsequently applied to technologies for removing arsenic from drinking water (Etmannski and Darton, 2014), river basins (Wu et al., 2015), bioprocessing (Sanchez et al., 2016), and extended to assess network processes (Neumüller et al., 2015). We have direct experience of applying PAM to the UK car fleet (Smith et al., 2013a). The purpose of the PAM is to assess how processes cause impacts which enhance or diminish the three stores of capital. The impacts cause observable issues for the recipient stakeholders which are measured by indicators and their metrics. In this way, the PAM is data-driven, transparent, robust, and repeatable. Darton (2017) details how to implement the PAM for a system of interest, but we summarise the seven steps:

1. Give a clear and concise high-level view of the processes which comprise the system.
2. Define the system boundary.
3. Define sustainability in the context of the system described.
4. Define the 'perspectives' – yardsticks by which to judge whether the change in an indicator moves the system towards or away from sustainability.
5. Identify broad groups representing the impact generators and receivers (the stakeholders).
6. Identify candidate indicators and their metrics.
7. Check the candidates against the definition of sustainability and that each has a complete chain linking processes to indicators.

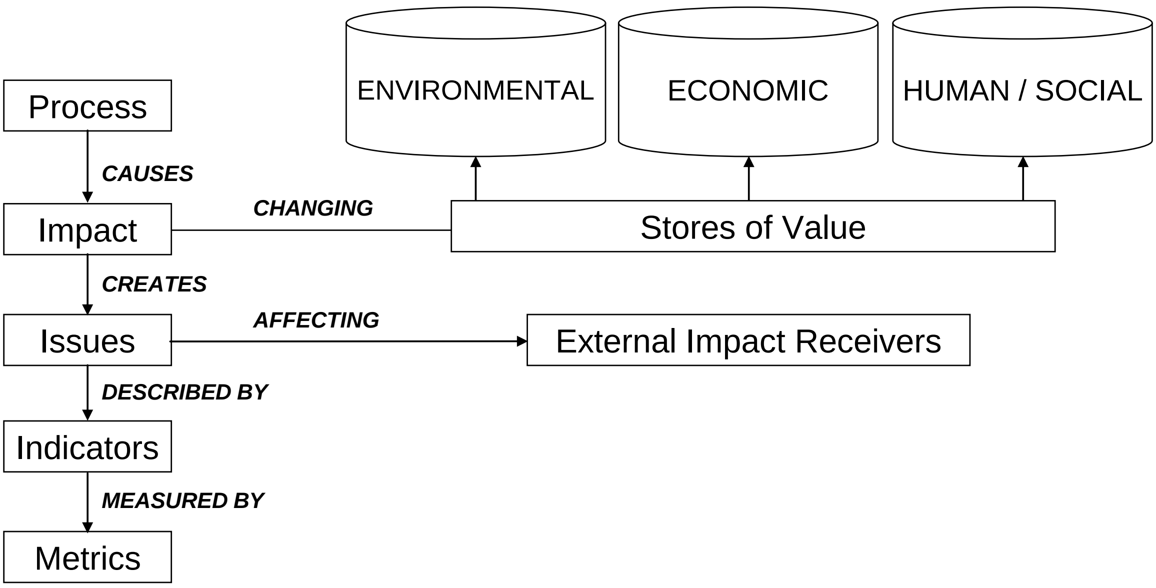


Figure 1.1 The PAM sustainability framework. After Smith et al. (2013).

In operating the PAM to generate candidate ES indicators we observed a key difference with sustainability. The difference manifested as an impact being a lack of or the absence of something (or an action) e.g. flight of capital with the issue being regulatory uncertainty. The question this generated was how would an indicator and metric be devised to represent something which by definition may not be measurable, and almost certainly would not have reliable data available. Experimenting with different formulations or proxies for what were clearly risks (extant or potential) did not improve the candidate indicators.

This arises because of the way that risk is considered and incorporated into the two concepts – security and sustainability. Broadly, sustainability analyses creates indicators or measures by gathering data and then considers how a perturbation e.g. a policy intervention or technological advance, might affect those indicators. A risk, however, might never occur. If it were to occur, then an assessment can be made in the sustainability framework, but if a risk has not yet manifested itself it cannot be readily accounted for in a sustainability assessment. Security assessment, whether in the realm of politics, business, cyber, or military, is wholly dependent on the consideration of risk.

The purpose of creating a risk register in our case is to assist in identifying impacts which a pure sustainability approach does not naturally capture, particularly where novel fuels or technologies are not yet in widespread use. In part it is a filter mechanism since the risk register may capture well-characterised risks such as health effects created by emissions. That is not to say that attempting to identify the impacts and issues directly is wrong, but we found that it was unsatisfactory in developing a comprehensive picture of all the impacts caused by the processes. We cannot measure what is not known about private decisions. Figure 1.2 schematically shows how we propose incorporating the risk register into a modified PAM for (energy) security studies. Furthermore, how the emergent properties of aggregated risks (a risk profile) for a portfolio of current and future fuels is not obvious from knowing detail about individual causes of risks. Henceforth, we concentrate on developing our understanding of the 'Process (Stages and Risks)' box.

Scenarios analysis is better at incorporating a view of the future, but it is not a sustainability method per se. From this point forward we only consider the risk analysis; the PAM for ES is addressed in section 11.4 on further work. For the purposes of developing a first comprehensive risk register suitable for ES assessment, we deem it necessary not to be restricted to the three stores of capital. The supply chain naturally starts with a resource, so 'fuel supply chains' makes sense as the unit (system) of analysis. Our method is developed in chapter 3.

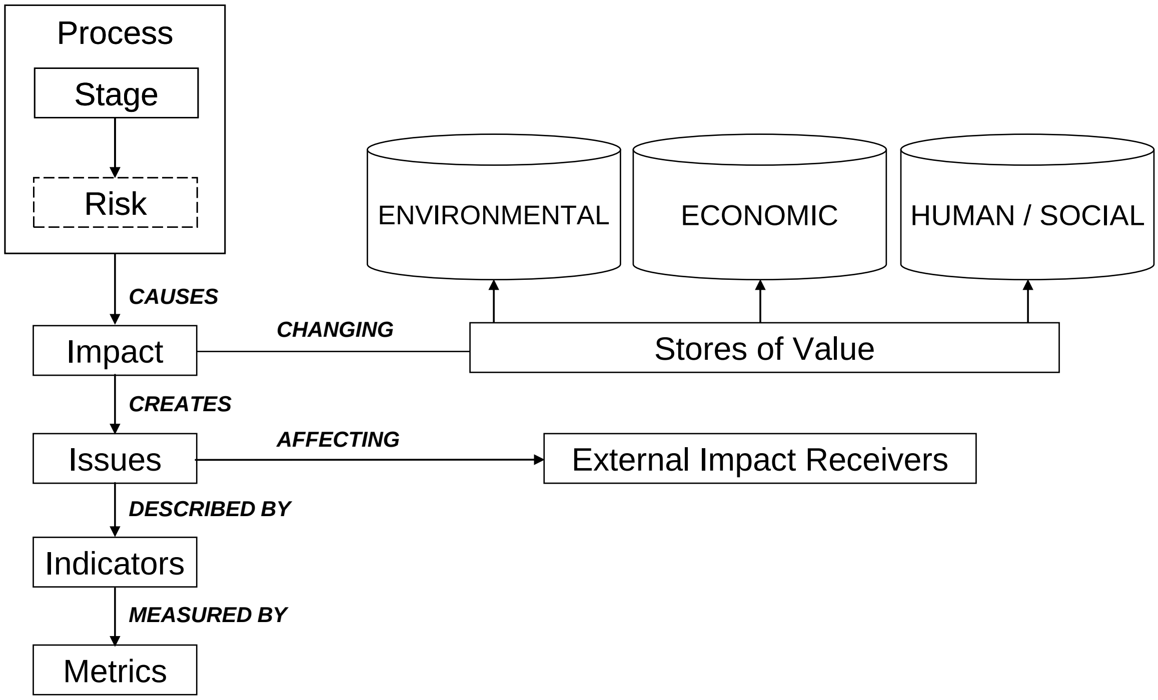


Figure 1.2 Schematic of a modified PAM incorporating risk for assessing security.

1.2 Aims and Objectives

The aim is to create a method – adhering to the princples of the PAM – to reveal detail of risks in current and proposed national energy systems portfolios whilst incorporating relevant international dimensions. The need is to be able to assess, as part of an ES strategy, whether or how policy support should be directed for particular technologies or fuel types in the context of creating a sustainable energy system. The objectives are:

1. Identify the set of fuels and dissaggregate the activities which make up the supply chains into an appropriate number of stages.
2. Create a set of risks by critical review of literature relevant to the supply of fuels.
3. Quantify these risks within a register (for the UK) in a transparent manner through each supply chain.
4. Seek expert feedback on the relative importance of risks identified.
5. Investigate for patterns in the types and classes of risk, and identify the most important causes of risks.

6. Apply the method to compare profiles of risk in energy system portfolios to understand the relative overall risks for future UK energy systems.

Objectives 1-4 relate to the design and performance of the method, whilst objectives 5 and 6 relate to the application of the method.

1.3 The Novelty of this Work

To the best of our knowledge, no attempt been made to create a risk register for energy systems or ES. Risks analysis for projects or businesses is commonplace, but not in terms of a national energy systems portfolio nor for forward projections (scenarios). Using risk as the basis for analysis aligns better with the priorities of those in the private and public sector who decide about support or investment. The relative importance of a broad and balanced set of risks in the context of energy systems has not previously been studied which allows for new understandings of trade-offs and interactions between competing fuels (and conversion technologies). The use of a formal sustainability assessment framework to analyse energy security or risk has not previosly been attempted.

1.4 The Structure of this Thesis

In chapter 2 we give a brief review of the more well-known ES assessment frameworks and indices, and a general overview of risk assessment methods. Following on from the point above where we start the risk assessment, our methodology (chapter 3) describes the working definitions of the process stages, fuels, the causes of risk, and the construction of the risk matrix. Chapters 4-7 provide evidence to support the numerical entries in the risk matrix for each fuel (grouped by type of fuel for convenience). We have adopted the same method and style for each of these evidence chapters, with each fuel section covering stages 1-4 plus any unique elements of distribution and use. Chapter 8 covers the common elements stages 5 and 6 for all fuels, and some miscellaneous items. We present the risk matrix for each stages in Appendix A. Observations and analyses of the final matrix are given in chapter 9, along with the calculations for the system risk profiles and the projections using two sets of well-known scenarios. In the final chapter we draw conclusions and present some of the ideas for further developing and applying this work.

2 Background: Risk and Energy Security Assessment

The World Economic Forum (WEF, 2017) highlights many risks related to energy and climate, but the most important point they make is the extent of the connections between these risks. Chilvers et al. (2017) suggest that energy policy and science are broadening to consider the energy trilemma i.e. the simultaneous delivery of low carbon, secure and affordable energy services. To make progress, assessment of future scenarios needs to link the impacts and constraints of energy and resource use on society, the environment, and the economy. In complicated systems, large numbers of small changes lead to uncertainty (RAE, 2015).

There are two bodies of literature which we need to survey, namely how risk is dealt with in ES assessments, and the methods of measuring risk independent of application area. It is clear that no attempt has been made to generate directly a risk register for ES, but we can gain insight into some of the important elements of risk to ES.

2.1 Energy Security Indicators and Assessment Frameworks

For more than a decade researchers have lamented the lack of a clear and consistent definition of ES (Azzuni and Breyer, 2018). Typically, definitions are drawn up from one of two perspectives: economics, or politics and strategy (Checchi et al., 2009). According to Winzer (2012) the reason is that authors create a definition based on the threats to ES which they have selected for their (limited) analysis. But Månsson et al. (2014) are more forthright in stating that studies depend on both the research question posed and the background of the researchers involved. They also note that different methods and approaches use conflicting assumptions. Furthermore, definitions of ES depend on the scope in terms of the fuels selected or how much of the process system is taken into the system boundary (Cherp et al., 2012), and the time horizon chosen (Azzuni and Breyer, 2018).

Many analyses are for the short-term being more concerned with 'security of supply' (keeping the lights on or fuel flowing) than sustained or long-term sustainable supplies of energy (or sources of fuel) at the multi-decadal scale. An example of the difficulties in developing a clear definition is captured by the one presented by Jewell et al. (2014): *"low vulnerability to vital energy systems"*. However, it is unclear what a non-vital energy system might be, though they define vulnerability as a combination of risk and resilience.

Recent useful and extensive reviews of the variants of ES definitions have been conducted by Winzer (2012), Ang et al. (2015), Jones and Dodds (2017), and Azzuni and Breyer (2018). Additionally, Cox (2016) surveys concepts relevant for electricity security specifically. The principles of measuring ES and the complexities of selecting indicators have been set out by Axon et al. (2013).

2.1.1 Energy Security and Sustainability

Several authors consider energy supply security to be linked with sustainability. Valdés (2018) identifies 16 studies which he considers to have their roots in sustainability. However, many of these studies use the term 'sustainability' in an ill-defined (or undefined) fashion. Keppler (2007) states that the only connection is that both operate the precautionary principle, but this is a limited interpretation of the UN's concept of sustainability (United Nations, 1987). This is also the case for The World Energy Council (WEC) World Energy Trilemma Index in which they consider energy sustainability to be defined by ES, energy equity, and environmental sustainability (WEC, 2018). WEC's definition of ES can be interpreted as acknowledging intergeneration equity (*"the ability to meet current and future energy demand"*), but their definition of sustainability (*"the ability to mitigate natural resource depletion and environmental degradation"*) is limited in scope and thus not concomitant with the United Nations definition of sustainable development.

APERC (2007) and Von Hippel et al. (2011) adopt the Bruntland definition of sustainability i.e. *"the sustainable development and use of energy resources that meets the needs of the present without compromising the ability of future generations to meet their own needs"* (United Nations, 1987). We concur with Narula and Reddy (2015) that ES and energy sustainability can have divergent trajectories, but conceptually should be closely coupled. There is some agreement that economic indicators are not suited to long-term timeframes (Jansen and Seebregts, 2010; Lefèvre, 2010; Månsson et al., 2014): this is another similarity between ES and sustainability. Stirling's 2x2 framework (Stirling, 2009) – adapted from his work on sustainability – incorporates the time period of a threat (risk) and the type of action taken in response (whether internal or external to the system).

2.1.2 It's All About Risk

According to Jansen et al. (2004) the key to assessing ES lies in assessing the different types of risk in the energy system. Likewise, Lieb-Dóczy et al. (2003) suggest that security [of supply] requires understanding of risk, though their approach is restricted to risks of system interruption. But in a curious misunderstanding of the term ‘risk’ Molyneaux et al. (2016) suggest that renewable energy is risk-free.

Although infrequently used as part of a definition of ES, the term ‘risk’ may be ill-defined, or used in a restricted or informal sense. The most frequently used restricted case is for security of supply (Stern, 2002; Lieb-Dóczy et al., 2003; de Joode et al., 2004; Grubb et al., 2006; Scheepers et al., 2006; Creti and Fabra, 2007; Hoogeveen and Perlot, 2007; O’Leary et al., 2007; Rutherford et al., 2007; Jamasb and Pollitt, 2008a; Le Coq and Paltseva, 2009; Cabalu, 2010; Löschel et al., 2010; Newbery and Grubb, 2015). Other researchers use ‘risk’ to express the threat that energy [in]security poses to society or specifically consumers e.g. de Joode et al. (2004) and Olz et al. (2007).

Some researchers use the term ‘risk’ to confer a sense of ‘undesirable’ without defining or stating what constitutes the risk itself. Examples of this practice are the ‘fuel-specific supply risk’ indicator (Frondel and Schmidt, 2008) (a Herfindahl-type measure of import shares) or the ‘Risky External Energy Supply’ index (Le Coq and Paltseva, 2009), both of which are concentration measures. Those devising such indicators and indices assume that an increasing or decreasing value is desirable or undesirable, and that if a value (or change in the value) is determined to be undesirable it is a ‘risk’.

Other terms used are threats and vulnerabilities which some authors use as synonyms for risk. Kucharski and Unesaki (2015) distinguish between risks and threats by defining risks (human or technical) as originating within the energy system and threats as impinging on the system. To some extent, they agree with Winzer’s (2012) characterisation. The distinction between risks and vulnerabilities is given by Krishnan (2016) as adverse implications and the inability to cope, respectively. The security studies research community use the terms ‘securitisation’ and ‘riskification’ (Stoddard, 2012; Judge and Maltby, 2017) by drawing the distinction that ES is more about risks than threats.

2.1.3 Dimensions Used in ‘ES Risk’ Frameworks

There are a limited number of specific risk assessments or frameworks for ES. The core set of dimension which many authors use comprise: economic, environmental, geological, (geo)political, and technical e.g. Checchi et al. (2009). However, the same scopes or definitions vary between authors. There are variations such as Winzer (2012) who uses only three categories namely technical, human, and natural risk (encompassing environmental and geological as others define them), and Johansson (2013) who groups together economic and political risk factors, but keeps the technological and environmental groups separate. Curiously Sun et al. (2017) use the 4As dimensions – availability, accessibility, acceptability, and affordability – as risk factors.

Despite Kucharski and Unesaki (2015) distinguishing between risks and threats, it is puzzling why they would then categorise external risks as economic, environmental, societal, geological, technological, and geopolitical, but exclude technical and human causes of risk (which they treat as internal to the system). Although the categorisation is interesting, their distinction is not self-consistent. For example, Kucharski and Unesaki have both anthropogenic and natural causes of environmental threats; the human-caused threats are self-induced. Moreover, the geological threats fit perfectly well into the environmental risk category. As part of the EU standard for ES the Crisis Capability Index (Scheepers et al., 2006) explicitly mentions only political risks, but includes environmental and technical constraints which are couched in terms of risks.

Using a risk management approach Keppler (2007) analyses the energy supply chain in what he calls dimensions (five) and eight different risks, namely supply and production (geopolitical, regulatory and technical risk), transport (safety and technical risk), distribution (regulatory risk), consumption (price and environmental risk), waste disposal (technical and regulatory risk). His approach is focused on the level of risk which consumers are willing to bear, and subsumes the dimensions in a set of processes.

Risk and resilience – with 'external' and 'domestic' dimensions – are used in the IEA Model of Short-term Energy Security (MOSES) (Jewell, 2011). Although this exercise is data-driven and clearly guides the user to assigning a risk level, MOSES is focused on infrastructure and specifies values of, say, the number of LNG terminals or interconnectors corresponding to each of five risk levels. It is not clear whether these are normalised or not e.g. to population size. Another drawback is that governance, institutional, and investment factors are not taken into account because, according to Jewell, they are not easily quantified. Furthermore, the MOSES system is limited only to IEA member nations and cannot be used to compare nations (only an individual fuel over time for each separate nation).

In assessing security and risk the Global Energy Institute (2018) state that the aim of their 'Energy Security Risk Index' is to understand the likelihood of an energy shock and its impacts on a country's economy. This is a limited view of risk and may better be described as resilience since a low score (meaning low risk) yields a higher rank (where 1 is high). The indicators they present are not couched in terms of risk, but they are an interesting indicator set.

Although there is no definitive rule for how many groups into which the risks should be disaggregated Kristensen et al. (2006) suggest five or six, and the PESTLE method for multi-criteria decision making (e.g. Kolios et al. (2016)) uses six (**p**olitical, **e**conomic, **s**ocial, **t**echnological, **l**egal, and **e**nvironmental). In their assessment of the food-energy-water nexus de Amorim et al. (2018) also use five categories similar to PESTLE, though omitting 'legal'. Hsu et al. (2017) group 'risk factors' (causes/sources of risk) into four 'constructs' (categories of risk) for assessing the operational safety of oil tankers. For projects in the oil and gas sector Schroeder and Jackson (2007) use eight categories of risk, namely health, safety, and environment; operational; procurement and materials; scope definition; market and commercial; organisational; planning and scheduling; and technology. We will consider these in our choice of categories and causes of risk.

2.1.4 Causes of Risk

There is no clear list of core risks used by most authors, though political (in)stability, price volatility, technical failure, and natural disasters broadly are often incorporated. To these, Olz et al. (2007) and Winzer (2012) add physical security threats. Winzer (2012) gives a further 12 causes of risk. The Technical Risk category comprises infrastructure interdependency, emissions, and mechanical and thermal failures. The Human Risk category covers demand, strategic withholding, capacity underinvestment, political instability, and geopolitical risk. The third category, Natural Risk, accounts for resource intermittency, resource depletion, and natural disasters. Of these, 'underinvestment' is particularly interesting, which is noted as insufficient investment in the UK ES strategy (DECC, 2012). Other interesting causes of risk are: the probability of disruption on transhipment routes (Sun et al., 2017), fatalities from accidents (Malkawi et al., 2017), the cost of the release of radioactive materials into the environment (de-Llano Paz et al., 2014), cyber security (Escribano Francés et al., 2013), and water consumption (Malkawi et al., 2017). Hammond and Waldron (2008) and Eskandari Torbaghan et al. (2015) consider risks generally for electricity distribution, and Foxon et al. (2005) and Wilson (2013) risks relevant to innovation in general. A number of reports and papers examine sets of risks in a broader context e.g. (Markusson et al., 2012; EY, 2013a, 2013b; WEF, 2017; de Amorim et al., 2018).

The lack of a coherent framework for identifying risks leads inevitably to inconsistency. Within the dimensions (categories) authors may apply any one to a single fuel, or mix and match the causes of risk for different fuels in the same dimension. For example, Checchi et al. (2009) use oil price in the economic dimension, but not gas prices. By the same token, they concentrate on gas transit (not oil) in the geopolitical category. In their assessment of UK gas security BEIS (2016a) only consider supply-side indicators such as continued supply from various sources (including interconnectors) and the state of the market (whether healthy and/or functioning).

The International Index of Energy Security Risk (Global Energy Institute, 2018) uses indicators such as import exposure (by fuel type), electricity prices (by user type), energy use intensity, electricity diversity capacity, CO_2 per capita. But none are couched as risks. In classifying risks (*"causes of threats"*) as primary, secondary, and tertiary, Johansson et al. (2016) imply that some have different levels of importance. However, they do not make clear why risks are allocated to a category, nor do they use any sort of weighting factor, nor do the categories correspond to likelihood or impact. In defence of Johansson et al., the risks they identify and their descriptive language is helpful, for example *"Lack of investment in search and exploration"*, *"lack of education"*, or *"Lack of physical energy resources"*. Oddly, other risks are not couched in the same way e.g. *"Unsuccessful development of alternative energy sources"*, *"Poorly functioning markets"*, and *"Imbalance between supply and demand"*, which are undesirable outcomes rather than causes of risk. Similarly, the IEA's MOSES (Jewell, 2011) uses *'political stability of suppliers'* rather than the lack of stability – there is no risk in a supplier-nation being stable. A further problem with MOSES is that the risk (and resilience) indicators used are not consistent across all fuels.

The ES literature contains a wealth of indicators describing the areas (broad or niche) of concern or interest. Using the principal studies of interest it is possible to discover from appropriate indicators what may be the associated risk and the underlying cause of that risk (Kruyt et al., 2009; Sovacool and Mukherjee, 2011; DECC, 2012; Axon et al., 2013; Brown et al., 2014; Portugal-Pereira and Esteban, 2014; Hughes et al., 2016; Cox, 2018).

2.2 Assessing Risk

Oxford Dictionaries define risk as ‘a situation involving exposure to danger’ or ‘the possibility that something unpleasant or unwelcome will happen’. The latter is more helpful in the context of ES and is sufficient for our use. This is in agreement with Molyneaux et al. (2016) who give a succinct review of definitions of risk and risk management in various engineering contexts. The evaluation of the level of risk is usually defined as the product of probability of occurrence and the consequence of the outcome of the risk materialising (Gardoni and Murphy, 2014). Historically, risks were evaluated in terms of single impacts of interest, such as financial loss or number of injuries per period of operation, but the methodology is equally applicable to any other impact – environmental or reputational damage, for example. We will observe these principles of risk assessment and adapt the risk matrix method widely used in the chemical process and other industries.

Techniques abound for assessing risk in different situations, types of organisations, projects, and industries with specific legal requirements for health and safety, and each assessment has a unique context and aim (Jordan et al. (2018) and references therein). The International Standards Organisation has developed protocols for assessing risk using this wide variety of techniques (ISO, 2009), which were updated during 2018. Both versions are designed for detailed application (using various techniques) to an organisation or closely bounded situation e.g. a laboratory or piece of equipment. The guidelines are not designed to accommodate national-scale assessments, though the 2018 release will be broader in context and apply to any type of decision and not just risks (Cross, 2017). Despite this, Aven (2016) considers that the foundations of risk assessment are not as firm as might be desired, and there is evidence that current techniques may be poor at capturing the true nature of risk quantification (Farooq et al., 2018).

In his general theory for characterising risk Aven (2017) examines consequence and uncertainty. Although developed in the well-defined context of hazard analysis there are principles which we can apply to creating a method for assessing risks relevant to fuel supply chains. In describing uncertainties Aven suggests that it is reasonable to provide subjective assessments of uncertainties where knowledge and judgments reflect expert opinion; this he captures as the concept of ‘strength of knowledge’ (SoK). A good level of SoK is judged as:

1. having reasonable assumptions,

2. there being data or information available,
3. a strong degree of agreement between experts,
4. how well the phenomena can be modelled, and
5. how rigorously the knowledge has been tested.

This approach reflects well the necessities for assessing risks for which expert opinion may be the main source of information.

By drawing lessons from disaster preparedness Gardoni and Murphy (2014) developed an understanding of the importance of the cause of a risk (person or organisation *"...whose actions create or help to maintain risks"*). In terms of the PAM these are the impact generators. They attach three characteristics ('subdimensions') to the cause of risk, namely causation and responsibility, whether the risk is voluntary or involuntary, and the relationship between who causes the risk (impact generator) and who is put at risk (impact receiver). The cause of risk concept allows for a single source to give rise to multiple risks. Gardoni and Murphy also have an interesting view of what constitutes a consequence. They suggest five characteristics, namely the kind of risk, extent of the risk, temporal aspects, whose consequences matter, and the distribution of the consequence. The first (kind of risk) is what most researchers consider as the level (size) of the consequence, but Gardoni and Murphy subtlety distinguish between kind (importance) and extent (amount) of the consequence. The fifth subdimension (distribution) does not fit with the first four since it is a value statement i.e. the assumption is that an equitable distribution is a good or desirable outcome. In terms of the PAM, this would be classed as a perspective, which are transparently labelled as the lens through which an analyst conducts the method.

Through their analysis of risks associated with terrorism Aven and Renn (2009) concluded that complex systems with elements of ambiguity require a more broad characterisation of the risk and its context than probability distributions alone can offer. They suggest using scenarios to understand impacts in a qualitative manner. Aven (2016) stresses the need to better understand the use of knowledge (and lack of knowledge) in risk assessment and management. Also important for systems where some risks are hard to quantify is separating 'understanding a risk' (using quantitative methods) and 'acknowledging a risk'. Although Amundrud and Aven (2015) discussed 'acknowledging' as the need to act upon 'understanding', we can remold the concept to account for 'known unknowns' where it will not be possible to acquire data for a risk that clearly exists.

Therefore we rely on the literature to help adapt an appropriate method, but our guiding principle is that the characterisation of the system of interest should meet the needs of the risk assessment and that of the decisions made subsequently (adapted from Aven (2017)).

2.2.1 Understanding Risk in Supply Chains

Supply chain risk (SCR) is defined in the context of a company or entity in a supply chain (Nakandala et al., 2017). However, Peck (2006) prefers to consider the supply system as a network, rather than a linear chain. For the purposes of our national-scale assessment of different fuel types, this distinction is not necessary. Often, SCRs are classified as either internal to the system (supply chain) or external e.g. national or international economics, natural disasters, or terrorism (Jüttner, 2005; Kleindorfer and Saad, 2005; Tang, 2006; Trkman and McCormack, 2009). Heckmann et al. (2015) also consider risks relative to the supply chain boundary, but they divide the *"sources of risk"* into those associated with network and process activities, with the *location* of the risk subsumed in the network category.

Although SCR is an under-researched topic (Nakandala et al., 2017) with a sparse literature, there are some important examples of risk assessment practice in the context of fuel supply chains: process safety in the chemical industries (Whipple and Pitblado, 2010), oil and gas (Schroeder and Jackson, 2007; Fernandes et al., 2010), oil tankers (Hsu et al., 2017), electricity transmission (Eskandari Torbaghan et al., 2015), physical security of energy assets (Bjerga and Aven, 2016), and infrastructure (IRM, 2013). Although in the context of ES (rather than SCR) Bradshaw and Solman (2018) split gas production into upstream (supply), midstream (transhipment), and downstream (demand).

2.2.2 **Systemic** Risk

A systemic risk is frequently defined as one with non-linear functional and structural interdependencies among system components leading to cascading effects (Haldane and May, 2011; Helbing, 2013; Battiston et al., 2016; Burkholz et al., 2016; Ledwoch et al., 2018; Scheibe and Blackhurst, 2018; Convertino et al., 2019). This definition was developed in a mostly economic context from the perspective of complex systems analysis; the key point is that 'systemic' is taken as dynamic (meaning able to cascade through the system under consideration). In contrast, Hochrainer-Stigler et al. (2019) contend that this 'contagion' approach downplays the importance of human agency. This leads them to state that systemic risk is usually due to an endogenous risk such as a cascading failure, and claim that volatility is a systemic risk (in the context of markets). This definition appears to be dependent on the viewpoint of the observer (it is not strictly a system boundary redefinition). Defining systemic risk more broadly to incorporate human–environment interactions is supported by Keys et al. (2019) in what they term 'Anthropocene risk'. Johannsdottir and Cook (2019) suggest that systemic social, cultural, environmental, economic, security, and policy factors combine to create an event which may cause a tipping point leading to the breakdown of the system itself (not just a component). Similarly Venkatasubramanian and Zhang (2016) use entire system collapse where the failure negatively impacts a large number of people and their environment, causing enormous financial losses. We consider the latter part of this definition to be unnecessarily restrictive.

A characteristic of a systemic risk is that the source of the risk may be obscured or redistributed to many other entities i.e. the source occurs everywhere and may be low risk, but the exact level of consequence is uncertain. The risk is that each entity will manifest simultaneously in an unpredictable pattern, or that a known risk is split amongst other entities with a non-uniform distribution.

Experts with different backgrounds give varying meanings to the term 'systemic' (Renn et al., 2019) with Boholm and Prutzer (2017) noting the major gaps in knowledge about risk interaction. In recent years popular discourse and the academic literature have linked systemic risk mostly with economics and finance (Haldane and May, 2011; Langsam and Fouque, 2013; Engle and Ruan, 2019; He and Krishnamurthy, 2019; Iqbal and Vähämaa, 2019; Simaan et al., 2020). Furthermore, analysis has too often been focussed on individual elements e.g. firms (Chen et al., 2013). However, engineered systems (broadly defined) are receiving some attention, though the scope of 'systemic' is more varied. Examples of non-economic or financial topics where systemic risk has been examined are: infrastructure resilience (Convertino and Valverde, 2019), managing the multi-factor components of eye conditions (Iyer et al., 2019), environmental factors presenting systemic risk to financial systems (Johannsdottir and Cook, 2019), climate change as a systemic risk to potable water provision (Boholm and Prutzer, 2017), toxicology (Fransway et al., 2019), flood management (Convertino et al., 2019), safety in the chemical process industry (Reniers et al., 2012; Venkatasubramanian and Zhang, 2016), terrorism (Goldin and Mariathasan, 2014), and oil and renewables stock prices (Reboredo, 2015).

Zare-Garizy et al. (2018) recognise the scarcity of real-world data relating to systemic risk in supply chain networks but much of the work on risk in networks has been for individual firms and their own supply chain, often through case studies. One notable exception is systemic risk caused by clustering chemical production plant. The co-location of companies producing unrelated products can arise because of the advantage in sharing facilities e.g. heat network or a trans-shipment facility. However, the physical proximity may introduce the risk of a cascading operational failure or more hazardous incident affecting multiple supply chains (Reniers et al., 2012). In the manufacturing sector, this has been described by Scheibe and Blackhurst (2018) as a trade-off between efficiency and systemic risk. An interesting conceptualisation of the dynamic nature of systemic risk in supply chains is that of Wu et al. (2017). They describe the systemic risk as a node at the nexus where the causes of risk arising in the supply chain and the range of possible cascading consequences meet. Both Ledwoch et al. (2018) and Zare-Garizy et al. (2018) use centrality measures to estimate overall risk, whilst Reniers et al. (2012) use an effect-distance metric (distance being physical or conceptual).

In considering systemic risk in terms of security, the interaction between energy security and the energy transition is identified as a systemic risk by Bellos (2018). Oil supply as a systemic risk to energy security in discussed by Sun et al. (2017). Pasqualino et al. (2019) recently attempted to model systemic risks for food and energy, and Sartori and Schiavo (2015) have examined food trade globalisation. More generally, systemic risks to environmental security (Liotta and Shearer, 2008) and access to, and security of, water supply (Distefano et al., 2018) have received attention. Ermolieva et al. (2016) have modelled (simultaneous) food, energy, water and environmental security, emphasising the emergent (systemic) risks.

From critically analysing the systemic risk literature, we suggest that there are two types of cause of systemic risk in fuel supply chains as an element of energy security, omnipresent and nodal:

1. Omnipresent: when a risk is present in most or all fuel (resource) supply chains, and perhaps most or all stages, irrespective of the consequence level.
2. Nodal: where a mechanism exists such that a single event may cause a cascading effect, though the cause of the risk need only occur occasionally through the supply chains.

The understanding of systemic risk we adopt for this study is that the whole system is affected to some extent, but not necessarily catastrophically. Thus a systemic risk would be one that affects whole of the fuel supply chain and not readily managed by a single actor (Government, company or regulator). This is in accord with Johannsdottir and Cook (2019) who – in their case study – treat oil spills from shipping as a systemic risk to the natural habitat of the arctic i.e. one source of risk might cause damage to all flora, fauna, and resources within a geographic boundary (the system boundary). Examples of outcomes of systemic risk affecting ES are international financial gridlock, world war, a climate catastrophe, solar flux interruption due to a super-volcano eruption, or the immediate cessation of all fossil fuel use due to a global agreement. A less restrictive definition of the sphere of operation of systemic risk could be taken as a risk that affects all fuels at a particular stage (though not all stages of a single fuel). Systemic risks do not necessarily have the high consequence levels.

2.2.3 What is the Point of a Register of Risks?

All companies and organisations will keep a risk register as a matter of good governance. According to Willams (1994) a risk register has two roles as *"a repository of a corpus of knowledge"* and that it should *"…initiate the analysis and plans that flow from it"*. Williams was writing in the context of projects, but many nations keep a risk register, often related to physical security (Hagmann and Cavelty, 2012). The UK risk register (Cabinet Office, 2017) also incorporates emergencies such as severe nuclear power plant accidents, maritime disasters, infectious disease outbreaks, cyber attacks, and civil unrest. In his analysis of the British and Dutch national risk registers Vlek (2013) suggests using a broader concept of risk which he defines as "*…an insufficient potential to meet external harmful demands.*". Aven and Cox (2016) bluntly suggest that (inter)national assessments need to incorporate risk analysis techniques to be more effective. Amongst their eight principles for governments on how to deal with risk Aven and Renn (2018) advise:

- that the risk level needs to be arrived at by balancing the different issues using a value and evidence/knowledge-informed context-dependent process,
- supplementing formal analyses with broader judgments of risk and stakeholder involvement,
- managing risk using discursive strategies leading to risk- and dialogue-oriented policy development, and

- openness and transparency with the public and about the processes in use.

2.2.4 Risk Matrices

Whilst observing the principles and examples from previous studies, we will use a modified risk matrix (RM) approach for our study. In many industries and businesses RM are used as a quantitative hazard prioritisation tool, though there are some drawbacks. However, many researchers and practitioners advocate RM as a semi-quantitative or fully quantitative tool.

Quantitative RMs are in widespread use because they are perceived as being easy to construct, explain, and score (Thomas et al., 2014), for example electricity generation (Hammond and Waldron, 2008), future (smart) electricity networks (Rossebø et al., 2017), human health (Schleier and Peterson, 2010; Vatanpour et al., 2015), pipelines (Henselwood and Phillips, 2006), process safety (Whipple and Pitblado, 2010), project management (Hillson and Simon, 2007), shipping (Hsu et al., 2017; Marchenko et al., 2018), agricultural pollution (Hewett et al., 2004), and water recycling (West et al., 2016). Several organisations give guidelines for using RMs in their sectors (NPSA, 2008; IMO, 2013; IPIECA and IOGP, 2013).

Despite their popularity quantitative RMs exhibit a number of drawbacks, though with careful design for a specific task, these can be mitigated. Hitherto identified drawbacks are spurious resolution i.e. lacking granularity (Cox, 2008; Smith et al., 2009), they cannot measure aggregated total risk for a process where the risk scores have units (Baybutt, 2016), they cannot account for correlated risks (Hubbard and Evans, 2010; Baybutt, 2016), can be subject to cognitive bias (Smith et al., 2009; Hubbard and Evans, 2010), mathematical inconsistency (Cox, 2008; Hubbard and Evans, 2010; Thomas et al., 2014), potential for ranking reversal errors (Baybutt, 2016), and range compression (Cox, 2008; Ni et al., 2010; Levine, 2012). By way of dealing with flaws Cox (2008), Levine (2012), and Baybutt (2016) suggest using logarithmic scales to increase the dynamic range of values, Smith et al. (2009) counteract cognitive bias by applying statistical tests such as maximum likelihood estimation, and Duijm (2015) suggests using probability-consequence diagrams with continuous scales. Despite the shortcomings, Duijm (2015) concludes that RMs *"…offer support in cases where explicit quantification cannot be agreed upon."*

For quantitative RMs we note a number of methodological advances. Some authors have exploited fuzzy logic combined with Analytical Hierarchy Protocol (Hsu et al., 2017) and hierarchical holographic modelling (Nakandala et al., 2017) to weight risk factors, and fuzzy mapping for aggregating risk matrices (Bao et al., 2018). Peace (2017) suggests using RM in conjunction with goal trees. Allan and Yin (2011) consider the likelihoods of pairs of risks occurring which they claim allows examination of dependencies.

More pertinent to our case, some authors comment that the important point is using the RM tool for the right job. Bao et al. (2018) consider that subjectivity is a useful characteristic of RMs since they are a risk management tool, thus effective for assessments where data are insufficient to use quantitative tools. Baybutt (2016) suggests that RMs should only be used for initial decision guidance, whilst Peace (2017) recommends that RMs are used as a reporting mechanism as part of a risk assessment using other tools and discussion. More generally, Johansen and Rausand (2014) suggest using deliberation, incorporating stakeholder views and other information, as part of risk-informed decision-making, and MacKenzie (2014) advises that categorical scales are best used when communicating with a wide variety of stakeholders and decision-makers.

There are some recent advances from which we can draw lessons. Fernandes et al. (2010) suggest using RM within a (hierarchical) framework for identifying the risk agents, risk sources, risk objects, and risk events. Goerlandt and Reniers (2016) advocate visualisation techniques as part of the RM method, and Aven (2017) has incorporated a method for assessing the ‘strength of knowledge’ where subjective judgments need to be made in the absence of sufficient data.

2.2.5 Summary

Many researchers have recognised the key elements of ES. But despite a plethora of well-intentioned and mostly self-consistent ES indicators, indicator sets, and frameworks of analysis, they are not often being taken-up in policy circles. In part, this may be attributed to terms such as ‘risk’, ‘resilience’, and ‘sustainability’ being used inconsistently. The principal gap is the need for coherent framework, and transparent analysis, using tried and tested ideas about risk and impact.

3 Constructing a Risk Assessment Methodology

The methodology is designed to be independent of any nation or source of fuel though inevitably a country-assessment will need to take account of opportunities or limitations presented by geography, specific political matters, or the economic state (level) for example. Therefore we are creating a way of assessing the risks of using a fuel type in general, not assessing the risks of any individual project. The application to a nation – the case study – will test the method and illustrate its potential use.

After defining the system boundary, there are five main steps for setting up the framework for the risk assessment (Figure 3.1). First we identify a set of classes of fuel sources and define their characteristics. Secondly we exploit the PAM to identify and define the process stages at an appropriate level of disaggregation. The level of aggregation chosen is dependent on the purpose of the study and the size of the team available to carry out the proposed study. Thirdly, from a combination of the PAM, review of literature, and expert input we identify and define seven categories of causes of risk. Fourthly, using review of literature and expert input we identify and define the causes of risks. In practice a feedback loop exists between the third and fourth steps to settle on a manageable list. Lastly, we construct and test the risk matrix to evaluate the performance of the interacting elements of the framework. Then we generate the risk register i.e. analyse the likelihood, level of impact, consequences, and scale of the causes of risk and use it to analyse the changing relative level of risk for different energy system scenarios.

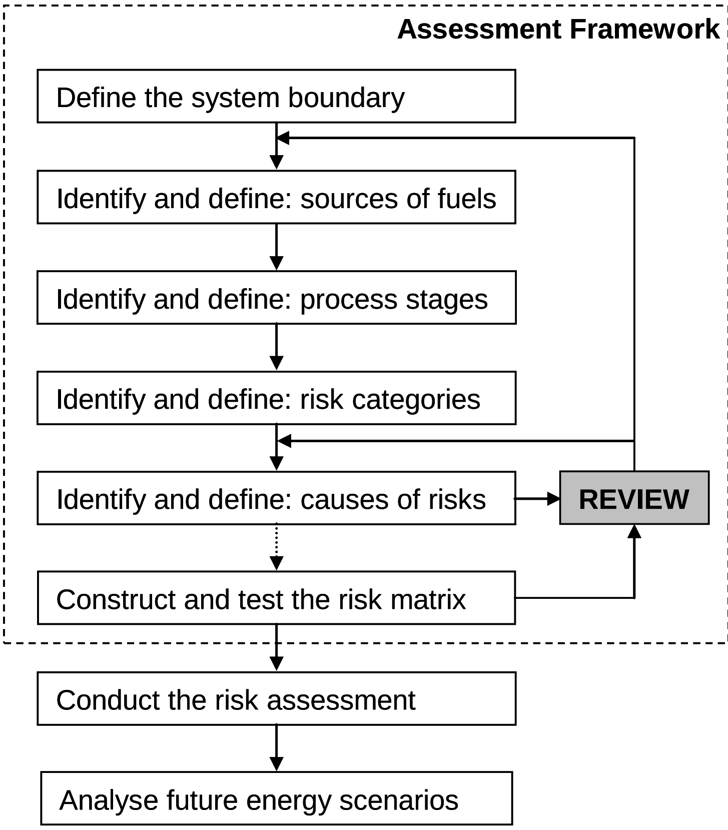


Figure 3.1 The steps taken (with feedback) to generate the assessment framework.

3.1 Raw Fuel Sources

The nomenclature for the fuel category (Table 3.1) is meant to name the fuel source directly and not the technology or conversion device. However, to be pragmatic it is not possible to be wholly consistent. Gas is a good example. The gas used for domestic and power generation purposes is methane. But so-called natural gas is made up of fractions with different molecular weights (ethane, butane, propane) and various impurities including water, and carbon monoxide/dioxide. Processing separates the different fractions for various uses, including butane and propane which can be blended to produce LPG for transport or gas heaters – clearly having a part to play in any ES analysis. Methane may also be produced from fast pyrolysis processes (along with hydrogen), anaerobic digestion, or landfill sites. Another source is methane hydrate deposits. There are also various other gases proposed as fuel sources, but which for the near future can only form a niche fuel or be a theoretical possibility. Thus it is helpful to aggregate some of these gaseous fuels into categories and to split the sources of methane as renewable and non-renewable.

Rules of thumb for deciding the groupings are the type of processing which the fuel requires, the stage of maturity of the technology, or the scale of operation. Although what may constitute ‘unconventional’ may become conventional in years to come, we should recognise that an ES analysis must take account of the current state as well as looking to the future. Some useful definitions (and references therein) for conventional / unconventional fuels are given by Rogner et al. (2012).

In Table 3.1 the ‘Fuel Transport Required’ column refers to whether Stages 2-4 are co-located or not. For many fuel sources the capture conditioning, and conversion processes are carried out in the same device (e.g. a wind turbine) meaning that the fuel is never transported. Another example is hydropower. Although to be able to capture the ‘fuel’ (water) a dam has to be built, which is a different device to the turbine required for conversion, the distinction is not meaningful for this scale of analysis. The fuels are mostly, but not exclusively, renewable. The criterion is that the captured fuel usually has only a single end-point at that location. Another way of looking at this is that the conversion technology is taken to the site of fuel source, never vice-versa. For some fuel categories the distinction is less clear-cut. Two examples are Solar (thermal, power) and Thermal (geological). Solar (thermal, power) was first devised to super-heat steam and drive a standard turbine to generate electricity which clearly requires no transport of the fuel. Recently however, hybrid fossil-CSP systems have been conceived for which gas would need to be transported. These two types of conversion system are often conflated. For Thermal (geological), the fuel source (heat) is extracted on-site, but the water required to inject into the rock formation may well have to be transported to the site – this is co-locating extraction and conditioning of the resource, but not the conversion. Thus Thermal (geological) is categorised as requiring transport, although this relates to the heat transfer medium.

We use the common classification of energy sources and fuels as renewable or non-renewable. An alternative for renewables – carbon-free – is proffered by Harvey (2010), but this is contentious since we are concerned about the whole of the supply chain. This leads to classifying Nuclear (fission) alongside Solar (electric) and Wind (off- and on-shore) as carbon-free, yet clearly fissionable fuel is exhaustible and non-renewable. Categorising a fuel as renewable or non-renewable is mostly self-explanatory, but two interesting cases emerge namely Thermal (geological) and Waste. Many authors categorise geothermal energy as renewable, for example Stefansson (2000), Turkenburg et al. (2012) and Skea (2015), whilst Harvey (2010) classes it as carbon-free. Geological reservoirs of thermal energy are exhaustible (Nazroo, 1989; Younger, 2014), only replenished (if at all) on geological timescales, and are therefore non-renewable. Waste, on the other hand, could be considered as renewable since replenishment is at a considerably faster rate. However, as the total amount of waste available is solely a function of societal behaviour, we take Waste to be non-renewable. There is precedent for considering demand reduction in the same framework as supply-side mechanisms. Eyre (2013) proffered a scheme for an energy efficiency feed-in tariff (FIT) to operate in a manner to FITs for renewable power generation.

The categorisation of the bio-derived fuel sources is difficult and for the sake of clarity we have broken our nomenclature rule. Biogas (except landfill gas (LFG) and sewage gas) and Bioliquid are not strictly sources, but end products, as both are derived from Biomass. However, their manufacture cannot be wholly incorporated into Biomass (solids) as the process pathways threaded through the stages are entwined and technically coupled to different degrees at different points making a complicated story. As there are several distinct end uses (and final energy vectors) the risks more readily relate to the conversion technology (Stages 3-4), the distribution method (Stage 5), and the use (Stage 6). In part, the complexity arises from the immaturity of some process pathways and the marginal economic benefits.

A categorisation more in keeping with our system of nomenclature would be, for example, Waste (agriculture, slurry), Waste (agriculture, solid), Waste (municipal, organic), and Waste (municipal, solid). However, in this case Biomass (wood) would still need to be used for virgin woody crops e.g. willow likewise Biomass (non-wood) for crops such as oilseed rape, aquatic biomass, or sugarbeet grown specifically for processing into bioliquids. In addition to these niche categories, the complications of common processing facilities will still occur. Furthermore some of these separate categories will have some proportion mixed with others before conversion to the final energy vector. Therefore we have adopted a pragmatic approach to distinguish the bio-based sources of fuel by the technology used for conditioning the raw fuel. In a more detailed or disaggregated study, the alternative categories could be adopted; likewise if bio-based fuels were a more significant proportion of a nation’s primary energy supply. Any biogenic material converted outside the system boundary and imported would be considered as Gas (unconventional) or Oil (unconventional), for example.

Fuel Category	Type	Fuel Transp. Required?	Notes
Biogas	Renewable	Yes	The production of methane from biogenic sources such as sewage, livestock manures, and agricultural waste for direct combustion or injection into the gas network. In some cases shares similar production methods to bioliquids. AD is a common route, the fuel being waste, however, it is renewable c.f. gas (unconventional). Off-gas from landfill sites is considered in this category.
Bioliquids	Renewable	Yes	Shares some production methods with biogas and biomass, but bioliquid manufacturing is likely to be a unified facility. Bioliquids can be produced from upgrading gases or as by-products from biomass processing. Mostly for transport fuels; products include methanol, ethanol, biodiesel.
Biomass (solids)	Renewable	Yes	For direct combustion alone or co-fired with coal. Mainly crop residues, SRC, aquatic biomass.
Coal	Non-renewable	Yes	Hard and soft (brown/lignite), but excluding peat.
Demand reduction	Non-renewable	No	Conceived as a ‘negative fuel’ – negafuel. There are two elements: energy efficiency through use of or redesign of devices, and change in behaviour by people. See Note 1.
Exotic gases and liquids	Non-renewable	Yes	Currently liquid nitrogen, ammonia, hydrogen, and carbon dioxide (CCU). See Note 2.
Gas	Non-renewable	Yes	Gas conventionally extracted. Including methane, propane, butane, LNG.

Gas (unconventional)	Non-renewable	Yes	Shale gas, methane hydrates, coal-bed methane (CBM), aquifer (water dissolved), coal gasification. Excluding pyrolysis as the fuel in that case is waste and methane is a by product from by processes. For AD, the fuel is also waste (animal and human waste), but it can be considered as renewable (see biogas).
Hydro	Renewable	No	Large devices at the MW scale not part of a two-level pumped storage scheme, nor tidal barrages.
Hydro (low head)	Renewable	No	Community-scale, kW devices for rivers.
Nuclear (fission)	Non-renewable	Yes	Including thorium.
Nuclear (fusion)	Non-renewable	Yes	Meaning deuterium and tritium.
Oil	Non-renewable	Yes	All grades of conventionally extracted oil. Most (85%) goes to transport fuels.
Oil (unconventional)	Non-renewable	Yes	Shale oils, tight oil, extra-heavy oil, bitumen. See Note 3.
Ocean (tidal)	Renewable	No	Subsurface stream devices and lagoons.
Ocean (unconventional)	Renewable	No	Including osmotic and thermal, but excluding wave and tidal.
Ocean (wave)	Renewable	No	
Peat	Non-renewable	Yes	See Note 4.

Solar (electric)	Renewable	No	Photovoltaic including IR wavelength devices.
Solar (thermal, power)	Renewable	No	Mostly MW-scale concentrated solar power (CSP) devices for raising steam, excluding solar water heating for buildings. See Note 5.
Solar (thermal, water)	Renewable	No	Mainly for building-scale uses, distinct from CSP.
Solar (updraft tower)	Renewable	No	See Note 5.
Thermal (geological)	Non-renewable	Yes	Producing hot water for direct heat exchange or superheated steam for turbines. Includes minewater systems.
Thermal (low temperature)	Renewable	No	Low grade thermal energy drawn from the near sub-surface environment. See Note 6.
Waste	Non-renewable	Yes	MSW, plastics, tyres, . Energy recovery (EfW) by incineration or pyrolysis, plus AD. For pyrolysis and AD, the processing to produce methane and hydrogen is a by-product of waste management in this study. For AD see Biogas.
Wind (offshore)	Renewable	No	
Wind (onshore)	Renewable	No	Excluding micro turbines.

Note 1: The direct provision of energy services e.g. heat networks with water as the energy vector (both industrial and residential) or the provision of lighting or cooling, may lead to a reduction in demand through efficiency gains of scale. However, the relevant causes of risk are included elsewhere, so to avoid the danger of double-counting we exclude these from the definition. The provision of heat is especially difficult to categorise as water is an energy vector and the plant supplying the hot water might be waste low-grade heat from industry or a dedicated CHP

unit fired by another fuel such as Biomass, Gas, or Gas (unconventional). We treat these in Stage 6 (Use) of the relevant fuel because the fuel is delivered to the heat producing device via the distribution stage (see section 8.2.2).

Note 2: These may not be primary fuels, however, each may have implications for ES.

Note 3: Unconventional Oil encompasses a wide range of sources. The main ones listed are marginal to current production and are uneconomic. Our definition excludes coal-to-liquid (CTL) since it has little impact on the UK.

Note 4: Peat cutting for energy use in the UK is a small scale activity concentrated in rural areas, especially Scotland, and mostly carried out by householders. The annual UK energy statistics dataset (BEIS, 2017b) does not record usage, though the International Peatland Society estimates 20 kt per annum (WEC, 2013) most of which is for horticulture. Although we could consider peat as biomass, it is non-renewable. Therefore peat has been excluded from our study.

Note 5: These do not have any practical possibility of deployment in the UK. Within the confines of the system boundary of the UK case study we will not consider these further. In the long-term future it may be possible that commercial Solar (thermal, power) may be sited in Southern Europe or North Africa, but their contribution to UK ES could only be through a European Supergrid transmission system and then via interconnectors.

Note 6: The ground temperature at 1-2m depth varies little seasonally and acts as bidirectional store from where thermal energy (the 'fuel') can be extracted and rejected thermal energy deposited. The principal technologies are ground-source heat pumps (GSHPs) and ground-water heat pumps (GWHPs). The fuel for an air-source heat pumps (ASHP) is the sun (by various mechanisms) heating the air. However, we treat ASHPs as an electrical device (demand) because the rejected heat during the summer is lost to the atmosphere – air cannot act to store thermal energy in the same way as the sub-surface. Systems for recovering thermal energy from minewater share technical characteristics with Thermal (geological) and are classified as such.

Table 3.1 Summary of the generic fuel categories and their definitions.

3.1.1 Grid-scale Storage and Interconnectors

Even though grid-scale storage would naturally be considered a security of supply matter (for balancing intermittent renewables) it cannot be considered as a primary fuel since it is agnostic to fuel sources and is mediated by an energy vector (the electron) which is already in the distribution system. The storage device will normally transform the electrical energy into another form e.g. chemical, kinetic, or gravitational potential. This may then be used as a store directly or in the case of pumped storage systems, operated to move water to a higher level lake. Grid-scale storage is also functionally indistinguishable from a generator.

Interconnectors (crossing the system boundary) possess an interesting status. Interconnectors are infrastructure, but they could be considered as a fuel with a geographical offset (with the conversion stage in another country). Moreover, interconnectors exhibit some of the characteristics which we associate with storage, such as acting as a balancing mechanism for National Grid. The definition becomes blurred with pure infrastructure when considering structures such as a 'North Sea Grid' linking off-shore wind with several countries including those operating two-level pumped storage systems.

Grid-scale storage and interconnectors are considered at the distribution stage as they may have impacts on the investment, development, or deployment of renewables.

3.1.2 The UK Case Study

The case study will not use all of the fuels outlined in Table 3.1, we indicated that Solar (thermal, power), Solar (updraft tower) are not relevant to the UK. We deem Exotic gases and liquids, Nuclear (fusion), and Ocean (unconventional) to have a very low probability of being deployed in the UK. Furthermore, we note that Hydro (low head) and Peat make a very small contribution to UK energy supply.

3.2 Process Stages

The descriptors for processes and activities have been made explicit where possible, but where the range is wide, generic labels have been used. The point is to give a link to the level of complexity or scale of the operation to assist in assessing the risk specific for that fuel at that stage. Furthermore, using the PAM, the identified impacts result from processes. Thus to assess risk we must first identify the processes (activities) involved with each fuel.

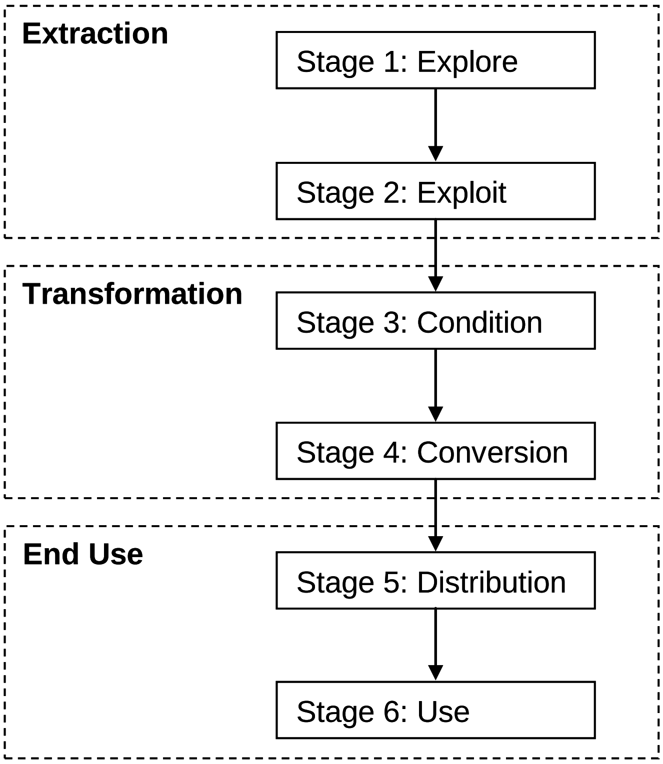


Figure 3.2 A schematic of the six process stages. The three groupings of extraction (stages 1-2, transformation (stages 3-4), and end use (stages 5-6) are broadly useful, though renewable fuels often have stages 2-4 co-located at the conversion site.

Analysing the fuel supply chain and processing system using the PAM, we suggest that the following high-level stages are appropriate for the scale of this study (Figure 3.2):

1. *Exploring* for energy resources: Measuring the potential is measuring the quality of the fuel source. Exploration and discovery activities include geological prospecting and seismology, wind surveys, assessments of water and plant resource together with ecology, collecting data relevant to specific sites (above or below ground / sea).
2. *Exploiting* the raw energy resource: Production, capture, and transport of raw resource. Design and construction of facilities, operation, import/export of product. Get resource (or raw material) to the mine/site entrance, and/or to the processing site for upgrading.
3. *Conditioning* the raw energy resource into fuel: Condition, process, and transport the raw energy resource to upgrade into a fuel which meets specifications for sale.

4. *Converting* the fuel to the final energy vector: Conversion of the fuel to the final form of the energy vector. This includes storage in the form of electricity, pumped (potential), thermal, and kinetic energy.
5. *Distributing* the energy vector for sale to the end user: Distribution of the energy vector including the monitoring, design, construction, and maintenance of the infrastructure.
6. *Using* the final energy vector: The users will be household, business, public sector and charitable organisations, and industrial consumers operating electrical devices, vehicles, and heating systems.

The aggregation of the processes is commensurate with the key processes in all extractive industries. All stages include consideration of disposal of waste, site decommissioning, technical innovation, and efficiency. Stages 2-6 include the risks of project development. An important reason for being explicit about use (Stage 6) is that impacts and risks can be readily associated with that stage. In terms of Winzer's (2012) continuity concept, Stages 1 and 2 align with commodity continuity and Stages 4-6 align with service continuity. However depending on the fuel type and geographical location, Stage 3 will fit into one or the other. This demonstrates an advantage of process decomposition over a simpler two-phase approach and strikes a balance of too many to be manageable and too few to be meaningful.

Transportation of resources, materials, and fuels is required within (intra-stage) and between stages (inter-stage). Although different forms of transport (bulk carriers, road, train, shipping) are required between world regions each with different risk profiles, we considered it unfeasible to have separate stages for each. Whilst there are fuels for which separate transport stages do make sense this is not universal. For example, where the fuel is exploited and converted at the same site (renewables) this does not work well since it is the final energy vector (the electron) which is transported. Electron transportation is readily absorbed into the distribution stage since the technologies are to all intents and purposes identical. The reason for making transport more prominent is that if it is considered in energy systems models at all, it usually only acknowledged through price. This underplays the importance of the risk associated with moving very large quantities of fuels. For the single country case study we account for the transport risks at each stage. The main risks which we identify are of nuclear fuel (new or spent), gas transit pipelines, and oil on the open seas, but some of this is covered by governance (theft, rule of law etc).

Stage	Fuel Category						
	Biogas		**Bioliquids**	**Biomass (solids)**		**Coal**	**Demand Reduction**
1. Explore	Find agricultural waste		Find energy and waste crops	Find woody crops		Geology, dig	Measure potential
2. Exploit	Gather agricultural waste		Gather energy and waste crops	Gather woody crops		Mine	Create devices, services and communication campaigns
3. Condition	Anaerobic digestion		Chemical processing	Mechanical processing		Mechanical processing	
4. Convert	Combustion (CCGT)			Combustion (CHP)		Combustion	Operate electrical devices, heat, vehicles, or social practice
5. Distribute	Electricity networks	Pipelines	Tankers	Electricity networks		Electricity networks	
6. Use	Electrical devices	Heat (onsite)	Vehicles	Electrical devices	Heat (network)	Electrical devices	
Final Energy Vector	Electron	Molecule (gas)	Molecule (liquid)	Electron	Molecule (liquid)	Electron	Behaviour

Stage	Fuel Category							
	Gas		**Gas (unconventional)**		**Hydro**	**Nuclear (fission)**	**Ocean (tidal)**	**Ocean (wave)**
1. Explore	Geology, drill		Geology, drill		Geology	Geology, dig	Measure potential	Measure potential
2. Exploit	Drill		Drill		Operate turbine	Mine	Operate device	Operate device
3. Condition	Chemical processing		Chemical processing			Chemical processing		
4. Convert	Combustion (CCGT)		Combustion (CCGT)			Reactor		
5. Distribute	Electricity networks	Pipelines	Electricity networks	Pipelines	Electricity networks	Electricity networks	Electricity networks	Electricity networks
6. Use	Electrical devices	Heat (onsite)	Electrical devices	Heat (onsite)	Electrical devices	Electrical devices	Electrical devices	Electrical devices
Final Energy Vector	Electron	Molecule (gas)	Electron	Molecule (gas)	Electron	Electron	Electron	Electron

Stage	Fuel Category									
	Oil		**Solar (electric)**	**Solar (thermal, water)**	**Thermal (geological)**		**Thermal (low temperature)**	**Waste**	**Wind (offshore)**	**Wind (onshore)**
1. Explore	Geology, drill		Measure potential	Measure potential	Geology, drill		Measure potential	Find waste	Measure potential	Measure potential
2. Exploit	Drill		Operate PV array	Operate panel	Drill		Operate HP	Gather waste	Operate turbine	Operate turbine
3. Condition	Chemical Processing							Mechanical processing		
4. Convert					ORC turbine			Combustion		
5. Distribute	Tankers	Pipelines	Electricity networks		Electricity networks	Pipelines (heat)		Electricity networks	Electricity networks	Electricity networks
6. Use	Vehicles		Electrical devices	Heat (onsite)	Electrical devices		Heat (onsite)	Electrical devices	Electrical devices	Electrical devices
Final Energy Vector	Molecule (liquid)		Electron	Molecule (liquid)	Electron	Molecule (liquid)	Molecule (liquid)	Electron	Electron	Electron

Table 3.2 Descriptors of the principal activities at each stage for the fuel sources. The co-location of stages is also shown.

Analysing the whole supply chain for each fuel in terms of the six stages (Figure 3.2) shows that some stages are not relevant for some fuels because those processes or activities are co-located (Table 3.2). For example, ‘conditioning of the fuel’ has no physical significance for wind turbines so the exploit, condition, and convert stages occur in the turbine installation itself. Therefore stages 2-4 may be combined for Wind (offshore) and Wind (onshore). This a pattern common to many renewables: Hydro, Ocean (tidal), Ocean (wave), and Solar (electric). For Solar (thermal, water) and Thermal (low temperature) there is no distribution stage as they generate low-grade thermal energy (low exergy value) which can only be used locally. The Biogas, Gas, and Gas (unconventional) chains share a different characteristic in that the fuel leads to two forms of final energy vector – electricity and heat – depending on whether the gas is used by a power generator or by end-users directly in buildings.

Mechanical processing generally refers to crushing, grinding, and sorting. Mining could be underground or open cast. Chemical processing has a wider definition, but the plant and site requirements will frequently be of similar complexity and size. Furthermore, the levels of safety requirements (and risks) will be generic. We specified ‘refining’ for Oil and Oil (unconventional) as that is a well-defined set of physical and chemical processes.

We take Demand Reduction to be applicable to activities of the end-user, including transport. In particular we consider that Stages 2 and 3 are best captured as information (and education) and design activity. Stages 4-6 concern the deployment and use of devices to aid energy efficiency and the practice of modified behaviours.

3.3 Categories and Causes of Risks

All risks originate in either the natural environment or human activity. Informed by the literature review, we have broken the two sources into sevens distinct groups which readily arise from ES considerations. The categories are chosen to reflect the concerns of the time expressed by public and private organisations e.g. skills has been separated from the political category. Other activities are diffused through categories e.g. activities of the public such as protest (political) and operations (technical).

In their work on risk metrics Johansen and Rausand (2014) describe 11 desirable criteria which a metric should meet: validity, reliability, transparency, unambiguous, contextuality, communicability, consistency, comparability, specificity, rationality, and acceptability. We use these as a guiding principle for selecting the causes of risk. There were a large number of generic risks which could have been included, but the list needed to be kept to a manageable number – a number just large enough to describe a complex system at a high level. From experience using the PAM to find indicators for complex systems, we consider that the number of generic risks should not exceed around forty. Our analysis is based on 34 currently.

Initially, from the literature, more than 80 risks were identified. Much of the literature highlights single risks or tightly defined groups and these are discussed in subsequent chapters supporting the judgements made for the likelihoods and impacts for the matrix. Many of the causes of risk identified in the literature review were found to be suitable for the scale we are considering, so could be captured in the generic definitions. Others were not likely to have impacts beyond a single project, thus were not suitable for a high-level analysis. Some were unique to a single fuel or nation, which could be incorporated into another broad category, often *political*. When constructing and reading this table it is important to note that:

1. The category is the cause or source of the risk, then the specific risk is interpreted in the context i.e. activity of each stage. The practice of interpreting the risks is manifest in the form of a question.
2. The risk being considered is the risk to the ES of the nation or bloc (within the system boundary), not the risk to a project or company.
3. In any single fuel supply chain (at any or all stages) there will be multiple supply-countries with different characteristics e.g. standard of governance.
4. Some risks will have two parts even within a single stage – one for inside the system boundary, one external. We judge which is the most important element to base our assessment. This is expressed in the risk matrix using the macro/meso/micro ‘scale’ characteristic identifier (section 3.4.2).
5. These are risks at the location of the activity (in a general sense) which could have an impact at the system boundary.

For each risk category we state the nature of the risks they encompass (summarised in Table 3.3), the desirable outcomes of the activities in each of the areas, and then some of the specific causes of risk, why they were selected, or their limitations. The interpretations of the full set of causes, summarised in Tables 3.3-3.9, explains the high-level generic risks used in the risk matrix. This cannot be considered as a complete look-up table for the risk matrix, but it guides the deliberations of the risks in each stage of the supply chain.

Category	Nature of the Risks
Economic	Uncertainty, lack of transparency, lack of access to capital
Environmental	Climate change, resource depletion, natural hazards
Innovation	Unsolved problems, scaling, competition
Manufacturing	Lack of capacity, lack of resilience
Political	Weak governance, corruption, lack of 'licence to operate'
Skills	Lack of capacity, lack of quality
Technical	Human error, lack of resilience

Table 3.3 Summary of the nature of the risks in each category.

3.3.1 Economic

The levels of macroeconomic activity and stability are important. The provision of capital is required for all scales of energy systems. The return on investment (ROI) should be stable and predictable for a time well beyond the payback period. Competition in any relevant markets needs to be fair – the market needs to be well-functioning.

The nature of the risk: A lack of predictability leads to uncertainty. In turn this affects access to capital since the projects are large (relative to the size of the borrower) and instability during the payback period is unacceptable. For commercial schemes, without a reasonable return on investment (ROI) access to capital is likely to be restricted.

The causes of risk (Table 3.4): Risks arising from competition take several forms, but are not exclusively economic. For the purposes of our study we have incorporated the following discussion in the economic category as a lack of well-functioning markets. A number of the associated risks would be most usefully considered at the individual company or project level. Competition at some stages of the supply chain (or energy system more generally) may reduce risk, at others it may increase risk. Too much or too little competition are both a risk. Too much competition leads to reduced margins, pressure on infrastructure (costs money) and other essential items (e.g. staff training, safety features) and increased risk of failure (or become inefficient at delivering benefit for a nation). Too much competition may also present an opportunity risk, as limited technical expertise is spread more thinly amongst R&D programmes (public or private) for a multitude of widely differing technologies. The well-known purely economic risks manifest as cartels either as a state-supported national company or as groups of companies or nation states. Too little competition and prices may be inflated unless regulated appropriately (where possible), or perhaps viable solutions to problems may not be discovered. At different stages in the fuel supply chains the risks may be summarised thus:

- too few / many sites competing for exploitation,
- too few / many companies competing for access to sites,
- too few / many companies supplying equipment and services,

Using wind turbines as an example, the risk arising is due to too few manufacturers of turbine blades (manufacturing capacity is a separate issue). The markets for generators and steelwork are more widely spread for other devices; there may be other risks arising due to materials criticality, but there are many suppliers in these markets. Uncertain decommissioning costs is not solely an issue for nuclear fuels. As more knowledge is discovered about environmental impacts of waste and spoil the legal requirements for disposal and treatment may become more stringent. Offshore wind turbine with pile foundations will provide an interesting future risk since clean-up is hard to ensure because access to the sea bed is difficult. Subsidies are incorporated in the risk of lack of access to capital because it may affect the price of that capital.

Cause of Risk	**Interpretation**
Lack of a well-functioning market	Are there plenty of suppliers for equipment, components, systems, or services for the required activities? Or is there evidence of monopolistic market actors?
Lack of access to capital	Are the required components, systems, or services considered as mature or immature, or how significant is the investment compared with normal business operations?
Unable to agree a price for licence or permits	Is the price of permits for access, extraction, siting, or disposal of waste a significant proportional of operating costs?
Uncertain decommissioning costs	If the decommissioning costs are unknown, what is the impact on the viability of the activities?
Price volatility	How significant is volatility in the price of equipment, components, systems, or services for the required activities?

Table 3.4 Summary of the definitions of the economic causes of risk (independent of fuel and stage).

3.3.2 Environmental

The stability and predictability of the environs of a scheme and the long-term stability of the climate are highly desirable (minimal likelihood of catastrophic natural hazards). The environment is the provider of the natural resources – fuels, water and minerals – required for the energy supply chains under examination. There is an argument to use the over-arching term 'ecosystem services' as this includes the provision of water. However, the only ecosystem service common to many fuels at various stages is the requirement for water. The requirement for biotic ecosystem services is restricted to the three classes of biofuels, and then will only be relevant at Stage 2 (Exploit). Therefore we refer to water-use explicitly, and account for the biotic ecosystem services as a variability in the quality of the fuel source with the consequences cascading through the subsequent process stages.

The nature of the risk: The continued use of fossil fuels is likely to lead to changes in the climate with impacts on the near- and long-term. The depletion of resources is a risk to all fuel supply chains, but more acute for some. Over-extraction of a resource may lead to the loss of ecosystem services. The environment will present unpredictable natural hazards.

The causes of risk (Table 3.5): Difficult physical access and the concept of 'physically isolated' resources can be interpreted in two ways. First the geographical remoteness of, say, Lithium deposits in the High Andes, or oil in the arctic. Although these two examples are outwith the boundary, UK companies may be exploiting or relying on the supply chain. However, it is not legitimate to treat anything outwith the boundary as remote; this is too wide a definition. For example, with respect to the UK, Saudi Arabia is remote to the system boundary, but access to the resources is relatively easy, but oil from the arctic is remote from everywhere. We can assume that if the commodity is widely traded, the market is easy to access. The level of the geographical remoteness external to the system boundary is mediated through price with volatility, in part, taking account for the ease of access. The second, and more directly useful definition to the Environmental risk category, is that any UK installation offshore requires special equipment to operate beyond what would be needed if the same resource were extracted onshore.

The quality of the fuel source relates to the impact on the activity in each stage of any variability in the physical or chemical constituents of the raw fuel. At the exploration stage quality and quantity of a deposit are what is being determined. Quality is interpreted as how the variability impacts on how difficult it is to determine the viability of the resource at any given site. We considered whether to interpret quality as long-term availability since this characteristic of a fuel source might determine whether exploration is undertaken, however, this would be better done in a resource availability normalisation exercise once the risk profiles are determined. This is beyond the scope of this study.

Cause of Risk	**Interpretation**
Difficult physical access	Is the site physically remote or with difficult terrain?
Natural hazards	Is the site subject to significant natural hazards?
Quality of fuel source	How significant is resource composition variability, including ecosystem services, on the required activities?
Lack of water availability	How dependent are the activities on water availability?
Lack of critical materials availability	How reliant (currently or projected) is the availability of critical materials for the activities?

Table 3.5 Summary of the definitions of the environmental causes of risk (independent of fuel and stage).

3.3.3 Innovation

The extraction and processing of fuels currently used (either bulk or niche) require on-going incremental technical development. For unconventional fuels or new sources, the need for innovation is essential if new devices to extract and exploit are to be developed successfully. Innovation of business models and structures are also important.

The nature of the risk: The inability to solve problems. A new device or process may not be scaled to a size that makes any significant difference, or be economically viable, or it may not be possible to engineer a practical, safe, and reliable commercial system. Market structures and regulation may prevent new opportunities developing. For mature technology, systems, processes, or business models the risk lies in competition from innovation.

The causes of risk (Table 3.6): The weak technology transfer environment risk aims to account for early-stage tech at TRL<7, say; for example, fourth generation nuclear fission reactors, any fuel classed as unconventional, tidal stream, or wave. This is not about improvements in current technology, but aims to capture the risk of relying on a proposed fuel, device, or technology 'fixing the problem tomorrow'.

The risk of activities in the supply chain having only marginal improvements consists of several components, namely the inability to: 1) improve efficiency, 2) reduce environmental impact, 3) reduce costs, 4) reduce material use, and 5) scale process or conversion device. The question is whether a physics or engineering limit has been reached, and if so how problematic would it be if no further reductions or improvements were made within that fuel supply chain? Of particular importance is the scalability of the process or conversion device to meet either global-scale demand, or to fit small-scale distributed systems. Scalability is frequently over-looked as a risk factor in energy systems. Thus innovation will be difficult and perhaps require large R&D programmes. We take as our definition of the marginal improvements risk that greater security is gained with technologies with scope to improve more. Thus mature technologies are associated with higher risk values. We set the definition this way around as we assume that mature technologies and business models offer low operational risk (high experience factor) in current operation. But that such technologies do not necessarily offer flexibility to changing circumstances – economic, environmental or societal. A burgeoning technology may be able to further improve the ES state. It should be noted that technologies for shale oil and gas extraction may have significant room for improvement and offer short-term ES or security of supply of oil and gas.

When considering R&D issues, one of the key questions is whether the current capacity is able to meet the level of the challenge i.e. are there are enough centres of expertise and can very long programmes of activity be sustained when the practical solutions may be decades away. Related to this is the question of whether too many competing technologies are a risk. How significant is the impact of too much competition having on spreading expertise amongst developing fuels and is this leading to an 'opportunity cost'. Are there high or expensive testing and validation requirements for public safety?

Cause of Risk	Interpretation
Weak technology transfer environment	Are there many opportunities for a new technology or practice to be deployed? Hard for niche or small-scale activities.
Lack of public subsidy	Would the R&D cease if no subsidies were available?
Only marginal improvements likely	Is the technology required mature with a history of only incremental improvement i.e. near the top of the S curve?
Lack of material substitutability	To what extent are the technologies dependent on the properties of particular materials? All materials e.g. high-grade steel.
R&D capacity or capability does not match the challenge	Are the barriers to start R&D so high that only large organisations can afford to participate? Is there a vibrant R&D landscape for the technology in question?
Optimism bias	To what extent does optimism bias of future improvements in technologies and efficiency gains over-inflate the value placed on the likelihood of an activity remaining competitive or becoming mainstream?

Table 3.6 Summary of the definitions of the causes of risk for innovation (independent of fuel and stage).

3.3.4 Manufacturing

We include construction relevant to energy systems within this definition of manufacturing. The manufacturing sector needs to provide capacity of facilities and processes, and that globally there is resilience i.e. multiple specialist manufacturers. This point of resilience is different from there being competition amongst manufacturers – it is about there not being a single point of failure geographically. Manufacturers should use resources efficiently, and operate safely with respect to the workforce and the environment.

The nature of the risk: A lack of resilience caused by too few centres of manufacturing expertise (capacity).

The causes of risk (Table 3.7): Moving beyond R&D to the manufacturing stage a risk is whether there is sufficient capacity (not competition) to manufacture the required system components or conversion devices. Although we have couched the question in terms of the present i.e. how significant would be the loss of some current manufacturing facilities globally, there is also an element of scale-up risk here. However, for the purposes of this study we place the scale-up question at the innovation stage. In terms of the capacity to construct sites, for the fuel Demand Reduction it is how significant might the impact be of a low rate of demolition of energy inefficient buildings?

Cause of Risk	Interpretation
Insufficient capacity to manufacture system components or conversion devices	Is there sufficient manufacturing capacity to meet demand? This is separate from the number of different manufactures (competition). How significant would be the loss of some manufacturing facilities globally?
Insufficient capacity to construct sites	How significant are demands (scale, complexity, number) for constructing the extraction, processing, or conversion sites?
Insufficient rate of infrastructure construction	If new infrastructure were not put in place, what is the impact on the activities (including ICT)?

Table 3.7 Summary of the definitions of the causes of risk for manufacturing (independent of fuel and stage).

3.3.5 Political

This is a broad category with risks that may apply equally to both the nation within the system boundary and those from which fuels are sourced. Putte et al. (2012) adapt the definition of political risk from the Multilateral Investment Guarantee Agency of the World Bank:

> *"The probability of disruption of the operations of companies by political forces and events, whether they occur in host countries or result from changes in the international environment. In host countries, political risk is largely determined by uncertainty over the actions not only of governments and political institutions, but also of minority groups and separatist movements"*.

We include actions of the public as they are part of the polity. The following discussion is in line with the view of good governance set out by the World Bank) (2018). The political system should be incorruptible. Stability is the key factor, both in terms of public safety and the socio-legal system. Specifically in relation to investment in energy systems, this means the stability of the policy environment and the regulatory framework. The legal system needs to be fair and robust, with an independent judiciary able to protect rights of property and provide prompt and fair dispute resolution. Furthermore, the system of taxation should be predictable and transparent. The legislature sets or adopts safety and employment laws, which should be enforced equally in all workplaces. Also required is the need for internationally acceptable ethical standards of behaviour (employment, legal, fiscal, etc) in public life. The nation being assessed should have normal international relations nor engage in violent internal suppression or external aggression i.e. the absence of violence. Public protest must be allowed, but the safety and security of both energy system sites and the public be protected. NGOs should be allowed to campaign openly.

The nature of the risk: In extremis instability may lead to public unrest affecting the ability to operate in a country or region. Instability also arises from a changing regulatory or policy framework. Both have an impact on operations and investment decisions. The presence of corruption or other unethical behaviours is a risk. Public protest (localised or orchestrated) poses a risk to the 'licence to operate'.

The causes of risk (Table 3.8): Poor institutional governance is a broad term which incorporates several elements which give rise to risks with different time-scales.

1. If a Government or supra-national body were to lack an independent judiciary and/or have a weak legal system insufficiently robust to resolve disputes in a fair and reliable way, the impact on the ability to exploit the fuel source in that region could be severely hampered. The risk of investing finances and people in such a region would be significant.
2. One possible consequence of poor institutional governance is the risk of corruption flourishing. The question is how significant is the concentration of the fuel source in regions where there is evidence of corruption taking place?
3. Poor diplomatic relations has a strongly time-varying component. The state of international relations can fluctuate significantly and quickly. On the short-term scale, this presents a problem for security of supply rather than long-term ES. The key question is whether, if a Government or supra-national body were to be subject to international sanctions, there would be an impact on the contribution of fuel source at the system boundary. However, even subject to sanctions (trade, investment, or personal travel bans) fuel sources may still be exploited.

4. The ‘licence to operate’ can be interpreted in two ways. First, the legal licence to explore for and extract resources, or to own and sell premises for example. The inability to obtain licences may be as a result of corruption or other illegal activity. The second form is more subtle and predicated on the willingness of the citizens to allow unhindered the exploration, extraction, processing, or conversion of resources. Their concerns may be connected with ownership of land, environmental issues, access to jobs, or fair and equitable distribution of proceeds of sales.
5. Connected with weak legal systems is the risk of a Government or supra-national body breaching contractual agreements. Short-term agreements are a security of supply issue rather than ES. The question is what would be the impact on the contribution of the fuel source at the system boundary should such a breach occur?

The trigger of social instability and unrest may be poor governance. One consequence of the lack of a fully-functioning legal system (and police force) may be theft of the extracted fuel, processed energy vector, or infrastructure assets. But how significant might the impact be of a major or prolonged incident on supply of the fuel at the system boundary? An additional consequence is a heightened risk of kidnap (for ransom) of staff. This includes any unwillingness of external workforce to relocate, rather than placing this in the Skills category. Poor governance may also lead to volatility in the national economic activity (where the fuel source is located) – the question is whether uncertainty of fiscal policy or unstable inflation is a sufficiently serious issue with an impact at the system boundary. Furthermore, a well-governed nation will consult, consider and meet the concerns of a wide range of stakeholders i.e. mechanisms should exist for considering and reconciling the differing views of stakeholders (including non-state actors).

In UK law landowners have no right to extract subsurface resources, namely Coal, Gas, Gas (unconventional), Oil, Oil (unconventional), and Thermal (geological) – ownership is retained by the Crown (Roberts, 2017). But a trespass case upheld by the Supreme Court in 2010 established that landowners did have the right to block anyone from deploying infrastructure such as piping, regardless of the operating depth. Thus, extraction licence-holders would have to negotiate with many landowners and the risk of denial of access would be significant. The Infrastructure Act of 2015 gave developers automatic access to ‘deep level land’ below 300 m (Burns et al., 2016).

Protests against a local scheme or a national or international campaign organised by an NGO is ambiguous in relation to ES risks. The protests may bring about change in policy to facilitate ES rather than pose a risk. As part of a US-UK cross country survey of attitudes toward shale gas extraction Evensen et al. (2017) also asked about support of some renewable and non-renewable fuels. They observed from the poll of UK adults (n = 3823) that Hydro, Solar, and Wind received strong support to be part of the UK energy supply portfolio, Gas had less support (but still well-supported), whilst Biomass, Coal, Gas (unconventional), and Nuclear (fission) had the least (but similar) level of support.

A changing policy or regulatory environment may be triggered by lobbying of politicians by industry actors or their representatives, NGOs, or public protests. A change is foreign policy may pose a risk.

Cause of Risk	**Interpretation**
Denial of permission to access sites	What impact if an individual, company, or Government were to prevent access to a specific site or region?
Lack of social stability	Are relevant nations or blocs subject to political unrest (including physical security of the workforce and assets from acts of sabotage and terror)?
Changing policy or regulatory framework	How significant would be (or has been) the impact on activities if a national or supra-national legislature were to change relevant laws, regulation, or policy direction?
Poor institutional governance	How significant is the concentration of activities in regions where there is evidence of weak or governance (corporate and legislative)? Levels of corruption, or law enforcement. How much confidence in the legal system to uphold agreements
Disputed landrights or resource ownership	How significant is the concentration of activities in regions where there is disputed landrights or ownership of resources?
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Are current regulations likely to be enforced and is there a record of improvement? This includes standards for vehicle emissions, quality and consistency of product, health and safety, and buildings codes.
Significant public concern	Protests (physical or online) against an activity representing each stage.

Table 3.8 Summary of the definitions of the political causes of risk (independent of fuel and stage).

3.3.6 Skills

The operation of sites and processes requires skills from basic manual tasks to specialised technical design and engineering expertise. The education sector should produce the variety of skills needed and sufficient numbers of people (capacity). The educated workforce should be flexible and the quality of the basic and advanced qualifications be reliable.

The nature of the risk: The lack of availability, flexibility, and quality.

The causes of risk (Table 3.9): For developed nations basic education levels can be assumed, with the differences showing in the supply of technicians and specialists. Most countries regard skills in the energy sector as important for the economy. Consequently there may well be restrictions on numbers of expatriate personnel employed, and requirements on employment and training of own nationals. Low levels of basic education or training will slow deployment rates and lower operational efficiency.

Cause of Risk	**Interpretation**
Lack of basic education levels in the local workforce	At the location of the activities, is there a sufficient supply of working-age citizens with basic numeracy and literacy?
Lack of vocational training of the local workforce	At the location of the activities, is there a sufficient supply of citizens trained with appropriate practical skills?
Lack of specialists in the local workforce	At the location of the activities, is there a sufficient supply of citizens with specialist skills or is it easy to persuade such people to relocate?

Table 3.9 Summary of the definitions of the causes of risk for skills (independent of fuel and stage).

3.3.7 Technical

The energy system should be reliable and with sufficient capacity to offer resilience when plant or infrastructure have planned or unplanned outages. Furthermore, the system should be safe with respect to the workforce and the environment.

The nature of the risk: Human error, sometimes due to inexperience, in design, operation, and management, is the cause of technical risk. Consequences may be financial loss, wasted resource, injury and death, or a pollution event. Although a lack of resilience in technical systems is in part due to design errors, constraints may have been imposed from decisions in other categories.

The causes of risk (Table 3.10): Pollution episodes may arise due to inappropriate waste management. The consideration is whether or not there is an impact of a chemical or mechanical failure of the spoil / waste storage facility on the viability of that fuel source. A related risk is dealing with waste at the decommissioning stage. If it is not possible to safely and completely deal with waste, there may be consequences of whether the fuel source remains viable in the long-term. Whilst this is highly pertinent for long-lived radionuclides, it is not exclusive to the nuclear industry. It is useful to consider separately the risk of a pollution event caused by any type of stored waste after a site has ceased operating. Although the generation of highly toxic waste causes a risk, it is the handling of the waste that presents the principal risk. Operational failure also encompasses injuries and deaths as this is a management failure to implement health and safety standards at a level comparable with those in the UK.

Cause of Risk	**Interpretation**
Pollution event	How much impact from operational pollution events on the environment (including ecosystem services)?
Unable to neutralise waste at decommissioning	If the waste cannot be made safe at the decommissioning stage, what impact might on the long-term viability of the fuel source?
Specialist equipment unavailable	How much impact or delay would the lack of specialist equipment have on activities?
Operational failure	How much of an impact would an outage of a major facility have on the activities? The cessation of production may be due to equipment failure, human error, or management failure.
Infrastructure failure	How much of an impact would an outage of a major infrastructure link have on the activities? This could be failure of transport, transmission, distribution, ICT, or a the discovery of an equipment design flaw.

Table 3.10 Summary of the definitions of the technical causes of risk (independent of fuel and stage).

3.4 The Risk Register

Our register (Appendix A) is a matrix consisting of the risk score (likelihood multiplied by impact) generated from the risk matrix, a visual indicator of the consequence level, the location of the cause of risk (inside or outside of the system boundary, a note to remind the reader of the main technology or activity for which the risk assessment is being made, and the scale at which the risk manifests.

We acknowledge that the completed risk matrix includes value judgements, but these have been taken on the basis of long experience, with support from literature and published sources, and a stakeholder consultation. The key point to note is that the final list of causes of risk remains generic, but that the numerical levels of impact and likelihood are specific to the nation or the bloc under consideration (the system boundary). It is important not to try to make a global risk assessment as this would be fruitless because there is great diversity in nations and their energy use. The detailed assessment (impact and likelihood) needs a sharp focus, but it is important to emphasise that the entries are not specific to projects or a company.

As the risks identified are generic, each stage is considered separately for whether the cause of the risk is relevant to that particular stage – it is only the actions in the stage that contribute to the potential risk. In the register, the same risk may occur at more than one stage. Double-counting is avoided because risks are risks whenever they occur and the activities by which the risks may manifest may be different. There are a small number of exceptions to this; poor institutional governance and lack of social stability are recorded once only. However, the risk is re-evaluated and recorded a second time if a process chain crosses the system boundary i.e. consecutive stages move from having a 'global' location signifier to 'UK'. The mechanism for selecting which causes of risks need to be considered for each stage is:

1. These are risks at the location of the activity associated with that stage for that fuel source – this is independent of the system boundary. The 'Principal Risk Location' identifier signifies the sources data which should used to make the assessment. Many fuel sources will not only be scattered globally, but may also be present inside the system boundary. In many cases, however, the concentration of that fuel inside the boundary will be low. Where the source is relatively evenly balanced e.g. oil and gas, assess which source is increasing. A detailed disaggregated study may separate these sources and conduct analysis on both.

2. Does the cause of risk have an impact on whether the activities in the stage can proceed or not? If there is little likelihood of the cause of risk stopping or hampering the activity, it is unlikely to be a relevant cause of risk for that stage.
3. If the level of the cause of risk were to fluctuate up and down without having an impact, then it is unlikely to be a relevant cause of risk for that stage.

This is not to say that any prior knowledge from earlier stages is ignored, but that it contributes – directly or indirectly – to the level of the risk. In the first stage – exploration – lack of access to capital is not uniformly relevant to the fuel sources at all stages. For example, exploration for oil and gas is costly whether on- or off-shore, but for biogas minimal effort is required for exploration. For exploitation and conversion, access to capital is likely to be important for most fuel sources. A second– and more clear-cut – example is uncertain decommissioning costs. By definition, the decommissioning costs must be well understood for the exploration stage, even if they are less well understood for full-scale exploitation. A third example is that a changing policy or regulatory framework (in the UK) might not deter exploration of a particular fuel source in the first place (whether that was by a UK or non-UK company). Using this criterion, causes of risk which are not fully relevant to at least one fuel at a particular stage are eliminated from consideration at that stage. Another clear example of why it is necessary to only consider risks within the stage can be drawn from the distribution stage. Once a fuel has been converted to, say electricity, the infrastructure is blind to the original fuel source or the conversion technology used.

Even so, the first stage (exploration) remains different in nature from the other stages since there is no possibility of material flow across the boundary as it is by definition not producing commercial volumes of resource. Exploration is only potential supply, not supply itself. Thus it does not seem to have an immediate impact on ES or risk to ES at the system boundary. The principle risk associated with exploration is that no resource is found, or for any discovered resource that the conditions to exploit it cannot be agreed upon. Scale of the risk is also important when considering which causes are most relevant. For example, a pollution event may occur at the exploration stage, but because for many fuel sources any exploration scheme is small by definition any spillage or escape of resource into the environment will have a limited impact. Once the most relevant causes of risk are identified for each stage, the specific issues for the nation or bloc within the system boundary are incorporated using the levels of impact and the likelihood.

The list of fuel categories needs to be thought about a little differently at the distribution and use stages – it is based on the final energy vector that is produced at conversion rather than the raw fuel source necessarily. For example, diverse fuel sources are converted into electricity by different technologies. However, it remains appropriate to keep the categories consistent since fuels for transport can be entirely different, with the fossil-derived vectors skipping the conversion stage (as defined). The impacts occur at the use stage where the public operate the 'conversion' devices.

The conversion, distribution and use stages predominantly take place inside the system boundary. Thus at the point where the final list of risk causes is drawn-up, some of the causes of risk may not be strongly relevant for the case study under scrutiny. It should also be borne in mind that these three stages are more closely associated with security of supply (than ES per se).

3.4.1 Principal Means or Technology Descriptors

There are two reasons to create short high-level descriptors for each fuel supply chain at each stage: 1) to show how various stages have no physical meaning for some fuels, and 2) a simple reminder as the risk matrix is spread across six large tables. The descriptors for each stage of each fuel characterise the most important high-level element of that stage i.e. the technology used or the means by which activities occur.

An implication for the risk matrix arising from co-located stages is that all the risk for that fuel supply chain is attached to the first of the merged stages. The other stage(s) merged with the first one are rated as zero risk. This is reasonable since once the first hurdle is overcome all other activities automatically follow. An interesting point is the possibility that although the first hurdle may be risky, the overall risk profile for the whole supply chain might be lower. By the same token, a set of merged stages might present a low risk as a prelude to a high risk stage. Analysts and commentators might easily focus on the low risk element (relating to a technology perhaps) without paying sufficient attention to the overall profile of the whole chain. Showing the whole profile in this way highlights the heterogeneity of risk in in fuel supply chains.

3.4.2 The Scale of the Risks

An interesting categorisation of the scale of risks to projects was proposed by (Bing et al., 2005) and used by Ke et al. (2010). The idea is that the scale is categorised by the origin of the risk in relation to the system boundary. This, it is claimed, can help identify areas or groups of risks that need treatment or monitoring. In particular 'meso' scale risks which Bing et al. consider are factors at the project scale, are different in nature to those arising from the relationships between actors involved within the project. We adapt this scheme (Table 3.11) and suggest that these definitions are likely to be useful for supply chains in general.

Scale	Definition for Projects (Bing et al)	Definition for Food Supply Chains (Nakandala et al)	Definition for Fuel Supply Chains (author)
Micro	Between agents within projects	Internal to a company	Site specific (company, project)
Meso	Whole-project factors	Supply chain operations beyond the company	National (Governmental)
Macro	Beyond the project system boundary	External to the supply chain	International (widespread or treaty-governed)

Table 3.11 Definitions for the scale of operation of a risk in fuel supply chains adapted from (Bing et al., 2005; Nakandala et al., 2017).

The scale of any risk may be different at each stage for any fuel because the technology or activity required may be different. Furthermore, we need to account for entities within and outwith the system boundary. The decision of which level is most appropriate should be screened against the 'principal risk location' identifier. Therefore the principal risk location is defined as either 'subject nation' or Global. Stages with activities predominantly outside the system boundary will be labelled as 'Global', and inside the boundary as 'subject nation' e.g. UK.

There are different implications for whether the micro, meso, macro scale is located as national or global. We suggest that appreciating the differences aids understanding of the risk profile and its dispersion. A more nuanced view of which fuels or parts (or proportions) of the supply chain are influenced by different scale actors may help shape approaches to policymaking. This is to say that micro and meso scale activities still have meaning in the international (Global) context. For example, governments set policy and regulate businesses – whether they are inside our outside the system boundary – but which stages and risk categories (or individual risks) are affected may change the way R&D programmes are funded perhaps, or may signal the need for negotiation or support for companies operating in that regime (if Global). Another example of the location difference is that an NGO may protest internationally about the use of fossil fuels (a macro scale activity) but the same NGO could campaign to halt drilling at a site through the planning process (a micro scale activity). The national Government sets the planning rules and the relevant environmental regulations (a meso scale activity). We consider this avenue to be worth exploring. The three scales may be characterised as:

Micro: company (or project) level which could include interactions between companies across the system boundary. Within the system boundary communities, regional authorities, or companies could be implementing projects or operating a specific site.

Meso: a national Government has the ability (if it chooses) to regulate or control the activity. Whether this is the Government within the system boundary (the UK Government in the case study) or an exogenous Government depends on the nature of the issue. Some stages or fuels will have a similar issue within and without the system boundary. Activities or companies part of regulated markets, or governments subsidising R&D support, are a good examples. Another indicator of this level is a significant number of companies within the system boundary supplying technology and services for that stage of the supply chain of that resource. In a more disaggregated study, the detailed differences between Governments can be drawn out.

Macro: generally taken to mean that the control rests with supra-national organisations, or that the market for the fuel source is dispersed internationally. Components of sub-systems are made by international or globalised companies. Projects, sites, or activities require international consortia which may raise finance directly from the international markets.

For our case study, Table 3.12 shows the working definitions of scale to guide our assessment.

Scale	Principal Risk Location	
	Global	**UK**
Micro	Site or activity outside the UK regardless whether a UK or non-UK company is conducting the activity	Site or company activity within the UK.
Meso	Non-UK Government activity or sphere of influence	UK only Government activity or sphere of influence
Macro	Activity dispersed internationally or influenced by a supra-national organisation	

Table 3.12 Definitions of scale for the UK case study with respect to the principal risk location.

The Risk Score and Consequence Level

First we define the likelihood and impact, and the consequence level implied by the risk score. Subject to the avoiding the pitfalls outlined in section 2.2.4 we draw on best practice guidelines for risk rating matrices given by (Standards Australia, 1999; IRM, 2013; Duijm, 2015; Baybutt, 2018).

Likelihood is commonly a five point scale, however, this is more appropriate for a clearly-defined project or well-bounded organisation such as a firm. Many of the risks to which a project or company are exposed are more readily described in detail where quantification is meaningful and often essential. For a high-level analysis of a system which has risks aggregated, it is not meaningful to quantify grouped risks in detail. Furthermore, as our study is examining long-term ES, the potential impacts of many risks which a national assessment needs to take into account are impossible to know in detail. The interesting and useful interpretation of long-term risks is in understanding the relative importance. Thus, broad bands representing likelihood are sufficient. For different types of risk, probability (number of occurrences of the risk per number of times the operation or action is carried out) or frequency may be more applicable. We have adopted a three-point frequency scale (Table 3.13).

Descriptor	Level	Frequency	Definition
Rare	1	< once per 10 y	Only occur in exceptional circumstances
Possible	2	Once per 10 y	May occur
Likely	3	Once per 1 y	Expected to occur

Table 3.13 Summary of the approximate timescales guiding the frequency of occurrence judgements.

The descriptions of the impacts and their levels need to be scale-independent i.e. not be related only to project- or company-level activity, however, they must encompass such. Many risk analyses will use three or five levels to describe the impacts of identified risks. However, we have chosen a four-point scale (Table 3.14) to force the analyst away from a 'middle way' and to positively select a slightly above or slightly below average response. Furthermore, for high-level analyses across the full range of fuel supply chains, subtle distinctions for broad categories are not always meaningful. For project-level analysis greater disaggregation is essential for operation efficacy. We tested a five-point scale with 'catastrophic' as the most extreme impact (enforced cessation of activity), but found such a definition for unconventional fuels not to be particularly helpful. The four broader descriptors make it easier to capture the essence of the risk for a fuel at different stages in the supply chain.

Descriptor	Level	Generic Definition
Insignificant	1	Any impact is only at the edge of 'normal' or accepted operation.
Minor	2	Recoverable short-term loss of activity, delay, or function.
Moderate	3	Recoverable, but sustained delay, loss, or change in function.
Major	4	Irrecoverable change or loss of function or enforced cessation of activity such as complete loss of fuel source, loss of life, closure of business / site / operation.

Table 3.14 Summary of the definitions of the impact levels.

As the product of the impact and likelihood scores (Table 3.15) determines the consequence level (Table 3.16) there cannot be overlap between these categories. In the circumstances that we are using a four-point scale and not five, it is defensible to leave rare-major events out of the high level category. Thus, as there is a gap between six and eight, this is used to delineate the high and moderate consequence levels. Likewise, an insignificant impact that has a likely occurrence could be at the low or moderate level. We judge that a likely impact is not one that should automatically be considered as having a low level consequence. Our risk rating matrix obeys both of Cox's lemmas governing the requirements for weak-consistency (Cox, 2008).

			Likelihood		
			Rare	Possible	Likely
			1	2	3
Impact	Insignificant	1	1	2	3
	Minor	2	2	4	6
	Moderate	3	3	6	9
	Major	4	4	8	12

Table 3.15 The possible combinations of likelihood and impact giving the risk score and consequence level.

Consequence Level	Required Response
Low	None – these risks are within the expected range for companies, governments, and societal organisations
Moderate	Ranges from 'watching brief' to some action required (technical or policy)
High	Mitigation plans must be in place, or policy needs immediate attention to formulate an alternative route to reduce the level

Table 3.16 A guide for considering the broad meanings of the consequence levels determined by the risk assessment.

3.4.3 Testing and Operation Methodology

The methodology for testing the matrix to establish the relative levels between causes of risk in different fuel supply chains has four steps:

1. test one cause of risk across the range of fuels at two stages,

2. select one renewable and one non-renewable fuel to test all sources of risk at the same stage,
3. revisit step 1) and 2) to revise decisions as necessary,
4. revisit and adjust definitions of causes of risk, and level and scale indicators.

The risk of lack of access to capital was selected from Stage 2 (exploit) and Stage 4 (convert) for the first step test. For the second step coal (non-renewable) and off-shore wind (renewable) were checked at stage 2 (exploit). Although this is not a large number to test, the number of individual entries is large enough to obtain consistency of assessment. We checked the relevance of risk causes for those fuel sources which have merged stages e.g. for Wind (offshore), the stages exploit, condition, and convert.

For risks which are not relevant to that fuel at that stage, or relevant to that stage at all, the risk matrix entry is highlighted in blue and scores as zero in the subsequent analysis. The merged stages for fuels such as wind are coloured grey; they too score zero. The zero score is justified as reflecting the lower risk associated with co-location of stages.

A key difficulty with such a large matrix is consistency. Each set of risks, levels, and scales was checked against the meanings. Similar fuels were checked against each other to understand why any differences occurred. It remains the case that some causes of risks are uncommon. Such situations are assessed on a case-by-case basis and recorded as part of the discussion of the justification for the decision made.

The evidence used to support the expert judgements of the likelihood and impact values is a type of meta-analysis in that we are using other studies and their observations (not usually directly articulated as risk) to inform our study. The methods for analysis of the risk matrix are discussed in chapter 9.

4 Assessing Risks for Renewables

The renewables group includes the large- and small-scale fuels. We discuss selected decisions in the risk matrix (Appendix A). Mostly these risks discussed are those assessed as having the highest risk rating, but also some of those with moderate ratings. We also comment if the likelihood score is high, even if the impact is low, if this presents an interesting point. Furthermore, the selection is based on some elements in different stages being repetitive and some fuels being similarly sharing characteristics e.g. conversion technologies.

4.1 Hydro

In 2016 large-scale hydro generated approximately 3.7 TWh of electricity (BEIS, 2017c), about 2% of UK supply. Commonly, hydro schemes are considered to be a good option for reducing carbon emissions (Whittington, 2002), but there are concerns about the total lifecycle emissions (Turkenburg et al., 2012) due to factors such as rotting vegetation from the flooded area (Song et al., 2018). In the UK there are 105 hydro plants with a generating capacity of greater than 1 MW. Scott and Molyneux (2001) give a clear description of the dam constructions used in the UK, but Bartle and Hallowes (2005) suggest that greater emphasis will be placed on low-head hydro schemes in the future.

Stage 1

For the most part, the risk profile for hydro at this stage is the same as most renewables, though as all hydro projects are site specific (Turkenburg et al., 2012) determining the potential requires detailed studies. The major difference, however, is that there will be significant public opposition to large-scale hydro schemes (Bartle and Hallowes, 2005) and having the potential to scupper a scheme even at the study stage.

Stages 2-4

The capital requirement for a hydro scheme is sufficiently great (Turkenburg et al., 2012; Ansar et al., 2014; Song et al., 2018) that if the risk occurs, the scheme cannot go ahead. Severe weather events (natural hazards) such as unusually heavy rainfall can pose a risk to hydroelectric facilities. So too can drought (quality of fuel) as the generator station inlet is not located at the bottom of the dam. If the lake level falls too far the power plant cannot operate. In the longer term climate change may have an adverse impact (Carless and

Whitehead, 2013). We consider the need for critical materials to be similar to that of wind because of the turbines, likewise for materials substitutability. We judge that the manufacturing causes of risk are all moderate, in part due to the site-specific nature of these large projects.

In the political category, the changing nature of UK policy will affect hydro in the same way as other renewables. However, the main risk is significant public concern. Opposition will not be restricted to the planning stage, but will continue into the early stages of construction too. However, it will be most likely to cause major delays but not derail the entire project.

Hydro schemes are not free from causing pollution, for example the alteration of the natural flow regime, creation of barriers to fish migration, temperature changes to the downstream aquatic environment caused by dam discharges, and CO_2 released by rotting vegetation once flooded (Song et al., 2018). Sediment transport is also a pollution event noted by Song et al. (2018), though Bartle and Hallowes (2005) do not consider this to be a significant problem in the UK. Although there have been notable dam failures even in Europe (Sovacool et al., 2016) with significant fatalities (Burgherr and Hirschberg, 2014) and property damage (Sovacool et al., 2015), we judge the likelihood of a failure in the UK to be low (though it would be catastrophic).

Stage 5

We judge the profile to be identical to that in section 8.1.1.

Stage 6

We do not see the need for any deviations from the description set out in section 8.2.1.

4.2 Ocean (Tidal and Wave)

There is a wide variety of devices to capture ocean energy with some (mostly tidal) schemes in test around the world (Turkenburg et al., 2012; Flynn, 2015; Khan et al., 2017). Activities in the UK have been reviewed by many authors (Kerr, 2005, 2007; Elliott, 2009; Bahaj, 2011; Lawrence et al., 2013) with a dedicated review of tidal barrages by Burrows et al. (2009) and wave energy converters by Rusu and Onea (2015). The total UK ocean energy resource has been estimated as 69 TWh yr^{-1} for wave and as 216 TWh yr^{-1} for tidal (stream, barrage, and lagoon) (The Crown Estate, 2012). Proponents claim that up to 40%

of the UK electricity demand could be met by ocean energy alone (Bryden, 2006). More recently Gove et al. (2016) claimed that renewables (including wave and tidal) could meet the whole of the UK demand without encroaching on biologically or environmentally sensitive areas. However, they did not correlate resource and grid connectivity. Specific geographical areas have been assessed, for example wave energy for Scotland (Venugopal and Nemalidinne, 2015) and the UK's western coast (Yates et al., 2013).

Specific sites have been studied in detail, for example the Severn barrage (DECC, 2010b; Kelly et al., 2012; Binnie, 2016), the Swansea Bay lagoon (Fairley et al., 2013; Petley and Aggidis, 2016; Waters and Aggidis, 2016), and Cardiff Bay (Crompton, 2002). The development of test facilities for wave devices ('Wave Hub') is described by Greaves et al. (2009) and the Orkney and Edinburgh sites by (Lawrence et al., 2013).

Opinion of tidal schemes have changed markedly over time; Baker (1991) considering tidal schemes to be benign, but Flynn (2015) stating that they were the most controversial. Recent work has led to a subtle understanding that island communities do not hold the same opinions as rural communities in respect of ocean energy (de Groot and Bailey, 2016).

Although the risk levels are not identical for wave and tidal, they are sufficiently similar to treat them together in the discussions for each stage. Specific differences are highlighted.

Stage 1

We judge that the risk profile broadly the same as for Wind (offshore), and note a number of issues particular to tidal and wave energy. The localised nature of wave energy persistence and distribution is noted (Coker et al., 2013) and that assessing its potential requires significant experimental facilities (Saulnier et al., 2012) and modelling capability (Venugopal and Nemalidinne, 2015). There are few organisations (including companies) with the capabilities, thus many detailed estimates for specific sites remain commercially confidential (Bahaj, 2011) leading to a lack of shared learning (Jeffrey et al., 2013). We note too that there are recent improvements to tidal stream measurement techniques (Sellar et al., 2015; Hashemi et al., 2016). On balance, we suggest that this raises the risk of lack of a well functioning market for measuring the potential resource to a moderate level.

Stage 2

For tidal, Kolios et al. (2016) consider the economic category of risks to be the most significant. Many authors note that the lack of access to capital is the most important risk (Mueller et al., 2010; Bassi et al., 2015; Bjørgum and Sørheim, 2015; Vazquez and Iglesias, 2016). Leete et al. (2013 and BVG Associates (2015) specifically cite revenue support (subsidies) as a key issue for capital investment, and MacDougall (2017) suggests that the timing of investment is affected by investors balancing their portfolios as they exercise their options on multiple seabed licences. We judge this risk to be in the highest category for both wave and tidal – it is clear that major delays have been experienced by technology developers. For similar reasons to stage 1, there is evidence of a lack of a well functioning market. There is uncertainty in the knowledge of decommissioning costs for tidal since there is infrastructure to remove (a great deal in the case of barrages).

A difference between wave and tidal is in the risk posed by the quality of the fuel source (Bryden, 2006). The timing of tides is predictable and the volume flow rates too, but with less certainty since flow rates are spatially heterogeneous in three dimensions (Evans et al., 2015). However, for wave even inter-seasonal variability is hard to predict (Neill et al., 2014) this is in addition to wave activity being a wind-driven process. Thus we assign a moderate level to wave. Natural hazards also present different risks to wave and tidal. The surface is a much more rough environment with severe storms completely destroying some wave devices on test. Therefore we assign the highest possible rating to wave. But tidal schemes also face natural hazards, for example, storm surges (Lewis et al., 2017) and sea-level rise due to climate change since the life-time of tidal barrages would be in excess of 100 years (Ahmadian et al., 2014). We consider the need for critical materials to be similar to that of wind because of the turbines, likewise for materials substitutability.

As wave and tidal are early-stage technologies we would expect the causes of risk in the innovation category to have some prominence. The most important of these is the lack of public subsidy for R&D (Kolios et al., 2016) which is sensitive to many factors (MacGillivray et al., 2014) including: publicly-funded research centres (Corsatea, 2014), demonstration sites and R&D grants and co-funding (BVG Associates, 2015), and commercialisation (LCICG, 2012a; Leete et al., 2013). Overlapping with the state of the technology transfer environment is an interesting observation by Vantoch-Wood and Connor (2013) which they coined as the ‘Matthew effect’ – to those who have, more shall be given. This may lead to new developers being locked out of access to support, whereas an existing developer with the same idea simply adding it to their existing portfolio might find it easier to obtain funding and other support as they are established. Zeyringer et al. (2018) claim that the UK market alone will not be large enough to bring costs down sufficiently to make wave and tidal competitive. Specific technology transfer issues noted are IP protection and spillover from other offshore industries (Foxon et al., 2005; LCICG, 2012a). Although innovation is thriving (Bahaj, 2011) there is some risk that innovation may become incremental due to the trade-off between the current consensus and the desire for design variety (Jeffrey et al., 2013). In terms of lack of capacity to meet the R&D challenge, Jeffrey et al. (2014) suggest that multi-agency interactions have led to a lack of investment in test facilities for devices at TRL 5-6 stages. A lack of materials substitutability for structures has also been noted (LCICG, 2012a). We judge that these risks are at the moderate level.

The ability to construct sites (Manufacturing) is identified by Mueller et al. (2010) with foundations and installation vessels specifically mentioned by LCICG (2012b). BVG Associates (2015) recommend that grants are made for this activity. Like Wind (offshore) the lack of infrastructure construction (grid connections points for example) can lead to the cessation of a project. As the UK is the lead nation for marine renewables, the capacity to manufacture components specific to wave and tidal devices is identified by several authors (Mueller et al., 2010; Bahaj, 2011; MacGillivray et al., 2014; BVG Associates, 2015). LCICG (2012b) specifically mention blade manufacturing capacity as high risk.

The Political category of risk causes is broadly similar to that of Wind (offshore), however there are key differences stemming from the maturity of the technology. The greatest cause of risk is that posed by a changing landscape of policy and regulation. General descriptions of the turnover of policy mechanisms are given by Lawrence et al. (2013 and BVG Associates (2015) with Corsatea (2014) suggesting that this has a disproportionate effect upon financing. Leete et al. (2013) observe that the way policy change is communicated as well as predictability is important, however, Iskandarova (2017) shows how experience of devices in the water is important for influencing policy at this stage of the technology development. We suggest that this risk for both wave and tidal will be in the highest category, but as some test devices have been deployed the risk will stop short of causing a complete halt to activity. Although the management of the ocean space is transparent in the UK, Wright (2016) notes security of tenure for deployed devices may be an issue.

The risk of significant public concern varies between wave and tidal. Wave devices may not raise a great deal of concern (Stokes et al., 2014) compared with tidal schemes, though a case study by Devine-Wright (2011) revealed public cynicism of political and planning procedures. Flynn (2015) notes some public concern due to the cost of subsidies being added to consumer electricity bills, though notes that the public are broadly supportive of wave and tidal. Public concern about marine renewables may be site specific, even for wave schemes (Bailey et al., 2011). For certain, high-profile schemes such as the Severn barrage have triggered well-organised opposition from special interest groups (Flynn, 2015) such as those interested in natural habitats (Jackson, 2011). Therefore we judge that this risk for Ocean (tidal) is likely to occur and could result in sustained, but recoverable, delays to projects.

Operational failure is the main Technical cause of risk. A minor point concerns the appropriate design of arrays to avoid shadowing or other interactions between individual devices, particularly for tidal stream (Vazquez and Iglesias, 2015; De Dominicis et al., 2017). The problem, however, is the operability, survivability, and reliability of devices (Mueller et al., 2010), which shakes investor confidence (Leete et al., 2013). This is recognised as a greater problem for wave than for tidal (Kerr, 2007) with slam loads (Bryden, 2006) and maintenance (Gray et al., 2017) identified as especially important. For tidal-stream devices Bryden (2006) notes that installation in high-flux streams is extremely difficult since slack water may last only minutes to a few hours.

Pollution events have the potential to cause harm to human, other animal, and plant life. In the context of marine renewables this can also manifest as changing the environment in such a way as to disrupt feeding grounds or behaviour patterns. This risk is lower for wave than for tidal, but the impact on coastal process is an important impact to consider for the siting of each array (Iglesias and Carballo, 2014; Abanades et al., 2015). An authoritative study by Witt et al. (2012) note that there may be positive in addition to negative effects from wave arrays. The negative effects identified include habitat loss, entanglement and collisions, noise disturbance, and electromagnetic fields, whilst the positive effects might be the creation of artificial reefs and protected areas.

The potential pollution events for tidal stream and for barrages diverges somewhat. For barrages, Hooper and Austen (2013) review a wide range of impacts but are optimistic that nature and wildlife can adapt. However, there are mismatches in the views of priorities and levels of importance of impacts between stakeholders (Mackinnon et al., 2018). The impacts identified include the consequences of geomorphological changes (Pethick et al., 2009), hydrodynamical impacts (Angeloudis et al., 2018), eutrophication (Kadiri et al., 2014), and sediment transport (Gao et al., 2013). Water quality issues for both barrage schemes and tidal stream are reviewed by (Kadiri et al., 2012). For tidal stream devices pollution events may arise from sediment transport (Neill et al., 2009; Martin-Short et al., 2015), biofouling (Want et al., 2017), and permanent submergence of habitat and rising groundwater levels (García-Oliva et al., 2017). Pollution events which receive significant attention are those affecting birds (Masden et al., 2013; Waggitt and Scott, 2014; Garcia-Oliva et al., 2017; Waggitt et al., 2017) and sea mammals (Dolman and Simmonds, 2010; Malinka et al., 2018; Nuuttila et al., 2018; Waggitt et al., 2018). Despite the clear evidence that a pollution event is likely to occur, we judge that the impact will only be marginal to continued operation of a site or array.

Stage 5

We do not see the need for any deviations from the description set out for stage 5 of Wind (offshore) and section 8.1.2.

Stage 6

We do not see the need for any deviations from the description set out in section 8.2.1.

4.3 Solar (electric)

A potted history of PV in the UK is given by Smith et al. (2014) and Gul et al. (2016) review the more recent technical trends. We are basing our analysis on pure photovoltaic panels, though hybrid thermal systems for electricity, heating and cooling (Ramos et al., 2017) and with hot water tanks (Parra et al., 2016) are being developed. The same is true for coupled battery storage systems whether for residential (Uddin et al., 2017) or commercial buildings (Mariaud et al., 2017). An interesting study by Ziyad and Stevenson (2018) reveals the complexity of the interactions between all of the stakeholders which lead to successful (or otherwise) deployment and operation of installations of all sizes. Their study goes some way to explaining why the adoption of PV is patchy and why some installations are sub-optimal. Gove et al. (2016) estimate that approximately 57×10^3 km^2 in the UK is available for solar farms, potentially yielding 986 TWh annually.

Stage 1

Solar irradiance levels are very well characterised in the UK (DECC, 2013a; Burnett et al., 2014; Colantuono et al., 2014) and Palmer et al. (2017) add that understanding the distribution of PV in relation to demand is important. We see no significant risks to note.

Stages 2-4

The only notable cause of economic risk is lack of access to capital (Heiskanen and Matschoss, 2017; Curtin et al., 2018). The detailed issues are rate of return (Balcombe et al., 2014), installation costs (Balcombe et al., 2014; Balta-Ozkan et al., 2015), and subsidies (Allan et al., 2015). Polzin et al. (2015) contend that – for small to medium scale installations – FITs provide a better long-term signal of support than grants. However, Criscuolo and Menon (2015) caution that too generous FITs may discourage investment. Georgitsioti et al. (2014) point out that economic analysis of PV is sensitive to the assumptions made.

By definition solar energy is variable (quality of fuel), but we raise the impact from marginal to operations to short-term because of weather variability and experimental work suggesting that dust may have more effect than previously considered (Ghazi and Ip, 2014). The lack of critical materials may occur (Davidsson and Höök, 2017) with Speirs and Roelich (2015) noting that thin-film PV cells are reliant on the availability of gallium, germanium, indium, selenium, and tellurium. Candelise et al. (2011) reviewed many assessments and found no prima facie evidence that indium and tellurium were likely to become scarce. However, their view is the minority, thus we judge that this is a moderate risk.

A brief timeline of PV innovation is given by Hanna et al. (2015). Although PV being relatively mature there remains significant scope for further improvement (Gul et al., 2016; Moro et al., 2018). One area noted which is lagging is building-integrated PV systems (LCICG, 2016a). Recent developments are introducing non-semiconductor materials (substitutability) and for semiconductor cells silver and selenium are potentially substitutable (Speirs et al., 2013a).

The key manufacturing category risk is the insufficient rate of infrastructure construction. PV add stress to some parts of the electricity distribution network, but improves others where voltage droop is a problem. Large-scale solar farms will need new network connection points which have a geospatial distribution (Colantuono et al., 2014) which may not match the current network (Palmer et al., 2017).

In the political category, changing policy and regulation is the most important cause of risk (Allan et al., 2015; Curtin et al., 2018). Candelise et al,(2010) and Hammond et al. (2012) made the case for increasing the policy support to make PV financially viable for householders and commercial developers. However, the sudden downgrade in the FIT in 2012 (Muhammad-Sukki et al., 2013) revised downwards the return-on-investment (Cherrington et al., 2013) which discouraged householder investment (Martínez Ceseña et al., 2018) and consequently many installation companies went out of business (Snape, 2016; Hanna et al., 2018). Allied to the boom of installations Hanna et al. (2018) suggest that standards and codes were unevenly enforced.

A second cause of risk in the political category is that of significant public concern, or rather resistance in the case of PV and other distributed generation (Allan et al., 2015). Willingness to pay (separate from access to capital) is noted by several authors (Faiers and Neame, 2006; Scarpa and Willis, 2010), but financial support alone is insufficient to increase uptake of PV (Bergman and Eyre, 2011; Fleiß et al., 2017). The difficulty in finding trustworthy advice, aesthetics, and the attitudes of neighbours are identified by Balcombe et al. (2014). However, Moran and Natarajan (2015) suggest that barriers to installation on historic buildings can be overcome. At the community level Clark and Roddy (2012) observe that engagement leads to trade-offs during negotiations leading to a sub-optimal solution. However, they regard this as a better outcome than outright rejection of the plans. We judge this risk to be moderate with short-term impacts only.

Although not a serious risk (operational failure) Allan et al., 2015 and Harrison and Jiang (2018) note the performance gap between modelled or predicted output and actual performance of installations. Also relating to operational failure are accident statistics. The figure for solar is 0.019 fatalities per TWh generated and this figure is lower for smaller installations (Sovacool et al., 2015). A modest-level cause of risk is the ability to neutralise waste at decommissioning, even the modules (Bogacka et al., 2017). For example thin-film PV cells exploit cadmium telluride and other hard to treat compounds (Turkenburg et al., 2012), chalcogenide/silicon cells contains elements such as cadmium, indium, selenium, and gallium (Lunardi et al., 2018), and the prospective perovskite cells contain lead (Alberola-Borràs et al., 2018).

Stage 5

We do not see the need for any deviations from the description set out in section 8.1.1.

Stage 6

We do not see the need for any deviations from the description set out in section 8.2.1.

4.4 Solar (thermal, water)

Solar collectors for producing hot water for sanitary use are a set of mature technologies (Chaudry et al., 2015), and considered by Turkenburg et al. (2012) to be the simplest way to harness solar energy. The number of installations in the UK is modest, though the carbon payback time is approximately two years (Allen et al., 2010). A more extensive LCA study comparing different water heating technologies (Greening and Azapagic, 2014) suggests that solar collectors do not necessarily out-perform other technologies on a wide range of environmental indicators. This work was replicated by Piroozfar et al. (2016). Recently, thermal systems have been hybridised with PV (Buker et al., 2014; Herrando and Markides, 2016), and integrated with facades of commercial buildings (Zhang et al., 2015).

Stage 1

We consider the risk profile to be identical to that of Solar (electric) in section 4.3 except for optimism bias which we judge to be higher since sunlight levels for thermal installation are less well characterised and modelled.

Stages 2-5

The UK market for solar collectors is mature, but with only a modest number of manufacturers (Chaudry et al., 2015). Access to capital is a cause of risk as solar hot water systems are more expensive than conventional gas boilers (Caird et al., 2008) requiring financial support (DECC, 2013b; Connor et al., 2015). Decommissioning costs might not be clear since components need to be removed from a roof, rather than a simple replacement compared with a gas boiler, however, we judge that these costs are marginal.

The operation of these installations will be determined by the solar irradiation levels (the fuel), therefore the quality of the fuel is variable. The likelihood of variability is certain, but we expect this to be at the margins of performance. Unlike most other heat sources, snow and high wind (natural hazards) may present a risk. We judge any disruption to be short-lived. The technology is less mature than alternative systems, so we suggest that further improvements may emerge. Boait et al. (2012) note an interesting trade-off. The trend to install gas-fired ‘combi’ boilers (with no storage tank) is encouraging house-builders to use the space saved for other purposes in new houses, which may hamper future Solar (thermal, water) installations.

Policy uncertainty is a key issue for heat (Turkenburg et al., 2012; Chaudry et al., 2015) and place this cause of risk in the highest category. Alongside other low carbon heating technologies there is evidence that the public has significant concerns about the performance and reliability of this technology (DECC, 2013b; Ipsos MORI and Energy Saving Trust, 2013). We judge that the risk is moderate but less severe than for heat pumps because the principles of the technology are more similar to conventional hot water systems. A pollution event is not relevant for this system.

Stage 6

We consider the use of onsite heating systems for this fuel and note the following deviations from the description set out in section 8.2.2. Because stages 2-5 are unified, the notion of a well-functioning market refers to the installed domestic heating system components such as radiators, pumps and storage tanks. For the most part, these are common components with firms manufacturing and installing such systems. We note that Lowes et al. (2018) suggest that suppliers of such components are at risk in a low carbon transition, thus we elevate the likelihood of the risk occurring. The R&D capacity is a lower risk compared with gas-fired systems because we are only considering components inside buildings.

As the sun intensity varies and the hot water store is of limited capacity, there may be variability in the quality of the heat available. We judge this to be a moderate risk with a short-term recoverable impact. We note that as this fuel is tied closely to a single type of device located at a site, the public concern is dealt with in earlier stages.

4.5 Thermal (low temperature)

For our purposes the key technologies are ground source heat pumps (GSHPs) and ground water heat pumps (GWHPs). Lucia et al. (2017) give a useful typology of the key variants and their characteristics. We exclude air source heat pumps (ASHPs) as in our classification (see section 3.1) they are a form of solar energy (the air is heated mostly by the sun) and cannot store thermal energy. GSHPs and GWHPs are acting as a thermal store from where thermal energy (the ‘fuel’) can be extracted; the ground temperature (at 1-2 m depth) is reasonably constant through the year (Busby, 2015). The use of GSHP close to underground railway tunnels has been proposed as a way to increase heat transfer away from the tunnels to reduce overheating for passengers (Revesz et al., 2016).

The origins of GSHP development in the UK can be traced back to the eighteenth-century (Banks, 2016). Staffell et al. (2012) given a useful overview of heat pumps for residential use. For commercial buildings, an interesting but limited heat pump system suitable for heating and cooling exploits seawater (Goodier et al., 2013), and an example of GWHP use is the cooling system for the Royal Festival Hall in London (Oldmeadow et al., 2011). Farr et al. (2017) mapped, for the first time, city-wide groundwater temperatures (of Cardiff). There is overlap with the systems proposed for heat recovery from minewater, but we have chosen to classify these as Thermal (geological) due to the depth and other technical similarities.

Stage 1

We consider the risk profile to be identical to that of Solar (electric) in section 4.3. We note that improved modelling of ground thermal resources can improve the assessment of a site (Herbert et al., 2013; Younger, 2015).

Stages 2-5

The UK market for GSHPs and GWHPs is not mature with only a modest number of manufacturers (Chaudry et al., 2015) and market failure of equipment manufacturers has been recognised (LCICG, 2016b). These technologies are complicated to install and, in the case of systems large enough for commercial buildings, requiring significant groundwork which leads to a high cost. The long period for return-on-investment (Oldmeadow et al., 2011) may give rise to significant delays or even scupper some projects, however, subsidies are available (Connor et al., 2015). Therefore access to capital may be an issue, but we do not consider it to be in the highest category. For such large or complicated systems the costs for decommissioning may not be wholly transparent, unlike ether onsite technologies.

The consistent temperature at depth gives assurance of fuel quality, but we note that these conditions are localised to the site. We consider natural hazards not to be relevant for this fuel.

The technology is less mature than alternative systems, so we suggest that further improvements may emerge. LCICG (2016b) suggest that there is a strong case for public sector intervention to drive the required R&D.

Policy uncertainty is a key issue (Chaudry et al., 2015) with Vijay and Hawkes (2017) suggesting that support needs to be stronger than at present. We place this cause of risk in the highest category. There is evidence for some lack of enforcement of rules and codes when under-sized GSHPs were installed in new housing developments simply to meet the renewable onsite generation target (Rees and Curtis, 2014; Younger, 2015). This corner-cutting forms part of the evidence that the public has significant concerns about the performance and reliability of this technology (Ipsos MORI and Energy Saving Trust, 2013) and sectors such as care homes for the elderly are strongly risk averse to technical failures (Neven et al., 2015). A study by Delta Energy and Environment (2012) suggests that awareness amongst the public contributes to this anxiety, and for GWHP systems the lack of precedence contributes to performance scepticism (Oldmeadow et al., 2011). Amongst others, Staffell et al. (2012) and Garber et al. (2013) note design-performance gaps for installed GSHP systems; we view this as a cause of technical risk. One further noteworthy cause of risk is that of overload of the LV electricity distribution network. There is significant concern that the widespread electrification of heating will require grid reinforcement (Navarro-Espinosa and Mancarella, 2014; Love et al., 2017).

Stage 6

We consider the use of onsite heating systems for this fuel and note the following deviations from the description set out in section 8.2.2. Like Solar (thermal, water), this stage is only concerned with the components required to transport heat around the building. For residential systems these will be different from Solar (thermal, water), and more complicated. For large systems in commercial buildings, common heating components such as radiators may be used. Access to capital is included in earlier stages as it is a single integrated system. Decommissioning costs might not be clear since components may be non-standard but we judge that these costs are a modest level risk.

As the components inside the building may be more complicated than for current gas-fired systems, we judge that improvements through innovation are likely. We observe that there is some optimism about the performance, and we elevate the likelihood of the risk accordingly.

All types of heat pump are slow acting so require buildings to be of sufficiently high thermal efficiency. The most important risk facing heat pumps is that of not constructing or refurbishing enough buildings to the required standard. Despite this widely accepted requirement McMahon et al. (2018) have demonstrated that a so-called ‘impossible to heat home’ can have a GSHP designed and installed to operate adequately. However, the design and installation process took approximately two years and the experimental seasonal performance factor is given as 2.9, which is low for a GSHP. We note that as this fuel is tied closely to a single type of device located at a site, the public concern is dealt with in earlier stages. However, Boait et al. (2011) and Caird et al. (2012) observed that some consumers were dissatisfied with the controls for their heat pumps. A pollution event from leakage of one of the heat transfer fluids is unlikely to occur, but should one manifest it will only cause short-term recoverable impact.

4.6 Wind (off and onshore)

The similarities of on- and off-shore wind extend beyond the engineering of the device and the infrastructure. The key differences are discussed stage by stage. Wide-ranging reviews of wind resources are given by Esteban et al. (2011) and Turkenburg et al. (2012). Gove et al. (2016) estimate that only 0.4-0.6% of the UK seabed is available for fixed base turbines in the low ecological risk category. But for floating turbines the low risk area increases to (230-250)x10^3 km^2. However, Gove et al. do not attempt to correlate their estimates with likely grid connection points. A useful overview of the issues facing the UK offshore wind industry is given by BVG Associates (2016). A comprehensive study of offshore wind speed variabilty has been conducted by DNV GL (2016) on behalf of The Crown Estate. For onshore wind, Gove et al. estimate that 2.4% of the UK has sufficient wind resource and has a low biodiversity sensitivity, potentially yielding 140 TWh per annum. There are a wide range of learning curves associated with wind power development, but it is likely to be incremental (E. Williams et al., 2017).

Stage 1

Overall, we consider there to be very little risk or possible impact. However, exploring offshore is more expensive than onshore and we consider that lack of access to capital might pose a risk, but if it occurred would only delay prospecting for a short period. Access to offshore sites is subject to weather conditions and may introduce delays, but not have a lasting impact. The risk of a natural hazard occurring is notable at this stage, but is only likely to introduce delays without risk to personnel or equipment.

Stages 2-4

The risk of a lack of access to capital for onshore schemes is considered to be low (Bassi et al., 2015), in part because cost reductions for onshore installations may be greater than for offshore (Wiser et al., 2016). Despite this Allan et al. (2015) suggest that onshore schemes still need subsidies, and Curtin et al. (2018) point out that FITs are insufficient to overcome the barrier to capital for community-owned schemes. The capital intensity of offshore schemes engenders an increased likelihood (Criscuolo and Menon, 2015). The level of investment required scales with distance to the shore (cable length) and depth of water (Voormolen et al., 2016), but Weaver (2012) suggests that the cost of capital is more important than the site to the cost of the electricity generated. Operating costs are also greater for offshore installations (Esteban et al., 2011). Wiser et al also consider that the learning rates for offshore wind are underestimated, which may help explain why port facilities in the North East of the UK have been attracting speculative investment in specialist staging facilities (BVG Associates, 2016). Some concern about a lack of competition in the offshore turbine market is noted by Voormolen et al. (2016), however they consider that this is likely to manifest as increased capital expenditure (rather than as delays in production and delivery). Overall our judgement is that the risk of a lack of access to capital is moderate in both cases. It is unlikely that the price of permits (offshore) cannot be agreed on (by auction), but should it occur a project will be halted.

Physical access to offshore sites is clearly an issue with installation and maintenance only possible at certain times of the year. The offshore environment can be hostile and a severe storm could cause sufficient damage to give a prolonged delay in repair. The future variability of wind speed (quality of fuel source) due to climate change creates long-term uncertainty (Hdidouan and Staffell, 2017). The lack of critical materials may occur (Kim et al., 2015) with Speirs et al. (2013b) noting that rare earth elements are the most important. We judge that this is a moderate risk.

Wind turbine development has been taking place for in excess of 60 years and that industry moved into the commercialisation phase in the 1980s (Hanna et al., 2015). Despite this level of maturity Gross and Watson (2015) maintain that innovation for Wind (offshore) still requires public subsidy.

The risk arising from an insufficient rate of infrastructure construction is significant for both on- and off-shore wind. We consider the scale of the risk for Wind (offshore) as meso because this requires a National Grid HV connection at landfall. Although BVG Associates (2016) note that there is sufficient specialist port capacity (a micro scale risk).

For Wind (onshore), the connection will usually be made on the distribution network owned and operated by a regionally defined DNO. Queuing for grid-connection is recognised as a cause of delay in deploying approved wind farms (IRENA, 2012). The likelihood of the risk occurring is frequent and the impact would be to cause a cessation of the project if permission were denied or delayed beyond the point that investors were willing to continue their support. Furthermore, recent UK Government policy changes to financial support (DECC, 2015b) and planning consent have increased the likelihood of this risk arising. The UK has lacked domestic industrial base for component manufacturing capacity (IRENA, 2012).

The changing landscape of UK energy policy and regulation with respect to wind is noted a major concern (Allan et al., 2015; Bunn and Yusupov, 2015; Hdidouan and Staffell, 2017). A clear overview of recent policy changes given by Curtin et al. (2018) is more relevant to onshore wind. Poorly crafted policy may lead to increased costs in power generation (Wiser et al., 2016), for example, the CfD mechanism restricts pre-competition co-operation (BVG Associates, 2016).

Disputed landrights is not a particular issue for on- or off-shore wind, but for Wind (onshore) access to a site may be controlled by a different or multiple parties which has the potential to completely halt a project. The insufficient rates of improvements in codes are relevant only to the conversion stage e.g. grid codes for power conditioning and quality (such as harmonics) prior to injection into the network; we judge this a low-level risk.

Significant public concern presents an interesting difference in risk between on- and off-shore wind. (Wüstenhagen et al., 2007) suggest that public acceptance has three elements, namely socio-political, community, and market acceptance. For Wind (offshore) both the level of risk and the potential impact are low, though it is interesting to note that concern may be raised by the fishing community (Hooper et al., 2015). For Wind (onshore), the lack of community acceptance is often articulated as visual intrusion (Gibbons, 2015; Jones and Eiser, 2010; Sims et al., 2008). Although not all communities oppose wind farms, almost all proposals for onshore wind projects will attract protest. Elliott (2003) gives a clear account of the development of public reactions by using several UK case studies. Elliott (2003), Breukers and Wolsink (2007), and Clark and Roddy (2012) emphasise the need for negotiation at the local level, with Wolsink (2007) suggesting that opposition may be driven by equity and fairness in decision-making; particularly in relation to the planning system (Haggett, 2011; Krohn and Damborg, 1999). The impact on the value of housing is often cited as a reason to oppose wind farm development (Allan et al., 2015). Wilson and Dyke (2016) show that in many communities, opposition diminishes over time post construction. However, for Wind (onshore) public opposition has indirectly contributed to the removal of support by the Government through the Renewables Obligation mechanism (DECC, 2015b) – a lack of socio-political acceptance.

In the Technical category, the most important risk is that of infrastructure failure. Although the risk is low, the impact could be sustained (though recoverable). Although not an issue in the UK, globally wind power accounted for a third of all accidents at our stages 2-4 (Sovacool et al., 2015). Using a subset of these data (1950-2014) Sovacool et al. (2016) categorise wind as high risk in respect of accidents because the frequency of occurrence was relatively high, but the number of fatalities low i.e. low impact incidents. Dockerty et al. (2014) give an overview of the impacts on natural capital – broadly interpreted as pollution events in the technical category – across all stages. Decommissioning in the marine environment presents some difficulties and may lead to a pollution event. The main issue is with removing foundations (Kerkvliet and Polatidis, 2016) which may require the use of explosives (Kaiser and Snyder, 2012). It is not obvious that operating wind turbines might be the source of a pollution event – the likelihood of a release of lubricants, say, is very small. However, interference with wildlife and noise could be considered as ‘pollution’ as the turbine is creating the disturbance. Harvey (2010) suggests that there is no evidence of a noticeable problem from operating noise or bird deaths due to colliding with blades and towers (Masden and Cook, 2016; Warwick-Evans et al., 2018). Regarding onshore turbines, early designs suffered from both mechanical and aerodynamic noise (Lago et al., 2015) but mechanical noise has been eliminated and aerodynamic noise much reduced (in part through better operating regimes). There is evidence that some people have suffered ill health from the proximity to wind turbines (Knopper and Ollson, 2011) but this is more due to stress caused by seeing the turbines than noise. It has been noted by Kikuchi (2010) that noise from offshore turbine arrays may deter fish, though Perrow et al. (2011) suggest that this effect is greater during construction, but that there is a knock-on effect for birds as their food source is disturbed. However, for impacts on wildlife Green et al. (2016) suggest that the evidence is not clear, with Lago et al. (2015) and Langston (2013) considering the impact on birds not to be trivial. Lago et al. (2015) suggest four risks: collisions, habitat disturbance (including from maintenance), interference with movement patterns, and the reduction of available habitat. The scale of deaths of birds from wind installations is of the order of a hundredth that due to cars or pesticides (Erickson et al., 2005). Furthermore, Pearce-Higgins et al. (2012) found that the effects on birds were greater during the relatively short construction phase than during operation. On balance we consider the likelihood of a pollution event to be low.

Stage 5

The basic description of the risks arising at this stage are discussed in sections 8.1.1 and 8.1.2. The ability to construct the infrastructure is a significant difference between on- and off-shore. The equipment required for Wind (onshore) is widely used in the construction industry. Separate from public concern is the risk from the denial of access to new sites for pylons for new Wind (onshore) installations. Individual landowners may withhold rights of access for different reasons, as part of negotiations but the impact may be more than short-lived. Public concern about the (generally) new pieces of network that wind farms require is almost always attracts formal objections (Cohen et al., 2014, 2016). Thus we put the likelihood at the highest level, but the impact is recoverable.

Stage 6

We do not see the need for any deviations from the description set out in section 8.2.1.

5 Assessing Risks for Renewables (Biofuels)

We discuss selected decisions in the risk matrix (Appendix A) for the biofuels fuel group (all of which are classed as renewable). Mostly these risks are those assessed as having the highest risk rating, but also some of those with moderate ratings. We also comment if the likelihood score is high, even if the impact is low, if this presents an interesting point. Furthermore, the selection is based on some elements in different stages being repetitive and some fuels being similarly sharing characteristics.

5.1 Biogas

There is a wide variety of technologies and routes to produce biogas (Watkins and McKendry, 2015a, 2015b). This is in part due to the variety of feedstocks, including farm wastes (Oreggioni et al., 2017), sewage sludge (Mills et al., 2014), food waste (Evangelisti et al., 2014), and algal biomass (Montingelli et al., 2015). Biomass wastes and residues can also be gassified (Faaij et al., 1997; Wang et al., 2008) to produce syngas (Guo et al., 2015) which can be upgraded to a liquid transport fuel (Patterson et al., 2011). The other important source is landfill gas (LFG) (Brown and Maunder, 1994) which must be captured (or vented) for safety. Frank et al. (2017) suggest that bacterial stimulation may be possible to enhance gas production.

The technology which we take as the case study for our assessment is anaerobic digestion (AD) which is well-established (Styles et al., 2016). Biomethane production using AD can meet the specification for direct injection to the gas grid (Fubara et al., 2018). Technology development has focused on farms (Gowreesunker and Tassou, 2016) and shown that bigger units are more efficient (Oreggioni et al., 2017). There remains some uncertainty about the merits on onsite use in a CHP unit versus grid injection. Mills et al. (2014) claim that grid injection is economically the best option but is poor for the environment, whilst Watkins and McKendry (2015b) state that onsite use is always the worst option (in part because of the very much higher efficiency of CCGTs). Our view is that AD is scalable because it can produce methane at grid specification and will base our assessment on this assumption.

Stage 1

We do not see any significant causes of risk at this stage. Though we note that the quality of fuel source will be variable from year to year which adds uncertainty into measuring the potential.

Stage 2

Note that this stage includes growing and gathering the fuel source, as appropriate. The main risk of the stage occurs in the Environment category and is the quality of the fuel source i.e. the variability (Zglobisz et al., 2010; Röder, 2016) e.g. some sources are seasonal. The variability in water content is only relevant to Stage 3. Natural hazards such as too much rain in the wrong part of the growing season or lack of sunshine will not affect the gathering of the crop, only the quality. We judge that this risk may occur and may lead to a significant temporary (annual or seasonal) change, but the crop is unlikely to fail in the UK. This is a risk which may be sensitive to climate change in the long term. Court (2017) suggests that this variability is less of a problem for syngas production.

Stage 3-4

Access to capital is recognised as a risk for AD whether at the single farm scale or larger (Watkins and McKendry, 2015b). Specifically, the rate of return (Tranter et al., 2011) and the cost of landfill (Zglobisz et al., 2010) are noted as the main influences. In the past the lack of access to capital has been a problem for LFG (Brown and Maunder, 1994).

Although the water content of the feedstock is an important signifier of the quality of the fuel source, it is the carbon to nitrogen ratio which is the principal factor (Divya et al., 2015). We consider this to be a moderate risk, but perhaps the most significant for this stage.

Despite AD being relatively mature, there is evidence of R&D potential in, for example pretreatment processes (Carrere et al., 2016). LCICG (2012a) note that R&D for AD will require continued public support. We suggest that the lack of public support programmes may occur, but might only lead to short-term disruption of activity. Connectivity of the gas grid (insufficient rate of infrastructure construction) is an issue for farms and other installations not located near urban areas, for example landfill sites (Brown and Maunder, 1994).

Although unlikely to occur, some farm tenancies may prohibit the deployment of facilities such as AD (Tranter et al., 2011) but if this were to occur it would stop a project completely. A risk more likely to occur is public concern through objections lodged to planning applications (Tranter et al., 2011; Clark and Roddy, 2012); this also occur for LFG (Brown and Maunder, 1994). Changing policy and regulation is recognised as a risk (Edwards et al., 2015; Röder, 2016). The uncertainty in support mechanisms (LCICG, 2012b) led to fluctuating levels of subsidy compared with PV and wind (Tate et al., 2012), which Gowreesunker and Tassou (2016) observe as policy driving technology and not environmental considerations.

In the technical category, pollution events will occur (Röder, 2016). Biogas combustion cannot be CO_2 neutral even when using wastes. The AD process will generate fugitive methane emissions (Adams et al., 2015) including from the storage of digestate in open tanks and lagoons (Styles et al., 2016), which also have the potential to leak. Operational failures may occur, but should only lead to short-term disruption. Although fatalities are rare in the UK they do occur in biogas production (Burgherr and Hirschberg, 2014; Sovacool et al., 2016), likewise for other accidents (Sovacool et al., 2015).

Stage 4

We do not see the need for any deviations from the description set out in section 6.2 (Gas).

Stage 5

We do not see the need for any deviations from the description set out in sections 8.1.3 (pipelines) and 8.1.1 (electricity networks).

Stage 6

We consider the use of onsite heating systems for this fuel and do not see the need for any deviations from the description set out in sections 8.2.1 (electrical devices) and 8.2.2 (heat).

5.2 Bioliquids

Here we consider the biomass sources most frequently proposed as suitable for conversion and upgrading to liquids, since the discourse has focused on biofuels as a substitute for oil (Levidow and Papaioannou, 2013). The key sources are corn (Acquaye et al., 2012), macro-algae (Gegg and Wells, 2017; Membere and Sallis, 2018), *Miscanthus* (Shemfe et al., 2016), rapeseed (van Duren et al., 2015), straw (Glithero et al., 2013a; Littlewood et al., 2013), starch slurry (UKPIA, 2016), sugar beet (Cárdenas-Fernández et al., 2017), tallow (RAE, 2017), waste cooking oil (Acquaye et al., 2012), and willow (LCICG, 2012b). Although research on future biofuels (3rd and 4th generation) is more concerned with better exploiting waste and by-products (Awudu and Zhang, 2012), the tension between land use for food versus fuel remains relevant (Kim et al., 2013). The discussion is turning to multi-purpose land-use to increase yields (Shortall et al., 2015) and Whitaker et al. (2018) give a useful overview of emissions arising from direct and indirect land-use change. For macro-algae production at scale, artificial cultivation will be required (Roberts and Upham, 2012) and may turn the discussion to inshore waters which are also suitable for fish farming. Roberts and Upham suggest that siting seaweed farms amongst offshore wind farms is a possibility.

Whilst there are some biochemical similarities between sources of biomass, the possible processing methods may be very different even for the same source (LCICG, 2012b). Milledge and Harvey (2016) show that for dry macro-algae direct combustion, pyrolysis, gasification, and trans-esterification to biodiesel are all possible processing routes, whilst for wet macro-algae hydrothermal treatment, fermentation, and AD are feasible. Gassified biomass (syngas) – or other biogas (Patterson et al., 2011) – can be liquefied using the Fischer-Tropsch process (Wang et al., 2008). Figure 5.1 summarises some general processing routes for biofuels. The hydrothermal liquefaction of biomass (Raikova et al., 2017) is a step towards biorefineries (Taylor, 2008a). Using data from the historical development of the UK petrochemical sector Bennett and Pearson (2009) make a strong case for co-evolving fuel and chemicals production in biorefineries to produce high-value molecules such as pharmaceutical intermediaries (Cárdenas-Fernández et al., 2017).

Stage 1

We do not see any significant causes of risk at this stage. Though we note that the quality of fuel source will be variable from year to year and Acquaye et al. (2012) note the wide variations in potential CO_2 savings from different sources both of which add uncertainty to measuring the potential. The geographical location of where crops are grown is an important factor (van Duren et al., 2015).

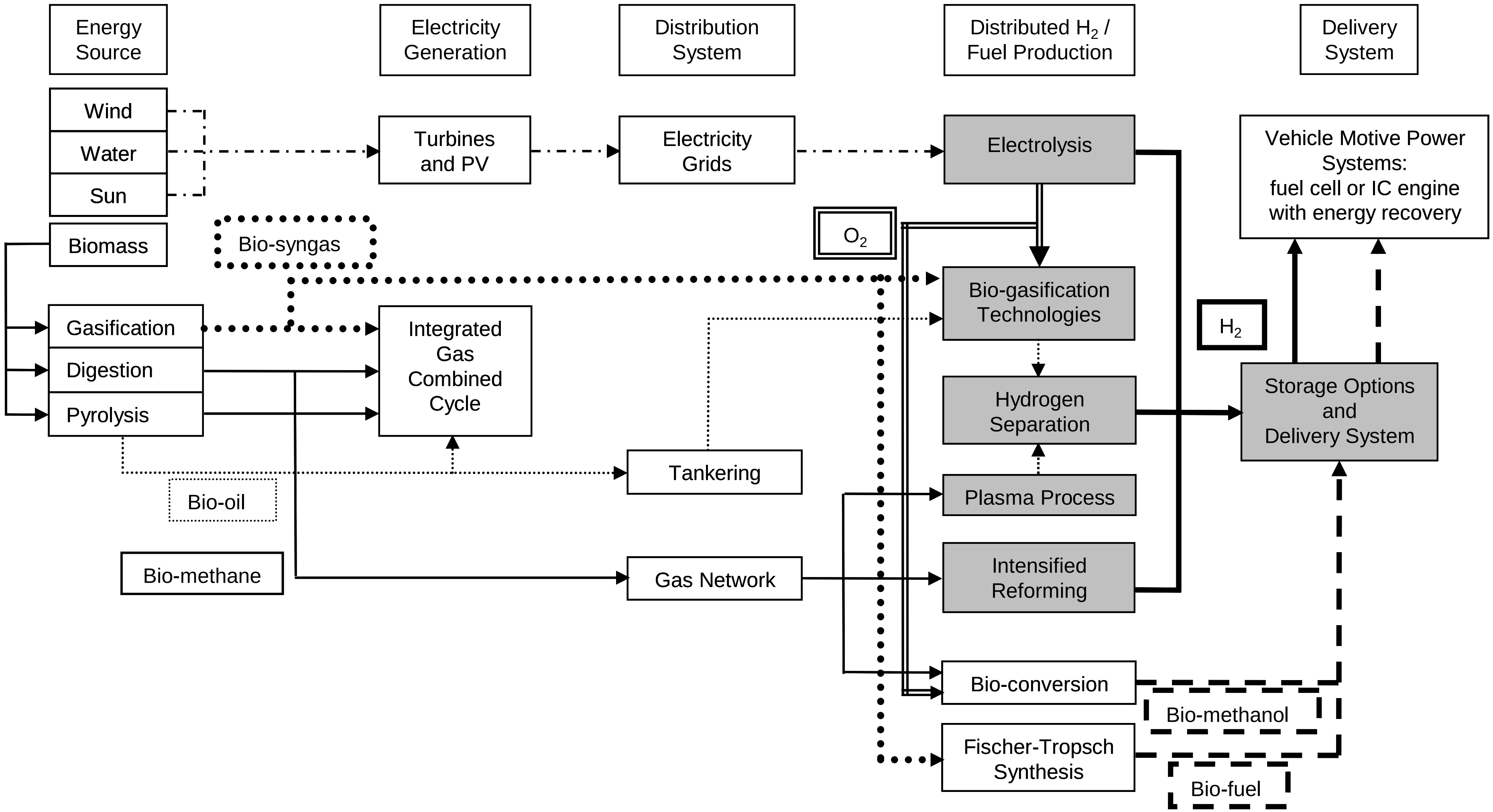


Figure 5.1 The principal processing routes for biofuels, illustrating the complex nature of exploiting bio-derived materials.

Stage 2

There are a few practical differences from Biogas which could arise, however, broadly we consider that the risk values are similar. Note that this stage includes growing and gathering the fuel source, as appropriate.

The quality of the fuel source is not an important risk for gathering of the source, though Firrisa et al. (2014) note that the quantity available may depend on fertilizer inputs. Water availability is not currently an issue in the UK, but will manifest periodically and may become more important in the future (Hammond and Li, 2016). The requirements for different sources varies widely (RAE, 2017).

Growing macro-algae whether inshore of farther out to sea requires a lease to use the seabed from The Crown Estate (Gegg and Wells, 2017) and it is coupled with obtaining a licence from the relevant maritime regulator. Thus access to sites may be denied. Each part of the UK has a different regulator, but each requires potential seaweed farms to conduct an environmental impact assessment (Wood et al., 2017). Even though Roberts and Upham (2012) consider the impact assessment stage difficult to satisfy we judge this is unlikely to occur, but may cause short-term delays in starting a venture. (Roberts and Upham, 2012). The capital requirement for starting a seaweed farm, say, may pose a risk. The Royal Academy of Engineering note that standards and codes for categorising wastes and residues are needed to avoid distorting the market (RAE, 2017). Public concern may arise connected with seaweed farms as it may affect marine users (Roberts and Upham, 2012). We consider that the use of genetically modified crops for fuel production is now very unlikely.

For the purposes of this study we classify ecosystem disturbance as a operational failure as it results from human decisions. Although difficult to quantify, disruption to ecosystem services does occur from growing energy crops (Styles et al., 2015). Land-use change is associated with increased emissions such as N_2O from fertilizer use (Whitaker et al., 2018).

Stage 3-4

The scale of capital expenditure required is noted by several authors including Popp et al. (2014) and Hodgson et al. (2016). Specific issues which will affect access to capital are demand uncertainty (Awudu and Zhang, 2012) with Hammond et al. (2012) suggesting that a lack of investor confidence may arise from EV competition and that the established oil and gas ‘majors’ have much of the capability to design and operate biorefineries if they chose to do so (presenting a high barrier to new entrants). Criscuolo and Menon (2015) classify biorefineries as high-risk technology with high intensity capital requirements. We judge that the risk of the lack of access to capital is likely to occur and that it could lead to a sustained but recoverable delay in projects.

The quality of the fuel source is the main risk in the environment category (Roberts and Upham, 2012; Hodgson et al., 2016). Popp et al. (2014) note that meeting tight modern fuel specifications is harder with biofuels. Although the chemical or energy content variations can be accommodated, they may lower the efficiency of a biorefinery through additional process steps. Strong process optimisation is premised on a narrow resource input specification. Water use at this stage is not likely to be higher than for most other fuels (Mielke et al., 2010).

Despite many elements of the process engineering required for biorefineries being well understood, there is considerable agreement that there is scope for innovation (Hammond et al., 2012; LCICG, 2012a); specific examples are cost reduction (Awudu and Zhang, 2012), pretreatments (Littlewood et al., 2013), and advances in biology (Taylor, 2008a; McLeod et al., 2017). Shortall et al. (2015) note that ongoing public subsidies will be required as will policy aimed at supporting a balanced approach to co-production of fuels and chemicals (Hodgson et al., 2016). Hodgson et al. also expressed concern that there was a lack of co-operation between the key players, including traditional oil and gas processors and new entrants; we interpret this as a risk that the R&D capacity may not be able to meet the challenge. We consider these risks to be moderate with only short-term effects.

Changing policy and regulation is noted as a significant cause of risk (Hodgson et al., 2016). The Royal Academy of Engineering (RAE, 2017) give a concise overview of the liquid biofuels policy landscape and the UKPIA (2016) summarise the recent changes. Regulation specifically is noted by Hammond et al. (2012) and Kim et al. (2013). According to Boucher (2012), in an unclear technological regime creating policy and regulation at all generates uncertainty, and may lead to technical lock-in with a consequential loss of flexibility for biofuel development (Berti and Levidow, 2014). Poorly formed policy allowed petrol and diesel producers to buy themselves out of obligations (Swinbank et al., 2011), or more generally may give rise to policy conflicts (LCICG, 2012b) such as the effect on hydrogen fuel cell funding (Levidow and Papaioannou, 2014). We judge that changes to policy and regulation will occur in the future, but are likely to only have short-term impacts. Although we do not consider there likely to be a lack of enforcement of standards and codes at this stage, Bailey (2013) contends that the current standards for biofuel production do not ensure sustainability.

We consider that a pollution event is likely, but may only cause short-term disruption. Proposed causes of pollution include increased NOx emissions (Hammond et al., 2012), eutrophication (Wang et al., 2013), alteration of sediment dynamics by seaweed farms (Wood et al., 2017), and effects on groundwater by spillages from refined products (Firth et al., 2014). Globally the accident frequency per TWh at biofuel facilities is similar to that of geothermal and solar, but the fatalities per TWh are lower (Sovacool et al., 2016). For the UK we judge the risk of operational failure to be the same at this stage as for oil and gas processing i.e. unlikely, but has the possibility to close a site should a severe accident occur.

Stage 5

We do not see the need for any deviations from the description set out in section 8.1.4.

Stage 6

We do not see the need for any deviations from the description set out in section 8.2.3, but we note that there is evidence that some air passengers are not comfortable with aeroplanes using a biogenic fuel rather than kerosene (Filimonau and Högström, 2017). Furthermore, the efficiency of modern ICEs is dependent on tight fuel specifications which are harder for biofuels to meet (Bergthorson and Thomson, 2015), and if the biofuel is not 100% compatible with fossil-derived fuels Popp et al. (2014) suggest that compatibility lists need to be compiled.

5.3 Biomass

We are considering sources of biomass used for combustion in this section. These sources include waste wood (Röder and Thornley, 2018), *Miscanthus*, switchgrass, willow, poplar (Robbins et al., 2012). This heterogeneity is in part why estimates of the available resource vary widely (Price et al., 2004; Slade et al., 2010; Mola-Yudego et al., 2017; Qi et al., 2018). Slade et al. (2011) give a clear overview of the problems plaguing estimation methodologies including the yield gap confirmed by experiments (Mola-Yudego et al., 2015). Some estimates of the land available for biomass production are set as high as 40% of the total area of Great Britain (Lovett et al., 2014). Some estimates put the total contribution of biomass to UK electricity generation in the 5-10% range (Dommett, 2009). A useful summary of the combustion techniques is given by Robbins et al. (2012).

Stage 1

We do not see any significant causes of risk at this stage. Though we note that the quality of fuel source will be variable from year to year which adds uncertainty into measuring the potential.

Stage 2

The discussion for Biomass is similar to that for Bioliquids, though macro-algae are not usually considered for combustion.

Lack of access to capital is a noticeable risk. The main problem is the return on investment compared with other uses of that land (Adams et al., 2011) with many crops uneconomic (Warren et al., 2016). Investment in new specialist harvesting machinery is a particular concern (Glithero et al., 2013b). Welfle et al. (2014) note that simple cashflow is a barrier to investment if crops take several years to mature. Furthermore, the costs of transporting biomass is higher than biogas (Wang et al., 2012).

There are four other notable points. Like the crops for bioliquids there is scope for innovation in crop science (Taylor, 2008b). In the political category changing policy and regulation present a risk (Adams and Lindegaard, 2016). And there are two notable sources of risk in the technical category, pollution events caused by emissions from changing crops (Drewer et al., 2017) and inflexibility introduced by using crops with roots which are hard to remove (Warren et al., 2016) which we class as an operation failure.

Stage 3

We do not see any significant causes of risk at this stage and judge the risk profile to be the same as for Coal (Stage 3).

Stage 4

As the UK has decided to phase-out the use of coal we are only considering the direct combustion of biomass which is most likely to be done using CHP plants. We assume many of these plants to be grid-connected with a minority powering a self-contained site and the heat to be distributed via DH networks.

The risk of a lack of access to capital is principally due to the rate of return on the investment (Wright et al., 2014) with several authors noting that subsidies are essential (Thornley et al., 2009; McIlveen-Wright et al., 2013; Huang et al., 2017). Also noted is a *"lottery approach to grant funding"* for small organisations, charities, or Councils needing support for CHP purchase (Sinclair et al., 2015), though Polzin et al. (2015) are of the view that FITs provide a better long-term signal than grants. Bassi et al. (2015) suggest that the risk perception of biomass is 'medium'. To an extent we agree, but interpret the essential nature of subsidies (whether by FIT or grant) as that the risk may occur but could halt a project entirely.

The quality of the fuel source is the main risk posed by the environment as the combustion properties vary (Forbes et al., 2014; Baxter et al., 2014; Al-Shemmeri et al., 2015; Röder and Thornley, 2018) which may affect the CHP plant's efficiency. The seasonal variation (Adams et al., 2011) will affect the efficacy of the unit or its economic performance. Thus we judge that the risk is likely to occur and may cause short-term disruption. For innovation, it is some evidence that public subsidy for technology development is required (Sinclair et al., 2015) even though CHP is moderately mature.

The changing policy and regulatory landscape is noted by many authors as a problem (Adams et al., 2011; Connor et al., 2015; Sinclair et al., 2015; Adams and Lindegaard, 2016; Levidow and Papaioannou, 2016). We judge that this cause of risk is likely to occur and that the biomass system is less robust than some other fuels, so we consider that the disruption could be sustained though recoverable which places it in the highest category. There is also strong evidence that significant public concern will arise. This will manifest through objections to planning applications (Thornley et al., 2009; Adams et al., 2011; Wright et al., 2014; Sinclair et al., 2015) but have only a short-term effect.

The burning of (woody) biomass is likely to lead to nett CO_2 emissions across the supply chain (Brack, 2017) which may exceed those of conventional gas. Biomass combustion will lead to other pollution events (Tagliaferri et al., 2018) detrimental to human health (Hall and Scrase, 1998). Air pollution is the main concern (Cordell et al., 2016), principally soot and other particulate matter (Mitchell et al., 2017) and NOx (Olave et al., 2017). Whilst this risk will occur we expect it only to have an effect at the margins of normal operation. We note that the ash from biomass will be high in potassium and phosphorous, which although valuable cannot be discharged directly into the environment without treatment (decommissioning).

Stage 5

We do not see the need for any deviations from the description set out in section 8.1.1/

Stage 6

For electricity generation we do not see the need for any deviations from the description set out in section 8.2.1. For the use of district heating networks we do not see the need for any deviations from the description set out in section 8.2.2.

6 Assessing Risks for Non-renewables (Fossil Fuels)

We discuss selected decisions in the risk matrix (Appendix A) for the non-renewables fuel group – coal, gas, and oil – including the unconventional sources. Mostly the risks discussed are those assessed as having the highest risk rating, but also some of those with moderate ratings. We also comment if the likelihood score is high, even if the impact is low, if this presents an interesting point. Furthermore, the selection is based on some elements in different stages being repetitive and some fuels being similarly sharing characteristics e.g. processing technologies.

6.1 Coal

The technology to enable the extraction of domestic reserves of coal accelerated the industrial revolution in Britain (Wrigley, 2010; Gentvilaite et al., 2014). Most UK mining was underground, but the last deep mine closed in 2015. Opencast mining still takes place in Scotland. The amount of coal used in UK homes fell from the mid 1970s as the introduction of natural gas grew, but the amount used for power generation remained high until the 1990s (BEIS, 2017c). The UK Government has stated that it will phase out unabated coal plants by 2025 (Rudd, 2015). Furthermore, the withdrawal of funding for the carbon-capture and storage (CCS) competition (HCECCC, 2016) has caused the cancellation of two demonstration projects. A comprehensive review of CCS has been conducted by Boot-Handford et al. (2013). Technology is not the barrier, but the price of carbon. For example, some estimates suggest that CCS could be viable at €115 /tCO_2 (Renner, 2014), whilst (Valentić et al., 2016) suggest that it can never be viable in Europe without a very significant rise in electricity price. Thus, without a change in policy the use of coal in the UK for electricity generation will cease entirely in 2025.

The introduction of the Large Combustion Plant Directive (LCPD) has foreshortened the operating life of a number of coal plants in the UK and elsewhere (Meyer and Pac, 2017). Some, such as Ratcliffe-on-Soar have been retro-fitted with soot particle capture, NOx scrubbers, and flue-gas desulphurisation to meet the LCPD requirements. Others such as Didcot 'A' and Ferrybridge were deemed uneconomic and worked out their remaining licensed operating hours before closing.

Mechanisation since the 1970s has cut the number of miners required to extract a tonne of coal in most developed and developing countries. The three main grades of coal (hard, brown, lignite) have differing chemical compositions, with the sulphur content being the main difference. The technologies used for large combustion plants are mature. Technologies such as CCS, supercritical systems, and pre-combustion gasification will be treated under innovation.

Stage 1

Coal is geographically widespread. The (global) market functions are in providing appropriate equipment and services to assess geologic deposits; we consider there to be little risk or possible impact. The denial of access to explore for resources might occur, but currently would have only marginal impact. As a non-renewable, the availability of coal is finite on time-scales much less than geological. However, the world reserves are sufficiently large with projected availability for more than 130 years at current rates of use (BP, 2018) such that multi-generation availability can be expected.

Some of the nations with reserves have poor ratings on the World Bank governance index (World Bank, 2018). This raises the likelihood of disruption to exploration activities marginally. The same is true for quality of institutional governance. In some well-governed nations there may be public concern if the exploitation of a deposit required opencast mining. As this stage is exploration, we judge that the impact is likely to be insignificant.

In the exploration phase, most of the required expertise could be provided by a non-local workforce because the numbers of people required is necessarily small, thus we suggest that this poses very low risk at this stage. There maybe a marginal requirement for some unskilled local labour in countries where educational standards are poor.

The risks from technical sources is very low since exploration operations are small. In the case of infrastructure failure, deemed to be not relevant since it is unlikely that infrastructure would be in place already.

Stage 2

The equipment required for coal extraction is used widely in many similar mining or quarrying sectors so the market for such equipment is mature. As with all specialised equipment, large items are made to order and short delays may occur, but will only have marginal impact. For example, in opencast mining large drag lines will take one to two years to construct and may cost in the order of $10m. The lack of access to capital is a significant risk. The risk may occur, and if access to capital is denied then the impact will be of the highest level; the project will not be able to go ahead in most countries. A current example is the proposed Carmichael mine in the Galilee basin in Australia which Buckley

(2015) states has been refused backing by 11 international finance corporations. The proposed project cleared the last major hurdle to permits, but remains dependant on infrastructure expansion for rail and shipping. Price volatility (on the world market) is a significant cause of risk. Volatility will occur and could cause some short loss of capacity since UK coal requirements are dependent on imports. However, as coal is widespread across the globe, the market has liquidity.

Difficult physical access may occur as a risk, but the impact is likely to only be short-term if the level of resource is economic. Although the formation of coal is an ecosystem service, the geological timespan is so great that we can consider the total reserves as fixed (the rate of new formation is too slow). But falling global extraction rates are not yet a problem; the global reserves of coal are large, even at current rates of demand. Within the UK is a different matter. The global price of coal has rendered the UK mining sector uneconomic, thus the extraction rate of UK coal has fallen significantly, but this picture is not reflected globally, thus the current impact is marginal. Mielke et al. (2010) estimate that the quantities of water required in mining operations (mainly for dust suppression and washing) range between 4-35 l/GJ. At some sites the cut coal is removed from the mine by creating and piping a slurry. Much of this water is reused, but the losses might double the quantity of water required. Currently this poses a low risk, but in a changing climate some regions are likely to experience lower rainfall. If the risk occurs, we suggest that it may have a major impact.

Improvements in extraction technology and methods are likely to only be incremental. But as there have been improvements over the last 30 years due to mechanisation, the impact of only marginal gains in efficiency or the efficacy of methods will only be of the lowest level.

The impact of policy uncertainty has been variable for coal as a fuel. The privatisation of UK coal mining led to consolidation in the industry. Inevitably, uneconomic mines closed and marginal ones lost-out to cheaper imports. The risk posed by poor institutional governance in coal supplier nations may occur, but as the known reserves are widely spread, we consider that it will have only a short-term impact. Disputed landrights is unlikely to occur, but if it should the impact could be moderate with sustained delays in establishing a site. This is more likely for opencast operations than underground mines.

One source of pollution resulting from mining operations is the emission of fugitive methane (Heede and Oreskes, 2016). The tailings from coal extraction contain contaminants, notably heavy metals including Mercury. The risks are well-understood, but a pollution event may occur. Minor earthquakes have been traced to underground coal mining activities in the UK (Wilson et al., 2015). There is evidence from the US that opencast mines present a particular risk to the health of inhabitants through the emission of particulates and pollutants (Hendryx, 2015). This could halt operations, but we consider that in most cases the situation would be recoverable. Likewise the decommissioning of a worked-out or uneconomic site. There are legacy issues for older sites, but for those which cease now safe and clean decommissioning should be possible. We suggest that the likelihood of not being able to neutralise waste at the decommissioning stage is low, but if it were to occur it could have a significant (but not irrecoverable) impact. The risk posed as a technical issue is one matter, but the willingness to enforce standards is covered by institutional governance. Coal mining has been considered a dangerous occupation, but when fatalities are normalised by TWh of electricity production, coal appears to have a risk factor of an order of magnitude lower than other power generation methods (Sovacool et al., 2015).

Stage 3

For current pulverised coal plants the processing for coal is straightforward – mechanical crushing and grinding to a powder. Some coarse crushing is done at the mining stage, but for the purposes of this analysis Stage 3 is only considering the final conditioning immediately prior to combustion. Different designs of combustor will have an optimum range of particle sizes. This final processing also takes account of coal coming from different sources. Even with modern extraction machinery at the mine cutting face the grade and size will vary. The variation from opencast mining will be greater. As the storage of coal as fine particles is both impractical and risky, the final pulverisation process and mixing is done at the last possible moment.

As the operation is uncomplicated, the levels of risks are low in the context of the conditioning stage. The UK Government is not permitting any new coal-fired power stations to be built, new equipment for the conditioning of coal is on a like-for-like basis on existing sites. Therefore, causes of risk such as being unable to agree a price for licence or permits, permission to access sites, or difficult physical access we deem not to be relevant. Of the political causes of risk a changing regulatory framework may occur and have a short-term recoverable impact. There are three technical risks of note. Pollution events are unlikely since the storage of coal, mechanisms of leaching, and control of dust are well-understood and subject to legislation. This was not the case in the UK in the distant past. If this risk were to occur the impact could be major, but recoverable. This inability to neutralise waste at decommissioning may occur, but should only have short-term impacts on the process. Given the robust nature of mechanical processing, operational failure is likely. However, as these are relatively simple mechanical systems any disruption should only be at the margins of normal operation.

Stage 4

This stage encompasses the design, operation, and decommissioning of a thermal power plant and its site.

Although the equipment is large-scale and specialised, pulverised coal-fired thermal plants are a mature market. The risk of delays in the supply of systems and components may occur, but the impacts are likely to be short-lived. The two key economic causes of risk are the lack of access to capital and the inability to agree on permits. Both have the capacity to terminate a project. The costs of building pulverised coal power stations has risen significantly between 2000-2010 (Larson et al., 2012). We suggest that both are likely to occur in the light of the UK Government's decision to close the remaining coal-fired plants . Should this decision be reversed, then the risks will lower, but will not be eliminated. Even if CCS were to become mainstream the risks will not be eliminated. We suggest that CCS might raise the risk of lack of access to capital since it would add a significant cost to a project. The costs of decommissioning should be able to be modelled successfully since these are well-understood systems. However, some uncertainty exists as aged plant may have incomplete plans or piping and instrumentation charts, and unknown quantities of asbestos. There is a possibility of accidents such as the fatal incident at Didcot 'A' in 2015 when part of the main boiler house collapsed. We suggest that even in such extreme circumstances, delays will be short-lived.

The availability of water is important for the operation of thermal plant, but the quantity required is determined by the cooling method used: once-through, closed loop, or dry. There are no UK data available (Murrant et al., 2015), but two meta-analyses from the USA give plausible estimates. The study by Mielke et al. (2010) suggests that the total consumed varies between 114-1930 $lMWh^{-1}$, whilst Macknick et al. (2011) suggest 242-4164 $lMWh^{-1}$. The discrepancy between these studies is due to literature selection with Macknick et al. (2011) being more comprehensive for the thermoelectric case, and less reliant on older studies by the Electric Power Research Institute e.g. EPRI (2003). What is common to all the studies is that water availability is considered a significant future risk. There is limited evidence that UK thermal plant may be abstracting proportionately more water, but consuming less (lower losses) per MWh of electricity generated (Murrant et al., 2015). The UK climate is different to that of the USA for the most part, however, we judge that the risk of a lack of water availability may occur and that if it does the impact could cause a sustained loss of a power station (but is a recoverable situation).

The prospects for technology transfer for coal-related innovations is relatively weak. The UK Government's aim of phasing out coal-fired generation and the withdrawal of support for CCS implies that UK companies creating IPR can only feasibly exploit this outside of the UK. Some fundamental work on technologies such as oxyfuel is still supported. We judge that the risk is likely to occur and could have a major impact. The most significant barrier to deploying CCS is cost (Bassi et al., 2015; USDoE, 2014). Projections by Levi and Pollitt (2015) of the near- and long-term LCOE for coal with CCS suggest that even by the mid 2030s it will still be higher than the agreed strike price of electricity from Hinkley Point 'C'. Furthermore, it will be significantly above the projected costs for offshore wind (CCSCRTF, 2013). For the permanent storage of carbon the main risk is leakage. In the early stages of storage site deployment Bassi et al. (2015) suggest that a cap on long-term liability be introduced until the risks are better understood and private insurance mechanisms develop. However, this misses the point that a price is irrelevant if the storage needs to be permanent. The scope of major improvements is low too i.e. the risk of only marginal improvement is likely to occur. The carbon capture process is well understood and a standard technique in the gas industry (Markewitz et al., 2012). Scale-up too is well understood; megatonne per annum plants are operating around the world e.g. urea production in Malaysia . This operation is unusual in that it is producing a saleable product, the risk faced by nearly all other CCS proposals is that there is no paying customer for the 'product' (CO_2), thus there is little incentive to invest in R&D capacity.

Coal-fired power stations have been subject to frequent public protests, including occupation by environmental protestors, particularly in connection with planning for extension or new-build (Kyllonen, 2014). Any plans to revive the use of coal-fired generation in the UK will attract opposition and are likely to cause any proposed project to be delayed and possibly cancelled – thus we consider this cause of risk to be in the highest category.

As it is certain that operating coal-fired stations will emit CO_2 (CCS will reduce not eliminate CO_2 emissions) the risk of a pollution event will occur. The combination of the LCPD and the recent UK Government's announcement demonstrates that pollution events will result in plant closure. The pollution risk from fly ash is modest as the processes for site clean-up are well understood. For the UK Larson et al. (2012) (and references therein) estimate the total health damage costs due to pollution from coal use for power production as 38 USD(2007) per MWh.

Stage 5

We do not see the need for any deviations from the description set out in section 8.1.1.

Stage 6

We do not see the need for any deviations from the description set out in section 8.2.1.

6.2 Gas

There are many practical similarities between the supply chains for oil and gas up to the distribution stage, and the risk profile reflect this. The gas business is more fragmented by region than oil (Mitchell and Mitchell, 2014) because of the relatively high inter-regional transport costs due to the basic physics of gases and liquids. They also differ in the final products, which require different distribution mechanisms and have completely different end uses. The arguments about the maturity and global nature of the extractive stages of the industry can be read across from the discussion of oil (section 6.4). The key differences are that gas is used for large-scale electricity generation and small-scale heat production. The importance of gas for electricity generation was demonstrated in 2015-2016 as the capacity gap created by the closure of coal-fired plants was plugged by expanding the use of CCGT (BEIS, 2017d). For small-scale heat production, gas is used in 91% in UK dwellings (Palmer and Cooper, 2014). Hanmer and Abram (2017) give an interesting description of the transition from coal and oil use to gas in residential dwellings.

There is a wide variety of methods – using three phases of matter – for transporting gas from producer to consumer (Thomas and Dawe, 2003), suggesting that compression and solidification might be cheaper than liquefaction. However, it is now clear that liquefied natural gas (LNG) became dominant despite its higher capital costs for the required processing plants. Floating LNG facilities are starting to appear (Won et al., 2014) which must do the full range of processing. The additional steps of the liquefaction and regasification are described by Tagliaferri et al. 2017). Bridge and Bradshaw (2017) argue that by decoupling gas supply from pipelines, LNG is changing the geography of the global gas market and creating what they term a 'global production network'. A consequence of this is to reallocate economic risk – in part from nation states to corporations.

In general terms for the oil and gas industries across all stages EY (2013) highlight risks such as spillages (technical), access to reserves (political), uncertainty in energy policy (political), and human capital (skills). Dockerty et al. (2014) give an overview of the impacts on natural capital – broadly interpreted as pollution events in the technical category – across all stages.

At the conversion stage, the comparison is with Coal. The development of the CCGT from the first patent in 1935 is charted by Olumayegun et al. (2016). Watson (1997) notes that rapid adoption of the CCGT in the UK was not triggered by success of public R&D support, but wider political and economic considerations. Indeed Olumayegun et al. note that the development of heat exchangers was crucial to the use of gas turbines in the power generation industry.

For stages 1-3 we discuss below only the differences between oil and gas, and for stage 4 only we discuss the differences with Coal. Stages 5-6 are common to many fuels.

Stage 1

We judge that there are no meaningful deviations to the risks, likelihoods, and impacts from that of Oil (section 6.4).

Stage 2

Produced (raw) gas is a mixture; the exact nature and proportions vary between regions and closely located wells (Burruss and Ryder, 2014). Mixtures typically consist of methane, ethane, propane, butane, sometimes pentane and hexane, hydrogen sulphide, carbon dioxide, water vapour, nitrogen, oxygen, hydrogen, trace amounts of helium and some other noble gases, mercury and some other heavy metals, some other sulphur compounds such as carbonyl sulphide, and particulates such as sand. Some of the impurities may need to be reduced (or removed) at the well-head, especially the water vapour and the heavier hydrocarbons which would otherwise condense out into the transmission pipes on the way to shore. All components emerge gaseous due to the elevated temperature deep in the well, but the seabed is only a few degrees above zero Celsius. The heavier hydrocarbons are saleable products, so too are the noble gases. If the water vapour content is dropped sufficiently, then the acid gas (hydrogen sulphide and carbon dioxide) restrictions can be relaxed for transmission to shore. If the acid gases are mixed with water corrosion will occur, but their removal presents a technical hazard. Minimising offshore conditioning is also important because the processing plant costs significantly more than onshore. Fortunately, the UKCS gas is relatively low in sulphur content. Once the gas reaches an onshore refinery (Stage 3) it can be conditioned to meet the UK domestic distribution specification.

The transport of gas is more reliant on pipelines than oil. More generally, Thomas and Dawe (2003) point out that companies, as well as governments, not only must address economic risks but also risks arising from terrorism, politics, and trade agreements. Stulberg (2012) notes that the research community has concentrated on utility maximising analysis, but suggests that value maximisation is a more useful approach. Stulberg suggests that states and other actors involved in pipeline agreements are most interested in return-on-investment, and this view is supported by Bouzarovski et al. (2015) who recognise that the structure of the European pipeline favours market mechanisms. A ‘clash of values’ over market arrangements is how Boussena and Locatelli (2013) describe the trading problems with Russia. However, the framing Stulberg uses is that of ‘credible commitment’ i.e. putting in place good governance measures such as legal transparency, thus is more optimistic about pipelines built in the post-Soviet era. The UK has bi-directional connections with Norway, Belgium and Holland, and an export connection to Ireland (Marchant, 1997; BEIS, 2016a). The European gas transmission network has a large number of nodes with multiple routes, offering resilience. It also means that the UK is not directly dependent on Russian supplies, furthermore, Russia is a transit country for gas from Kazakhstan and Turkmenistan (BEIS, 2016b). Although some gas reaching the UK through the European network will have originated in Russia, it is likely to be 1-2% of imports.

Although according to Burgherr and Hirschberg (2014) the accident and fatality rates for natural gas are lower than those for oil, they are not sufficiently different to change our assessment. Infrastructure failure is also unlikely, but an example of delays that can be caused is if a ship’s anchor snags a pipeline on the seabed (Espiner et al., 2008). Although the number of accidents and fatalities for the UKCS has been low for many years it should never be forgotten that this level of safe operation came about, in part, because of the Piper Alpha disaster in 1988 when 167 men lost their lives (The Hon. Lord Cullen, 1990; Redmond, 1990; Lyons, 2000).

There are two deviations from the description for Oil. First, the water requirement for the extraction of gas is lower than that for oil, thus we lower the likelihood score. Secondly, that we judge that the temporal impact of a pollution event to be lower (with the same likelihood) as there is less variety in the pollutants and the immediate clean-up of spilled liquids may be more difficult than for gaseous releases. Pollution events may also occur from well barrier and other integrity failures (Davies et al., 2014).

Stage 3

There are eight gas processing sites in the UK. Plus several terminals for LNG which are regasification facilities only. The sites are concentrated on the North Sea coast with one in Cumbria for the now declining Morecombe Bay field.

There are three points of difference with Oil to note. First, the quality of the fuel entering a gas refinery is a little more uniform than for oil, thus we lower the impact. Secondly, we judge that infrastructure failure is less of a risk as storage facilities for the conditioned gas are adequate (Le Fevre, 2013; BEIS, 2016a) i.e. the impact score is lower. There has been considerable discussion about the security of supply implications of the closure of the Rough facility. The CMA (2017) has decided that Rough can close without unduly increasing risk to the security of supply. Thirdly, the manner in which the public show concern. It is unlikely that a new site for an oil refinery will be required, but protest may occur and could lead to the proposed facility being abandoned. However, there is evidence (BEIS, 2016c) that new gas storage will attract protest, especially for underground facilities where a risk to groundwater is perceived. We judge that this may not actually lead to the proposal being abandoned.

Stage 4

The starting point for comparison in this stage for CCGT is with the use of steam turbines for coal-fired power stations. The basic differences in the process design are shown in Larson et al. (2012), which states that CCGTs are the most efficient of the fossil-fired technologies for electricity generation, reaching approximately 55% (thermal) at present. A gas-fired power station will also use steam turbines to recover thermal energy from the gas turbine exhaust gases.

For a CCGT plant access to capital remains possible (the risk is modest), unlike for a coal-fired station in the UK. Although the survey by Oxera (2011) suggested that the risk perception for CCGT was low, we judge that the risk is not minimal due to the large sums required. Furthermore, the Committee on Climate Change (CCC, 2015b) suggests that costs should be judged on the whole-life including those of emissions, and not solely the LCOE, and Qadrdan et al. (2015) note that their modelling of a high Nuclear (fission) and Wind (offshore) scenario suggests that investment in CCGTs will be hard to justify. The risk for permits is also lower as it is now impossible to obtain an operating licence for unabated coal. The decommissioning costs for a gas-fired station are considerably lower than those for Coal – there is much less equipment and waste to clean up.

Because of the increased efficiency of CCGTs the water requirements are lower, though insufficient to alter our risk assessment. Mielke et al. (2010) suggest a range of 114-795 $lMWh^{-1}$ for the total consumed, and (Macknick et al., 2011)15-1136 $lMWh^{-1}$. These figures are low as there will be some additional requirement for the steam turbines in the thermal energy recovery system. Variation in gas composition, even within specification, has implications for the operation and performance of gas turbines (Abbott et al., 2012) which they consider may be exacerbated as a wider range of sources is imported in the future.

The CCGT is a mature technology (Hanna et al., 2015) thus we suggest that the risk of only marginal improvements occurring is likely, but as it is already relatively efficient this risk will only have a low impact. Coal combustion carries a greater risk because of the need for CCS if it is to continue in the UK. We judge that that the R&D community for CCGT to be more vibrant with greater capacity than that for coal combustors, thus suggest that the likelihood of the risk of not meeting the challenge is lower.

The construction of CCGT power generation sites has not attracted public protest, unlike Coal. We judge the likelihood risk of significant public concern to be low, and if it were to occur it is only likely to give rise to short-term disruption. There is considerably less waste at the decommissioning stage for a CCGT than for Coal; we judge this risk to be in the lowest category.

Stage 5

For gas supplied to end users, we do not see the need for any deviations from the description set out in section 8.1.3. For the route describing the use of gas to generate electrical power for distribution, we do not see the need for any deviations from the description set out in section 8.1.1.

Stage 6

For the use of electrical devices we do not see the need for any deviations from the description set out in section 8.2.1. For heat we consider the use of onsite systems for this fuel and do not see the need for any deviations from the description set out in section 8.2.2.

6.3 Gas (Unconventional)

Several sources of hydrocarbons are considered as 'unconventional'. Our analysis considers only UK (onshore) shale gas using hydraulic fracturing as it is by far the most important in both the near and medium term, but we briefly discuss methane hydrates (clathrates), coal-bed methane (CBM), and coal gasification.

Shale gas is frequently thought of as a recent discovery in the UK, but this is not the case. In his succinct review Selley (2012) charts the first (accidental) discoveries from the late 19th century and the more intense academic analysis from the 1980s. Mustanen et al. (2017) note that hydraulic fracturing has been used onshore in the UK since 1956, on approximately 100 occasions to enhance oil and gas extraction. Globally, research activity has been accelerating since 2010 (Wang and Li, 2017), in part because of the amount of gas which may be available (McGlade et al., 2013a). The UK's geological conditions for shale gas reserves has been mapped in detail by the British Geological Survey (2014) with Scotchman (2016) giving a very clear interpretation of the typical subsurface conditions, and Hennissen et al. (2017) discuss in detail the geology of the central English region. Hammond and O'Grady (2017) and Al-Douri et al. (2017) give clear overviews of the upstream and downstream technologies, respectively. An important difference to conventional gas is that production from shale wells falls exponentially with time (Middleton et al., 2017). Using US data, Middleton et al. show that production drops by approximately two-thirds after two years and by 90% after 10 years. The Royal Society and Royal Academy of Engineering (2012) report also gives a good introduction to UK specific issues, particularly the regulatory regime. Christopherson and Rightor (2012) contend that the full costs of shale gas development go beyond economics and employment. Pre-drill assessments, according to McAleenan et al. (2015), should be developed using multidisciplinary value-engineering methodology. Hays et al. (2015) point out that there are useful lessons to be learned from the USA where the industry is more mature, and that UK policy should be informed by this experience and not by theoretical considerations. Cotton et al. (2014) and Partridge et al. (2017) observe that UK Government policy for unconventional hydrocarbons is incompatible with other policy drivers including the climate change targets.

Methane hydrates are distributed globally (U.S. Geological Survey, 2018), though there are no commercial operations currently. A thorough overview of methane hydrates and associated technologies is given by Beaudoin et al. (2014a, 2014b). Waters west of the Shetland Isles are deep enough with geology appropriate for methane hydrate formation, though it may not exist in great quantities and could be considered as a hazard for other conventional oil and gas drilling operations (Long, 2001). Should non-UK sources be extracted commercially, they would be sold into the global gas market. Although much of the equipment is likely to be similar to conventional offshore gas extraction R&D is required to adapt subsurface production processes (Decourt et al., 2015). Currently we judge the risk profile to be similar to that of Gas, but with enhanced likelihood and impact of lack of access to capital.

The term CBM encompasses a set of circumstances in which naturally occurring methane can be extracted, namely unworked seams, and working and abandoned mines. Creedy and Tilley (2003) review the principal extraction methods and Morad (2012) note that permeability if the most important factor for unworked seams. The total UK resource has long been uncertain (Mitchell, 1991), but there is renewed interest in directly coupled CBM-CCGT schemes to exploit deep unworked seams. Sarhosis et al. (2016) carried out an economic modelling exercise to ascertain the viability of a site in South Wales. They concluded that the site may be commercially viable, noted that many costs are site specific, and warned that hydraulic fracturing may be required to increase seam permeability and thus gas flowrate.

Although the UK ceased gasifying mined coal in the early 1970s, underground coal gasification (UGC) was first developed in Co. Durham in 1912 but was more widely adopted elsewhere. (Younger et al., 2010). UGC carries significant environmental risks (Hyder et al., 2016) including subsidence, groundwater contamination, and the release of organic and inorganic compounds. Younger et al. (2010) point out that groundwater depletion may occur as the hot vapour could be entrained as the syngas is extracted, though suggest that UGC could be combined with CCS. There is little current UK interest in this source of fuel.

The starting point for our analysis across all stages is that of Gas and discuss below the differences or other important risks. Some of the differences arise because we have chosen to considered UK resources, whereas conventional gas at Stage 1 is considered in the global context. Stages 5-6 are common to many fuels.

Stage 1

Physical access is much simpler as UK shale gas will be extracted onshore. The quantity and quality of shale gas can vary from well-to-well in the same area (McGlade et al., 2013b) which is much more noticeable than for conventional gas. Speirs et al. (2015) suggest that a lack of drilling experience in some countries or regions gives uncertainty about the reserves. We judge that this risk is likely to occur and that it could prevent further exploration at that site. There is better scope for innovation at this stage than for conventional gas. Better understanding of the relevant geology is one area, but also data analytics (Middleton et al., 2017).

Ownership of subsurface resource is not in dispute in the UK, hence a very low risk compared to other nations with conventional gas resources. However, permission is of landowners to access favourable drilling sites. Pyhäranta (2017) contends that one reason for the slow progress in exploiting onshore shale gas in the UK is the state ownership of the subsurface resources which does not give sufficient reward to landowners, and that the private ownership of the resources is a strong driver of the US industry. This point is supported by Thomas et al. (2017) who highlight the inequitable distribution of risks and benefits, and Harleman and Weber (2017) who suggests that this is a contributory factor in the level of public protest. Although payments are now be available to communities to mitigate this issue (Burns et al., 2016), we judge that this risk may occur, and if it does exploration could be halted for a prolonged period. Although much of the regulation governing onshore shale gas extraction is the same as for conventional UK gas (on- or off-shore) (Burns et al., 2016), Stokes (2016) argues that the regulatory requirement for shale gas are not exactly the same as for conventional sources, thus needs a new and distinct framework. The key question for Stokes is whether existing uncertainties due to the inadequacies of the current regime outweigh the risk caused by a wholesale change to a bespoke framework. Burns give three further examples of recent policy uncertainty:

1. the withdrawal of blocks in Scotland and Wales part way through the 14th licensing round (in 2014) because it was decided to devolve powers for onshore petroleum policy,

2. the majority of the blocks licensed were then made subject to further (previously unannounced) assessments, and
3. the creation of the Oil and Gas Authority as the new regulator.

UK citizens see more risks than benefits (Whitmarsh et al., 2015), with a modest majority opposing shale gas development (Andersson-Hudson et al., 2016), and recent activities have attracted significant public concern leading to protests e.g. Lancashire (Bradshaw and Waite, 2017) and Balcombe in East Sussex (L. Williams et al., 2017). The polarised nature of the unfolding debate in the UK print media is examined by Jaspal and Nerlich (2014). The pro-gas lobby are seen as lacking *'trustworthy messengers'* (Bomberg, 2017) and despite government and industry rhetoric influence of the public is minimal, leading to distrust (Whitton et al., 2017). Distrust leads to the withdrawal of the 'social licence to operate' (Bradshaw and Waite, 2017), however, activities can proceed as the social licence to operate has no legal standing; the Institute of Directors (IOD, 2013) down-play the level of this risk. Howell (2018) shows that greater knowledge leads to more polarised views (both positive and negative), though Williams et al. (2017) suggest that the debate is not just about objective risk but the ability and willingness of institutions to be flexible. In a US-UK deliberative study of public perceptions Thomas et al. (2017) found a common signature of risk, but they and Evensen et al. (2017) warn against translating US experience – including the level of importance placed on particular issues – directly to the UK. As a result, we suggest that the risk of significant public concern is likely to occur and that it will lead to significant but recoverable disruption.

We consider that the risk of a pollution event occurring at the exploration stage is not only greater, but in the highest category; if the risk occurs it may lead to a complete cessation of activity e.g. the seismic tremors in Lancashire (Prpich et al., 2016). As a result, calls have been made for baseline monitoring prior to exploration and exploitation of seismic activity (Royal Society and Royal Academy of Engineering, 2012; Wilson et al., 2015), groundwater conditions (Royal Society and Royal Academy of Engineering, 2012), methane emissions (Boothroyd et al., 2017), and naturally occurring radioactive material (NORM) such as radon (Daraktchieva et al., 2017). Fugitive emissions of methane will occur at this stage (Prpich et al., 2016).

Stage 2

Like gas from conventional wells, there needs to be some processing at the well-head to remove solids, water and any other liquids before it can be transported elsewhere (Last and Finn, 2015a). Transporting the produced gas to the main processing site is part of this stage.

Access to capital for unconventional gas carries an increased level of risk. UK shale gas is twice the cost of LNG imports and three times that of US production (Cooper et al., 2018), and Yuan et al. (2015) call for improved cost modelling to understand the capital requirements. Another part of the problem arises from a lack of economy of scale due to the licensing arrangements (Roberts, 2017), which leads Cooper et al. to suggest that the US success may not be replicated n the UK. However the UK Government offers subsidies (Bast et al., 2015).

Physical access and natural hazards are only a minor risk for onshore shale gas. However, the quality of the fuel source will be more variable, and predictions based on experience from previous wells may not extrapolate to a nearby well (McGlade et al., 2013b). Unlike conventional gas production, the water requirement for shale gas is concentrated during the drilling and well completion phase (Mielke et al., 2010). Estimates of water use are (10-30)x10^3 m^3 per fracking event (Hammond and O'Grady, 2017). Some more remote sites may be more difficult to supply, however we consider that this will only introduce a short-term disruption.

The Royal Society and Royal Academy of Engineering (2012) call for a programme of research, thus we judge that the lack of public subsidy for innovation is a risk which, if manifests, could cause major but recoverable delays to developments. Although there are good opportunities for tech-transfer from the offshore gas industry, the differences which exist suggest that there is significant scope for innovation. Some key areas have been identified: improved understanding of the effects of seismic events (Westaway and Younger, 2014), understanding the physical mechanisms and microstructural characteristics of hydraulic fracturing processes (Middleton et al., 2017; Striolo and Cole, 2017), transport properties of fluids and other materials (Striolo and Cole, 2017), process design and simulation (Gao and You, 2017), the application of various data analytical methods for modelling production data (Middleton et al., 2017), and the exploitation of ICT for operations management (Hassani et al., 2017). As a result, we suggest that optimism bias is likely to occur and that it would have a significant impact. We judge that the risk of insufficient capacity to construct sites might have a short-term impact, and that an insufficient rate of infrastructure construction would have a major impact.

The risk from the denial of permission to access sites is mostly dealt with in Stage 1, but we note here that until the 2015 infrastructure act a landowner could prevent drilling under their land even though they had no resource ownership rights (Burns et al., 2016). Some of the key regulatory differences from the US are drawn out by Roberts (2017), but the key points are dealt with in Stage 1. We note that some consider the current UK policy and regulatory framework to be inadequate (J. Cooper et al., 2016) suggesting that there is an increased likelihood of change in the future. A consistent concern raised by several authors is the risk of an insufficient rate of improvement in, or lack of enforcement of, standards and codes for technical operations (Royal Society and Royal Academy of Engineering, 2012; Hays et al., 2015; J. Cooper et al., 2016). Davies et al. (2014) state that the monitoring regime for abandoned wells is weak.

The risk of significant public concern is also mostly dealt with at Stage 1, principally because very few UK operations have gone beyond exploration at present. We judge that any well developed for exploitation will attract protest. We note also at this stage that participants in the study by Cotton (2015) cited increased road traffic and reductions in house prices would be a major issue at the gas production stage. Objections by the public to applications for planning consent is seen as a high level risk (IOD, 2013).

From the literature we identify five principal groups of pollution event (Table 6.1). The likelihood of pollution event is identical to conventional gas i.e. it will occur because of fugitive emissions, but we judge that because of public sensitivity an event could halt activities at that site completely. Although the Royal Society and Royal Academy of Engineering (2012) state that seismic events are very unlikely to be noticed, the two small earthquakes recorded near Blackpool (the Preese Hall drilling site) in 2011 triggered the Government to call a moratorium on further drilling across the UK and not just at that site. Mustanen et al. (2017) dispute that hydraulic fracturing triggers earthquakes and claim that the Preese Hall incident was an exception. The cocktail of gaseous emissions affect local air quality (Ahmadi and John, 2015; Peischl et al., 2015) with a consequential effect on human health (Saunders et al., 2018). The substantial review by Saunders et al. identifies approximately 350 separate chemical compounds used in the drilling, completion, and maintenance of shale gas wells. Exploiting US data Reap (2015) estimates that an increase in the incidence of cancer will occur in the UK if hydraulic fracturing goes ahead. Overall, we suggest that the impact has the highest possible potential.

Potential Pollution Event	Key References Recognising the Risk
Seepage into groundwater or aquifers	Vengosh et al. (2014) Scotchman (2016) Bell et al. (2017)
Surface disposal and spills of fracking and drilling fluids and wastewaters	Royal Society and Royal Academy of Engineering (2012) Cooper et al. (2014) Vengosh et al. (2014) Clancy et al. (2018) O'Donnell et al. (2018)
Gaseous emissions, principally fugitive methane	Cooper et al. (2014) Ahmadi and John (2015) Peischl et al. (2015) Prpich et al. (2016) Boothroyd et al. (2017)
Seismicity	Clarke et al. (2014) Wilson et al. (2015) Prpich et al. (2016) Westaway (2016a)
Naturally occurring radioactive material	Almond et al. (2014) Garner et al. (2015) O'Donnell et al. (2018)

Table 6.1 The principal references describing the potential pollution events.

Technical failure is one route by which a pollution event may occur with well integrity is identified as the main potential mechanism (Royal Society and Royal Academy of Engineering, 2012; Prpich et al., 2016; J. Cooper et al., 2016; Hammond and O'Grady, 2017). Prpich et al. (2016) also highlight well design and cementing as important. The statistical analysis of reported failures by Davies et al. (2014) shows that pollution events caused by failures are not common. In part because of being onshore, we judge the risk of technical failure for unconventional gas to be moderate and lower than that for conventional gas. By the same token, we consider that the likelihood of infrastructure failure also to be lower.

Although we judge the risk of being unable to neutralise waste at decommissioning to be the same as for conventional gas production facilities, there are two important differences. The geology of conventional oil and gas wells allows for the re-injection of wastewaters in underground formations, so although not treated the waste can be stored; shale formations do not allow for this. Contaminated wastewaters cannot be sent to landfill, but currently would be considered as mining waste by the UK environment authorities (O'Donnell et al., 2018), though the case for permitting the use of deep disposal wells has not yet been tested. In addition, Lewis et al. (2014) point out that each site (or pad) is small and adjacent licence blocks might well have different licensees and on that basis they advise that waste be treated at a central (or regional) facility to gain economies of scale and draw together sufficient technical expertise.

Stage 3

The technical processing is the same as natural gas (Last and Finn, 2015b). Although shale gas typically has a similar composition to that of natural gas, the exact proportion of the constituents varies not only between different geological conditions, but from well to well in the same area (Al-Douri et al., 2017). Depending upon location and the characteristics of the produced gas, processing may be done on site at the pad (or a shared small-scale regional facility) and injected directly into the distribution grid if the correct calorific value can be obtained (Lewis et al., 2014). For so-called wet gas, processing at an existing large-scale facility will be required, since the steps are significantly more complex. For the proposed wells in the North of England, the current gas processing facilities could be used. But wells in the South of England it is likely that at least one new processing site will be required. The analysis reflects the worst case i.e. new gas processing facilities are required. If the quantity of shale gas produced exceeds current processing capacity, then new facilities will be required. Only if the Northern fields (alone) are producing within the current processing are the risks minimal at this stage. Instead of decommissioning a shale gas site, there are proposals to reuse the subsurface infrastructure for low temperature thermal energy storage (Westaway, 2016b).

Stage 4

We judge this to be the same as for conventional gas (section 6.2).

Stage 5

As the distribution of gas is likely to be independent of the origin we suggest that the description of the gas distribution network set out in section 8.1.3 will be valid for Gas (unconventional), and we do not see the need for any deviations from the description for electricity distribution set out in section 8.1.18.1.1.

Stage 6

For the use of electrical devices we do not see the need for any deviations from the description set out in section 8.2.1. For heat we consider the use of onsite systems for this fuel and do not see the need for any deviations from the description set out in section 8.2.2.

6.4 Oil

A synthesis report by Larson et al. (2012) suggests that global reserves are increasing, but there is a significant mismatch between the locations of supply and demand. Control over these reserves rests with state actors. Over 90% of the proven and probable reserves are owned by nations or national oil companies (Heede and Oreskes, 2016).

Exploring for, producing, processing, and supplying oil and its derivatives is a mature global industry. Technically and logistically complex projects requiring expensive equipment characterise the supply chain, leading to high impact at micro and macro economic levels (Fernandes et al., 2010). By the same token, this exposes the industry to risk with Fernandes et al. (2010) suggesting that the key areas of risk are from business operations, technical operations, and finance. The capital intensive nature of the oil business is exacerbated by the need for frequent reinvestment. Mitchell and Mitchell (2014) describe the industry as being in perpetual crisis. The UK became a net importer of petroleum in 2013 (BEIS, 2017c), therefore the scale of the causes of risks arising from elsewhere are important. It should be noted that the security afforded by trading internationally is a separate discussion from whether risks arise from the UK's use of oil as a fuel.

The production of fuels for vehicles is relevant for passenger and light goods vehicles, heavy goods vehicles, buses, locomotives, aircraft, and shipping. Each requires a different grade of refinery product, but the supply chain is identical. In Stage 6 (Use) we will concentrate on road vehicles and principally passenger and light goods vehicles.

One notable variation for vehicles is the production of marine bunker fuel for shipping, but it forms a small proportion of the UK market. Bunker fuel has a wide range of molecular weights and is mostly the residual from the oil distillation process. Although marine diesel engines are relatively efficient due to the low rate of revolution and long crank length, the emissions standards are much weaker than for road vehicles. Thus there is little incentive to process bunker fuel into a cleaner fuel.

Stage 1

The exploration for oil is more capital intensive than many other fuels, particularly in the off-shore environment where wells are moving to deeper water (greater than 150m). Although the risk is elevated, delays are most likely only to be short-term. Likewise for the cost and availability of the specialist equipment required. The UK oil industry receives investment allowances and other financial support for geophysical surveys which in part reduce the costs of exploration (Bast et al., 2015).

The move to deeper water or other less accessible sites suggests that the risk of difficult physical access is manifest, however, the impact remains short-term and recoverable. The quality of the fuel source is a recognisable risk; less accessible deposits are more difficult to assess accurately. Should a test well prove to be too poor quality, the well will be abandoned, thus we judge the impact major in such a case. Oil is an exhaustible resource (Bentley, 2002; ITPOES, 2010) and the UK is no exception with discoveries on the continental shelf getting progressively smaller. Despite this, the mechanism for reaching peak oil remains in debate. Hubbert (1956, 1981) suggested that the ability to extract and supply will peak, Brecha (2012) prefers a hybrid approach of logistics curves and cost, whilst Verbruggen and Van de Graaf (2013) suggest inducing ‘peak demand’. Bentley and Bentley (2015) and Sorrell et al. (2009) warn of the pitfalls in data sources and Speirs et al. (2015) point out the use of incommensurate methodologies for classifying resource availability.

Although oil deposits are geographically widespread, not all grades of crude are equally distributed, requiring oil to be a globally traded commodity. However, many producer nations score poorly in the World Bank governance index (Table 6.2). At the exploration stage the risk presented by the variability of social stability (e.g. Khatib, 2014) and of poor institutional governance is moderate since withdrawal could be fast. On-going military action (e.g. Yenikeyeff, 2008) would prevent even initial exploration. The risk posed by on-going threats of disturbance or disruption once a large scale production facility has been established (Stage 2) is considerably greater. Chatham House (2016) suggest that even at the exploration stage there is risk in selecting the most appropriate partner, particularly for nations as ‘emerging producers’ with previously uneconomic small oil deposits (Patey, 2015). Disputed landrights or ownership are a risk which would prevent an exploration project from commencing, but usually would not arise during a project. Analysis by Wegenast (2016) suggests that the onset of civil unrest with production is statistically significant where the extraction is carried out by state-owned companies. We have assessed this risk as moderate as disputes are more likely to arise with emerging producer nations (Butcher, 2013).

Rank	**Country**	**Total Proven Res, t ($x10^9$)**	**Share**	**Governance Score†**	**State-owned**
1	Venezuela	47.3	17.9%	-1.40	Yes
2	Saudi Arabia	36.6	15.7%	0.25	Yes
3	Canada	27.2	10.0%	1.85	No
4	Iran	21.6	9.3%	-0.19	Yes
5	Iraq	20.1	8.8%	-1.27	Yes
6	Russian Federation	14.5	6.3%	-0.08	Yes
7	Kuwait	14.0	6.0%	-0.17	Yes
8	United Arab Emirates	13.0	5.8%	1.40	Yes
9	Libya	6.3	2.9%	-1.77	Yes
10	USA	6.0	2.9%	1.55	No
11	Nigeria	5.1	2.2%	-0.96	Yes
12	Kazakhstan	3.9	1.8%	0.01	Yes
13	China	3.5	1.5%	0.42	Yes
14	Qatar	2.6	1.5%	0.74	Yes
15	Brazil	1.9	0.8%	-0.29	Partial

† Estimate of governance, ranges from approximately -2.5 (weak) to 2.5 (strong).

Table 6.2 Countries ranked by total proven (currently economic) reserves as of 2017 end. Sources: (BP, 2018; World Bank, 2018).

Stage 2

At this second stage, exploit encompasses production and transport. Following the location of an oil reservoir there is a significant amount of skilled work preparing it for production, more so than many other fuels. Then the oil can be brought to the surface by drilling wells, but this may require the use of water or steam, and CO_2 (re-)injection. The produced oil usually requires on-site conditioning by removing water, separating any sand and other solids, and reducing the vapour pressure by separating any light fractions. Acidic components are also separated, though UK crude contains very little sulphur. Then the oil can be shipped or piped for refining (Stage 3, conditioning).

The UK supply chain strategy (OGA, 2016a) recognises lack of access to finance as a risk. Despite the high level of investment required, we judge that risk caused by a lack of access to capital to be moderate. The principal mitigating factors being the size and distribution of the demand for petroleum products and that the investment is spread over a long period. However, Hilton (1992) warned of a *"credit crunch"* with the availability of financing being more important than the price of the money (borrowing costs). The UK oil industry receives 'field allowances' and reduced taxation which lower the costs of operating off-shore (Bast et al., 2015). Upstream capital expenditure follows the market price for any particular weight of crude (Humphries, 1995) with syndicated debt as the most widely used financing instrument. When considering financing (Stages 2 and 3) the investment is often based on projections of NPV which arises because of a mismatch between planned and actual investment at implementation (Vianello et al., 2014). According to Salameh (2000) there is also risk in over-investment giving rise to excess capacity, whilst Tempest (1993) noted that a lack of investment leads to a lower rate of return. These points are encapsulated by Carruth et al. (2000) in considering the irreversible nature of large-scale investment. In the long-term, Bentley (2002) maintains that the main risk to investment is peak oil. Being unable to agree a price for permits is also a moderate risk (Stroebel and van Benthem, 2012) which may occur but should only lead to short-term delays. An associated risk for the licensee is the bidding process which may lead to paying more than the profit-maximising value (Kretzer, 1993). The costs of decommissioning are usually subject to legislative constraints at the end-of-life of the installation rather than construction. Ekins et al. (2006) describe well the complexities of decommissioning which give rise to uncertainty in the costs. Salter and Ford (2001) recommend a holistic assessment, but recognise that cost-benefit analysis cannot capture the full value of the ecosystem. For onshore wells, there is a possibility to defray decommissioning costs by repurposing wells for geothermal energy extraction (Gluyas et al., 2018), however, Nian and Cheng (2018) suggest that only fields with multiple wells would be economic. The UK decommissioning delivery strategy (OGA, 2016b) recognises cost uncertainty as a risk. Whilst the costs are not likely to be insurmountable, they could cause delays.

As the ‘easy’ oil is gradually exhausted, physical access is already becoming more difficult, for example drilling in deeper waters and/or in climates of extreme cold (Henderson and Loe, 2014). The industry has already demonstrated that operations can be carried out in extreme conditions, so we judge that sustained delays may occur but probably will not prevent a project from starting. A consequence of operating in such conditions is that the risk from natural hazards is greatly increased. Between 2004 and 2008 five hurricanes only in the Gulf of Mexico destroyed 181 structures (Kaiser, 2015). In addition, natural hazards have forced the abandonment of wells (Kaiser, 2015; Krausmann et al., 2011; Petrova, 2010). Climate change is likely to affect a wider range of existing facilities (Cruz and Krausmann, 2013). Although oil production is intensive in its use of water (USDoE, 2014) most geographical areas where oil is extracted are not facing water scarcity, with the notable exception of the Middle East (Mielke et al., 2010).

Although a mature industry where incremental improvements in technologies and practice might be expected to be the norm, the oil and gas industries have remained innovative. Hassani et al. (2017) group innovations into three categories with (cited) examples, namely cost reduction and time-saving, efficiency gains, and sustainable growth. The latter category is concerned with lowering environmental impact for the most part. Hassani et al. include the development of supercomputing and big data analytics as innovations in addition to process engineering improvements. Some of the drive for innovation has been dictated by the increasingly physical access to deposits with, for example, horizontal drilling and operating in several kilometres of water now being common techniques. Further innovation may come from seabed well-head operations and robotic techniques. However, Duch-Brown and Costa-Campi (2015) argue that stronger environmental policies could enhance innovation in the oil and gas sector. A barrier which they identify is that policies tend to be designed and implemented nationally, while the level of international co-operation is insufficient. There is also some evidence that large-scale incumbents across the energy sector inhibit innovation (Costa-Campi et al., 2014). In the UK, tax credits are available to companies for R&D on upstream activities (Deloitte, 2013). Thus we suggest that this cause of risk is moderate. Likewise for the manufacturing of the required systems, the market is large and globalised.

The next key risks are those in the political category, most notably lack of social stability (El-Katiri et al., 2014) and poor institutional governance (Dannreuther, 2015). Several oil-producing regions have been subject to social unrest. Sometimes separately, producer nations have been involved in, or subject to, military conflict (Lu and Thies, 2013). A lack of social stability may become manifest through a lack of law and order resulting in the sabotage of facilities (Anifowose et al., 2012; Yeeles and Akporiaye, 2016), the kidnap and ransom of employees (Eke, 2014), or piracy (Liss, 2011). At the political level Chatham House (2016) suggest that transparency and accountability are key factors. Risk may arise through disputes between nations over the governance of transnational infrastructure such as pipelines even though bi- or multi-lateral agreements have been reached (Yafimava, 2011). Frynas (2012) found that Government regulation played a significant part in oil spill prevention, but that corporate social responsibility had a much less significant role. Also of importance are the governance of international environmental legislation for shipping (Lister et al., 2015) and the national registration of ships (Miller et al., 2015). Putte et al. (2012) suggest that the scale and intensity of investment for oil and gas exposes companies to greater political risk, especially those operating outside of OPEC. For example corruption through theft of oil (Katsouris and Sayne, 2013) and the expropriation of assets if product prices rise more than anticipated (Stroebel and Benthem, 2012).

Even in the wake of a disaster such as the Deepwater Horizon (Gulf of Mexico) platform blowout, the risk of significant public concern may not be long-lasting (Mukherjee and Rahman, 2016). However, they found the statistically significant indicators which could give future campaigners starting points for engaging the citizenry. The decommissioning of Brent Spar storage buoy (North Sea), whilst a publicly controversial episode (Löfstedt and Renn, 1997; Rice and Owen, 1999), did have long-term effects on legislation (Side, 1997). Chatham House (2016) suggest that for community engagement trust is a key ingredient. Conventional oil in the UK does not attract significant attention as most is off-shore. Should protest occur, we judge that any delays or disruption are recoverable.

A lack of technicians and engineers is an issue for many nations, including the UK (Energy Institute et al., 2008). Many producer countries or regions rely on overseas staff and technologies (Khatib, 2014). For the UK we suggest that the basic levels of education required are available, but that a lack of higher levels is occurring with the mismatch being made up by importing engineers from overseas. The UK supply chain strategy (OGA, 2016a) recognises experienced staff leaving as a result of declining production as a risk. There is some possibility of redeploying those with drilling experience to deep geothermal developments (Gluyas et al., 2018).

Pollution events not only occur following natural hazards, technical failures (Haney et al., 2014), well barrier and other integrity failures (Davies et al., 2014), flaring and venting (OGUK, 2016), or day-to-day operations (Baumuller et al., 2011), but also from fugitive emissions of various GHGs including CO_2 and methane (Heede and Oreskes, 2016). Incidents also occur during maritime transit (Banks et al., 2008; Goerlandt et al., 2017; Kirby and Law, 2010; Neuparth et al., 2012), but Burgherr (2007) reports that the number of incidents has been falling since 1970. Kontovas et al. (2010) attempt to assign costs to spills, though this is controversial. Major pollution events can bring a temporary or prolonged cessation to operations, for example the Deepwater Horizon blowout (Douglas, 2011). For UK operations it is mandatory to report hydrocarbon releases to the HSE and to BEIS. The chemicals released (deliberately or accidentally) assist in drilling, production, and pipeline operations and maintenance. They include demulsifiers, corrosion and scale inhibitors, water- and oil-based drilling lubricants, oxygen scavengers, and biocides. Between 2006-2015 the total number of reported releases (of all severities) has fallen from 190 to 91, but the rate per million barrels of oil equivalent produced per day (Mboe/d) has not declined (HSE, 2016). The rate between 2006-2015 is 69±10 Mboe/d. However, the tonnages are high, approximately 103 Kt in 2015, of which 72% was from drilling activities (OGUK, 2016). Approximately 3-4 times this mass is returned to shore for processing. The majority of these chemical releases are classified as posing little or no risk by BEIS. The OGUK (2016) environmental survey claims that 17 t of oil (product) was released in 2015, but approximately 2300 t was released in contaminated water as part of the production process. We consider the consequence from pollution events as a cause of risk to be high.

The risk of being unable to neutralise waste at the decommissioning stage is likely to occur. The oil and gas industry is mature as a whole, but experience of decommissioning offshore installations is still growing. Even in jurisdictions with good governance, incidents such as Brent Spar (Rice and Owen, 1999) shows that there are gaps in understanding the marine environment (Gage and Gordon, 1995) with Salter and Ford (2001) suggesting that a multidisciplinary approach must be taken. Analysis of environmental impact statements by Anifowose et al. (2016) shows significant deficiencies at the decommissioning stage. Drill cuttings stored on the seabed are noted by Ekins et al. (2006) as a difficult residue with which to deal. Even when decommissioning is complete Boothroyd et al. (2016) measured elevated levels of fugitive methane in soils above 30% of abandoned onshore wells. We judge that the risk of being unable to neutralise waste at decommissioning is high, particularly as the knowledge of long-term effects is not understood.

Operational failures may occur, even if with low frequency in well regulated jurisdictions. However, should a catastrophic failure occur, such as Piper Alpha (Broadribb, 2015) the incident could close their operation completely. Overall, fatalities in the oil industry are lower in comparison with other energy industries (Sovacool et al., 2015). For all UK offshore activities there have been a total of seven fatalities in ten years, with the number of other injuries also falling (HSE, 2016). Though exploration and production (Stages 1 and 2) are safer than other stages (Burgherr and Hirschberg, 2014) maritime transit of oil shows a greater risk. But, according to Lordan et al. (2015) this masks the fact that the average number of fatalities is increasing in non-OECD nations and decreasing in OECD countries (likewise for the number of severe accidents). In the UK, one reason for this is the legislative framework (OGA, 2016c) and inspection regime (HSE, 2006). There is evidence that developing producer nations are attempting to follow best international practice (Mendes et al., 2014). In comparing the UK and US safety regimes and practices Barua et al. (2016) noted that although the philosophies were different, both had advantages and disadvantages for reducing accidents and technical failures.

Stages 3-4

The refining of crude oil is a well-understood industrial process with about 85% going to transport fuels and 15% to petrochemical feedstocks for non-energy purposes. Refineries are processing and conversion installations thus Stages 3 and 4 are combined. Refineries are distributed globally and located near to the market since it is logistically simpler to transport the crude only. As of 2017, the UK has six operating refineries with a total processing capacity of approximately 232,600 m^3 per day (1.47 Mbbl per day), providing about 85% of UK oil consumption (UKPIA, 2016). The refining process has five principal elements each of which require energy and other resource inputs, and produce waste:

- Distillation (by heating) separates the crude oil into different fractions.

- Conversion and reforming which adjust the yields of these different product streams.
- Clean-up processes such as desulphurisation.
- Blending to meet product specifications and legal regulations.

The newest refineries are 2-4 times larger than the UK installations, with costs into several billion USD. This results in the growth of global refining capacity being quantised – the demand for the output of a new refinery takes time to become apparent. Domestically, UKPIA (2011) recognise that future investment needs to take account of risks posed by environmental standards and legislation, tightening product specifications, and what they term 'demand destruction'. Therefore, the risk posed by a lack of access to capital is of high significance. Most components and operational units in a refinery are widely used in the chemical process industries, however, units such as a catalytic cracker are designed to be optimised for a feedstock and may be subject to significant but recoverable delays in production and installation.

Although in the UK we judge the risk posed by natural hazards to be low, we note that flooding is a risk (Krausmann et al., 2011) and lightning strikes at crude and refined product storage facilities (Wu and Chen, 2016). The only issue of critical materials availability is for platinum group elements used in catalytic cracking units (Nieto et al., 2013) and we judge this as a low risk. However, substituting platinum catalysts is very difficult.

Should a new site for a refinery in the UK be proposed we would expect significant public opposition. Although disruption to production occurred, the fuel duty protests in the early 2000s were not primarily aimed at the refinery operators. The protest concerned prices and is discussed in stage 6.

The likelihood of a pollution event occurring is high. For example, using Pollution Release and Transfer Register data Gouldson et al. (2014) showed that releases of benzene from UK refineries was 3-4 times greater than the rest of the EU15 average. An indirect pollution event measured amongst UK oil refinery workers was an increased incidence of mesothelioma (Sorahan, 2007). Lekka and Sugden (2011) demonstrate that human error and implementing high reliability principles is a key factor in avoiding incidents leading to a pollution event, and Jain et al. (2017) suggest that no national legislative or safety approach is better than another. Therefore we judge that there is an ever-present risk. In terms of operational failures leading to accidents with fatalities, analysis by Burgherr and

Hirschberg (2014) suggests that the economic cost per kWh for oil are about twice that for renewables. The likelihood of a significant failure occurring is low, but it has the potential to close the facility (Jain et al., 2017). Oil refineries generally require steady and continuous operation. Thus disruption to the infrastructure for inputs of raw materials, water, heat or electricity, and for the outputs of intermediaries or final products, can cause short-term (but recoverable) impacts.

Stage 5

Pipelines in this context are restricted to the national distribution network for aviation kerosene to airports, and to petrol and diesel from the Stanlow and Shell Haven refineries which are distributed to a small number of regional depots.

For pipelines we note a few deviations from the description set out in section 8.1.3. We judge that the impact from a lack of access to capital may be more significant than for gas networks. This is on the basis that there are fewer oil distribution pipelines and only to large specialist sites. It is unlikely that a new pipeline will be built, but maintenance and renewal of the current network needs to be conducted. Petrol, diesel, and other petroleum products are distributed by road tanker. We suggest that price volatility of steel may have greater impact than for polyethylene. As the network is significantly less extensive than for gas, we suggest that should a new oil pipeline be required the risk of denial to access sites may occur and cause significant (but recoverable) delays. This would be coupled with significant public concern. Whilst a pollution event such as the fire at the Buncefield fuel depot (Mather et al., 2007) could be significant, the disruption is likely to be recoverable.

For the tankering of petroleum products we do not see the need for any deviations from the description set out in section 8.1.4.

Stage 6

We do not see the need for any deviations from the description set out in section 8.2.3.

7 Assessing Risks for Non-renewables (Other)

The remaining non-renewables are Demand Reduction, Nuclear (fission), Thermal (geological), and Waste. Mostly the risks discussed are those assessed (Appendix A) as having the highest risk rating, but also some of those with moderate ratings. The exception is Demand Reduction, since it is unusual to consider it as a fuel.

7.1 Demand Reduction

We have defined demand reduction (DR) as comprising two elements: energy efficiency through use of or redesign of devices, and change in behaviour by people. This excludes small-scale generation technologies (covered in other sections) but does include technologies such as a metering and control (Hinnells, 2008). Eyre (2011) notes that one of the main difficulties in reducing demand is that the percentage cost savings for the individual consumer are often less than the percentage carbon savings benefiting society as a whole. The energy efficiency of homes and businesses is in part about the interaction of technical innovations and the willingness of people to adopt them, and adapt their behaviours. Defrosting a freezer (Shove and Southerton, 2000) is an example of how technological innovation changes social practice and aids energy efficiency; automatically preventing frost build-up lowers energy use.

In their international comparison of measures and policies the IEA (2017) claim that energy efficiency has improved the economic competitiveness of energy-intensive industries. Other claims made for improving energy efficiency include: reducing energy poverty and GHG emissions, and improving thermal comfort, health, well-being, ES and economic productivity (POST, 2017). A useful overview of the relevant UK policy since the early 1970s is given by Mallaburn and Eyre (2014), and Hanmer and Abram (2017) stress the need to learn lessons from previous transitions. Most studies on DR are for buildings (Palmer and Cooper, 2014), but also of importance are industrial processes (Griffin et al., 2016, 2017, 2018) and heat (Eyre, 2011; Delta Energy & Environment, 2012; DECC, 2013b). Monahan and Powell (2011) claim that reducing heating demand will have the greatest effect on reducing GHG emissions. The third principal source of energy demand is transport. According to Upham et al. (2013) low-carbon transport cannot be realised by technology alone, yet policy remains focussed on technology innovation and not on transport and mobility as a service. Furthermore, the widely discredited ‘predict and provide' model persists in Government policy albeit sometimes disguised (Goulden et al., 2014).

Shove (2003) contends that the population desires convenience which happens to demand energy. Recent detailed studies have shone light on household activities, practices, and the enabling products (Butler et al., 2016) which gradually become normalised (Shove and Southerton, 2000). As practices change there is a ratcheting-up of demand which acts to recalibrate societal expectations (Shove, 2003). In a meta-study for DECC, RAND Europe (2012) drew three conclusions that:

1. programmes combining information feedback on comparative consumption alongside energy efficiency advice did lead to residential DR,
2. knowing pre-intervention consumption had a statistically measurable effect on the level of energy saving (independent of other factors), and
3. the structure and level personalisation of the intervention affect the level of energy saving.

Due to the complications of small studies and the constraints imposed by field studies Hamilton et al. (2017) make a compelling case for paying special attention to data management and the importance of using multivariate statistical methods. We agree with Sorrell (2015) that *"Reducing energy demand may prove more difficult than commonly assumed"*.

The stages for DR are less distinct than for other fuels, and their aggregation can be thought of as follows. Exploration (Stage 1, measuring potential) is about public/consumer surveying or the theoretical modelling of energy efficiency devices or processes. Stages 2-3 (exploit and condition the fuel) can be considered as small-scale tests or pilot studies (a few households to city-wide), the planning (or modelling) of major activities, or energy efficiency devices/processes at the research stage of development. Stages 4-6 (convert, distribute, use) are more closely associated with deployment of activities, policies, devices, and processes, or the investigation and evaluation of large-scale (national) or mainstream energy-using activities. Inevitably there is blurring at the interfaces, reflecting the nature of social systems. Furthermore, incorporating explicitly social practices in this assessment leads to considering their lack of take-up or the rebound effect (Sorrell, 2009) as a 'technical failure'.

Stage 1

Although some companies are creating products and services, measuring the potential, for the most part, is at the research stage in the UK. The main problem identified is the lack of continuity of funding (De Laurentis et al., 2017), interpreted as lack of access to capital. For energy efficiency products and services, however, Stiehler and Gantori (2016) report that the market may grow by 7-8% p.a. One example of this potential is the comparatively poor U-values of the UK's housing stock (Guertler, 2016).

In the context of DR, quality of fuel source can be interpreted as a combination of the variability of savings gained in trials and the headroom for potential savings. Strictly the latter is abundance or resource availability, but pragmatically it does not make sense to use this distinction because of the levels of uncertainty in such estimates. From the individual studies (modelling and trials) described below, we suggest that the 'quality of the fuel' as a cause of risk is in the highest category – the risk is likely to occur and that the variability may give rise to major delays in exploiting this 'resource' i.e. designing and implementing effective DR programmes.

A synthesis report compiled by DECC (2013b) suggests that interventions in the home may save between 1-10% depending on the sophistication of the scheme, and Rosenow et al. (2018) claim that through a combination of current technologies – including energy efficiency – a 50% saving could be made. LCICG (2016a) estimate that a total of 64 $MtCO_2$ could be saved in residential buildings. A potential saving of 7% of household electricity use could be made by eliminating the stand-by mode of devices (Coleman et al., 2012). However, Buchanan et al. (2015) observe that there is little evidence that feedback via in-home displays reduces demand. There is some evidence that installing residential PV may also reduce demand by raising awareness of energy use and cost (Keirstead, 2007). Looking to the second half of this century there is uncertainty in the level of demand for cooling in dwellings due to climate change (Gupta et al., 2015). Both electricity and gas are used for space heating, though gas is the majority in the UK; city-wide mapping has been conducted by Gupta and Gregg (2018). A field study by Wyatt (2013) suggested that installing a condensing boiler and cavity-wall insulation simultaneously might yield a reduction in gas use of 14-20%, but only 8-12% when the boiler was in combination with loft insulation. The quantity of hot water use (Allen et al., 2010) and heat use (Brook Lyndhurst, 2012) vary between similar households. The patterns of use of heating vary substantially (Huebner et al., 2013a, 2013b, 2015; Kane et al., 2015), in part explained by a wide range of system set-point temperatures (Jones et al., 2016). Experiments using zoning of dwellings might save approximately 12% of energy for space heating (Beizaee et al., 2015). Usually the size of the DR quoted are what could be described as ‘peak’ values. Batey and Mourik (2016) show the difficulty in retaining the levels of reductions post-study i.e. the quality of the fuel source can degrade quickly with time.

Commercial buildings have received less interest. Using US data, modelling by Sun et al. (2016) estimates that energy demand for cooling, lighting, space heating and water heating could be reduced by 15%, 5%, 16%, and 20%, respectively by 2035. Other estimates suggest that a total saving of 70 $MtCO_2$ could be made by 2050 (LCICG, 2016d)

For industry, modelling suggests that by 2050 it may be possible to achieve total energy reduction of 77% (Fais et al., 2016) and 500 $MtCO_2$ (LCICG, 2012c). However, a case study of a cement production facility showed that a 4% reduction was possible at that site (Summerbell et al., 2017), and Mylona et al. (2017) show that using better management of the HVAC system in supermarkets a 4% reduction in electricity use may be possible. A wide range of savings have been identified throughout the entire food chain (Tassou et al., 2014).

Since 2002 the number of trips shorter than one mile made by motorised transport has increased by about 5% and in 2016 the proportion of trips between 1-2 miles made by private motorised transport is about 60% (DfT, 2018). Also using modelling Lovelace et al. (2011) examined energy savings from a range of scenarios by which short trips could be switched from car to bicycle, and Anable et al. (2012) suggest that the distance travelled could be reduced by 74% by 2050. The seemingly misaligned theoretical savings and field measurements suggests that the ‘quality of the fuel’ as a cause of risk has been underestimated. A very under-researched topic is energy use for shipping. Much of the discussion would either fall outside the system boundary of our study or be incorporated within stages defined as ‘global’. However, Walsh et al. (2017) note the trade-off between speed and patterns of demand for goods and services. They conclude that deep decarbonisation of maritime transport can only come about by a fleet-wide speed reduction.

Turning to the causes of risk in the innovation category, Hannon and Skea (2014) make a compelling case for the necessity of public support for basic research into assessing the possibilities and scale for DR. The risk may occur and without public funding many programmes would suffer significant disruption, therefore we judge this to be a moderate risk.

We consider that the risk of a changing policy and regulatory framework may occur and have a short-term effect at this stage, a study by Ó Broin et al. (2015) suggests that further policy interventions will be required as price signals will not be sufficient to achieve DR. Significant public concern may arise (Brook Lyndhurst, 2012), though at this stage it may be more accurately described as resistance to change. Gill et al. (2011) conclude that residents need 'recalibrating' as to what high and low means in terms of energy use.

Stages 2-3

The services to deliver behaviour change are not part of a well functioning market because the understanding is at the basic research stage. Some energy efficiency products are in a mature market, but the design for low carbon homes and some products are not (Heffernan et al., 2015). Overall we consider this cause of risk to be moderate, but the impact could be sustained if the effects of behaviour change programmes do not prove to be sustained and therefore not scalable. Macroeconomic modelling by Figus et al. (2018) suggests that reductions in fuel use for private transport will not be achieved through technical efficiency improvements, but by either travel mode switching, or wholesale substitution of fossil fuel for electric or hydrogen, say.

Although we do not consider access to capital a significant problem at this stage, it is worth noting that the payback period is important for industry (Eiholzer et al., 2017). The expected return-on-investment periods for efficiency projects in industry are short – perhaps one to two years. If the payback is quick there is no risk of lack of access to capital, but longer than, say, three years will be very difficult to raise the required investment.

When considering innovation in transport planning to reduce energy use, Banister and Hickman (2013) recommend the use of robust scenario methods at all stages of decision making and policy planning. However, these principles are not applied universally – in the policy context, this can be considered as an example of weak technology transfer. Killip et al. (2018) observe technology transfer issues for low carbon in the construction industry, specifically for supply chains, designers, and installers. They suggest that these are overlooked at the policy level, thus there is not a sufficiently strong driving force to enact change. There is strong evidence of the significant scope for innovation in, for example, new and renovated domestic buildings (Killip et al., 2014; LCICG, 2016c), non-domestic buildings (LCICG, 2016d), energy efficiency policy (POST, 2017), and demand management technologies for industry (Dyer et al., 2008). Despite this open R&D landscape Gupta and Gregg (2012) claim that public subsidy in housing research is essential i.e. a lack of public subsidy is a significant cause risk for future development. Likewise, Griffin et al. (2012) showed that the UK's energy efficiency demonstrator scheme was responsible for 25% total industrial DR between 1979-89.

The rate of improvement in energy efficiency of dwellings is not only related to the rate building at the best current standards but also the rate of demolition of inefficient stock (Boardman, 2007a). This lack of capacity in the construction of housing has been prevalent for a significant period in the UK (Boardman et al., 2005; Boardman, 2007b). Planning also plays a role in the insufficient rate of housing construction (Boardman, 2007a; Heffernan et al., 2015) and industrial facilities (LCICG, 2012c).

In considering the political category of risks, there is some overlap with stages 4-6., but this section concentrates on the design of measures and programmes and less about the results of market-led products and services. In the policy-making process (Boardman, 2007a; Heffernan et al., 2015) suggest that the ability to use research feedback requires robust assessment of pilot and other schemes, but that such assessments are contextual for both consumers and policy-makers. Furthermore, Rosenow and Eyre (2013) note that *"…UK energy efficiency policy is very fluid…"* and remains true currently including for road vehicles. The importance of policy on pricing and taxation instruments is emphasised by Brand et al. (2013) who conclude that policy design should concentrate on incentive schemes with strong signals to prioritise low carbon systems. In their thorough review of European community-based behaviour change initiatives (Axon et al., 2018) observe that communications are the focus of most programmes with little emphasis on the role of fiscal support or regulation and legislation. Modelling work by Figus et al. (2017) suggests that it is hard to simultaneously satisfy all targets and expected outcomes, but nevertheless Dato (2018) makes the case that *not* combining policy for energy efficiency and renewable energy presents a risk. Boardman (2004) notes that weak efficiency standards have long-term effects as devices take many years to exit the stock, and there is evidence that building regulations are not strictly followed (Boardman, 2007a) though this may in part be due to the standard of construction skills in the UK. Stiehler and Gantori (2016) recognise that stricter regulation would be a driver to increase energy efficiency and increase market opportunities.

The risk of public concern of energy technologies and services aimed at achieving DR has already occurred, for example in smart metering (Buchanan et al., 2016) and dynamic tariffs (Darby and Pisica, 2013). The provision of information alone is insufficient (Lange et al., 2014; Busic-Sontic et al., 2017) which is described by Stephen Axon (2017) as the 'information-involvement gap'. An example is that of the Kirklees Warm Zone scheme where even though the interventions were free there was less than 100% take-up (Long et al., 2015), with the main concern being the physical disruption to the home. When questioned about the possibility of adopting heat networks members of the public liked the idea that someone else would be responsible for the maintenance, but disliked the necessarily long contracts and the level of disruption. Trust has emerged as an issue in the design of programmes for DR e.g. energy advisors (Owen et al., 2014) and Government and businesses (Cotton et al., 2016). However, work by Volland (2017) on residential consumers indicates that greater trust in institutions is associated with lower energy use and a greater tolerance to risk is associated with higher energy use.

Within the Technical risk category, we can define the rebound effect as a failure of policy design and operation. Using a combination of modelling tools Chitnis et al. (2013) suggest that a shift to a low carbon energy system will lead to an increased rebound effect. In a small field study, Jones et al. (2016a) demonstrated a rebound effect of space heating in social housing. And an example from the long-running smart meter design process Pullinger et al. (2014) claim that the developing SMETS smart metering standard will not facilitate the best practice and knowledge in consumer feedback techniques. The concept of the 'prosumer' (producer-consumer) is widely considered as positive for the take-up of microgeneration, however, Ellsworth-Krebs and Reid (2016) question whether this is just a technical fix which could be considered in opposition to demand reduction.

Stages 4-6

There is evidence of a lack of well functioning markets. For improving energy efficiency Pyrko and Darby (2011) note that the ownership and operations of networks are problematic and particularly noticeable in the UK smart meter roll-out programme. The energy service company market is noted as having high transaction costs which inhibit market entry (Bertoldi and Boza-Kiss, 2017). Two other indicators of a weak market structure are *"green over-pricing"* observed by Heffernan et al. (2015) and low energy price elasticity e.g. Eyre (2013). The lack of access to capital is described in general by Rosenow and Eyre (2013) and POST (2017). According to Booth and Choudhary (2013) risk arises because the benefits are not all measured in the reduction of consumer energy bills, but financially unquantifiable improvements such as thermal comfort or health. They claim that only loft insulation and draught excluders show an NPV greater than zero. In the residential housing sector there are specific issues for private landlords (Reid et al., 2015), social landlords (Liu, 2018), adopting zero-carbon technologies (Caird et al., 2008), and renewable energy systems specifically (Dato, 2018). Dato also makes the case that poorer households need additional financial support, even for energy efficiency measures. In the previous stage we noted that the expected payback periods in industry for energy efficiency measures might scupper projects, but even if they go ahead access to capital may still be a barrier (LCICG, 2012c). In commercial buildings the rate of turnover of tenants and the rate of return for investors is noted by Elliott et al. (2015). We suggest that both the lack of well functioning markets and access to capital are moderate.

Although some areas of energy efficiency are mature, others – including retrofitable technologies (Gooding and Gul, 2017) – have plenty of scope. The energy efficiency of homes and businesses is in part about the interaction of technical innovations and the willingness of people to adopt them, and adapt their behaviours. This led Shove (1998) to question whether people really do have technologies *"transferred upon them"*. The somewhat reductionist process assuming that the transfer of energy efficiency technologies (for buildings) is simply about overcoming non-technical barriers may well be missing the point, and perhaps explains the hit-and-miss nature of the take-up of devices and practices. We judge this to be an underestimated cause of risk. The cost of financing R&D is widely accepted as requiring public support, but (LCICG, 2012a) add that due to the high absolute costs early adopters of industry energy efficiency measures may also need subsidies. Analysis of patents by Bonilla et al. (2014) shows the importance of public R&D (in addition to oil price) for innovation in diesel engines.

We suggest that the main risk for innovation in DR is optimism bias. For example, so-called smart homes have long been touted as a way to reduce energy consumption, but Darby (2018) suggests that this will simply lead to increased parasitic loads. Darby considers that smart homes have little to do with energy efficiency or DR. The introduction of simpler systems such as heating controls have also not realised projected savings (Shipworth, 2011). There is a well-documented performance gap with technologies and other interventions. Where this is about new proposed technologies (in the abstract) we consider this to be an issue of optimism bias and not the measured failure of installed systems or the rebound effect (risk of operational failure in the Technical category). Estimates or projections of energy savings carry uncertainty, for example, retrofitting of various solutions for dwellings (Loucari et al., 2016), Passivhaus standards (Johnston and

Siddall, 2016), the fabric performance of new-build dwellings (Johnston et al., 2015), and the performance of non-domestic buildings (Pritchard and Kelly, 2017). Batey and Mourik (2016) consider the performance explicitly to be a risk. In the light of the wide range of systems and situations where optimism bias manifests, we judge this to be a risk in the highest category with an impact that could lead to significant delays in energy efficiency improvements and DR.

The widely accepted changing policy and regulatory framework in the UK is acknowledged to extend to energy efficiency and DR in industry (LCICG, 2012c). An important, but subtle, observation is that UK energy policy is in conflict with the aims of DR (Sun et al., 2016) i.e. the targets are for CO_2 reduction, not DR. UK policy is supply-side dominated, the CO_2 target incentivises fuel-switching and increased renewable generation. Unstable policy and legislation (including unclear definitions) is hampering the ESCO market development (Bertoldi and Boza-Kiss, 2017), whilst O'Keeffe et al. (2016) observe discontinuities in policy and its objectives. O'Keeffe et al. focus on the UK Government's Green Deal scheme, noting that SMEs express concern about the Government's long-term commitment to the programme and the lack of a visible co-ordinating body. The lack of long-term monitoring of projects (Santangelo and Tondelli, 2017) can be viewed as not only a problem about measuring the potential for DR, but also a failure of regulation particularly as invariably public subsidies were supporting the projects. We suggest that this risk lies in the highest category.

The development and enforcement of codes and standards are a recognised risk in several areas of residential (LCICG, 2016c) and commercial buildings (LCICG, 2016d). Two examples are the current building regulations (Heffernan et al., 2015) and the installation of zero carbon technologies (Caird et al., 2008). The lack of standardisation is put forward by Fawkes, (2015) as a deterrent to investment. Finally, Gavin Killip (2013) calls for a regulatory body to draw together training, standard setting, and compliance for the house-building sector. Hamilton et al. (2014) note that legislation works and in the case of annual inspections of gas boilers in the private rented sector, has improved safety and efficiency. We judge that this risk is likely to occur, but it is most likely to have only short-term impacts.

In the context of DR, significant public concern manifests as lack of engagement or willingness to make changes. An important tool available to the Government is taxation and although it could be effective at driving policy for DR, it is deeply disliked by the citizenry (Eyre, 2013). Homeowners posses scepticism about the effectiveness of some new technologies (Ipsos MORI and Energy Saving Trust, 2013), and will not even undertake all of the easiest efficiency measures (Palmer et al., 2012). The latter may be due to the low level of importance they place on energy or the level of disruption caused (Rosenow and Eyre, 2013), or because of aesthetic reasons (Sunikka-Blank and Galvin, 2016). Although we have established that communication is a necessary but not sufficient criterion Bright et al. (2018) note its importance in deep retrofit of mixed tenure tower blocks. Another group of reasons for public opposition of lack of engagement with DR can be described as cultural. Conservatism is observed amongst professionals and customers in the house-building (Heffernan et al., 2015; LCICG, 2016c), commercial building (Scrase, 2001; LCICG, 2016d), and the industrial sectors (LCICG, 2012c). A particularly poorly understood factor is that of conspicuous consumption (Hards, 2013). Consumers may want to avoid the stigma of being labelled as *"stingy"*, or may use high-use devices such as tumble dryers to mitigate the risk of visitors being faced with an unsightly scene. The social gains of, say, a new kitchen outweigh those of energy saving measures (Dowson et al., 2012). Olaniyan and Evans (2014) suggest that for policies to successfully tackle DR they must address behavioural, lifestyle, and cultural factors. Despite a plethora of evidence for public concern, we also note that the UK economy's energy intensity per job has been falling steadily since at least 1990 (Roberts et al., 2019), as has the thermal demand per unit output (Roberts et al., 2015). This tension between home and work might be summed up as a lot of fuss by the public disliking change, but quietly the workforce get-on and adopt new technologies and practices without knowing or being bothered in practice. Thus we judge this to be a moderate risk with short-term impacts.

The main risk in the technical category is that of operational failure of which there are several components, some are engineering failures others are policy or behaviour 'failure'. Many authors identify the split incentive problem, which has several variants occurring in different circumstances. We can class this as a policy failure, since it is not clear where the responsibility lies between the parties and no policy framework exists to guide or instruct them. An example of the split incentive problem is the case of the landlord-tenant relationship in a multi-occupancy commercial building (Scrase, 2001; Axon et al., 2012; LCICG, 2016d). It is the landlord only who can improve the energy efficiency of the building, but it is the tenant who pays the energy bills (without the control over the building environment). The problem is similar in the private rented sector (Hamilton et al., 2014; Hope and Booth, 2014; Reid et al., 2015; LCICG, 2016c), with Dato (2018) investigating household investment in renewable energy systems specifically.

A variant of the split incentive problem arises in deep retrofit projects in mixed tenure tower blocks (Bright et al., 2018) where the question is whether the private co-owners should have to pay the bill for the improvements that can only be justified as wider community benefits.

The performance gap is well-documented and refers to either the modelled and measured performance (Marshall et al., 2017) or lower performance due to installation or operation issues (Dowson et al., 2012; Watson, 2015; Johnston et al., 2016), for example. An important observation is that there is no legal requirement to fix any performance gap in the finished building (LCICG, 2016c). Some operational issues of a building will be due to human factors (a 'behavioural failure'), other examples are data visualisation for industrial processes (Challis et al., 2017) and installers making engineering errors due the heterogeneity of installations (Fylan et al., 2016). Another common failure is retrofitting of low U-value cladding leading to over heating (Baborska-Narozny and Grudzinska, 2017). The rebound effect (Chitnis and Sorrell, 2015) is also considered as an operational failure in the context of DR, with Baborska-Narozny et al. (2016) showing that the marketing of PV systems as 'free green electricity' undermined DR, creating an unintended rebound. Turning briefly to transport, Brand et al. (2014) discovered that the provision of well-used cycle routes and increases in active travel did not lead to reductions in transport CO_2 emissions. Furthermore, the passenger vehicle rebound effect (general) is estimated as 26% (Stapleton et al., 2017). As this cause of risk has occurred and has the capacity to halt projects (particularly the split incentive problem), we place operational failure in the highest category.

7.2 Nuclear (Fission)

The similarities of nuclear fission and fusion are relatively few, thus we treat the two supply chains and technologies separately. Greenhalgh and Azapagic (2009) review the broad drivers and barriers for nuclear fission, and Taylor (2016) the history, in the UK context. An important observation to bear in mind for the UK when considering risks at all stages is how the debate is viewed in the public arena. According to Peoples (2014) the framing of new nuclear build as a "*security*" issue has given the impression that other concerns and risks should be overridden or down-played and be thought of as secondary considerations only. It should also be noted that the total life-cycle GHG emissions and whether nuclear fission is sustainable are strongly contested (Beerten et al., 2009;

Verbruggen et al., 2014). Dockerty et al. (2014) give an overview of the impacts on natural capital – broadly interpreted as pollution events in the technical category – across all stages. A review by DBIS (2013) gives useful high-level statistics about the UK civil nuclear industry.

In this fuel category we consider the well-understood uranium process using U-235, and the novel thorium (Th-232) process. Although there are proposals for thorium reactors which are completely different to those for the uranium-based process, we are considering the fuel source alone and not the technologies. Furthermore, as thorium does not contain sufficient fissile material to sustain a chain reaction it has to be irradiated in a neutron beam to produce U-233. Thus it is a hidden uranium process, but with less and different (though still long-lived) fissile products (Revol, 2015).

Uranium is most often extracted in opencast mines, but insitu processing of underground reserves is now technically possible. Some uranium-bearing ores are co-located with gold, silver, and copper. Thorium is abundant and present in low concentrations on all continents. However, the higher concentration (potentially economically viable) deposits are present principally in India, Australia, USA, Turkey, Venezuela, and Brazil (NEA and IAEA, 2016). The UK has no significant high concentration deposits. Thorium is co-located with many rare earth elements (REE) leading to significant additional chemical processing. At the aggregated level of this analysis there is no reason to consider the uranium and thorium processes separately. The main uranium deposits are located in Kazakhstan, Canada, Australia, Niger, Namibia, Russia, Uzbekistan, USA, China, and Ukraine (NEA and IAEA, 2016).

Stage 1

For Stage 1 the (global) market functions are in providing appropriate equipment and services to assess geologic deposits of uranium- and thorium-bearing ores; we consider there to be little risk or possible impact. Both elements are globally well-distributed (NEA and IAEA, 2016), with the largest deposits in Australia and North America. However there are significant deposits in Central Asia, West Africa, and the Middle East, thus denial of access to explore for resources might occur, but currently would have only marginal impact.

Some of the nations with reserves have poor ratings on the World Bank political stability index (World Bank, 2018). This too raises the likelihood of disruption to exploration activities marginally. The same is true for quality of institutional governance.

In some well-governed nations there may be public concern at prospecting for uranium and thorium resources, since this may lead to opencast mining operations. As this stage is exploration, we judge that the impact is likely to be insignificant.

In the exploration phase, most of the required expertise could be provided by a non-local workforce because the numbers of people required is necessarily small, thus we suggest that this is not relevant at this stage. There maybe a marginal requirement for some unskilled local labour in countries where educational standards are poor.

Stage 2

Following extraction, a certain level of processing is carried out near to the mining operation to minimise the quantity of waste materials being transported. This can be considered as equivalent to well-head processing for gas. Furthermore, as it is a distinct process from enrichment (Stage 3) we have included the analysis in Stage 2. In some mines it is possible to exploit insitu leaching processing using a similar chemical technique to that of surface processing. Both pose environmental hazards. If the mine is opencast, rock needs to be crushed, and ground to approximately 100 µm. Water needs to be used to reduce dust. The next stage uses a strongly acidic or alkaline solution to leach out the uranium content from the ore to produce a slurry. The tailings are then disposed of. The slurry is then filtered and the uranium extracted by ion-exchange. This concentrate has relatively low levels of radioactivity. Thorium being co-located with REE it could be considered as a by-product of mining other valuable commodities. Uranium is not so frequently co-located with other valuable commodities.. Uranium is a single industry resource and therefore entirely dependent on the demand from the nuclear industry.

The meaning of a well functioning market here is that for the supply of mining and processing equipment and components. Underground mining equipment is ubiquitous and we suggest presents no issues on availability. However, opencast mining is a large-scale operation. For example, the risk arising due to too few manufacturers of draglines or very large capacity trucks (a separate issue to manufacturing capacity) may cause short-term delays in the supply. The expense of mining operations is so great that if capital is not forthcoming a project cannot go ahead. For example, following the Fukushima incident, mining operations (Nickel, 2014) and investment in expansion (Komnenic, 2014) have been suspended. Thus must be assigned the highest impact level. Uncertainty of the costs of decommissioning and site remediation is likely to occur, but it is probable that this would only cause a short-term delay. This may change in well-governed nations if environmental requirements were tightened for new sites.

The mines are frequently located in remote areas with little infrastructure for power or transport. But these obstacles are only short-term and will not usually prevent a project from proceeding. The quality or variability of the fuel source is of some concern, especially for thorium as it is always co-located with other minerals. The lack of the availability of water is a notable risk. As the sites are usually remote, transporting wholly untreated ores is undesirable. The current methods for processing uranium ore require similar quantities of water to that of coal mining. All are an order of magnitude lower than coal (or gas) to liquids and several orders of magnitude lower than biofuels (Mielke et al., 2010). However, the mines and processing facilities are frequently in arid zones and it is likely that water will need to be transported to the site. For some underground uranium mines, it may be possible (or necessary) to use an in-situ recovery process. However, this requires a very large supply of water, often extracted from underground aquifers. We judge that in such cases a shortage of water could have a sustained, but recoverable, impact.

Like all other hard rock mining operations, uranium and thorium extraction is a mature industry. It does not require public subsidies and the equipment required is widely used throughout the world. Interestingly, the technology and processes for exploiting lower grades ores are in some cases becoming less complicated. A cost-effective process for extracting uranium from lower grade ores is to use heap leaching – it is simply not economically viable to use a more complex process on low grade material. Although research and development is required, deploying the process is limited more by environmental legislation than process innovation. As a mature industry with low margins there is little incentive to innovate, thus there is a risk that improving equipment and making processes more energy efficient is slow or lacking.

The denial of permission to access sites may form part of a negotiation and that it may lead to more than moderate delays. It is possible, though not likely, that the nations rich in uranium reserves will be subject to social unrest (World Bank, 2018). However, the resources are widespread across the globe with a number of well-governed nations in the ten largest producer/processors. Any disruption due to social unrest or poor institutional governance in a nation will mostly cause a medium-term supply problem. A cause of risk with potentially much greater impact is the lack of institutional governance. In extremis, this may close a mining operation or force a company to withdraw completely. Disputed land rights is an issue carrying risk in some areas, especially those in First Nation territories. Although this occurrence now may be unlikely, its impact could be moderate. The global nuclear industry is subject to significant public concern, mostly the location, operation, and decommissioning of reactor sites (discussed at Stage 4). Mining operations, independent of resource, may attract significant public concern and protest for different reasons, frequently environmental impact and employee welfare. But as the resource is spread globally, the impact is likely to only be short-term. Changing environmental protection regulations may cause some temporary disruption to supply from one of the well-governed nations, but this is likely to be short-lived. A lack of vocational skills in the workforce presents a moderate level of risk.

It could be argued that a pollution event at a single mine is of little consequence to the UK nuclear industry. If one operation is halted the global nature of the industry will supply the demand. However, there have been a number of significant episodes including in the USA (Voyles, 2015; Hoover et al., 2017). Thorium extraction also poses radiological risks (Ault et al., 2016). If sufficient pollution events occur this could affect supply, or an ES analysis could place value on avoiding fuel sources which give rise to such events. This issue is connected to the inability to neutralise waste at the decommissioning of a mine site. Although technology and processes are known for neutralising most of the tailings waste (solid and liquid), it may prove difficult to force a company to carry it through correctly. Furthermore, there will be items of machinery and concentrated wastes which some nations will find hard to manage correctly. With the increase in the use of heap leaching, the risk rises. A serious event has the potential to be catastrophic for a site. Thus we judge that this risk may occur and the impact may be at the major level.

Stage 3

The conditioning of the concentrate derived from the extraction operations to fissile fuel is more complex than for most other sources. Although there is competition to supply the concentrate, there is only one destination for manufactured fuel. There is no competition between process routes, since the route depends on the nature of the reactor. This can take one of several routes with different chemical and mechanical processing, depending on the nature of the reactor type. There are wet and dry chemical conversion routes, but typically, the concentrate is gassified and converted to uranium hexafluoride (UF_6). There are six plants globally in: Brazil, Canada, China, France, Russia, and USA. None of the plants listed are operating at full capacity; until it closed in 2014 there was a plant in the UK. Therefore this operation is separated from pre-processing of the ores (Stage 2), and the isotope separation and fuel manufacturing (Stage 4). Following chemical conversion, UF_6 is cooled and shipped as a solid to separation and fuel manufacturing facilities which are nearer to the reactors, including a site in the UK.

The meaning of a well-functioning market is that for processing equipment. Many components required are similar to that used in other chemical process industries. However, specialised equipment for radiation handling might be subject to short-term delays in delivery and there could be some price volatility. The key causes of economic risk are the lack of access to capital and the uncertain cost of decommissioning. Although the site is not as complex as a reactor, it is an expensive operation, most of the plants are state-backed. The sites produce low and medium radioactive waste, requiring long-term storage. We judge that scope for further significant R&D improvement are limited, posing a modest risk.

The risks posed by a lack of social stability and a lack of institutional governance are at a modest level. Although three of the six nations pose risk, this is mitigated by the spare capacity at the three which pose no significant risk. The notable technical risks which may arise are due to a pollution event and the inability to neutralise waste at decommissioning.

Stage 4

The production of reactors and their systems is a niche activity, not a mass market. In this stage we included the production of the final fuel rods or pellets. Isotope separation in the UK plant is achieved by using thousands of mechanical centrifuges, enriching the U-235 isotope to 3.5%-5%. The enriched UF_6 is then converted to uranium dioxide (UO_2) (solid phase) pellets for manufacturing into fuel rods.

Some processes to manufacture components, such as the steel reactor vessels, are so specialised that only a single company has the facilities and expertise. (LCICG, 2016e) state that the barriers to market entry are high, in part because the regulatory requirements are stringent. Consequently there is a lack of competition. .Thus the risk posed by the lack of a functioning market is significant and may lead to sustained delays. Even for more common components, modifications may need to be made to accommodate (even moderately) radioactive process streams.

The cost of building a complete reactor and site is high and hard to quantify (Harris et al., 2013; Linares and Conchado, 2013) with Thomas (2005) stating that operators are reluctant to reveal their true on-going spend, and Du and Parsons (2009) suggesting that estimates of build costs doubling since 2003. Thomas (2010) observed that institutions lending to the then (and still) on-going nuclear build projects considered their investments to be at high risk, with Ansar and Flyvbjerg (2016) describing new nuclear build projects as 'fragile' and Thomas (2015) questioning whether the Generation III+ are any more buildable that previous designs. The need for the industry to realise the promised cost reductions is highlighted by Watson et al. (2014). Modelling by Green and Staffell (2013) suggests that the private sector alone cannot deliver nuclear stations without subsidy from a Government. The well-publicised difficulties of raising the finance for, and the total costs of, the UK's Hinkley Point 'C' project led the NAO (2016) to raise concerns they term as 'value for money risks'. Therefore, we suggest that the risk arising from the lack of access to capital is at the highest possible level. The risk is classed as macro as the finance is raised from globally distributed investors (including sovereign funds). The risk posed by being unable to agree a price for permits or subsidies (by whichever mechanism) is likely to occur. Although this impact may cause significant delay, it should be a recoverable situation. For example, the negotiations to agree a price for the power generated by Hinkley Point 'C' were protracted, but a price was settled.

Nuclear decommissioning costs have an interesting 'split cost' problem. The owner/operator of the reactor facility receives the benefit of selling the power produced, but the nation (and future generations of citizens) pays for the long-term decommissioning and storage of the waste i.e. the costs are socialised. Kula (2015), and Freeman et al. (2015) report on the effects of the wide variety of both discount rates (private and social) and the total lifetime of the complete nuclear cycle. Thomas (2005) provides evidence that decommissioning on a commercial scale is unproven and that forecasts are likely to be too low by a significant margin. In the case of Hinkley Point 'C' the deal indicates that the consortium building and operating the site will set aside some of the revenues to cover decommissioning, but Thomas (2005) shows that this is a higher risk strategy. As the value of the Hinkley figure is not clear, it is not possible to say whether it will cover all of the costs Furthermore, the long-term storage of high-level waste has not yet got an agreed technical solution, nor a firm cost (Verbruggen et al., 2014). However, the Government has agreed to take responsibility for all of the intermediate- and high-level waste (NAO, 2016). Using the UK Government methodology (DECC, 2010c), Harris et al. (2013) estimated a total decommissioning cost of approximately £3 / MWh_e. To give commercial investors confidence the decommissioning cost is set as the 99^{th} percentile of a modelled figure. Thus for the Hinkley Point 'C' project DECC state that the financial risk to the UK taxpayer due to decommissioning is "very low" (NAO, 2016). We suggest that the risk arising from uncertainty in the decommissioning costs will occur and that it will introduce sustained delays. But we must assume that however slowly decommissioning happens and whatever length of time storage of radioactive wastes require, that the process will be carried out i.e. no matter what the cost or uncertainty, progress will be made.

According to the IAEA (2012) a typical 1 GW_e nuclear plant with a once-through cooling system requires 26-64 m^3s^{-1} of water, depending on the reactor type. These flow rates are 20-25% greater than for coal-fired plant due to the lower thermal efficiency of nuclear plant. There is a small likelihood that water supply from a river may be inadequate but the impact could be moderate, including the temporary shutdown. Grimston et al. (2014) give a useful account of how UK policy for radiological protection with respect to siting has changed over post-war period. The harsh radiation environment requirements the use of (exotic) critical materials. Although there is some demand for silver (Speirs et al., 2013a), it may be substitutable.

The risk from a weak technology transfer environment is possible and may result in short-term delays. We do not consider it likely that the impact would be more severe than minor as nuclear is a high-value low-volume industry and as such can readily procure solutions (whether these work or not is a different matter). However, (LCICG, 2016e) acknowledge that there has been market failure in all areas of innovation for the nuclear industry, with UK spending lagging significantly behind Japan, the USA, and France (DBIS, 2013). In the light of a finite supply of uranium Verbruggen et al. (2014) suggest that breeder reactors will be required in the last quarter of the 21st century, but that little progress has been made since the first generation of this technology. The risk from a lack of public subsidy is of the highest level; a plant cannot be developed and built using private investment alone (Badcock and Lenzen, 2010; Bradford, 2013; Gross and Watson, 2015). For safety licensing considerations, improvements to current reactor designs will be incremental. But there are many designs for significantly different types of reactor (von Hippel et al., 2012; Peakman et al., 2018) suggesting that fission reactors may not always be at risk of only incremental improvement. Without a buoyant market for new-build the risk of the lack of willingness to invest to innovate in nuclear technology is high. We do not judge this to be at the highest level of risk, since the existing reactor fleets require innovation and improvement. In their review of UK R&D capability, Sherry et al. (2010) provide evidence from UK and overseas experts that the UK is lacking in several areas.

Optimism bias is widespread in the nuclear industry: the ways in which arguments for nuclear power are relativised (Teräväinen et al., 2011) to the borrowing costs (Thomas, 2010), construction times (Harris et al., 2013; Thomas, 2015), construction costs (Du and Parsons, 2009), and the operational and maintenance costs (Koomey and Hultman, 2007). In the case of Hinkley Point 'C', these "*fragilities*" lead Ansar and Flyvbjerg (2016) to suggest that the project should be abandoned.

The risk of lack of capacity to manufacture components is modest, but not insignificant since many subsystems are not mass-market items. Many are required to survive in hard radiation environments. The steam turbine side presents no significant risk since these are standard for all thermal plant with a worldwide manufacturing base. The risk of lack of capacity to construct sites we judge also to be modest, but more significant. The techniques required to reach safety standards present more of a challenge with a smaller number of construction companies able to take on a project of that scale.

Of the causes of risk in the political category, a changing regulatory or policy framework is by far the greatest. The UK policy landscape since the 1980s has been characterised by swings in policy (Connor, 2003; Mitchell, 2007) and institutional change (Kern et al., 2014). There is strong evidence to suggest that this presents a risk at a high level, though not unrecoverable. Any new nuclear project will certainly attract public concern even though the nuclear industry has attempted to relativise the risks (Teräväinen et al., 2011). According to Greenhalgh and Azapagic (2009) the responses to the UK Government's white paper 'Our Energy Challenge' showed that the three greatest concerns were waste disposal, the cost of the electricity generated, and terrorist risk. But as Corner et al. (2011) show that there is 'reluctant acceptance' of nuclear power we judge that the impact will be short-lived.

The skills shortage in the civil nuclear industry have been discussed widely by many commentators including Pitt (2014) and Thomas (2015). Data from across the EU (Simonovska and Estorff, 2012) shows that both the technician and engineer levels are affected significantly. A shortage of engineering skills also poses a risk in terms of the UK acting as an expert customer (LCICG, 2016e). The situation is retrievable, governed by a time-constant, through training programmes in Further Education colleges and universities (Roberts, 2009; DECC, 2015b). The NAO (2016) suggest that the lack of specialist skills has increased the costs for the Hinkley Point 'C' project.

Technical causes of risk mainly arise from pollution, operations, and decommissioning. The likelihood of a radiological pollution event is low, though it may occur. In the UK, licensed sites must report incidents and events to the Office for Nuclear Regulation (ONR) using the International Nuclear and Radiological Event Scale (INES) ratings of events (Level 0 – level 7). Between 2010-2013 there was a single INES 2 event, requiring enforcement action by the ONR. By a large majority events were rated as zero, which is within all safe operating limits (ONR, 2013). According to Sovacool et al. (2015) incidents in the nuclear industry account for 70% of damages (by cost) caused by energy systems globally. This is likely to be a maximum figure since reporting in the nuclear industry is easier to track historically and geographically than in some other sectors. Using a subset of these data (1950-2014) Sovacool et al. (2016) categorise nuclear as high risk in respect of accidents.

However, events occurring on site or externally may result in a shutdown of the reactor or whole site whilst remedial action is taken. The risk due to operational failure has a medium likelihood as there have been instances of systems failure such as a voltage droop which triggered Sizewell B to temporary shutdown (BBC News, 2012; EDF, 2016). The risks posed by the inability to neutralise radioactive waste at decommissioning is certain; the Selafield site is storing (at the surface) all of the UK's nuclear waste since the 1940s (NDA, 2015, 2016). To date, no underground long-term storage facility has been built despite several proposals (NDA, 2016). Although, the short-term storage programme operates safely, the lack of a long-term solution may have a significant impact on the viability of future nuclear build programmes.

Stage 5

We do not see the need for any deviations from the description set out in section 8.1.1.

Stage 6

We do not see the need for any deviations from the description set out in section 8.2.1.

7.3 Thermal (Geological)

Geothermal resources in the UK can be grouped into so-called 'low enthalpy' and 'Hot Dry Rock' types. Estimating the deep geothermal resource of the UK requires modelling and fieldwork, and remains uncertain (Busby et al., 2011). Radiologically active geological formations are normally expected to offer suitable temperatures, but this is not always the case (Busby et al., 2015). Furthermore, the classification of resource temperature is inconsistent globally. We adopt the classification proposed by Younger (2014, 2015) which defines UK resources as mostly ‘very low’ (less than 50 °C) and ‘low’ (51-200 °C). The very low grade heat (down to 1000 m depth) has been mapped by Busby et al. (2011) observing that the temperature gradient might be 28 $°Ckm^{-1}$, 3 °C greater than previously thought. Turkenburg et al. (2012) suggest that applications for very low grade thermal energy include heating of commercial buildings, horticulture, aquaculture, timber drying, and mineral extraction. Total UK low grade heat (40-100 °C) has been mapped by Downing and Gray (1986), and estimated by Barker et al. (2000) as approximately 70 EJ. A borehole study in Weardale suggests that a temperature of 100 °C may be achievable at depths of approximately 2 km in the right geological formation (Younger and Manning, 2010) and underlines the uniqueness of every potential project. Modelling well depths of 5-7 km Busby and Terrington (2017) speculate that temperatures up to 300 °C may be possible, which would afford electricity generation. Currently there are no deep geothermal sites operating commercially, though one is planned in Cornwall to heat a swimming pool complex (Cornwall and Isles of Scilly Growth Programme, 2016).

For the fuel categorisation to be fully generalised, the definition of Thermal (geological) could be split. The nature of the renewability of (deep) geothermal energy differs between sites and in different parts of the world. For the highest temperature resources Axelsson et al. (2005) and Bromley et al. (2010) consider well lifetimes of 100 years or more to be renewable. For the UK and the majority of other countries the temperatures available are low to intermediate and exhaustible (non-renewable). However, for the purposes of analysing risk in the supply chain, this may not be an important distinction as the fuel realistically can only be used locally.

There is potential for heat recovery from minewater (Bailey et al., 2016; Al-Habaibeh et al., 2018) and deep saline aquifers (Younger et al., 2015). Nian and Cheng (2018) review the possibility of using abandoned oil and gas wells for geothermal energy, whilst (Westaway, 2016b) suggests that subsurface infrastructure of exhausted shale gas sites might be repurposed as borehole thermal energy storage (BTES) in the UK.

For Stage 1-3 inclusive, the likelihood and impact of the causes of risks are broadly similar to those of Gas (unconventional) e.g. the drilling rig required is the same (Batchelor, 1987), but there are notable differences.

Stage 1

Younger (2015) points out that access to capital is a particular problem for deep geothermal energy systems because of the necessary concentration of expenditure in the early stages of the development of a site. Furthermore, projects require significant public subsidy (Younger and Manning, 2010; Younger et al., 2016) Although test bores are not made to the ultimate working depth, most of the cost is incurred in drilling any bore of sufficient depth. This requirement stems from the risk posed by the fact that the quality of the fuel – the reservoir geometry and its physical/thermal properties – cannot be fully determined without drilling a test well (Nazroo, 1989; Busby, 2014; Younger, 2015; Younger et al., 2016). Therefore we judge the 'quality of fuel' cause of risk to be in the highest category, but even a test bore may not yield sufficient information (Busby and Terrington, 2017). We suggest that if the risk occurs it may end the project.

Also arising from the uncertainty of the quality of the fuel is optimism bias, but we judge this to be at a moderate level. Although many fuels at the explore stage are not particularly sensitive to a changing regulatory and policy framework, for deep geothermal it is more serious. There is the element relating to planning, but particularly as the heat is most likely to be used directly rather than for electricity generation.

Compared with Gas (unconventional) we suggest that there will be little public concern, even though the same surface equipment issues may arise. We also suggest that pollution event significantly lower.

Stages 2-3

The capital requirements increase at this stage as according to Augustine et al. (2006) and Lukawski et al. (2016) drilling costs scale non-linearly with depth. The main factors are depth, diameter, casing design, and site-specific characteristics (Augustine et al., 2006). According to Sovacool et al. (2016) drilling for geothermal resources is considerably more difficult than for onshore oil and gas. Thus even a technically viable site may not be able to raise sufficient funds; we judge this risk now to be at the highest possible rating. We note that unlike Gas (unconventional) permit costs are not relevant. In most cases decommissioning costs are less of an issue than for Gas (unconventional) as there will less contaminated waste of which to dispose. However, worked-out oil and gas wells repurposed for geothermal will incur additional decommissioning costs.

The precise quality of the fuel source is only discovered once the borehole system is completed and it remains a risk that the temperature gradient is not sufficient or the geological conditions are not as predicted; this could be severe enough to terminate a project. The range of estimates of water requirements is wide (Mielke et al., 2010) with the different thermal grades of resource having intrinsically different needs. For wells in the UK Younger (2015) considers water availability not to be a significant problem. However, Batchelor (1987) warns that wells away from the coast or an estuary need to keep losses to below 5%, and maintaining injection pressure also requires (parasitic) pumping energy.

Although some elements for geothermal energy are mature (Turkenburg et al., 2012) there is good scope for technology transfer from the oil and gas sector e.g. drilling techniques (Younger et al., 2012; Busby and Terrington, 2017). Though it should be noted that modelling by Mazzucato and Semieniuk (2018) suggests that private companies are not likely to fund innovation in such large undertakings. As the risk level is too great, public subsidy is likely to be required. Younger et al. (2012) and Younger (2015) suggest that there is significant scope for improvements in reservoir modelling, which will assist resource management and maintenance. A less obvious cause of risk is the lack of materials substitutability. The underground conditions for deep geothermal energy are significantly more harsh than for oil and gas extraction (Younger, 2015).

In comparison with Gas (unconventional) infrastructure is less of an issue since DH networks are easier to construct than long distance gas transport pipes. A combination of the longevity of geothermal projects and that most sites likely to be workable in the UK will produce low-grade thermal energy for water and space heating implies that a changing policy environment presents a risk in the highest category because heat policy is very uncertain. To lessen this uncertainty Gluyas et al. (2018) are calling for a Contract for Difference scheme for heat. Public concern about Thermal (geological) is much lower than for Gas (unconventional), but lack of awareness of the potential of UK geothermal energy is recognised as a problem (Bromley et al., 2010; Turkenburg et al., 2012). Prior to the Infrastructure Act of 2015, landowners in principle could treat geothermal energy extraction infrastructure under their land as trespass (Burns et al., 2016), though now automatic access is allowed below 300 m.

As geothermal systems are inherently low risk (Sovacool et al., 2016) the accident rate (globally) is very low with an estimated fatality rate of approximately 1.6×10^{-3} deaths per $GW_e yr^{-1}$ (Burgherr and Hirschberg, 2014), therefore a low likelihood of catastrophic technical failure. Failures which do occur appear to be related to the action of corrosive geothermal fluids degrading piping and other process equipment (Sovacool et al., 2016). Drilling will require the same drilling lubricants as the oil and gas industry, and opening pathways at the well bottom or horizontal sections may need the high viscosity gels used for fracturing shale deposits (Batchelor, 1987). These present some risk from a pollution event, however these processes and compounds are well understood. Deep and hot geological environments contain a variety of chemical species such as boron, mercury, arsenic, radon (radioactive) and hydrogen sulphide (Batchelor, 1987), which will be transported to the surface during drilling and operation. Wastewaters will need to be treated to remove relatively small quantities, but it does present a risk. An additional pollutant released during drilling and routine operation is CO_2 (Turkenburg et al., 2012; Davies et al., 2014). Therefore a pollution event will occur, though the amount of CO_2 released is less than that for oil and gas production.

Stage 4

For electricity generation, the Organic Rankine (ORC) (Smith, 1993) and the Kalina cycles (Fiaschi et al., 2017) are the most suitable for low temperature sources. Devices based on these thermodynamic cycles are not prevalent and there is no large established market; this may lead to some price volatility for the components. Access to capital may be a problem as these devices are currently expensive (Nian and Cheng, 2018), but much less so than for the drilling phase. We judge this to be of moderate risk. The inability to agree a price of permits is not relevant (no carbon credits required), neither are lack of physical access, lack of water availability, the denial of permission to access sites, and disputed landrights because the borehole and the conversion device are co-located.

Improvements are likely as it is an immature technology with R&D active on system architecture and cycle modification, components (expanders and heat exchangers), control strategies, and working fluids (Quoilin et al., 2013; Lecompte et al., 2015). Public subsidies are likely to be required as it is always likely to be a niche market, and R&D may not be sufficient to meet the challenge posed by the harsh underground environment. We judge the optimism bias may arise. The ability to create infrastructure may be an issue for some geothermal projects which may generate electricity requiring a medium or high voltage grid connection. We suggest that the policy and regulatory environment will be the same as renewables e.g. Wind (onshore), and that the skills risks are the same as for CCGT systems.

Stage 5

We do not see the need for any deviations from the description set out in section 8.1.1.

Stage 6

We consider the use of district heating networks for this fuel and do not see the need for any deviations from the description set out in section 8.2.2.

7.4 Waste

An overview of the processes for energy-from-waste (EfW) facilities is given by DEFRA and DECC (2014). Although most municipal solid waste (MSW) is from households (DEFRA, 2018) some commercial and industrial waste can also be used (Lupa et al., 2011).

There are a variety of technologies other than dedicated incineration (DEFRA, 2013) including co-firing with coal in cement kilns (Garg et al., 2009) and fluidised-bed combustion (Yassin et al., 2009). Nixon et al. (2013) have compared the technical details of operational performance of a range of incinerators in the UK. Even though the cost of landfill is rising the trade-off against incineration is difficult since its operational costs remain high (Mills et al., 2014). According to Jeswani and Azapagic (2016) the environmental impacts of MSW incineration are less than for landfill.

Stage 1

Although the UK has programmes to improve recycling rates which might reduce the total MSW available, we do not observe any notable risks at this stage.

Stage 2

The collection of household, commercial, and industrial waste is a well-understood process. There are no notable risks at this stage.

Stage 3

The waste is not considered as a fuel until the recyclates are removed and the moisture content reduced (DEFRA and DECC, 2014). The wide variety of the mixed wastes is interpreted as the quality of fuel. We note that innovation in recycling methods may also improve waste collection and sorting methods. Waste sorting facilities are large and there is some risk of accessing capital, though if long-term contracts for appropriate minimum supply levels are negotiated this should only be a moderate risk.

Stage 4

DEFRA and DECC (2014) describe raising capital for EfW projects as *"challenging"* perhaps requiring grants (DEFRA, 2013) or other subsidies (Jamasb and Nepal, 2010). We consider that this cause of risk may occur, but is likely only to have a short-term effect. The only notable risk from the environment is the quality of fuel. It will be highly variable, but operating experience (Nixon et al., 2013) suggests that it is unlikely to cause disruption. However, the variability will also affect the treatment of the post-combustion residues (Shirley et al., 2015).

There is a moderate risk of changing policy and regulation (DEFRA and DECC, 2014). The principal risk in the political category is that of significant public concern (Bull et al., 2010; DEFRA, 2013; Phillips et al., 2014; Levidow and Upham, 2017). Public opposition will occur with the consultation and planning process causing a major delay.

Waste incineration will generate air pollution (Bogush et al., 2015) including heavy metals which have been detected in soils in the vicinity of incinerators (Rimmer et al., 2006). Although we expect environmental standards to continue tightening any facility breeching the regulations is likely to have its permits suspended. Incinerator bottom ash will also contain contaminants requiring treatment, carrying implications for site decommissioning.

Stage 5

We do not see the need for any deviations from the description set out in section 8.1.1.

Stage 6

We do not see the need for any deviations from the description set out in section 8.2.2.

8 Assessing Risks for Distribution, Use, and Cross-cutting Issues

The distribution and use stages are treated together because the differences between the fuels types reduces significantly once the final energy vector is produced. The cross-cutting issues are those of critical materials requirements, skills, and negotiation. These are discussed independent of stages for the most part. Critical materials availability is a single cause of risk, but skills are a category in their own right. Negotiation was not listed explicitly as a unique risk as it is suffused through almost all public and commercial operations at all stages. The decisions should be read across the risk matrix (Appendix A) for each stage of each fuel supply chain.

8.1 The Distribution Stage

As there is a smaller number of final energy vectors compared to the fuel sources, there is significant commonality in the modes of distribution. Many of the vectors are using the same system directly. Therefore many of the risks, likelihoods, and impacts are identical. For brevity, we present a commentary applicable generally, with only exceptions or interesting circumstances mentioned individually in each fuel source discussion. There are three principal types of distribution: electricity networks (on- and off-shore), pipelines (gas and liquid), and tankering of liquid transport fuels for road vehicles. For liquid pipelines we consider three discrete systems, namely oil, kerosene, and water. Scott and Evans (2007) lament the lack of innovation in electricity networks evident in the 1950-60s upon which we still rely. Overviews of energy network regulation and future infrastructure needs for the UK are given by the Office of Gas and Electricity Markets (Ofgem, 2009a) the National Infrastructure Commission (NIC, 2018), respectively.

8.1.1 Electricity Networks

The distribution of electrical power is a well understood and mature industry. For the majority of the identified causes of risk, electricity distribution networks present mostly low level risks with mostly short-term impacts were they to occur. The three principal groups which share risk ratings are large-scale plant where the site is very unlikely to change status, new onshore connections (usually to the medium voltage network), and networks and connections for offshore / ocean technologies. The default description which follows is for existing sites which covers the majority of instances.

The well-functioning market refers to that of network equipment, cables, and monitoring and control devices. As this is a mature global market, there are a variety of manufacturers from which to select. Therefore the risks are low and any impact short-lived. Although individual network items may be relatively inexpensive, HV transformers for example may cost several millions of dollars apiece. Major projects of replacement or new build will require access to significant capital, which we judge poses a modest level of risk. Future networks integrated with sophisticated ICT may have a significant capital requirement (Leal-Arcas et al., 2017). For a generating plant at an existing site, there will not be a need to ask for a new connection point. But to create a new connection point requires the permission of the (distribution) network operator. This requirement can pose a risk if it is technically or commercially inconvenient for the DNO to allow the connection to be installed, the process can be delayed or be costed at an unrealistic level. Although not strictly a licence or permit, only the DNO can physically make the connection and sign-off the installation. For a fuel category that is exploited by an existing large-scale generator, this risk deemed irrelevant. The moderate score associated with the risk of a lack of critical materials accounts for grid-scale battery storage (either Li-ion or flow cell).

There is a modest risk posed by natural hazards such as storms and flooding. There are examples of substations being inundated when rivers burst their banks and winter weather bringing down power lines, but service is usually restored in a few days or a week i.e. short-term disruption only.

Industry maturity might suggest that the level of risk that innovation will only be incremental is high (Bolton and Foxon, 2015), indeed innovation to improve efficiency and to lessen losses is incremental but steady. However, integrating ICT (Taylor et al., 2011; NIC, 2016) and data analytics are likely to be the most significant changes, leading to the so-called 'smart grid' (Balta-Ozkan et al., 2014; Xenias et al., 2014). Thus we consider that there is significant space for innovation to occur in electricity networks. Whilst the drivers and barriers are well understood (Xenias et al., 2015) there remain risks and uncertainties (Connor et al., 2018) including a lack of innovation from under investment. For the development and deployment of smart grids, novel technologies exploiting ICT are required which are beyond the current core expertise of the power industry (Xenias et al., 2015). We suggest that this is coupled to a raised level of risk that the capacity to engage in R&D in the UK will not meet the challenge (Connor et al., 2014). Ofgem addressed the falling levels of R&D investment (Jamasb and Pollitt, 2008b) in the networks industry through programmes such as the Low Carbon Networks Fund and incentive mechanisms (Ofgem, 2009b, 2010a, 2010b). Although these are not in name a subsidy, it is enforced or incentivised spending of income from a regulated market. It is considered that a requirement for public support for R&D will be on-going (LCICG, 2012d; Jamasb and Pollitt, 2015) It is interesting to note that Ofgem consider innovation to encompass products and equipment, communications and commercial interactions, and the cultural approach to risk (Ofgem, 2009b).

A useful overview of the complicated policy and regulation landscape is given by (Connor et al., 2014). The National Audit Office reviewed UK planning for infrastructure (NAO, 2013) noting that energy networks:

- are privately owned,
- are subject to policy formed by (DECC) BEIS,
- are regulated by Ofgem,
- have investment needs identified by a combination of private companies and the regulator,
- have investment raised by private companies alone, and
- are paid for by consumers.

Bolton and Foxon (2015) suggest that the governance of networks (policy and regulatory framework) in a liberalised market makes it difficult to align stakeholder requirements in a coherent manner, which Leal-Arcas et al. (2017) suggest inculcates a short-term attitude. Respondents to surveys and interviews carried out by Connor et al. (2018) observed a lack of co-operation between power generation companies and DNOs. We interpret this as a risk from a changing policy and regulation. For large-scale generators, whether established technologies or in development, the risk is low as the current network is well suited. However, new technologies small-scale require a coherent strategy for regulatory change, but continual change in policy presents a significant risk. For established small-scale distributed generation, the risk lies somewhere in between. Significant public concern will arise for new power lines and other infrastructure in sensitive areas (Cain and Nelson, 2013; Cohen et al., 2014, 2016; Raimi and Carrico, 2016) and could cause major delays. A prominent controversial example being the Beauly-Denny upgrade (Ritchie et al., 2013).

The technical causes of risk are not considered to be significant in such as well-regulated industry. Although pollution may arise through leakage of oils and insulation materials, any event is likely to be localised. Alternatives to the most hazardous high-voltage insulating material – sulphur hexafluoride (SF_6) – are being sought (Christophorou et al., 1997; Rabie and Franck, 2018). The compound SF_6 is the most potent greenhouse gas with a 100-year global warming potential (GWP) estimated at approximately 24,000 (Myhre et al., 2013).

8.1.2 Offshore Electricity Networks

The risk arising from the lack of a well-functioning market is enhanced for offshore and subsea network equipment. Although it is a global market, the number of specialist manufacturers is lower. This risk of the lack of manufacturing capacity for some components, for example subsea power cables. The likelihood and impact of a lack of access to capital is significant for operating offshore. We suggest that the impact is recoverable, but would delay projects beyond the short-term. The uncertainty of decommissioning costs is raised to being a possible risk, but the impact should still be at the margins of normal operation. We consider that the likelihood of equipment price volatility to be the same for on- and off-shore networks, but for offshore the impact may lead to short-term delays in the execution of projects.

The offshore environment will for certain present difficulties of physical access.. As delays are due to seasonal weather conditions, the impact will only be short-lived. The offshore environment will also give rise to natural hazards that are more severe than onshore. Although offshore equipment is designed to be robust, if the risk occurs the impact on operations could be significant (though recoverable).

A weak technology transfer environment is a more significant risk for offshore networks than for onshore. Although at the deployment stage HVDC networks are relatively new technology with significant scope for further development (Elahidoost and Tedeschi, 2017). This is reflected by the likelihood of only incremental development being lower for offshore systems. The risk arising from the lack of public subsidy also differs and the impact for offshore networks will be higher. For the UK, the risk of the indigenous R&D capability not being able to meet the challenge for offshore networks is higher. The specialist equipment for offshore construction, such as cable laying barges, has a restricted supply leading to delays and a limited deployment rate. Whilst this is a recoverable position for any individual project, the impact is felt throughout the supply chain.

We judge that the impact of a pollution event offshore has the potential to be greater than onshore. However, the likelihood remains low for both cases. The specialist equipment required for installing and decommissioning offshore wind infrastructure is subject to international demand and therefore delays in securing its services is likely and raised with respect to that for onshore networks. Operational failure of installed network equipment is no more likely than for onshore, however, we consider that the impact may be greater. If a failure occurs in poor weather conditions it may be weeks or months before repairs could be made.

8.1.3 Pipelines

The two main types of pipeline for distribution which we need to consider are for gas(es) and oil products. Pipelines for transferring unprocessed gas and crude oil are considered as part of Stage 2 (Exploit). At the distribution stage, the pipelines required share many characteristics and risks. A third type of pipe network is to transport hot water for district heating. This is considered as part of Stage 6 for the relevant fuels for two reasons. First, it does not (and cannot) form a national network. Secondly, only Thermal (geological) and Biomass would use a heating network exclusively. Systems using gas will require the gas to be distributed first and the gas may also be used by households for heating and cooking. This is an anomaly, but can be handled within the constraints of the analytical framework.

There are two natural gas distribution networks in the UK. One is a high pressure (85 atm, 7600 km long) system[1] akin to the 400/275 KV electricity transmission network. This gas transmission network links the gas import terminals, the UK gas refineries, and the large-scale industrial users. There are 23 compressor stations with connections to the low pressure distribution system which supplies all other customers. The high pressure system requires steel pipes, which the low pressure network (approximately 130,000 km) is being replaced with polyethylene pipes. Modelling by Qadrdan et al. (2015) suggests that although demand for gas declines out to 2050 it remains significant. Pearson and Arapostathis (2017) have described six completed transitions in the development of the networks with a seventh in train. Some have questioned the long-term viability of the low pressure network e.g. Dodds and McDowall (2013). Their modelling suggests that the only viable future for the network is to deliver hydrogen for use in micro-CHP fuel cells. However, Ma and Spataru (2015) suggest that a combination of biogas and hydrogen

[1] http://www2.nationalgrid.com/uk/services/gas-transmission-connections/about/

would be a sustainable outcome. Lowes et al. (2018) suggest that the widespread deployment of decentralised low carbon heat networks may pose a “major” risk to the gas distribution networks. In part, this level of risk is driven by their suggestion that if the on-site and DH networks supply residential and commercial heat demand, the demand for gas for cooking would be insufficient to justify keeping the gas distribution grid. However, this seems to be at odds with their idea of using bio-derived (low carbon) gas in decentralised generators – the gas will still need to be distributed to those units.

Some of the equipment required is relatively specialised, so we suggest that the risk of a lack of a well functioning market is in line with other stages relying on process systems manufacturers. Thus the risk may occur, but is likely to only cause short-term delays. Likewise for access to capital; networks are thousands of kilometres long, so although pipes may be relatively cheap the installation is expensive.

Although almost all pipelines at this stage are located on land, physical access is not trivial as nearly all are buried. At the level of city streets, delays in accessing sites may occur due to scheduling issues to keep the network operating. Despite most of the transmission system being buried, some elements and stretches are exposed and will attract public concern (Groves, 2015) though delays are not likely to occur. An interesting point raised by Groves et al. (2013) is that a different approach is required for public engagement about energy infrastructure if that infrastructure is privately owned rather than by the state. Intrinsically the levels of innovation for pipelines are low in this case.

8.1.4 Road Tankering

We consider road tankering to be a low risk activity. There are only two points to note. The first is that as a mature technology we judge innovation to be low, thus little room for improvement, and secondly that a diesel powered truck always causes pollution during its operation (thus a pollution event is a certainty).

8.2 The Use Stage

There are only three principal ways of exploiting the energy vectors in their final forms i.e. electrical power for devices, heat, or motive power (vehicles). Electrical devices and vehicles are strongly regulated with internationally compatible standards (less strict for marine fuels). This uniformity leads to the causes of risk showing little variation between initial fuel types. However, heat has a wide variety of energy vectors (liquids and gases), thus being subject to a wider set of risk causes. The discussion is based on the energy vector.

A common thread is the treatment of natural hazards which we assign the same value regardless of energy vector. Even though we cannot find a reason to distinguish between uses, we consider that it is relevant in the sense that it describes society's reliance on complex technology. Accordingly, we draw a distinction between the impact of natural hazards on the infrastructure and that which affect the consumer. If a house is flooded neither electrical nor heating can be used. But the occupant will be sheltered somewhere else and use other devices, so the effect is neutral. For devices used outside of a building, natural hazards such as flood events may prevent customers from using vehicles safely – EV or conventional. The point is the reliance on powered vehicles. For heat, it is industrial use which may be most disrupted.

For this stage significant public concern does not refer to the technology in use (except for exotic gases and liquids). Technologies allowed into the marketplace in the UK are safe (unless individual items counterfeit or illegally imported). We restrict significant public concern to the level of action regarding the 'energy market' i.e. the sale of electricity, gas, petrol, and diesel. Although this could be considered in the economic category as a lack of a well-functioning market, it is useful to retain that for the technology in line with all of the other stages. The functioning of the energy market has led to protests and the formation of charities and pressure groups to lobby the Government. Price volatility is the total cost of ownership which includes the purchasing price of the final energy vector.

8.2.1 Electrical Power for Devices

The majority of the causes of risk at this stage arise from the innovation and skills categories.

We draw a distinction between the impact of natural hazards on the infrastructure and that which affect the building in which consumers' electrical devices are used. Thus for devices used within an indoor environment, whether residential, commercial, or industrial this cause of risk is not relevant. However, ASHPs are affected which is accounted for at this stage. The quality of the fuel source in this context is the quality of the supply of electrons i.e. characteristics such as frequency and voltage level or variability. For the UK, the risk is low and any disruptions to the supply (impact) are likely to be short-term. For most devices, especially semiconductor electronics, critical materials are not an issue. However, electric vehicles require the use of several chemical elements for which there are, or are likely to be shortages (Pavel et al., 2017). We judge that the level and severity of this cause of risk to be moderate. This risk is linked to the risk of the lack of materials substitutability (innovation category) and of the same level. Both are of global concern.

The innovation category has two other causes of risk with moderate concern, namely UK R&D capacity/capability and optimism bias. The main issue for optimism bias is the rebound effect for energy efficiency (Sorrell, 2009, 2015). We judge both the likelihood high and impact to be significant but recoverable.

For the use of electrical devices we are not concerned about the manufacturing capacity of electrical devices as this is clearly a globally successful activity, though improving operating efficiency remains important. Instead, we take the cause of risk of an insufficient capacity of site construction as the replacement of energy inefficient buildings by refurbishment or demolition and new build. The rate is also important and is a matter within the control of a national Government. This risk is specifically about the (re)electrification of heating. Resistance heating was abandoned many years ago, though it was a reasonable alternative to using coal in homes. Heat pumps are slow acting and therefore require a thermally efficient building in which to operate. Although the rate of new stock built is important, it is the demolition or complete refurbishment of existing buildings which is the determinant factor. Between 2006/07 and 2016/17 demolitions of residential property fell from approximately 22K to 10K per annum (DCLG, 2017) of the 26M total dwellings i.e. a rate (unadjusted for stock age) of about 0.04%. As roughly 20% of the stock was built before 1919, 55% between 1920-1979, and 25% 1980 or later (MHCLG, 2018) less than 2% of older dwellings will be demolished over the next 30 years, assuming that only pre-1980 stock is demolished. This means that 98% of the dwellings in 2050 are extant in 2018. With low demolition rates of inefficient buildings, high efficiency electrical heating cannot replace gas boilers. We judge this cause of risk to be highly likely with a sustained impact.

The political category presents three relevant risks, and they are moderately high and have components within and outwith the system boundary. A changing policy and regulatory regime brings uncertainty. In the European context the change is slow and well-signalled, thus any adverse impact is likely to be recoverable in the short-term. In contrast, slow changing legislative mechanisms may not be able to react to innovations quickly enough to mandate energy efficiency products or processes. The enforcement of any standards and codes are a matter for a national Government. We judge these to have equal status. However, an insufficient rate of improvement in, or lack of enforcement of, standards and codes has greater impact for buildings.

The risk of significant public concern arises from the functioning of the energy market due to the number of electricity retailers (commercial, industrial, and residential). Ofgem sets the rules by which consumer interests are protected whilst promoting a competitive market for the sale of electricity and gas. The need for a regulator demonstrates that it is not a natural market so must carry an elevated likelihood of the risk occurring. Following a consultation exercise Ofgem decided that there were sufficient grounds to refer the matter to the Competition and Markets Authority (CMA) (Ofgem, 2014). The CMA levelled a number of criticisms which might adversely affect competition (CMA, 2016). As there is reasonable grounds for suspicion that this risk will become manifest, we assign the highest likelihood level. For the commercial and residential consumer, price volatility is low. The retailers hedge against wholesale price volatility as a means of levelling costs for small consumers and making extra margin where possible. Residential consumers in particular see prices move up more frequently than down which formed part of the CMA investigation. Industrial consumers have different arrangements including time-varying tariffs and demand response. For small consumers the low risk of price volatility has an impact on prices i.e. low volatility carries a negative impact (prices ratchet upwards over the long term).

The only notable technical cause of risk may arise with the inability to deal with electronic waste. Although European standards and legislation exists innovation and the use of new materials and processes may present difficulties. It is the processing and disposal of this electrical and electronic waste that may present the risk of a pollution event. We consider this risk to be low in the UK as this is a well-regulated sector.

8.2.2 Heat

As an end-use energy vector – usually a molecule of water – heat encompasses a wide variety of scales and users, namely domestic hot water (including for space heating), communal (intra-building) heating, district heating networks, and industrial process heat. The technologies required are very different too. A clear overview of all uses of heat is given in DECC (2013a, 2013b), whilst CCC (2016) deal with heat use in the residential and commercial buildings, MacLean et al. (2016a, 2016b) focus on residential only, and

Griffin et al. (2016) on industrial use. Boait et al. (2012) compare the efficiencies of five technology combinations for producing domestic hot water for sanitary use.

Surveys of evidence and practice for policy development have focused on the provision of heat and improved efficiencies. This results in a complicated technical and policy landscape for ‘heat’ (Hanna et al., 2016) which in part explains why relatively little progress has been made in the decarbonisation of the supply of thermal energy. We are analysing fuel sources which requires the data and categorisation used in the aforementioned references to be sliced in a unique way. For example, for our purposes we treat ASHPs solely as an electrical device (demand) because they cannot act to store thermal energy (see section 3.1) – rejected heat during the summer is lost to the atmosphere. The ‘source’ of fuel for an ASHP is the sun (by various mechanisms) heating the air. On the other hand GSHPs and GWHPs are acting as a thermal store from where thermal energy (the ‘fuel’) can be extracted, even though the near surface is heated by the sun directly. Therefore we need to briefly distinguish between the mechanisms for the seven fuels delivering heat as an end use (Table 8.1). Arguably Waste (EfW) could also deliver heat, but we consider this as a by-product of the waste management. EfW will always be a small number of units (incinerators), primarily generate electricity, and likely to have a bespoke heat recovery system with long-term contracts with industrial customers. We can consider it as process heat with no need to treat separately.

Fuel	**Industrial Process Heat**	**Self-contained Residential and Commercial Buildings**	**District Heating Network**
Biogas	✓	✓*	✓
Biomass		✓	✓*
Gas	✓	✓*	✓
Gas (unconventional)	✓	✓*	✓
Solar (thermal, water)		✓*	
Thermal (geological)	✓		✓*
Thermal (low temperature)		✓*	

* Denotes implementation as the Stage 6 example in the risk matrix (Appendix A).

Table 8.1 Potential destinations of heat as the final use.

For the purpose of this study, we will assess only the dominant use for each fuel source. In most cases this will be onsite self-contained systems, but for Biomass and Thermal (geological) we will assume district heating as the main use; the differences in terms of the risk levels are marginal. Separately we will briefly address some aspects of industrial process heat. It is worth noting that the deployment is more mixed than the coarse-scale (**Error! Reference source not found.**) process descriptions suggest. For example, the dual nature of CHP using Biomass is not completely captured.

For heat, equipment used inside buildings will not be affected by natural hazards and the quality of fuel source refers to the variability in temperature of the final energy vector.

The DH water distribution network ought to be considered as part of Stage 5, but this can only be done for Thermal (geological) and Biomass. An expanded, more detailed, and non-unified analysis of single fuel may allow the framework to accommodate this anomaly. However, we do not consider that the outcomes of our aggregated analysis are unduly affected.

Industrial Process Heat

Companies with high industrial process heat use (e.g. steel production, petrochemicals, and electronics fabrication) have always had an incentive to reduce demand and improve efficiency. As such, any risks identified for the provision of heat for industry will not be central in our assessment at this stage.

According to Hammond and Norman (2012) UK industry has reduced it CO_2 emissions by an average of 20% annually between 1990-2007, which they ascribe to improved efficiency and a falling carbon intensity of electricity. The same authors estimated that the maximum recoverable heat surplus heat was 52 PJ/yr (Hammond and Norman, 2014). Arguably, in a low carbon future, the use of gas (conventional, unconventional, or biogas) could be reserved for industries operating high temperature or heat intensive processes because of their contribution to GDP and employment. There is some evidence (Atkins et al., 2010; Eiholzer et al., 2017) that low temperature industrial processes, particularly in the food, beverage, and textile industries, can be supplemented or perhaps fully supplied by solar thermal (see section 4.4). Cooper et al. (2016) point out that industrial waste heat could be made substantially more useful if the maximum range for heat transmission could be doubled from 16 to 32 km, and residential district heating (DH) networks could be the main beneficiary. In a synthesis report, DECC (2013a, 2013b) identify some barriers which policy and industry face. We interpret these as risks. Access to capital was cited in respect of short payback terms i.e. a project requiring capital would go ahead if the payback time was longer than two years in some cases. Other barriers identified were skills gaps, lack of long-term policy signals (interpreted as changing policy or regulatory frameworks), misalignment of requirements for sharing infrastructure. This last point was set out as different customers needing (or generating) heat at different or irregular times and we interpret as a risk of technical failure i.e. the heat service might be unavailable when required. It was noted that although heat processes are well understood, there was good scope for innovation.

District Heating Networks

District heating has a chequered history in the UK (Russell, 1993) and not had widespread use, though it is a mature technology (Hawkey, 2012). Self-evidently DH is considerably simpler to install in new developments than to retrofit. But Russell makes a more subtle point that it is the lack of a national co-ordinating body for heat that is the key to low deployment rates; compare this with the nuclear industry. The reasonability for DH was devolved to local authorities, which were under the financial control of central Government. Frequently, DH schemes were considered as marginal, but Russell asks who was the beneficiary of a narrow (economic) assessment, and casts doubt on whether other energy sources were treated in exactly the same way. Indeed, Russell noted bias in the economic assessments depending on the contributing organisations and the constraints under which they operated. Despite these barriers, successful examples are schemes in Aberdeen (Webb, 2015), Woking, Milton Keynes, and Birmingham (Hawkey et al., 2013), and the Sheffield region (Finney et al., 2012).

Lowes et al. (2018) also associate the risks of creating DH networks with different actors such as consultants, manufacturers, installers, and fuel suppliers. Their aggregation of activities implies that we can only link their work to our risk categories or a subset of fuels. For example, manufacturers of biomass, gas, and oil boilers, and micro-CHP units are considered to be at a “major” risk, but the nature of the risk is indeterminate.

A study commissioned by DECC and conducted by BRE et al. (2013) examined the barriers to deployment of DH networks by surveying and interviewing actors involved in local authority and property developer led schemes which were completed (N=34, of various sizes), planned (N=7), or had failed (N=3). A total of 17 risks were identified. It is notable that for both impact and prevalence (number of times mentioned) only the local authority led schemes generated risks with the potential to halt a project. We consider that impact and prevalence are correlated, thus we only use the impact ranking. Furthermore, it is unclear whether there was bias in the way the two groups of respondents viewed risk. In Table 8.2 the risks identified are grouped and compared with our categories and risks. The range of risks identified by BRE et al. is narrow, only four of our seven categories. The three high-level risks were all about financing. Both the medium- and low-level risks are characterised by policy and regulation, and the lack of specialist skills.

Kelly and Pollitt (2010) BRE et al. (2013), Chaudry et al. (2015), and LCICG (2016b) recognise that the upfront infrastructure costs are a barrier, increasing the risk of a lack of access to capital. Therefore we judge that the risk will occur and may cause a long-term disruption to a project. LCICG (2016b) also recognised a lack of innovation of installation methods as a significant risk to greater deployment. As systems can still be installed, the impact is minimal, but the risk does occur. In considering DH, Webb (2015) notes that technical and economic feasibility are insufficient to enable a project to go forward.

Considering manufacturing at this stage, Roberts (2008) notes that any district energy scheme should only be considered in the context of improving building energy efficiency, but we judge this as less critical than for electrical heating using heat pumps (air or ground source). An extra consideration for this case is that a site for the combustor has to be constructed, but this does not present a notable risk. One notable point is that we distinguish infrastructure as the hot water distribution pipes and not that required to deliver the fuel to the boiler or CHP unit. We judge this to be in the highest risk category. As most of the urban environment is privately owned the risk of a lack of access to sites is relevant for DH at this stage (unlike electrical devices), though we expect that any negotiations would only lead to short-term delays.

Level	Barrier	Category and Risk
High	Obtaining money for feasibility/viability work	Economic: lack of access to capital
	Paying the upfront capital cost	Economic: lack of access to capital
	Obtaining money for independent legal advice	Economic: lack of access to capital
Medium	Identifying internal resources to instigate scheme and overcome lack of knowledge	Skills: lack of specialists in the local workforce
	Identifying and/or selecting suitably qualified consultants	Skills: lack of specialists in the local workforce
	Lack of generally accepted contract mechanisms	Political: changing policy or regulatory framework
	Inconsistent pricing of heat	Political: changing policy or regulatory framework
	Concluding agreement with energy services provider including obtaining a contribution to the capital cost	Political: changing policy or regulatory framework
Low	Customer scepticism of technology	Political: significant public concern
	Persuading building occupants to accept communal heat (mandated by the planning authority)	Political: significant public concern
	Uncertainty regarding longevity and reliability of heat demand	Political: changing policy or regulatory framework
	Uncertainty regarding reliability of heat sources	Technical: operation and/or infrastructure failure
	Correctly interpreting reports prepared by consultants	Skills: lack of specialists in the local workforce
	Up-skilling local authority procurement team	Skills: lack of specialists in the local workforce

Table 8.2 Summary of the barriers identified by BRE et al. (2013) for DH schemes and translated to the categories and risks identified here.

Change in the policy and regulatory environment is a risk for many fuels and stages, but for heat it is a lack of policy which is the risk (Hawkey et al., 2013). The international comparison study conducted by Hawkey and Webb (2014) shows that a key feature of success in exploiting heat networks in Norway and the Netherlands was regulatory alignment of business interests. Without such direction, localised markets for heat could not form. More recent work reiterates the problem of policy responsibility in the heat sector historically tracked by Russell (1993). Hawkey and Webb (2014) and Bolton and Foxon (2015) contest that the policy and regulation risk is driven by a disconnect between national and regional actors. Ways of bridging this divide are examined by Bush et al. (2017). They consider the role of intermediaries such as hospital energy managers (embedded in a national organisation, the NHS) and Local Enterprise Partnerships (with a regional remit). A changing policy or regulatory framework can be characterised as a lack of generally accepted contract mechanisms or inconsistent pricing of heat (BRE et al., 2013). As the situation for heat is more fragmented than for electricity, we assign a higher risk. We note too that this is occurs within the system boundary.

Both BRE et al. (2013) and Chaudry et al. (2015) recognise that public perception as a risk; we judge this to be a short-term risk. As a technical risk, uncertainty regarding reliability of heat sources has been flagged by BRE et al. (2013). We judge too that an infrastructure failure is more likely for DH.

Onsite Self-contained Systems

Residential space and water heating demand is principally met using gas-fired boilers (Kane et al., 2015) though use patterns vary considerably (Huebner et al., 2015; Jones et al., 2016). Modelling by Li (2017) and Vijay and Hawkes (2017) suggests that even under optimal policy conditions gas boilers are likely to remain dominant until at least the mid 2030s, and perhaps remain so in anything other than strong policy conditions.

For commercial-building scale equipment there is some evidence that access to capital is a risk (DECC, 2013a). For residential systems, a study by Ipsos MORI and Energy Saving Trust (2013) for DECC yielded some evidence that purchase of a boiler was delayed because of the need to raise capital. This led to distress purchases when the equipment failed, thus we judge this risk to be marginal due to their ubiquity (Hanmer and Abram, 2017). The quality of the fuel source in this context is the quality of the supply of heat i.e. characteristics such as temperature and variability.

Small-scale boilers are a mature technology with an already high (factory) efficiency of around 90%, therefore we judge that the risk of only incremental improvement will occur. Any further CO_2 reductions will need to come from Demand Reduction (section 7.1) or the substitution by a gas with a much lower carbon content. Alternative combustion technologies such as micro-CHP have faltered (Hudson et al., 2011) although some devices were at the market stage. Therefore although capacity for R&D advances exists, it is currently not meeting the challenge.

In addition to the lack of capacity to construct sites (homes) to the required energy efficiency standards set out in the building codes affecting the heating efficiency (Eyre, 2011; LCICG, 2016b), a further problem is the lack of understanding of how buildings are used which leads to poor design. For example, a post-occupancy evaluation by Burzynski et al. (2012) of 200 flats in the UK showed that hot water use could be over-estimated by 90% on average. However, like DH networks, the impact of housing quality to deliver heat is impaired only at the margin of normal activity.

The enforcement of any standards and codes are a matter for a national Government; there are two elements to consider for heat. First is the building regulations for insulation standards which can be considered as a trade-off with affordable housing (DECC, 2013a). We judge this to be moderate that will have a long-term impact because of the longevity of buildings, thus has the potential to have a greater impact than for electrical devices. The second element is that of the required standards for boiler design and manufacture. DECC (2013a) state this as a lack of certainty in future standards. The transition from using manufactured (‘town’) gas to natural gas in the late 1960s into the 1970s (Arapostathis et al., 2013) is a good example of how the risk of significant public concern can be mitigated for a nationwide project. A current aspect of public concern is raised by Mitchell and Mitchell (2014) who suggest that there is a lack of a well-functioning wholesale market, which can lead to price volatility in the domestic market. Other evidence of public concern manifest as undervaluing energy efficiency and savings in replacing equipment, and awareness and the perception of technologies i.e. a lack of reliable data (DECC, 2013a).

As we are considering combustion of a gas, there will certainly be a pollution event, but this will not cause a system to cease operating. The neutralisation of waste at the end of life of boilers is easy to deal with, though the control electronics has specific handling requirements.

8.2.3 Motive Power for Vehicles

Liquid fuels are the most widely used globally for transport applications, but we restrict the discussion to passenger and light goods vehicles. There are a relatively small number of aircraft and ships, most of which will cross our system boundary; considering multi-destination vehicles is beyond the scope of this study.

The only sector with any appreciable proportion using electricity is the railway. For the purposes of this study, pure-electric cars and vans are considered as ‘electrical devices’ and discussed in section 8.2.1. Hybrid vehicles with an internal combustion engine (ICE) and battery configured in series (including buses) are single (liquid) fuel use; whereas parallel plug-in hybrid electric vehicles (PHEV) are discussed separately below. In this study we are not considering exotic gases and liquids, thus we omit vehicles exploiting fuel cells, though if they use a home electrolyser, they are considered an electrical device.

The ICE for road vehicles using petrol or diesel has been dominant since the early twentieth century. The growth in the number of vehicles globally has been delivered through advances in manufacturing and increasing GDP (Gilbert and Perl, 2010). In the UK the numbers in all classes of road vehicle have grown, but passenger and light goods vehicles have increased the most in recent years (DfT, 2017). Some efficiency gain is due to PHEVs as they are dual fuel vehicles; the electrical power demand is considered in section 8.2.1. Currently, the number of PHEVs is very low and will remain so even with high annual growth. As time progresses there are implications for the sources of the electrical power.

It is notable that the use of liquid-fuel powered vehicles presents little risk, with none in the highest category. There being a similar number of passenger and light goods vehicles to the number of adults in the UK population, the cost of owning and operating a vehicle is not prohibitive. The most significant risk was found to be that only marginal improvements to the technology were likely to occur. Martin et al. (2017) show that fuel efficiency of light duty vehicles improved by 26% between 2001–2011. However, they show that this improvement could have been better if the acceleration capability of vehicles remained the same as that in 2001. Furthermore, most of the ‘quick wins’ have been made, thus future improvements will be harder to come by. Using the product generational dematerialisation (PGD) indicator (Ziolkowska and Ziolkowski (2015) suggest that between 2000–2010 the UK transport sector (in general) is showing a clear trend of higher energy efficiency and lower energy consumption. An extensive study by Bishop et al. (2012) created a unique set of well-to-wheel (WTW) estimates by combining well-to-tank (WTT) estimates for current and future fuels for road vehicles coupled with tank-to-wheel (TTW) estimates for different engine technologies. They show that the port-injected and the direct-injected spark ignition technologies have the potential to meet EU emissions standards into the 2020s, but unless emissions are reduced in the fuel supply chain the total GHG emissions are unlikely to reduce beyond that point. However, the record of the industry to innovate has been sustained over a long period with continuous improvements, especially in emissions reductions technologies (Bonilla et al., 2014) pushed by regulation and publicly-funded R&D. Privately-funded R&D levels in the automotive sector are not known exactly, however, a PwC study (Jaruzelski and Hirsh, 2016) suggests that total spending rose from $70 bn to $109 bn between 2005-2015.

In the political category, significant public concern rates as a medium risk. It is interesting because motorists who show concern are both the recipients and generators of impacts (Smith et al., 2013a). Thus it is clear that factors such as the utility of vehicles are more important than, say, fuel price or environmental and health impacts. The so-called ‘fuel duty protests’ in 2000, 2005, and 2007 were primarily about the price of fuel, but disrupted operations and supplies at oil refineries and distribution depots (Noland et al., 2003; Robinson, 2003). Although these protests were led by hauliers and not aimed at refinery operations directly, the consequence was to cause short-term loss of activity. There have not been protests since, but unlike for gas and electricity prices the concern has manifest itself as short-term disruption. With the same level of risk is the changing policy or regulatory framework. The mass-market vehicle manufacturers are global in nature and specify vehicle platforms to meet simultaneously several country codes.

For petrol and diesel vehicles there is by definition a pollution event at every use, with attendant risks to human health (Smith et al., 2013b; Brand, 2016). It is noteworthy that although decommissioning does not present a risk, the nature of the risk will shift with time as more electronics components and non-metallic body panel are built into mass-market vehicles.

8.3 Cross-cutting Causes of Risk

8.3.1 Critical Materials Availability and Substitution

These two risks are linked, but straddle the environment and innovation categories. Many renewable conversion technologies exploit chemical elements which are either rare, expensive to produce, or are concentrated geographically. The level of dependence varies, but the use of critical materials improves efficiency or efficacy of such items as generators, solar cells, high-power electric motors, and high-density batteries. The UK Energy Research Centre handbook gives a quick guide to the main elements in question, their properties and some statistics (Speirs et al., 2013a), a list which extends well-beyond the rare earth elements. Speirs and Roelich (2015) review the case for critical metals. Estimates of the total recoverable quantities (resource availability) are disputed. Speirs et al. (2015) point out the use of incommensurate methodologies for classifying resource availability as a key problem. With respect to the rare earth elements Speirs et al. (2013b) suggest that there is no clear evidence of future shortage, despite recognising the paucity of estimates for supply and demand. However, this view is supported by Nassar et al. (2015) who consider the supply risk to be moderate in the near- to medium-term and low in the long-term. A number of mitigation mechanisms have been discussed and modelled (Sprecher et al., 2017), but they all take time to implement. We concur and judge this as a moderate risk. We note, however, that there are a number of other elements and alloys which are important to other fuels, for example platinum group elements as catalysts in oil refining. These are discussed in the relevant sections.

Substitutability is a more broad matter. For example, the use of steel in the offshore environment is not an issue of materials availability, but there are no plausible alternatives. Likewise for zirconium alloys in the nuclear industry. Some rare earth elements can be substituted (Speirs et al., 2013a) though Tkaczyk et al. (2018) point out that cobalt is very hard to exchange. We consider substitutability to be a harder technical problem as there may be hard ‘physics limits’ with which to contend. Thus we judge that the risk may occur, but that it may create a sustained (but recoverable) delay to innovation.

8.3.2 Skills

There are many examples of the media proclaiming that the UK has a skills shortage (Wall, 2014; Chapman, 2017; Pozniak, 2017) usually based on surveys from various industry or trade bodies (UKPIA, 2011; Engineering UK, 2018), professional bodies

(Energy Institute et al., 2008), or from modelling (Wilson et al., 2016a, 2016b). Similar reports appear in the specialist press (Hines, 2017; The Engineer, 2017). But hard data supporting these claims is lacking and it is likely that many studies are double-counting and not allowing for the phasing of major projects i.e. some or all of the workforce can move from one project to another successively. There is a paucity of academic studies, fewer still focussing on the UK.

One noteworthy academic study is that by (Jagger et al., 2013) which considers skills for the low-carbon transition though not the whole energy sector. They note that a key problem is the uncertainty of which technologies (and pathways) will be deployed i.e. it is hard for citizens (and companies) to invest in training if they see a risk that it will be wasted. Jagger et al. also consider that most studies and reports are too general for Government to interpret and act on in a detailed or effective manner. This in their view leads to increased costs of current staff, increased time to complete projects, reduced competitiveness and capabilities, and reduced employment.

As the UK has a well-organised school education system, we consider that the risk of a lack of basic education levels in the workforce is low. However, the lack of trained and skilled operatives and engineers is highlighted for some specific areas. Where there is some evidence of a skills shortage or knowledge gap in one fuel with installation, for example, we assume that other fuels requiring similar skills at the same stage will also be experiencing shortages. Broadly, the greatest concern is with a lack of vocational (technician level) skills and principally at stages 2-4. The distribution stage, mostly electricity networks, has specific shortages. In general terms, many segments of the renewable energy industry is thought to be at risk of recruitment difficulties in the future (JRC, 2014).

The installation and operation of AD is noted as lacking the availability of technical skills (Tranter et al., 2011). For biofuel processing, surveying by Hammond et al. (2012) recorded the lack of high-level biofuel expertise particularly in biochemistry, chemistry, and automotive engineering, noting that industry instability made it unattractive to skilled people of all levels. (Hodgson et al., 2016) technical level skills are lacking.

Demand Reduction has a wide variety of skills gaps. In the industrial sector there is a lack of energy management professionals, with the food and drink industry considered as critical (LCICG, 2012c). For commercial buildings , the installation, commissioning, and operation of building services has been identified as having a skills shortage (LCICG, 2016d; Engineering UK, 2018). In the residential sector Pitts (2017) and Heffernan et al.

(2015) recognises that designers lack knowledge to create dwellings to passive house and zero-carbon standards (respectively), Glass et al. (2008) that specifying and estimating skills are a problem, and that technical skills for retrofit are lacking (Killip, 2013; Fylan et al., 2016; LCICG, 2016c; Gooding and Gul, 2017). According to Fylan et al. installers lack the knowledge of the technologies and products to make good adaptations, which is less of a problem in volume new-build. There is also some evidence of a lack of facilitators in the ESCO market (Bertoldi and Boza-Kiss, 2017).

A lack of installers or poor quality installation was noted for PV (Baborska-Narozny et al., 2016; LCICG, 2016a; Curtin et al., 2018; Hanna et al., 2018) and specifically the handover from installer to owner/operator (Baborska-Narozny et al., 2016). Ziyad and Stevenson (2018) report a lack of detailed understanding about PV amongst architects, designers, and project managers. There is evidence of technical level skills being in short supply for the installation of wind turbines (Curtin et al., 2018).

The decline of the UK civil nuclear industry lead to a well-documented shortage of staff at all levels once a renaissance started (Roberts, 2009; Cogent, 2010a, 2010b, 2010c; DBIS, 2013; JRC, 2014). The importance of the experience embodied in the aging workforce is recognised (DECC, 2015c) and that training for many roles takes a long time (LCICG, 2016e). Subsequent to a parliamentary inquiry (HLSCST, 2011) the Nuclear Skills Strategy Group formulated a plan (NSSG, 2016) for skills development. In a recent report (NSSG, 2017) they identified the current most important occupations with skills shortages, namely: safety case preparation, control and instrumentation,162 reactor operation, site inspectors, project planning and control, commissioning engineers, emergency planners, quality assurance staff, and chemists.

For fossil fuels, there is a risk that as the industry declines, as has been seen for Nuclear (fission), there will a gradual loss of expertise as people retire but too few new people enter the industry. There are reports of skills gaps in the UK refining and downstream oil and petrochemical industry (UKPIA, 2011). For the burgeoning shale gas industry Lewis et al. (2014) report that the UK has very few onshore technical specialists. In particular technical people for drilling operations, planning, and environmental monitoring, though the Institute of Directors (IOD, 2013) suggest that this is a moderate risk. Gluyas et al. (2018) express the hope that people with oil and gas drilling expertise can redeploy to geothermal operations.

Turning to the distribution stage, the power systems industry (electricity networks especially) has a recognised staffing shortage (Energy Institute et al., 2008; Engineering

UK, 2018). Whilst it may be possible to recruit engineers from outside the system boundary, the national grid codes require specialist knowledge which can only be gained through in-country training. The industry response was to set up scholarship under the title of The Power Academy (IET, 2018).

The provision of low-carbon heat devices, services, and infrastructure is recognised as having skills shortages (Wade et al., 2016). At the residential scale this includes technical level installation skills for thermal solar panels for hot water (Connor et al., 2015), heat pumps for low temperature thermal water and space heating (LCICG, 2016b), and micro-CHP (Hudson et al., 2011), though we do not consider the latter more than a moderate level risk. Perhaps more important, though, is advice for homeowners and industry regarding low carbon alternative heating systems (DECC, 2013b). Concerns have been raised about high-level skills gaps for DH (BRE et al., 2013; LCICG, 2016b).

8.3.3 Negotiation

Negotiation is not a stage in its own right as it occurs throughout the whole supply chain. Moreover, negotiation is not a risk which can be attached to a single category. We have taken account of the risk that 'a negotiated agreement cannot be reached' in context where appropriate. In Table 8.3 we have grouped fuels by four common signifiers of perhaps the most important – though not the only – negotiation hurdle or phase. Each signifier could occur at different stages for each fuel and will have a different level of importance. The examples we discuss raise interesting questions about how negotiation affects the overall risk profile for a stage or a fuel and is a topic for further work (section 11.4).

Key Negotiation Phase / Hurdle	Source of Fuel
Access to distribution	Biogas, Wind (offshore), Wind (onshore)
Access to suppliers	Bioliquids, Biomass (solids), Waste
Legislation and regulation	Coal, Demand Reduction, Gas (unconventional), Solar (electric),
Access to capital	Gas, Hydro, Nuclear (fission), Ocean (tidal), Ocean (wave), Oil, Solar (thermal, water), Thermal (geological), Thermal (low temperature)

Table 8.3 The main classes of negotiation occuring at different stages for the sources of fuels.

The most widely considered use of negotiation is the development of viable projects, but it is not the only use but incorporate several interesting elements each with an attendant risk. Project development includes issues such as the social licence to operate, identifying technology and staff, business planning, accessing capital funding, obtaining licences / permits / contracts, and environmental impact assessment. The upfront negotiation of long-term contracts may be important for some major investments. For example, companies proposing EfW facilities will need to negotiate with Councils or other local authorities for a minimum tonnage supply rate of MSW (DEFRA and DECC, 2014). Another example, discussed by Thomas and Dawe (2003), Stroebel and van Benthem (2012), and Stulberg (2012), is long-term contracts for gas transportation.

Whilst we have used evidence of objections to planning applications as a measure of public concern, planning is a form of negotiation at the community level for several sources of fuel. Objections to planning applications and subsequent compromises for Biomass combustion, Biogas production using AD, Solar (electric), and Wind (onshore) may lead to non-ideal solutions. But Clark and Roddy (2012) contend that this is a better outcome than plans being rejected. For LFG, Brown and Maunder (1994) also found obtaining planning consent to be difficult, which they considered as a negotiation rather than as a manifestation of public concern. A specific issue for LFG which they noted was the need to negotiate rights to exploit the gas if multiple parties were stakeholders in the site. This is also a risk for EfW facilities.

Several risks occur for DH networks (BRE et al., 2013) which, although classified as Political (Changing policy or regulatory framework), could be considered as an example of negotiation. We see the key negotiating hurdle as regulation and legislation to create a level playing field with supply-side activities.

Because ownership of subsurface resources resides with the Crown, shale gas extraction has a particular regulatory problem stemming from the geological dispersion of the gas (Roberts, 2017). Companies exploring for unconventional gas in the UK need to negotiate with landowners to gain access, but there is little return to the landowner as they do not own the subsurface resources. Roberts suggests that shale gas licencees need to collaborate to enable economies of scale.

9 Observations and Analysis of the Matrix

The objective of the risk analysis is to give an evidence base for policy discussions in ES. We describe some characteristics of the risk profile of the UK's energy provision, modelled as a number of supply chains. As a further example of how the method can illuminate policy discussion we estimate risk profiles for some existing respected future UK energy scenarios. Detailed policy discussions are beyond the scope of this work, but we will note some implications in the Conclusions.

There are 3114 separate risk estimates for 34 risks across six stages, for 19 fuels, and five final energy vectors. Therefore the number of possible ways to slice the data set are greater than can be practically presented in a single document. Indeed, not all views of the data set yield statistics which are likely to be useful and therefore selection is imperative. We note that because the categories of risk have some fuzzy boundaries, they can be considered to be of secondary importance. For ease of comparison, we present most data in a normalised form, which illustrates differences and trends. The raw risk scores are not meaningful in themselves. The interesting questions to ask are which are the most and least riskiest fuels, which risks (or types) are most important, and whether there are any patterns to the stages or scales at which these risks are located. The combined risk profiles for future energy systems as they change over time are also interesting.

In approaching analysis of such a complicated risk matrix the aim is to find a useful indicator for overall comparison of stages, fuel types, risk categories, or for building risk profiles for different transition pathways to a low(er) carbon economy. The question is whether to cascade a risk impact value through all subsequent stages, or use a simple, but transparent, additive method. A difficulty with the first method is that if one high barrier is overcome, subsequent stages may be very low risk, thus the effort expended to mitigate the high-level risks may pay dividends that would be poorly represented. This is why statistical methods should only support expert discussion and not replace it. Given that these causes of risk are generic and the analysis is at a high-level, a simple method is preferable to maintain confidence of interpretation.

9.1 Assessing Fuels by their Overall Risk

In devising a method to reach a composite score which is fully representative of the overall risk several characteristics of the whole fuel supply chain need to be taken into account, namely:

- five fuels branch at different stages into pathways which produce different energy vectors (Biogas, Biomass, Gas, Gas (unconventional), and Thermal (geological)),
- the 19 fuels share only five different distribution systems (electricity networks, road tankers, and pipeline for gas, oil, and water), and
- four different end-use types.

It is not reasonable to attribute the full risk score to every fuel, indeed this would be a form of double-counting. Furthermore, shared infrastructure and end-use type suggests that using a new fuel which produces an existing energy vector presents only a marginal increase in risk (and cost) for its introduction. It is a separate matter whether this reduces system resilience.

Stages 1-4 are independent for each fuel thus can be simply summed for each fuel. At stage 4 the branching points score zero. We assume that the risk for end-use type (stage 6) is shared equitably, but there are some minor deviations for some distribution systems (stage 5), e.g. the offshore network portion for marine and wind technologies. These fuels then share the onshore electricity networks with other fuels. We assume that the common elements are shared, but we need to account for the unique risk associated with some fuels over and above that of the common elements. The total (composite) risk score (TRS) for a fuel *f* can be expressed as

$$\mathrm{TRS}_f = \underbrace{\sum_{i=1}^{4} S_i}_{\text{Sum of stages 1-4}} + \underbrace{\sum_{j=1}^{m}\left[\left(S_{5,j} - U_j\right) + \frac{U_j}{m_j}\right]}_{\text{Share of distribution risk corrected for any elements unique to that fuel}} + \underbrace{\sum_{k=1}^{n}\frac{S_{6,k}}{n_k}}_{\text{Share of risk for end use}} \qquad (1)$$

where:

S_i = sum of the risk score for the *ith* stage,

U_j = risk score of the underlying distribution *jth* infrastructure type,

m_j = number of fuels sharing the *jth* infrastructure type,

n_k = number of fuels sharing the *kth* use type.

We consider this approach to be reasonable since it supports the marginal risk element of shared infrastructure. This also explains and why nations find introducing a fuel (or new use of an existing fuel) so difficult when it requires a new dedicated distribution mechanism.

In Table 9.1 we show the total risk score calculated using Eq. 1 and the normalised risk score (0-100). From this point forward we will usually only show normalised scores as it is the relative differences which are more meaningful and/or easier to comprehend.

Fuel	**Total Risk Score (a.u.)**	**Normalised Risk Score (a.u.)**	**Rank**
Gas (unconventional)	436	100	1
Gas	430	99	2
Oil	427	98	3
Nuclear (fission)	409	94	4
Thermal (geological)	351	80	5
Biomass (solids)	285	65	6
Coal	283	65	7
Biogas	264	61	8
Bioliquids	209	48	9
Ocean (wave)	205	47	10
Demand reduction	195	45	11
Waste	189	43	12
Ocean (tidal)	183	42	13
Thermal (low temperature)	162	37	14
Wind (offshore)	149	34	15
Wind (onshore)	139	32	16
Hydro	136	31	17
Solar (electric)	111	25	18
Solar (thermal, water)	88	20	19

Table 9.1 Overall risk ranking for the fuels (most risky at the top of the table).

Non-renewables appear towards the top of the table (conferring more risk on the energy system) and renewables towards the bottom. There are seven fuels in the centre which are a mix of renewable and non-renewables. The mean raw total for renewables is 175 and for non-renewables 340, approaching a factor of two greater. It is noticeable that the top four are all non-renewables and score much more highly than the main group (rank 6 onwards). There is a factor of five between the most and least risky fuels.

The bio-derived fuels are higher ranking than might be judged at first sight. For Biogas and Biomass stages 4-6 all carry significant risk, and for Bioliquids it is stage 3. Thermal (geological) is also a fuel source which would be perceived as low risk, however, all stages present significant risks. The scale of the operations and the high likelihood of failure account for these levels of risk.

It is perhaps surprising that DR is not at the bottom of the ranking since it is often described as ‘the first fuel’ (Rosenow et al., 2017) i.e. it should have the lowest risk profile. But it does not, which ties with the evidence that DR appears to be difficult in practice and never delivers the supposed levels of saving, even accounting for the rebound effect. The lens of risk brings into focus the elements which are integral to the relative lack of success of DR programmes. In comparing this negafuel with other fuel sources it is clear to see that meeting demand with supply from Solar (electric), Wind (offshore), and Wind (onshore) is a more straight-forward task.

9.1.1 Error propagation and uncertainty estimation in the risk scores

In any multi-step calculation it is possible to estimate the compound error (Squires, 2008; Hughes and Hase, 2010). Estimating the uncertainty in the final risk total gives a handle on whether and by how much the spread in risk scores overlap for different fuels. Uncertainty arises from incorrect estimates of the likelihood or impact of a cause of risk. As it is likely that the broad level of the risk (low, moderate, high) will be estimated correctly, the error in any consequence score is most probably ±1 and at worst ±2 (termed uncertainty in the risk, ΔR). An uncertainty analysis serves two purposes 1) to see which fuels have statistically significant similar scores, and 2) to gain understanding of whether reappraisal of the likelihood and impact scores in future analysis will significantly affect the ranking. The precise ranking of different fuels is not important for ES policy discussions, but broad groupings may be a useful shortcut.

In Eq. 1 n_k, m_j, *and U* in the elements for stages five and six are constants which have no uncertainty, therefore Eq. 1 is of the form

$$\mathrm{TRS}_f = S_1 + S_2 + S_3 + S_4 + S_{5,i} + S_{5,j} + S_{6,i} + S_{6,j} \tag{2}$$

where *S* is the sum at each stage. The general form of the uncertainty for a sum is

$$(\Delta \mathrm{Z})^2 = (\Delta \mathrm{A})^2 + (\Delta \mathrm{B})^2 \tag{3}$$

Thus the uncertainty in the composite risk score can be expressed as

$$\left(\Delta \mathrm{TRS}_f\right)^2 = \left(\Delta S_1\right)^2 + \left(\Delta S_2\right)^2 + \left(\Delta S_3\right)^2 + \left(\Delta S_4\right)^2 + \sum_{j=1}^{n}\left(\Delta S_{5,j}\right)^2 + \sum_{k=1}^{n}\left(\Delta S_{6,k}\right)^2 \tag{4}$$

But as ΔR is an integer we can state that

$$\left(\Delta S_i\right)^2 = \sum_{p=1}^{N}\left(\Delta R_p\right)^2 = \left(\Delta R_1\right)^2 + \left(\Delta R_2\right)^2 + \cdots + \left(\Delta R_N\right)^2 \tag{5}$$

where N = number of relevant (non-zero) risks at the *ith* stage. If we take ΔR=1, then

$$\begin{aligned}\left(\Delta S_i\right)^2 &= \left(1^2 + 1^2 + \cdots + 1^2\right)_N = N \\ \Delta S_i &= \sqrt{N}\end{aligned} \tag{6}$$

Therefore the uncertainty in the composite risk score for any fuel f (Eq. 4) is:

$$\begin{aligned}\left(\Delta \mathrm{TRS}_f\right)^2 &= \sum_{i=1}^{4}\left(\sqrt{N_i}\right)^2 + \sum_{j=1}^{p}\left(\sqrt{N_{5,j}}\right)^2 + \sum_{k=1}^{q}\left(\sqrt{N_{6,k}}\right)^2 \\ \Delta \mathrm{TRS}_f &= \left[\sum_{i=1}^{4} N_i + \sum_{j=1}^{p} N_{5,j} + \sum_{k=1}^{q} N_{6,k}\right]^{1/2}\end{aligned} \tag{7}$$

Eq. 7 can be described as the uncertainty in the total risk score for a fuel is the square root of the sum of the number of relevant (non-zero) risks for that fuel. Similarly, if the error ΔR=2 on each risk then the uncertainty is multiplied by √2. In Figure 9.1 we show the effect of assuming the worst case i.e. that all individual consequence scores (likelihood * impact) carry an uncertainty of ±2. This is the practical outer limit of misattributing likelihood and impact values. Figure 9.1 also shows which groups of overall risk scores can be considered unique (a form of simple clustering). The four riskiest (non-renewable) fuels have such similar scores that they can be considered to be in any order. Biomass, Coal, and Biogas have indistinguishable scores, as too does the group encompassed by Bioliquids and Ocean (tidal). Thermal (low temperature) to Hydro form a cluster, with Solar (electric) and Solar (thermal, water) forming the least riskiest pair. Thermal (geological) is difficult to attribute as it is located equidistant from two groups, but for convenience we make it part of the Biomass group.

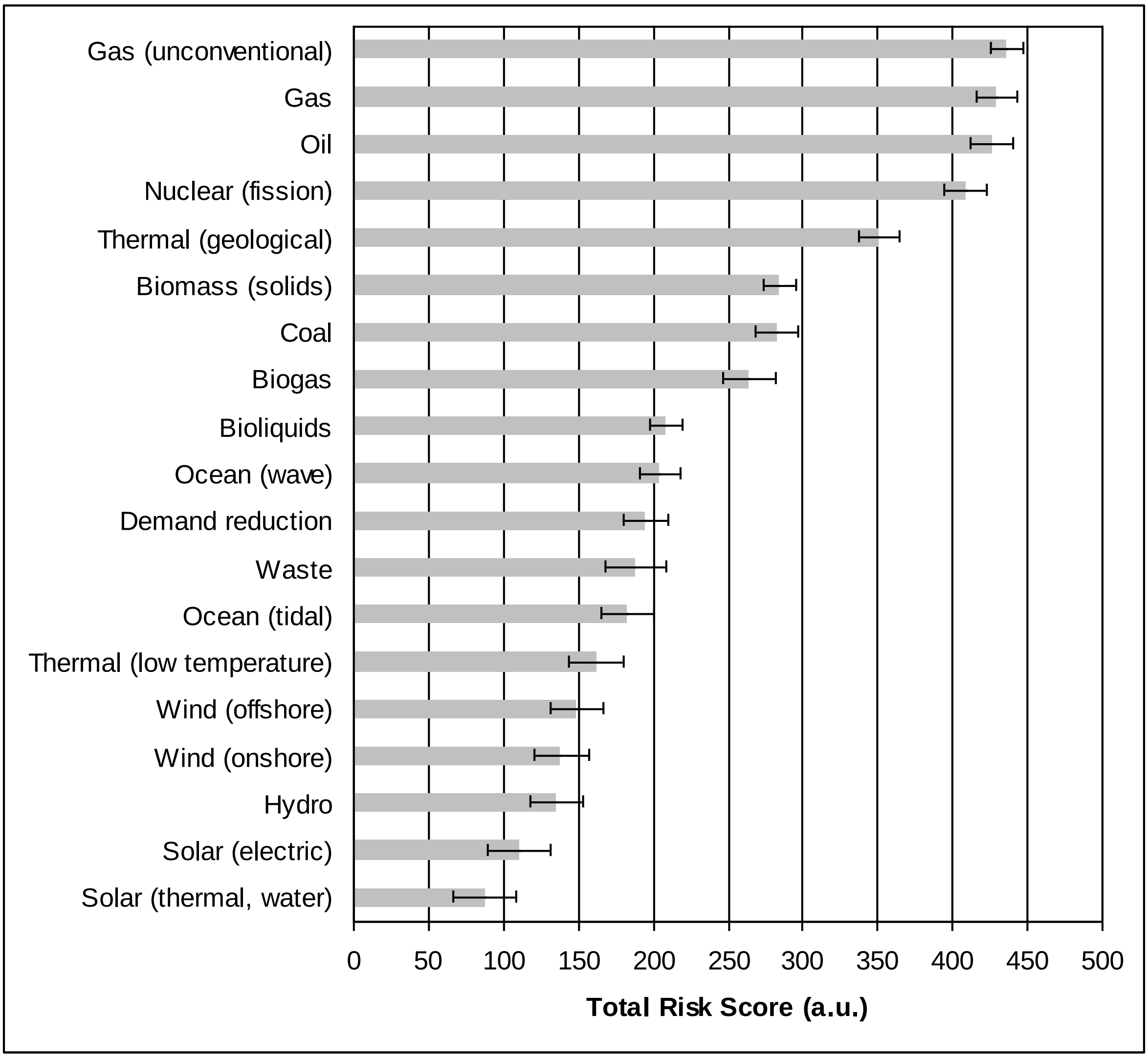


Figure 9.1 The total risk score for all fuels with a worst-case error of ΔR=2 for each individual cause of risk for each fuel at every stage. In this case it is more intuitive to use the raw risk score rather than the normalised score as it keeps the uncertainty in the risk (ΔR) in native units.

We suggest that the groupings (Table 9.2) are unlikely to switch membership without radical changes in at least several categories of causes of risk. This implies that the risk scores we have calculated are sufficiently robust to project using sets of scenarios into the medium-term – 20 years hence, say. There is evidence from the slow-moving nature of national economies that 20 years is a reasonable time-constant (Roberts et al., 2016).

Group Members	Average Normalised Risk Score (a.u.)
Gas, Gas (unconventional), Oil, Nuclear (fission)	97
Biogas, Biomass, Coal, Thermal (geological)	68
Bioliquids, Demand Reduction, Ocean (tidal), Ocean (wave), Waste	45
Hydro, Thermal (low temperature), Wind (offshore), Wind (onshore)	33
Solar (electric), Solar (thermal, water)	23

Table 9.2 Cluster memberships which are unlikely to switch, though the ranking of individual fuels may change over the medium-term.

9.1.2 Summary of Risk Characteristics by Fuel Type

We have categorised fuels as either renewable or non-renewable; in Table 9.3 we give an overview of some important characteristics of the risk matrix.

Characteristic	Non-renewable	Renewable
Average total normalised risk score (a.u.)	78	40
Most significant cause of risk	Lack of access to capital	Changing policy or regulatory framework
Most significant risk category (sum)	Political	Innovation
Most significant stage (sum)	Stage 2: Exploit	Stage 2: Exploit
Total number of high-level risks	75	45
Fuel carrying the greatest risk	Gas (unconventional)	Thermal (geological)
Fuel carrying the lowest risk	Waste	Solar (thermal, water)

Table 9.3 Significant characteristics for the renewable or non-renewable fuel categories.

9.2 The Relative Importance of the Causes of Risk

As we have used a consistent set of causes throughout all stages of the supply chain, we can compare how important different risks are at different stages. There are three possible approaches. The first is that we can calculate a rank order of these risks by summing the individual consequence scores across all fuels. Secondly, we can count the number of risks which fall into the high-level group. Thirdly, we can examine the pattern of distribution of micro, meso, and macro scale risks as these are assigned independent of the likelihood and impact evaluations.

Table 9.4 ranks the risks by the sum of their scores across all fuels and stages. We can see that the categories of risks are well-spread through the ranked list (Table 9.4). Although the spread is not completely even, this shows that the causes of risk selected represent a range of levels of importance. It is likely that these levels will differ from country to country. All seven categories of risk appear in the first 10 places demonstrating that both the selection of risks is appropriate and that important risks are spread widely in their nature.

An unexpected top 10 risk is the lack of specialists in the local workforce. It appears that this may be driven by the electricity distribution industry. The available (grey) literature may be subject to double-counting and over emphasising this risk. It is not surprising that the lack of access to capital is at the top, since this affects both large and small projects. A residential-scale installation may cost six orders of magnitude less that a power station, say, but it is the cost relative to the income of the buyer which is important. Furthermore, the availability of capital tends to be framed as a ‘go / no go’ question. This capability to force the cessation of an activity places this risk at the highest level.

It is notable that the five causes of risk (Table 9.4) with the number of high-level individual consequence scores in double figures are all in the top 10 ranks (ranked 1st, 2nd, 3rd, 5th, and 8th); two of these are in the Political category. Outside of the top risks, only quality of the fuel source has an appreciable number of high-level individual consequence scores. The correlation between the sum of the scores for each cause of risk and the number in the high-level category is modest (R^2=0.4488, Table 9.5) and indicates that the ranking of all other causes of risk is driven by the frequency of which they occur.

Rank	Cause of Risk	Micro	Meso	Macro
1	Lack of access to capital	13	25	46
2	Changing policy or regulatory framework	0	87	2
3	Significant public concern	55	39	0
4	Lack of vocational training of the local workforce	0	99	0
5	Insufficient capacity to construct sites	42	27	6
6	Optimism bias	0	61	32
7	Lack of specialists in the local workforce	0	97	0
8	Pollution event	82	0	4
9	Operational failure	86	10	0
10	Natural hazards	87	0	0
11	Only marginal improvements likely	0	12	73
12	Unable to neutralise waste at decommissioning	81	7	0
13	Insufficient capacity to manufacture system components or conversion devices	0	8	79
14	R&D capacity or capability does not match the challenge	0	44	40
15	Quality of fuel source	44	28	4
16	Lack of a well-functioning market	0	22	77
17	Lack of public subsidy	0	56	0
18	Weak technology transfer environment	0	35	49
19	Insufficient rate of improvement in, or lack of enforcement of, standards and codes	0	80	0
20	Price volatility	14	12	69
21	Lack of material substitutability	0	0	72
22	Denial of permission to access sites	58	10	0
23	Lack of critical materials availability	0	0	65
24	Difficult physical access	57	0	0
25	Insufficient rate of infrastructure construction	4	37	0
26	Specialist equipment unavailable	19	34	18
27	Uncertain decommissioning costs	66	1	0
28	Infrastructure failure	42	24	0
29	Disputed landrights or resource ownership	50	7	0
30	Unable to agree a price for licence or permits	7	30	0
31	Lack of basic education levels in the local workforce	0	76	0
32	Lack of water availability	23	0	0
33	Lack of social stability	0	26	0
34	Poor institutional governance	0	26	0

Table 9.4 Rank order of the causes of risk with the prevalence of the different scales. The categories to which risks are associated are colour-coded as:

Economic	Environmental	Innovation	Manufacturing	Political	Skills	Technical

We note that comparing renewables and non-renewables across all stages the score for individual causes of risk, renewables score higher than non-renewables in 44% of the assessments. Intuitively this appears high, but progress in developing and deploying some renewable technologies is slow.

There are no correlations between the number of risks classed as macro-, meso-, or micro-scale with the total score for the causes of risk (Table 9.5). This result is expected and confirms that the causes of risk are not defined in such a way that introduces any form of bias.

	Micro	Meso	Macro	High-level (number)
R^2	0.0046	0.1116	0.0170	0.4488

Table 9.5 Correlation coefficients for the number of micro-, meso-, and macro-scale risks with the scores for each individual cause of risk and total number of high-level risks.

Constructing the risk matrix revealed areas for which there is relatively little understanding of the risks to the fuel supply chain, and by extension ES. These blindspots have received little academic attention in this context e.g. manufacturing for energy supply chains. Although concern is shown by Government, the assessment is not in terms of risk to ES. We note that it proved difficult to be consistent with interpreting Optimism bias.

Although a detailed analysis of systemic risks is beyond the scope of the current work, we can look at the risks that are common and widespread in the fuel chains examined. Using the tables in Appendix A we can show that only two causes of risk occur at every stage for all fuels: ‘lack of a well-functioning market’ (Economic) and ‘lack of vocational training in the local workforce’ (Skills). If we set an arbitrary cut-off point of a risk appearing in 90% or more fuels (at all stages) then a further seven risks (from five categories) may be consider ‘systemic’ (the complete list is shown in Table 9.6. Looking at the overall rank (Table 9.4) the lack of vocational training in the local workforce is highly ranked, but the lack of a well-functioning market is ranked mid-table. Furthermore, the other cause of risk with a prevalence higher than its ranking might indicate is ‘Price volatility’ – also in the Economic category. This result supports our suggestion that the consequence level may be less important.

Prevalence	Cause of Risk	Risk Category	Overall Rank (of 34)
100%	Lack of vocational training of the local workforce	Skills	4
100%	Lack of a well-functioning market	Economic	16
98%	Lack of specialists in the local workforce	Skills	7
97%	Operational failure	Technical	9
96%	Price volatility	Economic	20
96%	Significant public concern	Political	3
95%	Optimism bias	Innovation	6
91%	Changing policy or regulatory framework	Political	2
90%	Unable to neutralise waste at decommissioning	Technical	12

Table 9.6 The most prevalent causes of risk occurring in the matrix across all stages for all fuels. The overall rank is that given in Table 9.4.

A further four causes of risk have a prevalence of 89% and this captures the remaining two risk categories (Manufacturing and Environmental). However, there is a clear gap between ‘Optimism bias’ and ‘Changing policy or regulatory framework’ suggesting that only the first seven causes of risk might be consider to be characteristics consistent with being systemic.

9.3 Risk Variation by Stage

We consider the type and size of risks not only for individual fuels, but also by fuel category and cumulative score. Disaggregating the process into stages in particular highlights the differences between renewables and non-renewables. The total risk score is dominated by whether stages are merged or not. This lowers the overall scores for renewables, in general. The distribution of the score of a particular cause of risk across stages may not be the most important outcome, however, where the risk occurs and at what scale will be for policy considerations. At the level of individual fuels, we visualise how the risk score varies at each stage using radar plots.

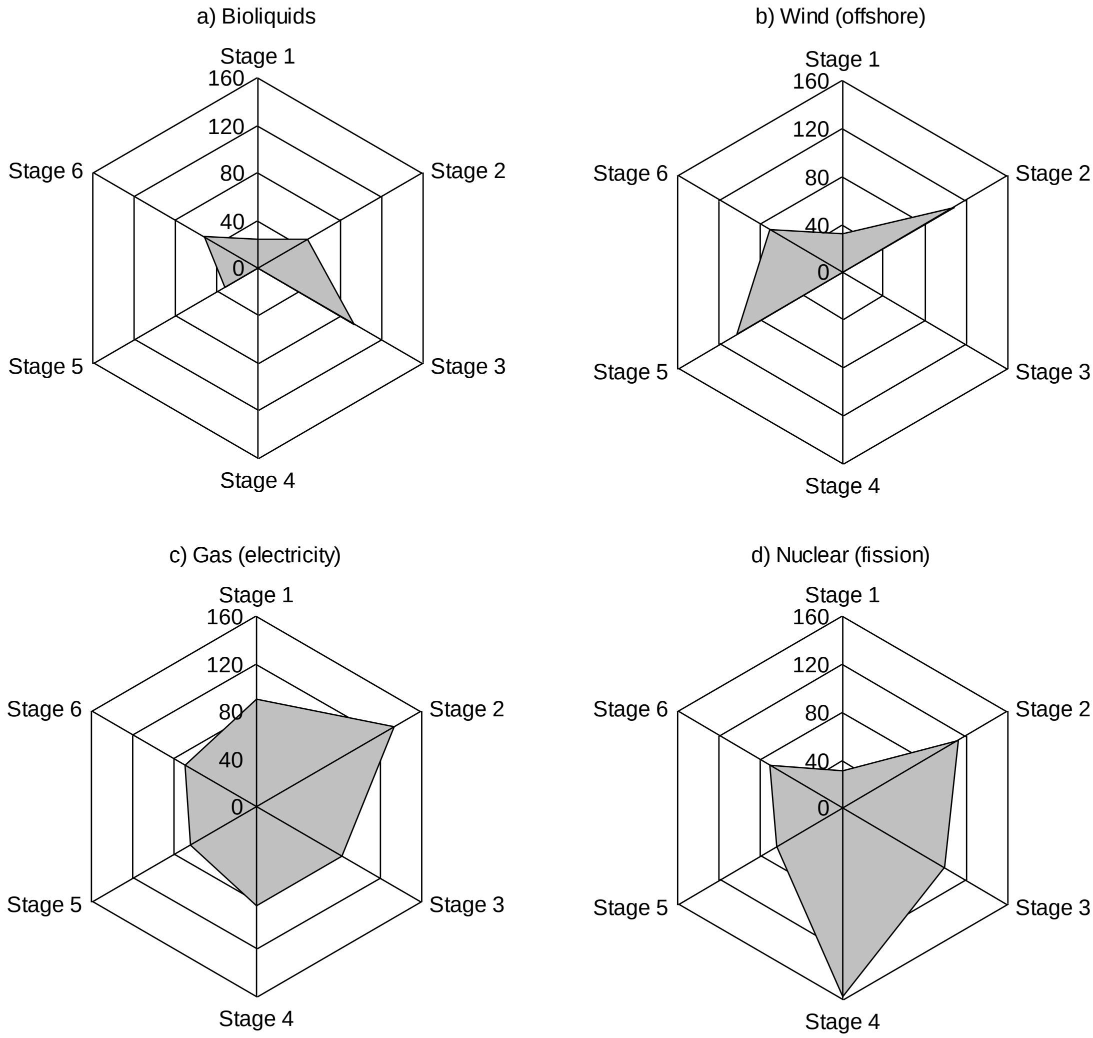


Figure 9.2 Four examples (two renewable, two non-renewable) of how the stage total risk score varies for a) Bioliquids, b) Wind (offshore), c) Gas, and d) Nuclear (fission). The Gas (electricity) chart shows how this method distinguishes fuels with branching points. Gas used for electricity generation yields a risk pattern different from gas used for heating.

The cumulative total risk score across stages for an individual fuel gives an indicator of whether there is an especially high hurdle to overcome along the supply chain (Figure 9.3). A step-change in the profile may indicate the need for attention to policy or regulation. The size of the step or the ratio of the upper to lower value do not appear to be important, but only by drilling down into the causes of risk which give rise to the jump in cumulative risk score can a meaningful picture be drawn. The profiles of the cumulative total risk scores for renewables, non-renewables, and all fuels combined is shown in Figure 9.4. When considering the full range of fuels, the profile for renewables flattens more quickly that for non-renewables. This shows that risk continues to accumulate in stages four and five for non-renewables, and that risk is front-loaded into stages 1-3 for renewables.

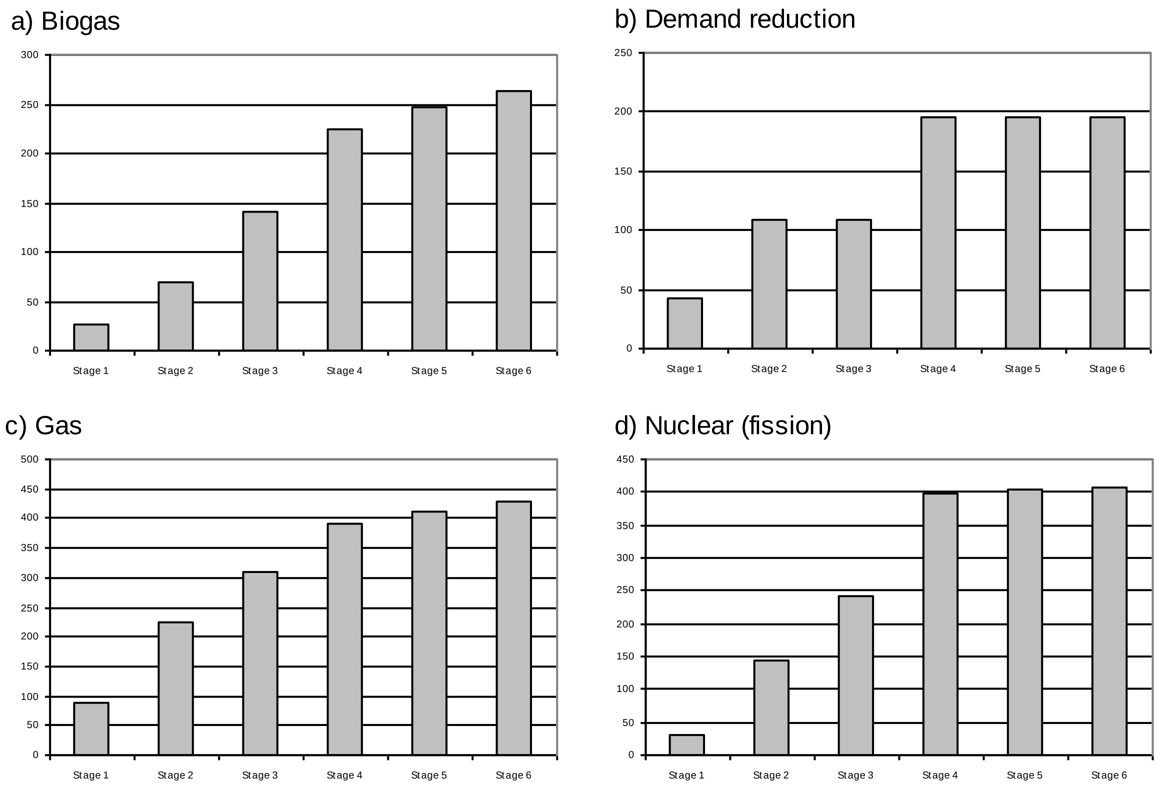


Figure 9.3 Four examples (two renewable, two non-renewable) of how the cumulative total risk score profile changes with the process stages for a) Biogas, b) Demand reduction, c) Gas, and d) Nuclear (fission).

This point is amply demonstrated by looking at the average risk score at each stage (Figure 9.5). The average score for renewables at stages one, three, and four is very much less than that for non-renewables. At stages 5-6 the scores are similar and higher for renewables, unlike all other stages.

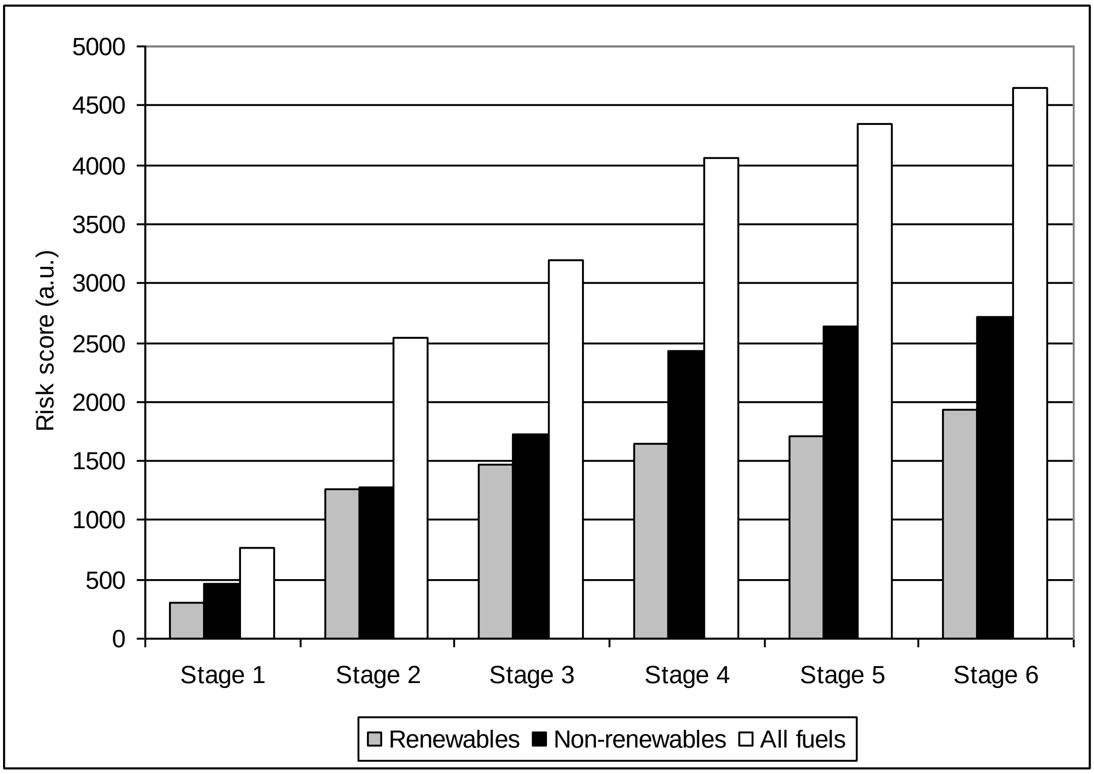


Figure 9.4 The cumulative total risk score profiles for renewables, non-renewables, and all fuels.

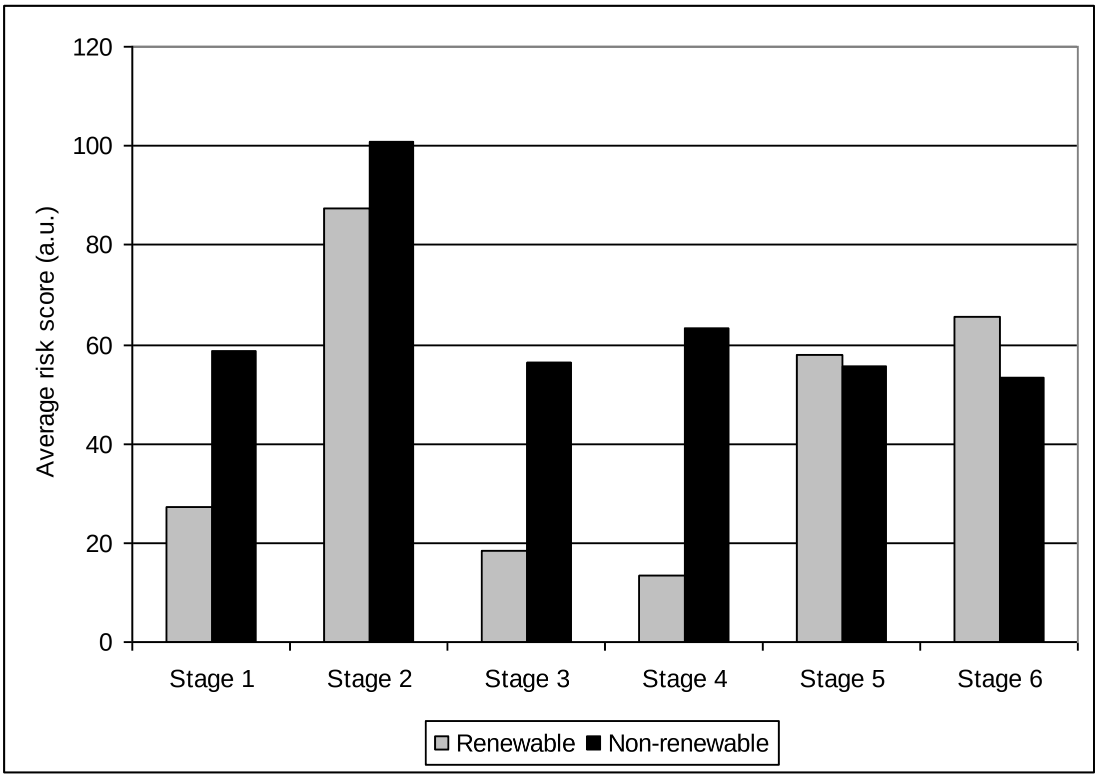


Figure 9.5 Average risk score at each stage for renewables and non-renewables.

The number of relevant risks at each stage (for all fuels) follows a similar pattern to Figure 9.5 i.e. fewer risks at stages three and four and there is strong correlation between this number and the stage risk score (R^2=0.8284). However, the distribution of the number of high-level risks does not follow the same pattern (Figure 9.6). We observe that stages two and four are the most prominent, with stage two having double the number of high-level risks of stage four. The split of these high-level risks with respect to their scale is also shown in Figure 9.6. As expected, there is no pattern to their distribution, but it is interesting to note that stages one and three do not have any high-level meso-scale risks, and that at stage six, the only high-level risks are meso-scale.

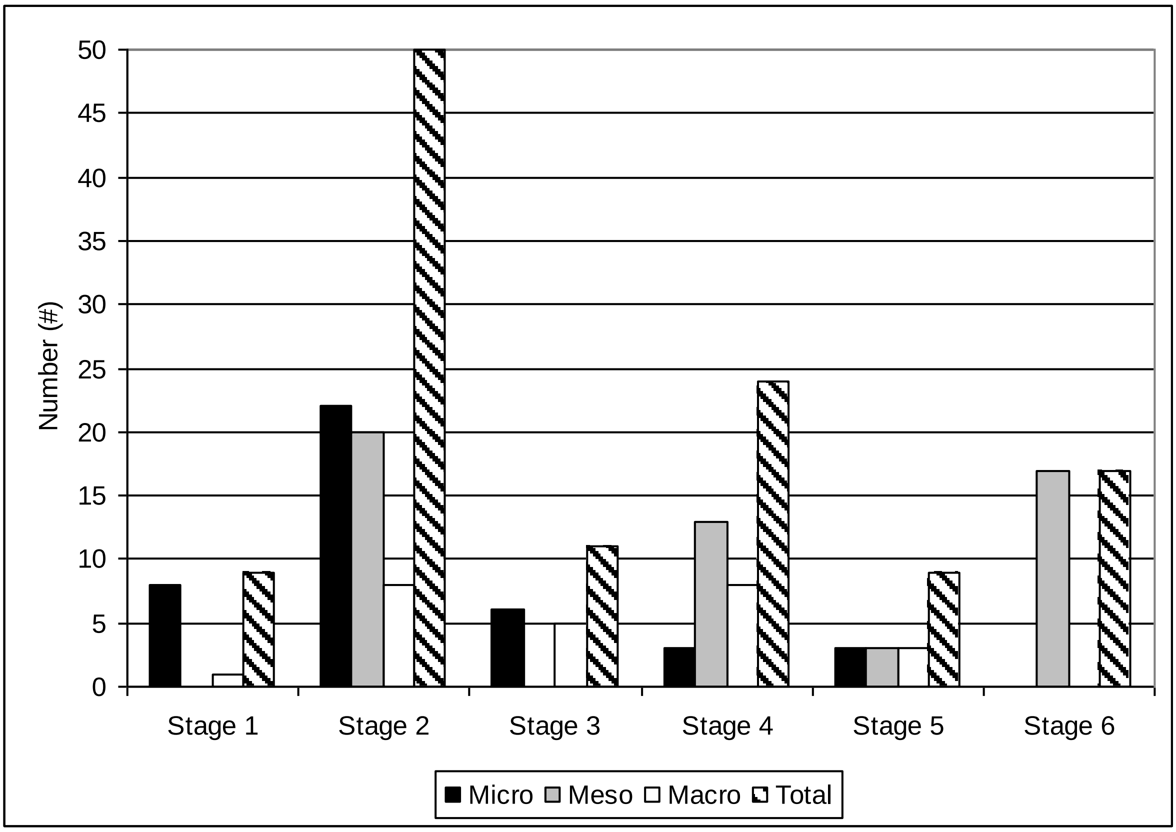


Figure 9.6 The distribution of high-level risks, and their scale, for all fuels by stage.

These statistics combined reveal the overall order of the stages by risk score (Table 9.7). The exploitation stage is the most risky because Oil, Gas, and Gas (unconventional) have high scores and many of the renewables have stages 2-4 combined (exploiting, conditioning, and converting the fuel are co-located) and accounted for in this stage. Stages five and six score highly in part because every fuel supply has these stages. Although interesting, this ranking does not give useful detail by which to analyse the reasons i.e. the important causes of risk.

Rank	Stage	Risk Score (a.u.)
1	2: Exploit	1768
2	6: Use	1439
3	5: Distribute	1418
4	4: Convert	872
5	1: Explore	769
6	3: Condition	652

Table 9.7 Rank order of the stages by their total risk score across all fuels.

The complete list of causes of risk which account for more than half of the risk score at each stage are set out in Table B.1 and summarised in Table 9.8. Stages 1-3 and 6 each have a risk which is significantly more important that the second most important.

Stage	Cause of Risk	Category	Score (a.u.)
1: Explore	Quality of fuel source	Environmental	87
2: Exploit	Lack of access to capital	Economic	121
3: Condition	Lack of access to capital	Economic	59
4: Convert	Pollution event	Technical	66
5: Distribute	Lack of access to capital	Economic	102
6: Use	Insufficient capacity to construct sites	Manufacturing	153

Table 9.8 Summary of the most significant risk at each stage and the category to which it belongs.

9.4 Scale and Risk Location

The scale is our indicator by which we judge at what level the risk is concentrated i.e. at the level of the individual company or organisation (or household), a national Government, or diffuse and driven by international regulations or markets. This may be interpreted as which type of organisation has most control or is more directly affected by the cause of risk in question. The number of micro, meso, or macro risks is not important, but the proportions for each fuel are interesting (Figure 9.8). The scale indicates whether, or what type of, policy instrument may be appropriate for mitigating or minimising a cause of risk. There is no obvious strong pattern to the distribution of the number of each scale, though Figure 9.7 shows the renewables and non-renewables classes exhibiting a similar pattern in that for both meso-scale is the most frequent and macro-scale the least. This pattern holds for the distribution of high-level risks amongst the three scales i.e. meso has the most and macro the least. We assessed the correlation between the number of risks at each scale and the total risk score for the renewables and non-renewables classes of fuels (Table 9.9).

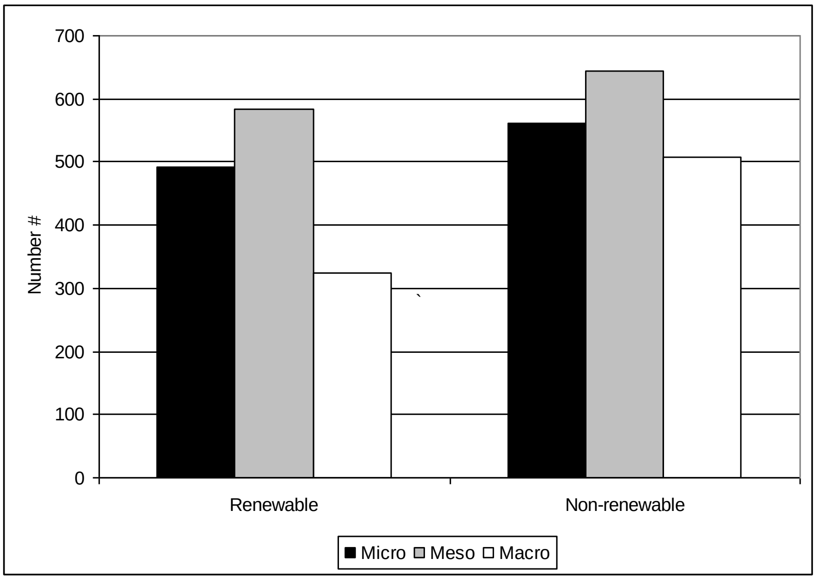
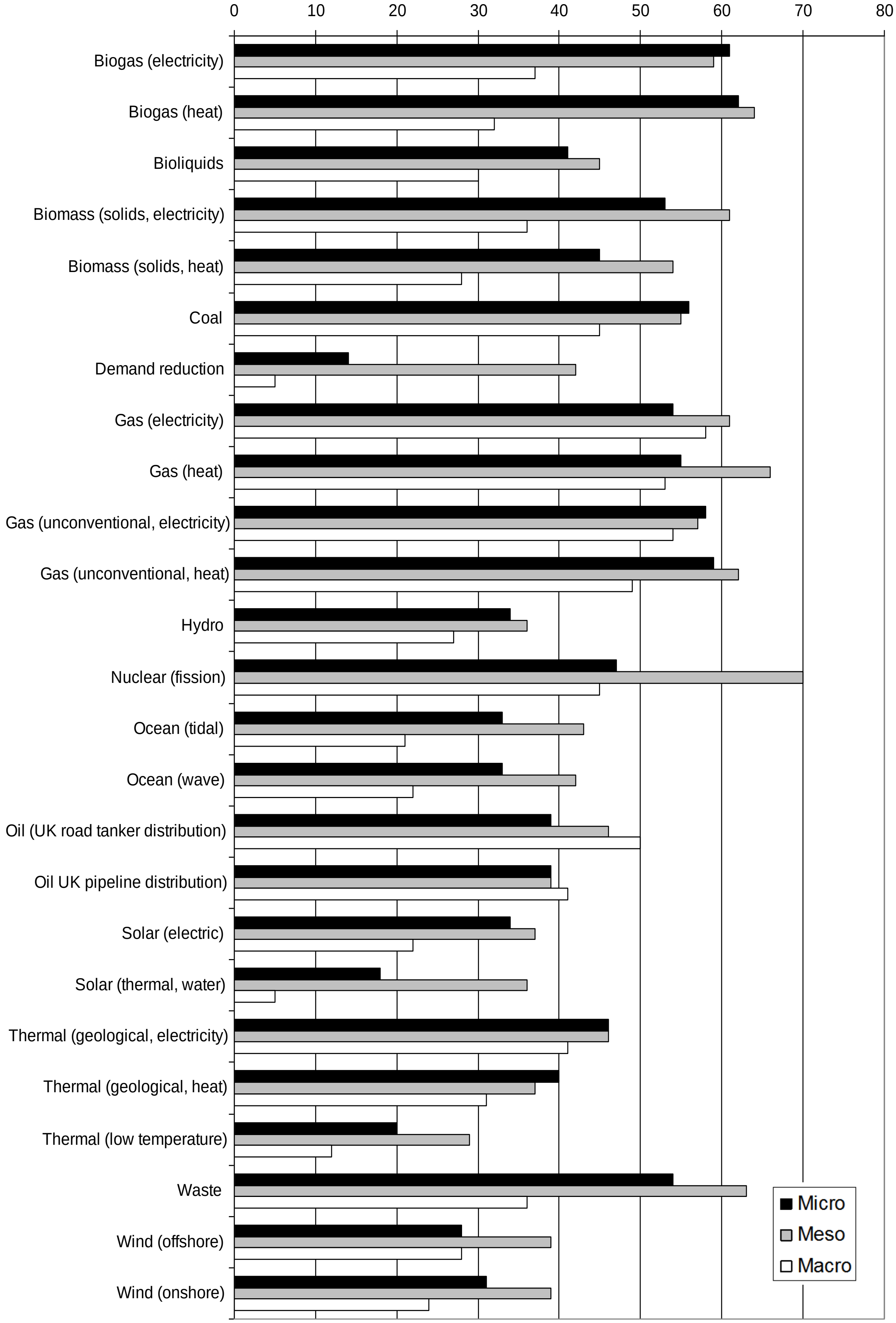


Figure 9.7 The number of micro-, meso-, and macro-scale risks for renewables and non-renewables.

Scale	Renewables (R^2)	Non-renewables (R^2)
Micro	0.6993	0.1701
Meso	0.7720	0.0305
Macro	0.5302	0.5788

Table 9.9 Correlation coefficients for the number of risks at each scale and the total risk score for the renewables and non-renewables.

Figure 9.8 [next page] The number of micro-, meso-, and macro-scale risks for each source of fuel. The branching points are split out for each use end-point (energy vector) where appropriate).



0
10
20
30
40
50
60
70
80
Biogas (electricity)
Biogas (heat)
Bioliquids
Biomass (solids, electricity)
Biomass (solids, heat)
Coal
Demand reduction
Gas (electricity)
Gas (heat)
Gas (unconventional, electricity)
Gas (unconventional, heat)
Hydro
Nuclear (fission)
Ocean (tidal)
Ocean (wave)
Oil (UK road tanker distribution)
Oil UK pipeline distribution)
Solar (electric)
Solar (thermal, water)
Thermal (geological, electricity)
Thermal (geological, heat)
Thermal (low temperature)
Waste
Wind (offshore)
Wind (onshore)
Micro
Meso
Macro

When considering scale at each stage, the distribution pattern is not so clear-cut (Figure 9.9). The meso-scale risks are most prominent except for Stage 3 (Condition) where macro are the most important (though all three scales were similar). At Stage 4 (Convert), micro were the least important.

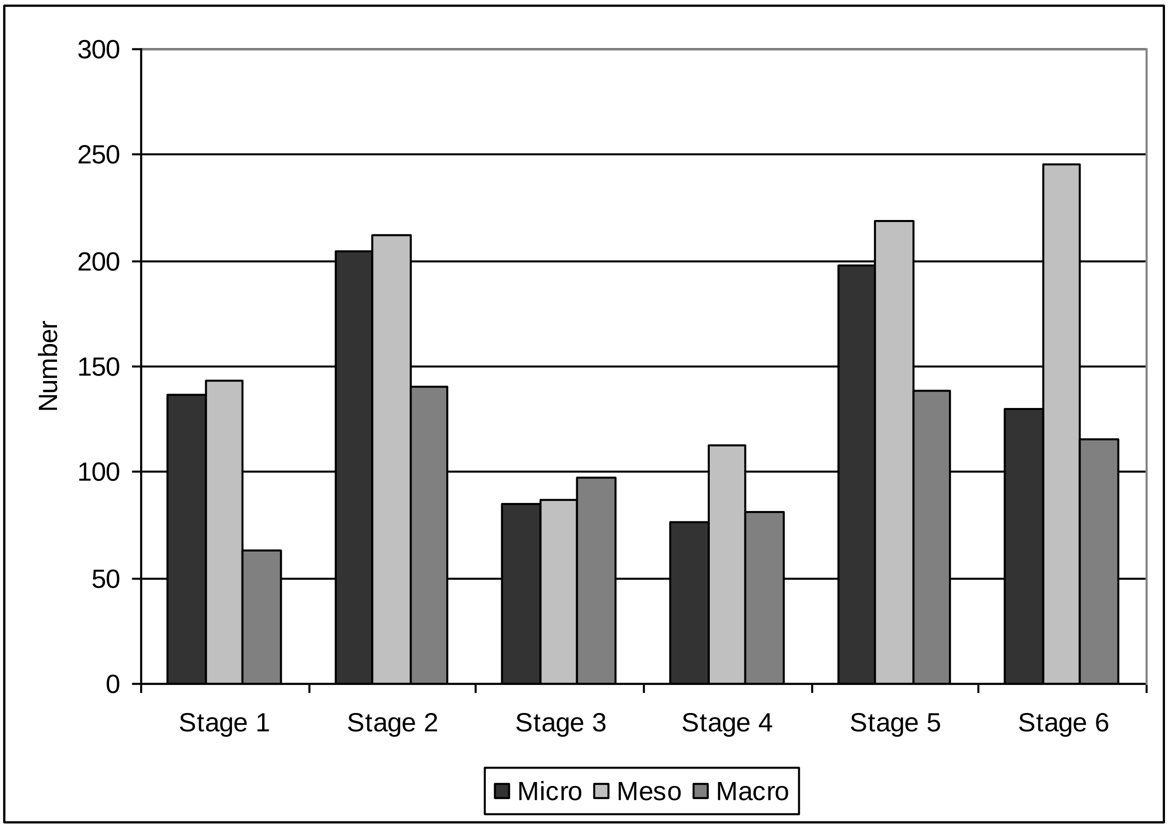


Figure 9.9 The number of micro-, meso-, and macro-scale risks at each stage.

9.4.1 Crossing the System Boundary

Whilst constructing the matrix and recording the scale of risk, we noted whether the principal location of the risk was within or outwith the system boundary (the UK territorial border). With respect to the number of risks at each of the three scales of risk we performed a chi-square test to ascertain whether there is any statistical difference between those inside (labelled as UK) and outside (labelled as Global) the system boundary (Table 9.10). Only stages 1-3 have any risks located outside of the system boundary; for stages 1-2 the fuels are Coal, Gas, Nuclear (fission), and Oil, and for Stage 3 only Nuclear (fission).

Stage	Scale	Global (#)	UK (#)	All Fuels (#)	Expected Global (#)	χ^2	p	Stat Sig.
1	Micro	35	102	137	35	0.00	0.95	N
	Meso	25	118	143	37	3.72	0.10	Y
	Macro	28	35	63	16	8.67	0.01	Y
2	Micro	48	156	204	48	0.00	0.95	N
	Meso	42	170	212	50	1.16	0.50	N
	Macro	40	100	140	33	1.61	0.50	N
3	Micro	7	78	85	10	0.96	0.50	N
	Meso	13	74	87	10	0.68	0.70	N
	Macro	12	85	97	12	0.02	0.95	N
Total	Micro	90	336	426	91	0.02	0.95	N
	Meso	80	362	442	95	2.26	0.30	N
	Macro	80	220	300	64	3.88	0.10	Y

Table 9.10 Chi-square test results for the three risk scales inside and outside of the system boundary. This data has two degrees of freedom.

The chi-square test shows that mostly there is no statistical difference between the prevalence of each scale inside and outside of the system boundary. However, there are two marginal cases, namely at Stage 1 (Meso) and the Total (Macro). There is one clearly significant case which is Stage 1 (Macro), showing that risks located outside of the system boundary attract more macro-scale risks than expected. This can be interpreted as the fuels which the UK uses as having causes of risk for exploration more frequently subject to global pressures and markets; a possible explanation for which is that the fossil fuel industry is globally distributed (low density) requiring very large levels of investment to create a viable project. This is not altogether surprising. What is more curious is that the meso-scale causes of risk (Government level) were not clearly different inside and outside of the boundary given that many sources of fossil and nuclear fuels are located in countries with poor governance records.

9.5 The Categories of Risk

Although the division of the causes of risk into the seven categories is convenient, but to some extent arbitrary, it is interesting to see the risk scores. The disparities are in part a function of the varying number of risks in each category; the largest has twice as many risks as the smallest. Table 9.11 shows the effect that scoring by total and per risk has on the perceived importance of categories.

Rank	Category	Normalised Risk Score per Risk (a.u.)	Category	Normalised Risk Score, Total (a.u.)
1	Skills	100	Political	100
2	Manufacturing	98	Innovation	97
3	Innovation	96	Economic	77
4	Economic	91	Technical	74
5	Technical	88	Environmental	63
6	Political	85	Skills	50
7	Environmental	75	Manufacturing	50

Table 9.11 The rank order of the normalised risk scores by total and on a per cause of risk basis.

We note that the Skills, Manufacturing, and Political categories shift significantly. We note too that ratio between the high and low rank for each group is significantly different – 1.3 for the per risk basis, and 2.0 for the total risk. We note too in Figure 9.10 that the average score does not vary greatly between categories. We conclude that ranking by category is not a useful statistic. However, as Figure 9.10 also shows that each category has a significant variation in the minimum and maximum scores, it is valid to examine how the score for a category varies across stages (Figure 9.11). This shows that no category has a uniform profile, implying that detailed analysis for policy action for any cause of risk should be considered in the context of the position and role in the supply chain.

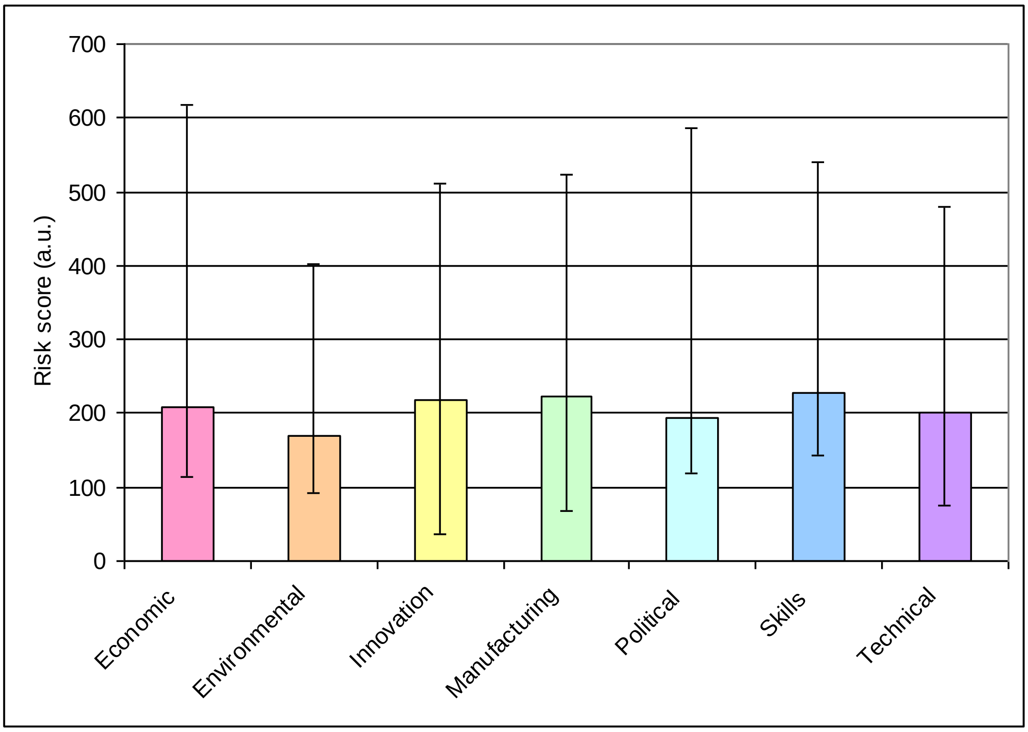


Figure 9.10 The average score per cause of risk in each category (absolute values) across all stages. The error bars display the minimum and maximum score for causes of risk in each category.

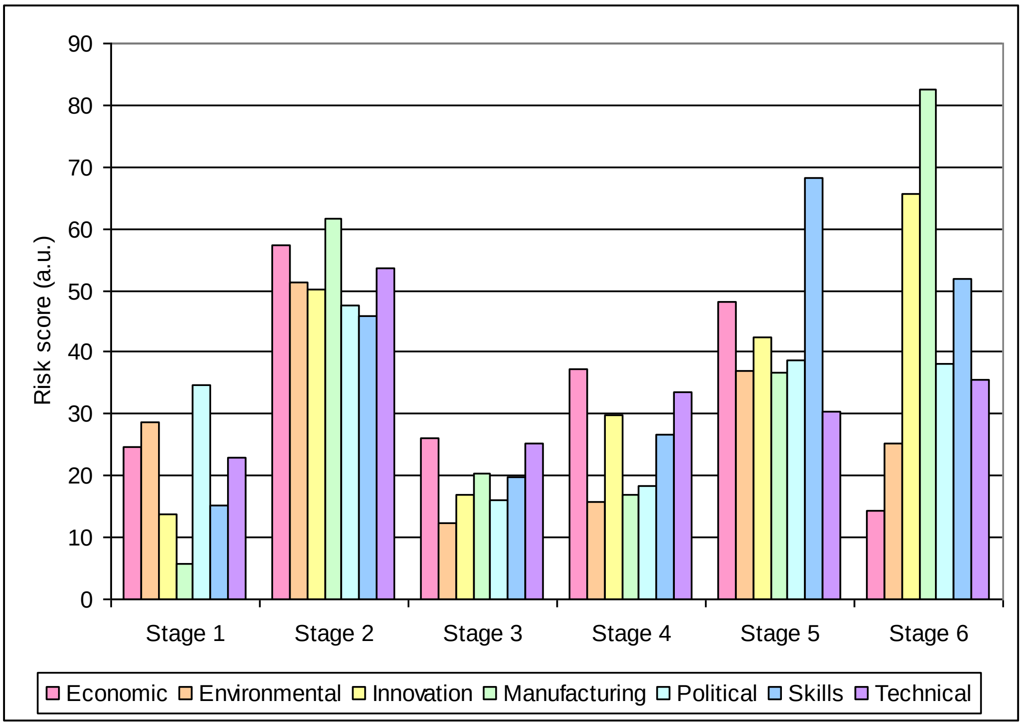


Figure 9.11 Risk scores for each category at each stage showing the variation of the profile along thee process supply chain.

9.6 Projections of Risk in Future Energy Scenarios

Using the total (normalised) risk score for a fuel, we can calculate the total comparative risk for a portfolio of energy sources for future energy systems. In this way, we can assess how the total system risk changes with different mixes of fuel sources over time. Such a projection of risk allows us to see effects of policy options other than on GHG emissions. For this UK case study we select two of the more well-considered sets of long-term scenarios, namely those produced by the UK Energy Research Centre (UKERC) (Ekins et al., 2013) and National Grid (NG) (National Grid, 2017).

There are a number of pre-processing operations which need to be conducted before a risk analysis can be performed, or to allow comparison between scenario set created by different organisations. Experienced developers specify and generate their scenarios to address specific issues or questions. The NG scenarios examine installed capacity on the electricity system, which makes these scenarios technology-driven, not fuel-centric. However, we can discern or judge which fuels correspond to which technology. NG do not account explicitly for heat or transport, though electrified transport is accounted for in the installed capacity figures. The work by UKERC mixes primary fuels and technologies, meaning that we must devise a method of rationalisation for compatibility with the fuel supply chains we have used throughout. The definitions of fuels may also differ. Finally, differences in the basis of the time-series used or of the end-points need to be reconciled.

9.6.1 UKERC 2050 Scenarios

We are using the 2013 UKERC scenario set (Ekins et al., 2013), which are updated from the original set (Skea et al., 2011). UKERC developed four scenarios, but we will consider only the reference scenario (henceforth REF) and the most aggressive low carbon scenario (henceforth LC). These are the two most widely differing scenarios. For both scenarios we have calculated the temporal risk profiles for primary energy demand, final energy demand by fuel, and installed electricity generating capacity. We use the term ‘portfolio’ to denote the list of fuel groups (or categories) used by UKERC. The fuels in each group (G) used by UKERC are comprised of a subset of the individual fuels we have analysed. Therefore, each UKERC fuel-group (G) has a different set of pre-processing steps. At each timestep, the normalised total risk calculation can be generalised in the following manner.

Let the average risk for a fuel group (G) be R_{fuel}. If G is the set of n fuels which comprise the group of individual fuels each with a normalised risk score *(NRS)* then

$$\overline{R_{fuel}} = \frac{1}{n}\sum_{x\in G} NRS_{fuel}(x), \tag{8}$$

and the total demand E_{total} of the whole portfolio (*P)* is

$$E_{total} = \sum_{x\in P} e_G(x). \tag{9}$$

Therefore the total risk T for the portfolio in each year is the proportional demand e_G for each group (G) as a ratio of the total demand multiplied by the average risk for the fuel group,

$$\begin{aligned} T_P &= \frac{e_G}{E_{total}} \cdot \left(\overline{R_{fuel}}\right) \\ &= \frac{e_G}{\sum_{x\in P} e_G(x)} \cdot \frac{1}{n}\sum_{x\in G} NRS_{fuel}(x). \end{aligned} \tag{10}$$

We apply this method to several ways of grouping the portfolio of fuels.

Primary Energy Demand

The groups of fuels used by UKERC are: renewable electricity, biomass and waste, natural gas, oil, imported refined oil (IRO), coal, nuclear electricity, imported electricity, and imported hydrogen. The pre-processing steps are:

1. Hydrogen use is zero for all years, thus is removed from further analysis.
2. The item ‘imported electricity’ is treated as 50:50 renewable and non-renewable, for all years. This is reasonable since the UK is connected to Ireland which supplies surplus wind power and to France which has mostly nuclear generation.
3. Until 2050 UKERC’s modelling shows IRO as a net export. Therefore we subtract IRO from the oil time-series (except 2050) as our analysis is about the UK reliance on fuels. Even though the stages 2-4 infrastructure is needed for the IRO component, it is marginal to domestic use because the UK would not create the infrastructure solely for export purposes. For all years, IRO is a small proportion which will have little effect on the risk profile.
4. UKERC have paired biomass and waste in their modelling; we take the compound risk as the average.

5. UKERC have a collective entry of 'renewable electricity'. For 2000-2020 for this item we calculate risk score as the average of Hydro, Solar (electric), Wind (offshore), and Wind (onshore). For 2025-2050, we calculate the average of the aforementioned plus Biogas, Ocean (tidal), Ocean (wave), Solar (thermal, water), Thermal (geological), and Thermal (low temperature). This calculation assumes that all are equally demanding of the distribution networks.
6. We interpret UKERC's modelling of energy conservation as demand reduction in our terms. This is not an exact equivalence as our definition is wider. We add the 'conservation' time-series to the primary energy demand since that energy would otherwise have to be produced.

In Figure 9.12 we see that the primary energy demand in the REF scenario drops until 2025 (8500 PJ) and then rises to 2050 (9800 PJ). Meanwhile, the risk profile falls, except for 2020-2025 when UKERC assume that new-build nuclear will come on-stream. The deployment of Nuclear (fission) increases the risk before the remaining coal-fired power generating stations are closed.

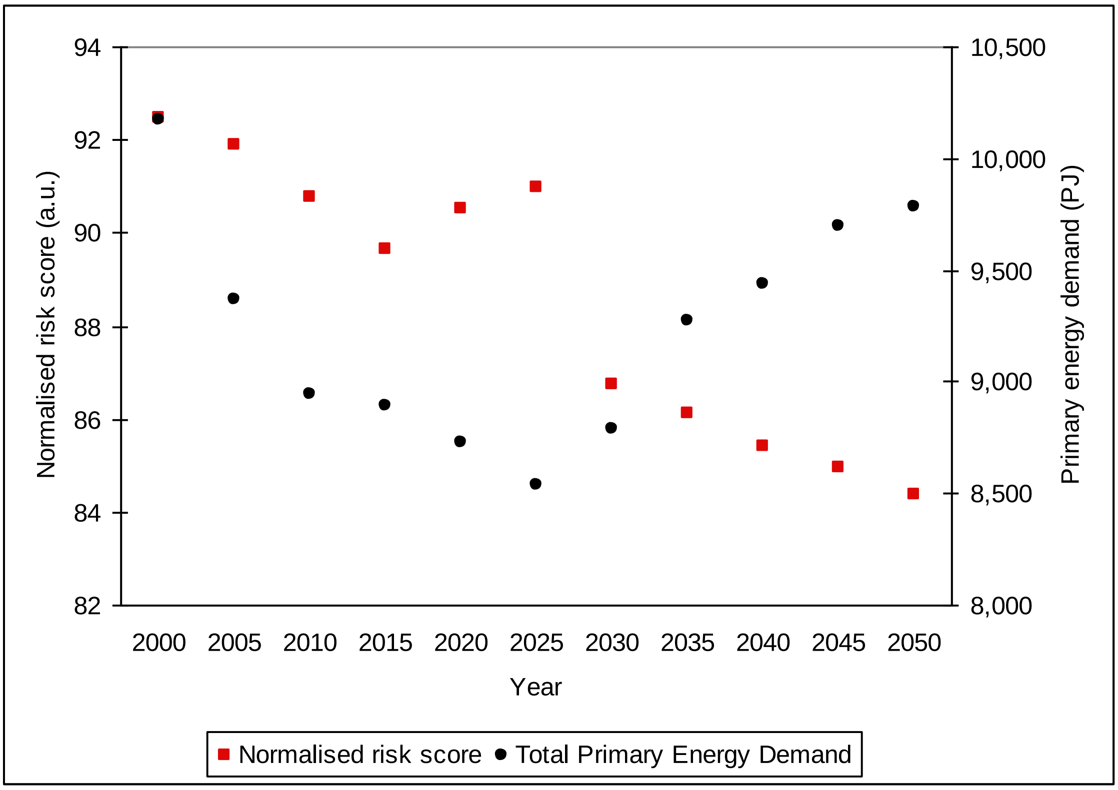


Figure 9.12 The risk profile of primary energy demand by fuel for the UKERC REF(2013) scenario.

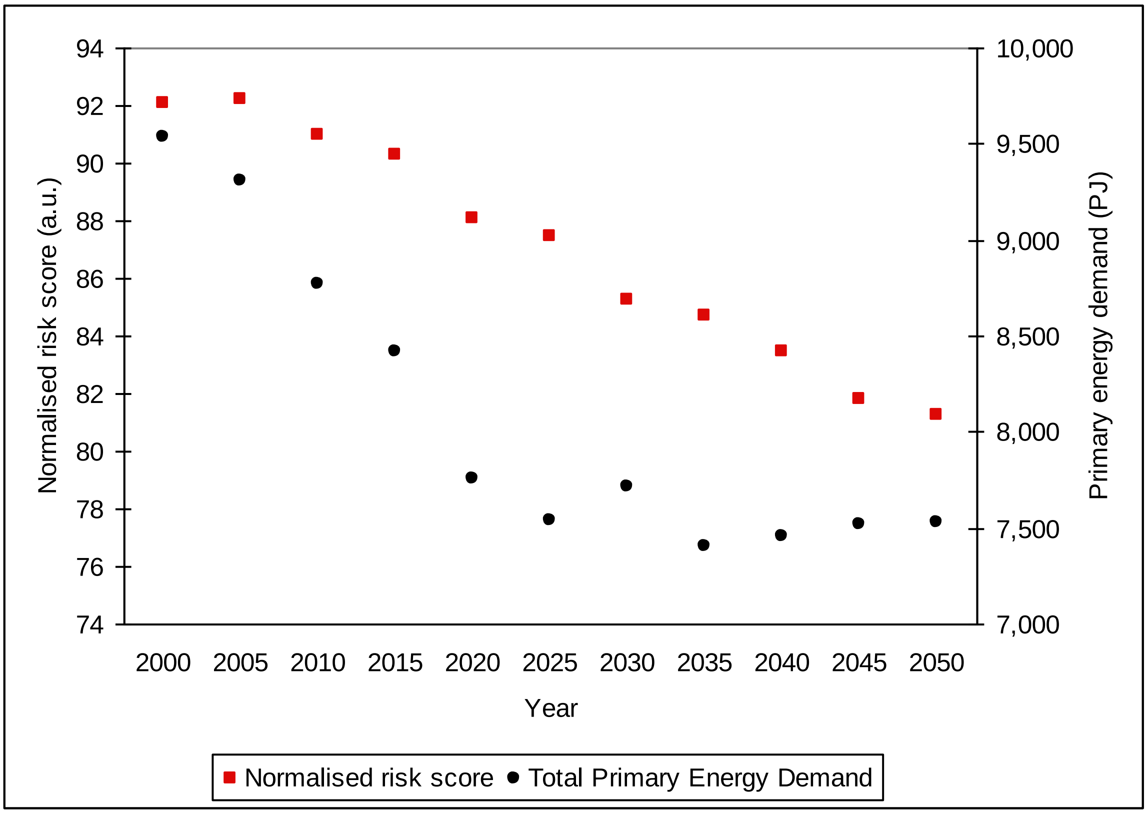


Figure 9.13 The risk profile of primary energy demand by fuel for the UKERC LC(2013) scenario.

For the LC scenario (Figure 9.13) the primary energy demand falls until 2025 (7500 PJ, approximately 1000 PJ per year less than the REF scenario) and remains at about that level out to 2050. The risk profile shows a smooth decline, unlike the REF scenario. The normalised risk score for the LC scenario in 2050 is 81, compared to 84 for REF.

Final Demand by Fuel

The fuels used by UKERC in their modelling of final demand are rationalised into end-use groups compatible with our fuel set (Table 9.12).

UKERC Fuels	End Use Group	Constituent fuels
Ethanol / methanol, bio diesels, bio-oil	Bioliquids	Bioliquids
Bio-solids / waste	Biomass Waste	Biomass Waste
Coal, manufactured fuel, hydrogen	Coal	Coal
Energy conservation	Demand reduction	Demand reduction
Electricity, others	Electricity	Coal, Gas, Gas (unconventional), Hydro, Nuclear (fission), Ocean (tidal), Ocean (wave), Solar (electric), Thermal (geological), Wind (offshore), and Wind (onshore)
Biomethane, gas, LPG	Gas	Biogas, Gas, Gas (unconventional)
Heat	Heat	Gas, Gas (unconventional), Solar (thermal, water), Thermal (geological), Thermal (low temperature)
Fuel oil, petrol, diesel, jet fuel	Oil	Oil

Table 9.12 The fuels modelled by UKERC in their Final Energy Demand by Fuel scenario are mapped on to end-use groups which consist of one or more of the fuel supply chains analysed.

The remaining pre-processing steps are:

1. Allocate the total energy (PJ) for bio-solids / waste as 50% each to Biomass and Waste throughout the time-series.
2. Allocate the total energy (PJ) for bio-oil / fuel oil as 50% each to Bioliquids and Oil throughout the time-series.
3. Derive the value for Heat from the branches in the specified fuel chains where thermal energy is the final form.
4. For the LC scenario, the hydrogen demand is added to gas because UKERC assume that the hydrogen is generated by steam reforming methane.

Figure 9.14 shows that the risk profile for final energy demand by fuel falls steadily. The final energy demand falls steeply until 2010, then more gently until 2035. It is interesting to note that the sharp increase in final demand anticipated by UKERC in this scenario has only modest perturbation on the risk score. This is due to the switch from oil to bioliquids for transport, and decreasing coal and gas use as demand reduction increases.

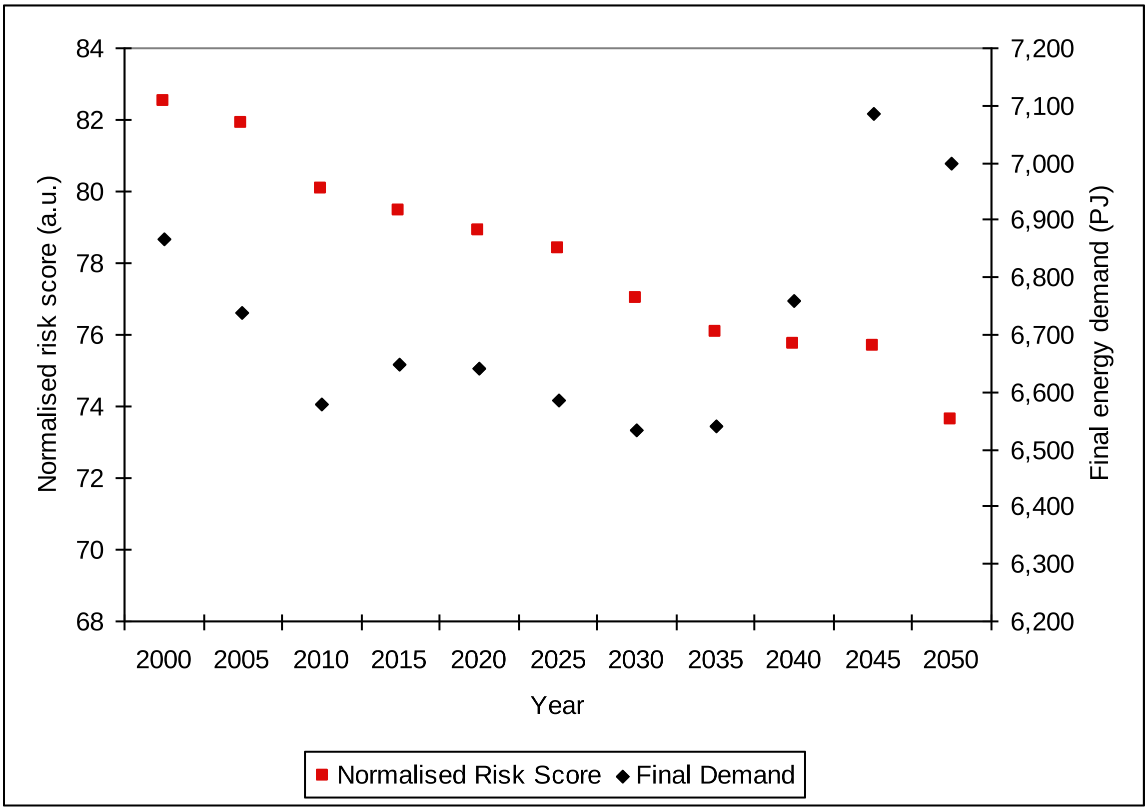


Figure 9.14 The risk profile of final energy demand by fuel for the UKERC REF(2013) scenario.

For the low carbon scenario (Figure 9.15) the demand drops until 2025 when it levels off, similar to the total primary energy supply by fuel. Likewise the normalised risk score falls steadily.

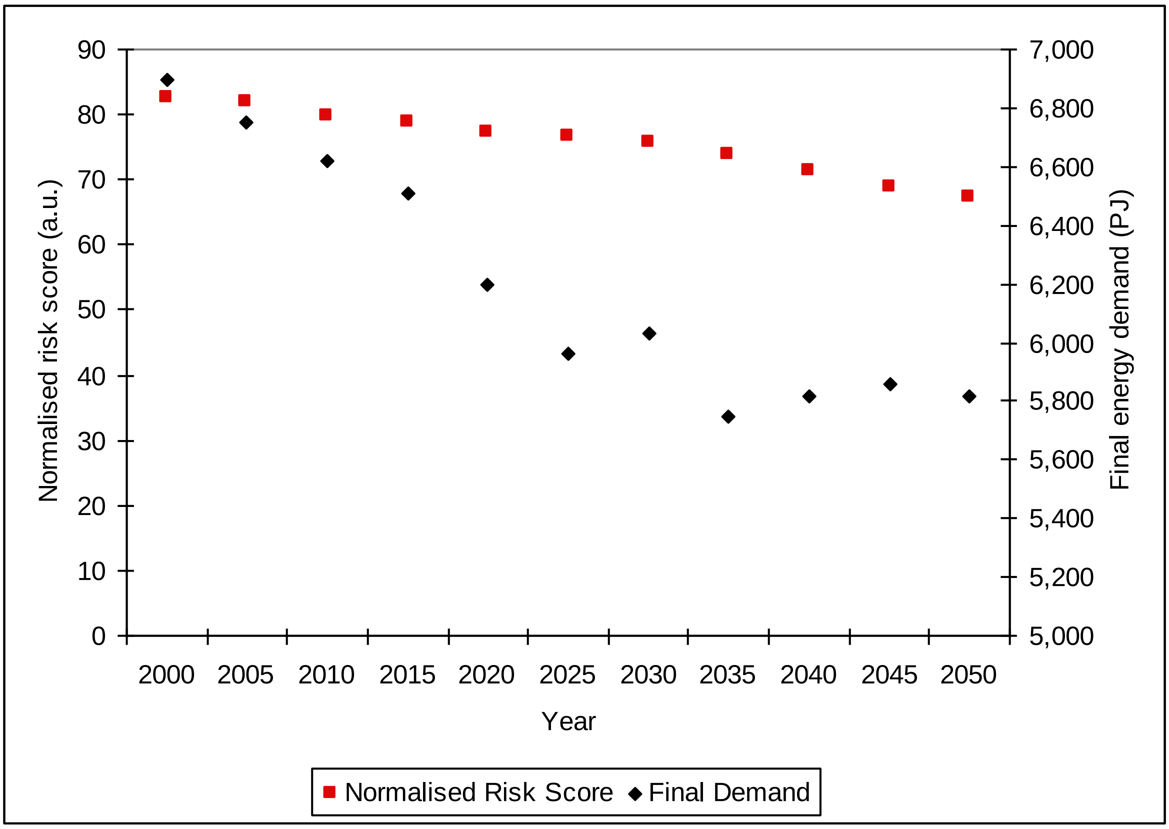


Figure 9.15 The risk profile of final energy demand by fuel for the UKERC LC(2013) scenario.

Installed Electricity Generating Capacity

In this scenario UKERC have included carbon capture and storage (CCS) for biomass, coal, and gas, plus for the co-firing of coal and biomass. Storage is also added to this scenario explicitly. The pre-processing steps are:

1. Incorporate the co-firing and CCS entries into their principal fuels i.e. coal and gas. As the normalised risk scores for coal and biomass are the same, we can simply add them together.
2. Treat 'bio-waste and others' as biogas.
3. As 'storage' is not a fuel it is removed from further analysis. We define storage as a distribution system attribute only. Any risk associated with storage is included in stage 5 for electricity networks. Keeping storage as an explicit entry would be double counting that portion of risk.
4. 'Imported electricity' is treated as 50:50 renewable and non-renewable, for all years, since the UK is connected to Ireland which supplies surplus wind power and to France which has mostly nuclear generation.

5. UKERC do not split wind into on- and off-shore. We assume the risk is equally split.
6. Marine is not disaggregated by UKERC, we share the projected generating capacity equally between Ocean (tidal) and Ocean (wave).

The installed electricity capacity is level until 2010 from when it steadily rises to 2050 (Figure 9.16). The risk profile, however, follows a completely different pattern. The quasi-sinusoidal profile rises a little to 2010, falls until 2030 when it bottoms out at a value of 74 (a.u.). This fall is mostly due to falling use of gas and oil, and rising capacity of wind generators. It then rises continuously to 2050, driven by new-build nuclear coming on-stream.

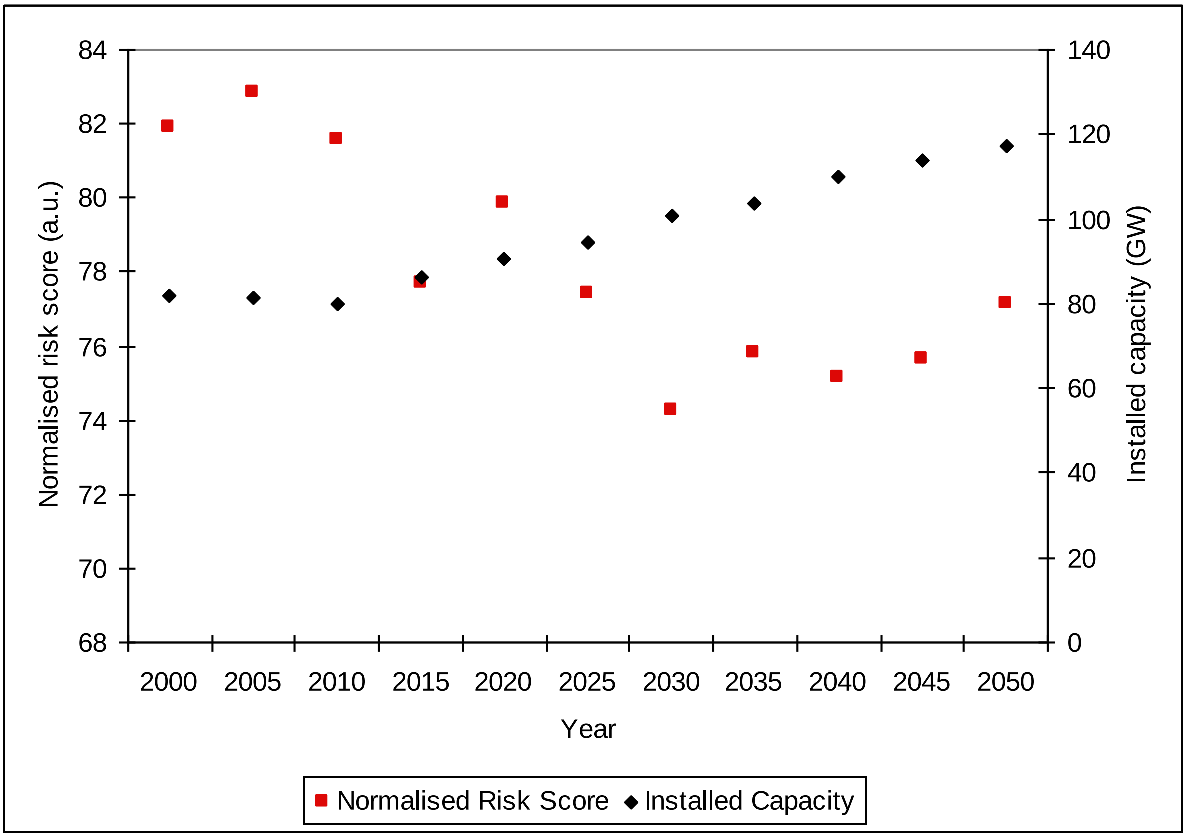


Figure 9.16 The risk profile of the installed electricity generating capacity by fuel for the UKERC REF(2013) scenario.

In the LC scenario (Figure 9.17) the installed capacity also rises at a faster rate than the REF, but shows signs of levelling off after 2040. The final installed capacity is approximately 15 GW greater than REF, and the normalised risk score is somewhat lower at 70 a.u. (compared with 77 a.u.). The profile of the risk is falling, but also levels off after 2035.

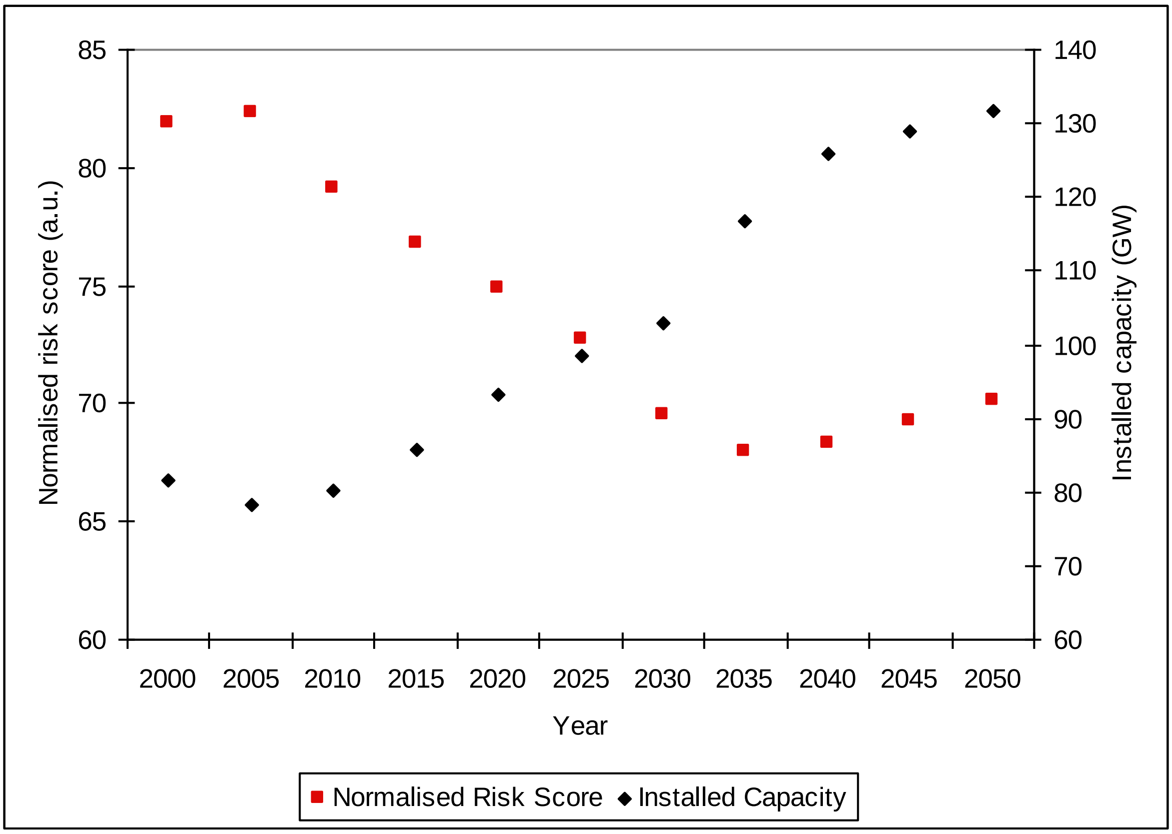


Figure 9.17 The risk profile of the installed electricity generating capacity by fuel for the UKERC LC(2013) scenario.

By plotting the risk profiles for the REF and LC scenarios (Figure 9.18) we can see more readily how they diverge. We note that even though the risk associated with the LC pathway is lower after 2025, both rise from 2035 onwards.

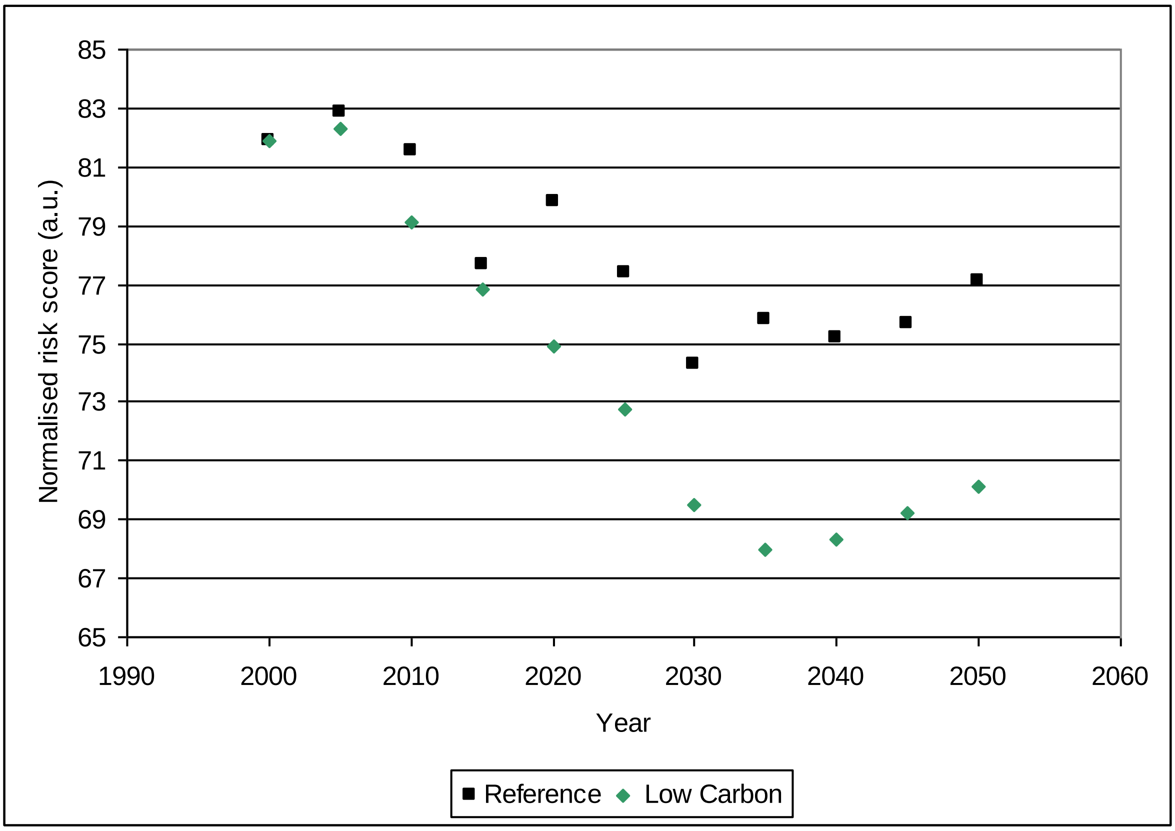


Figure 9.18 A comparison showing how the UKERC REF and LC scenarios diverge for installed generating capacity.

Transport fuel demand

The UKERC scenarios examine transport in detail with one element of their modelling being fuel demand (in PJ) in terms of the final energy vector. The fuels which UKERC consider are petrol, diesel, electricity, hydrogen, jet fuel, bio-diesel / kerosene, and ethanol / methanol.

To make the UKERC transport fuel use figures compatible with our framework, we need to account for the way in which UKERC have implemented their assumption that the total energy used by transport falls continuously over the modelled period. The UKERC figures show the use of petrol, diesel, and bioliquids all decreasing, but that the demand by transport for electricity remains constant. This can only be achieved if efficiency (Demand Reduction in our terms) increases significantly – this is a strong assumption. UKERC's methodology incorporates the efficiency figure into their model of 'Conservation' and is not explicitly listed in the transport model. However, it can be calculated as follows:

$$DR_{transport} = \text{Proportion of DR due to transport} \times \text{Total DR}$$

$$= \frac{Demand_{transport}}{Demand_{total}} \cdot DR_{total} \qquad (11)$$

The remaining pre-processing steps are:

1. Petrol, diesel, and jet fuel are grouped and given the risk score for oil.
2. Bio-diesel / kerosene, and ethanol / methanol are treated as bioliquids.
3. Electricity is given the mean risk score for electricity from all sources.

For the REF scenario the fuel demand for transport falls until 2030 after which it levels off (Figure 9.19). The normalised risk score also falls gradually, until 2050 when there is a significant drop due to a swing from oil to hydrogen use (in fuel cell vehicles).

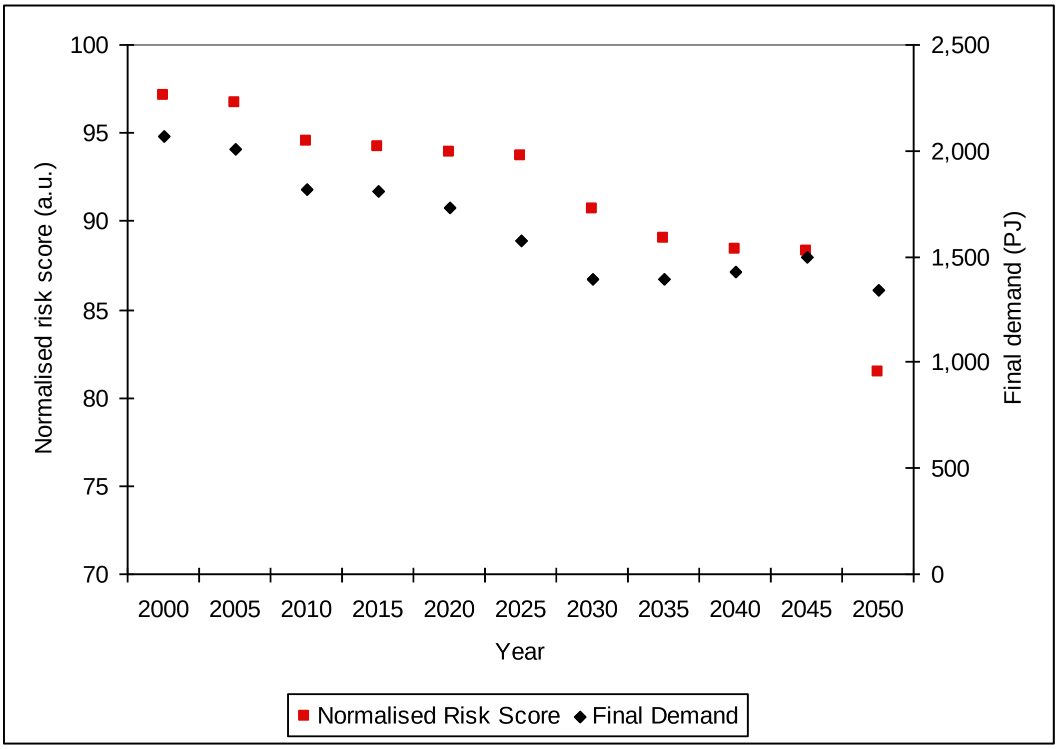


Figure 9.19 The risk profile of the fuel demand for transport for the UKERC REF(2013) scenario.

Figure 9.20 shows that the LC scenario demand profile is similar to REF i.e. decreases steadily and then levels off after 2030 to almost the same value (1300-1400 PJ). However, the risk profile is smoother with two distinct parts: 2000-2025 and 2030-2050 with the slope of the latter stage being steeper. Despite the total energy demand being the same for both REF and LC, the normalised risk score for the LC pathway is significantly lower at 60 a.u. (compared with 81 a.u.). As a proportion of total demand, the LC scenario has transport making up a slightly larger part than for REF. This is to be expected since the overall LC scenario has demand falling across all sectors of use. These statistics are summarised in Table 3.1. By plotting the risk profiles for the REF and LC scenarios (Figure 9.21) we can see more readily how they diverge.

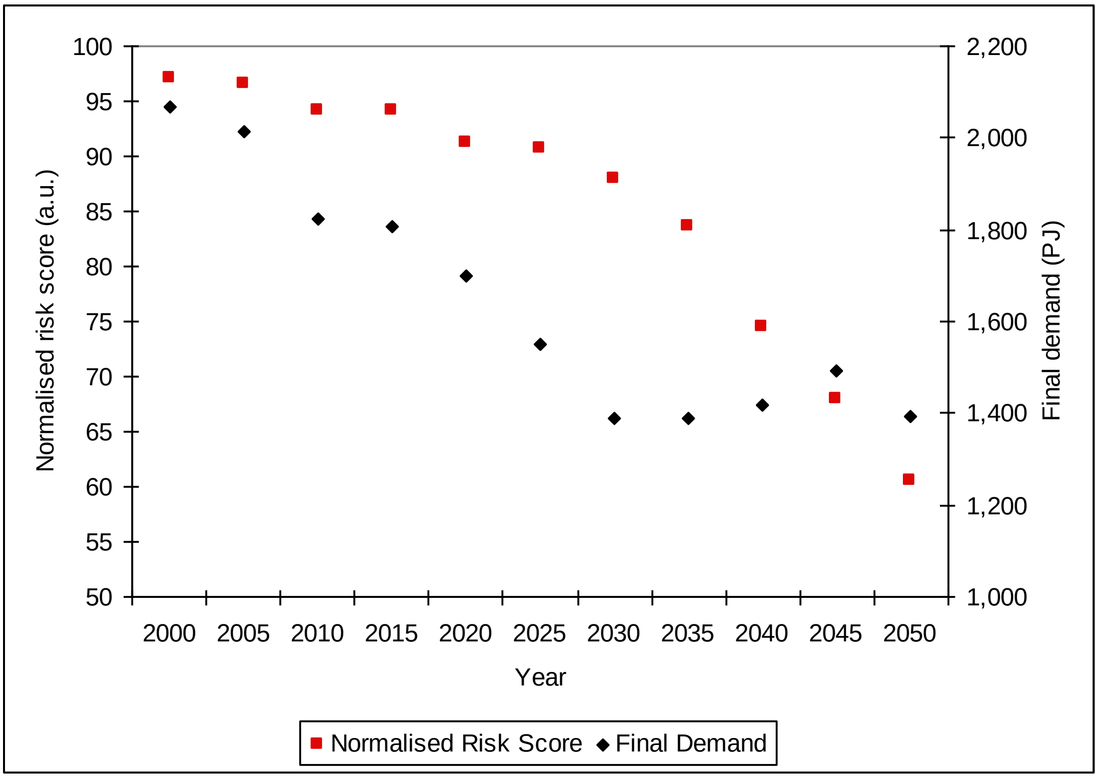


Figure 9.20 The risk profile of the fuel demand for transport for the UKERC LC(2013) scenario.

Statistic		**REF(2013)**	**LC(2013)**
Energy demand, annual (PJ)	Initial	2066	2066
	2050	1345	1393
Normalised risk score (a.u.)	Initial	97	97
	2050	81	60
Proportion of total demand (%)	Initial	30	30
	2050	18	22

Table 9.13 Summary to compare the demand and risk profile statistics for the transport fuel demand in the UKERC REF(2013) and LC(2013) scenarios.

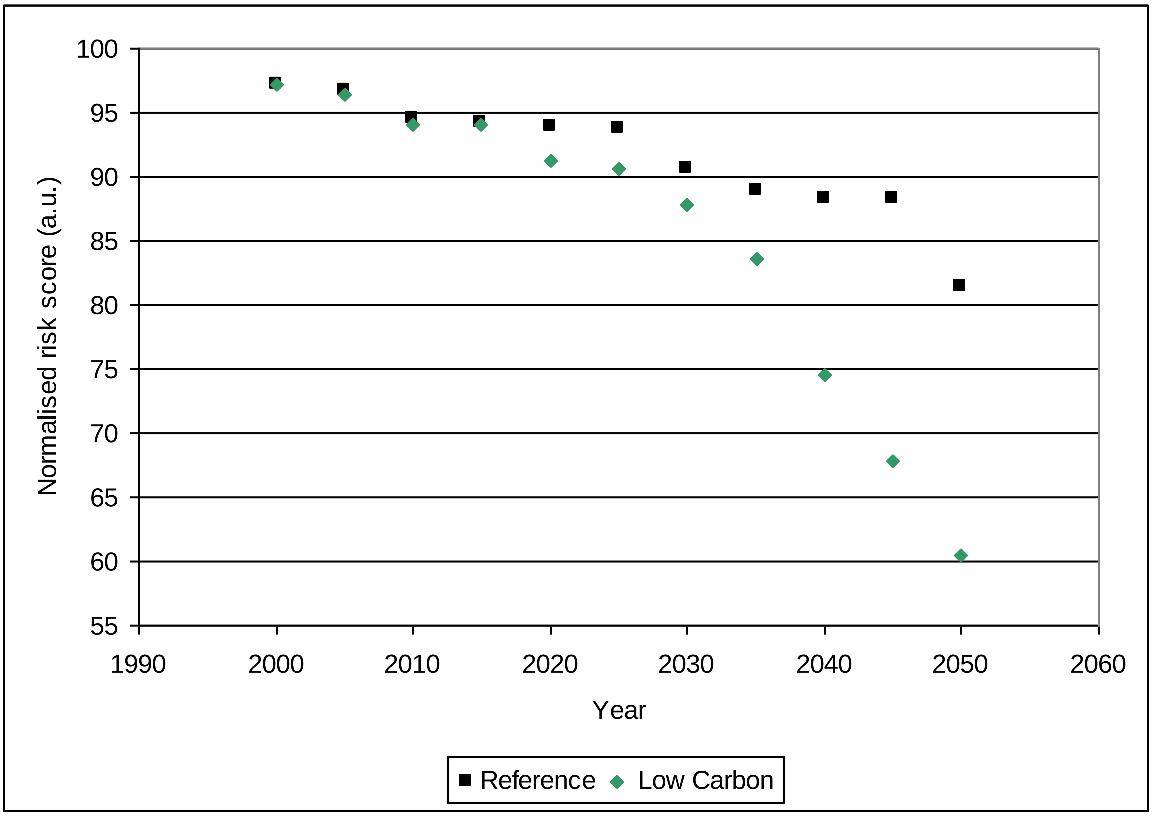


Figure 9.21 A comparison showing how the UKERC REF and LC scenarios diverge for transport energy demand.

9.6.2 National Grid (NG) Future Energy Scenarios

Like UKERC, NG created four scenarios. We note that the UKERC Reference scenario is not formally termed as 'business as usual' (BAU), though it functions as such. The NG 'Steady State' scenario is described as *"...current levels of progress and innovation continue."* which implies BAU. However, according to Roberts et al. (2019) neither scenario is a true BAU case. The two most extreme NG scenarios are 'Two Degrees' (henceforth 2DEG) and 'Consumer Power' (henceforth CP). The 2DEG scenario represents a pathway to meet the Paris agreement commitments and is comparable with UKEC LC i.e. the fastest to reduce carbon emissions. The NG CP scenario, like UKERC REF, is the worst case in the set i.e. the slowest to reduce carbon emissions.

Fuel	CP Scenario		2DEG Scenario	
	2030	**2050**	**2030**	**2050**
Gas	71%	45%	98%	89%
Gas (unconventional)	28%	48%	–	–
Biogas	1%	7%	2%	11%
	100%	100%	100%	100%

Table 9.14 The percentage of the three gas groups for the single 'gas' entry for the NG electricity scenarios. These are calculated from the NG gas model.

The NG modelling also goes out to 2050, but they only provide data for one intermediate year (2030). Neither does NG explicitly incorporate energy efficiency (or demand reduction) in their modelling. The NG scenarios are best suited to examining installed capacity for electricity.

NG have separate calculations for the supply of gas for residential and industrial on-site heating. This element of their modelling gives projected figures for the split between natural gas from various sources (UKCS, Norway, European continent, LNG, other imports), shale gas, and 'green gas'[2]. In our terms the NG definitions translate to Gas, Gas (unconventional), and Biogas. The figures for gas used in electricity generation give the envelope, thus using the splits suggested by the gas modelling, we can calculate the proportions used for electricity generation. Each scenario has separate a gas model and the proportions we calculate are shown in Table 9.14. These proportions are then applied to the risk scores to calculate the compound risk score for gas in the NG electricity time-series. In doing this we are assuming that the proportions are the same regardless of the end use of gas. This is a reasonable assumption because once a source of gas is determined to have reached the specification for chemical composition it will be injected into the share distribution system (stage 5) and simply used as required. The remaining pre-processing steps are:

1. CCS is added to gas since coal is assumed to be zero in both 2030 and 2050.

[2] The gas model time-series are available in the Data Workbook (v2 updated 17 July 2018): http://fes.nationalgrid.com/fes-document/

2. ‘Interconnections’ (imported electricity) is treated as 50:50 renewable and non-renewable, for both years, since the UK is connected to Ireland which supplies surplus wind power and to France which has mostly nuclear generation.
3. ‘Storage and ‘vehicle to grid’ are removed since the power has already been generated.
4. Treat the entry ‘Other renewables’ as bioliquids and biogas.
5. Treat the entry ‘Other thermal’ as Solar (thermal), Thermal (geological), and Thermal (low temperature). Consider this entry as renewable, since this group is a small proportion of the total installed capacity.
6. Marine is not disaggregated by NG, we share the projected generating capacity equally between Ocean (tidal) and Ocean (wave).

The final computed risk scores for the NG scenarios are shown in Figure 9.22. This shows that the differences are small between the two most extreme scenarios created by NG. Both show a continued decrease in risk from 2017 to 2050, and as expected the 2DEG scenario is a little less risky than CP. We make three suggestions as to why this is the case. First, fuels for transport and heating are excluded. Fuels for these tend to have higher risk scores, and these sectors are considered the hardest to decarbonise. Solely electricity scenarios will be relatively similar if some measures of decarbonisation are enacted e.g. nuclear replacing gas, both of which have similar risk scores. NG as a private company acting as the transmission system operator might be expected to be risk averse. Secondly, it is possible that the electricity generating system is becoming less diverse in its technical nature. Thirdly, the assumptions chosen by NG are too similar and their scenario building exercise can be improved.

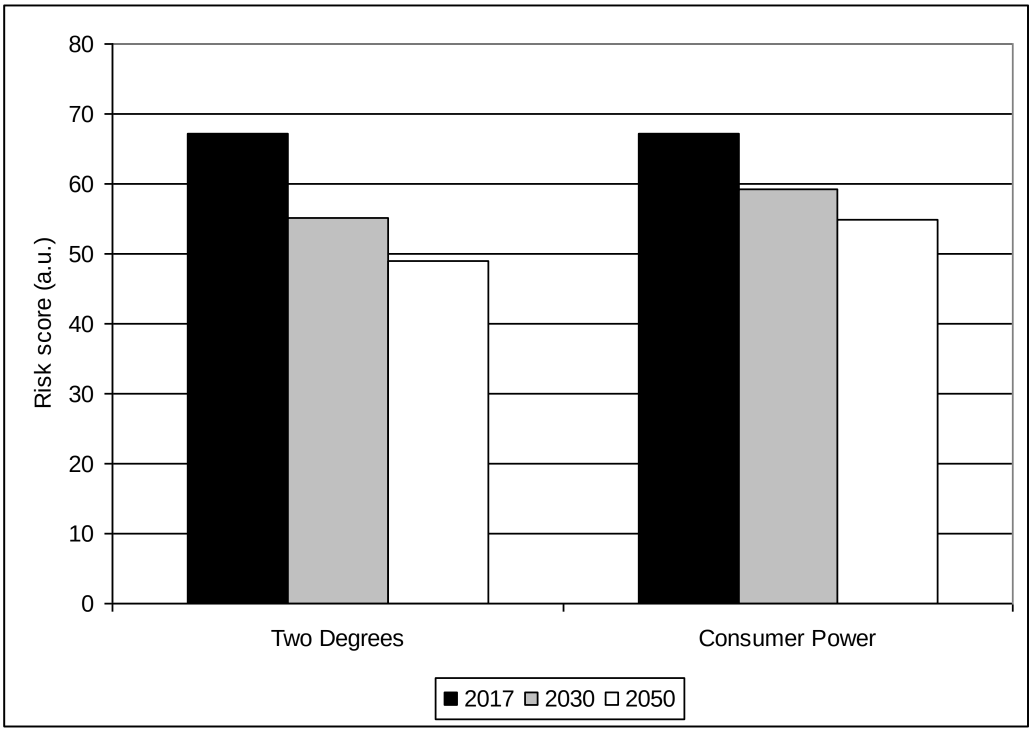


Figure 9.22 The normalised risk scores for the NG scenarios in the three years specified.

9.6.3 Comparing Scenarios

In addition to comparing the UKERC and NG scenarios, it is helpful to compare elements of the UKERC scenarios since there is annual time-series data.

The risk profiles for the UKERC REF and LC scenarios for total primary energy demand by fuel, final demand by fuel, installed electricity generating capacity, and transport fuel demand are compared in Figure 9.23. The main point is to show that there are differences depending on which measure is used to examine the energy system. For example, the difference between total primary energy demand by fuel and final demand by fuel is the efficiency of the conversion technologies (stage 4) and the losses in the distribution systems (stage 5).

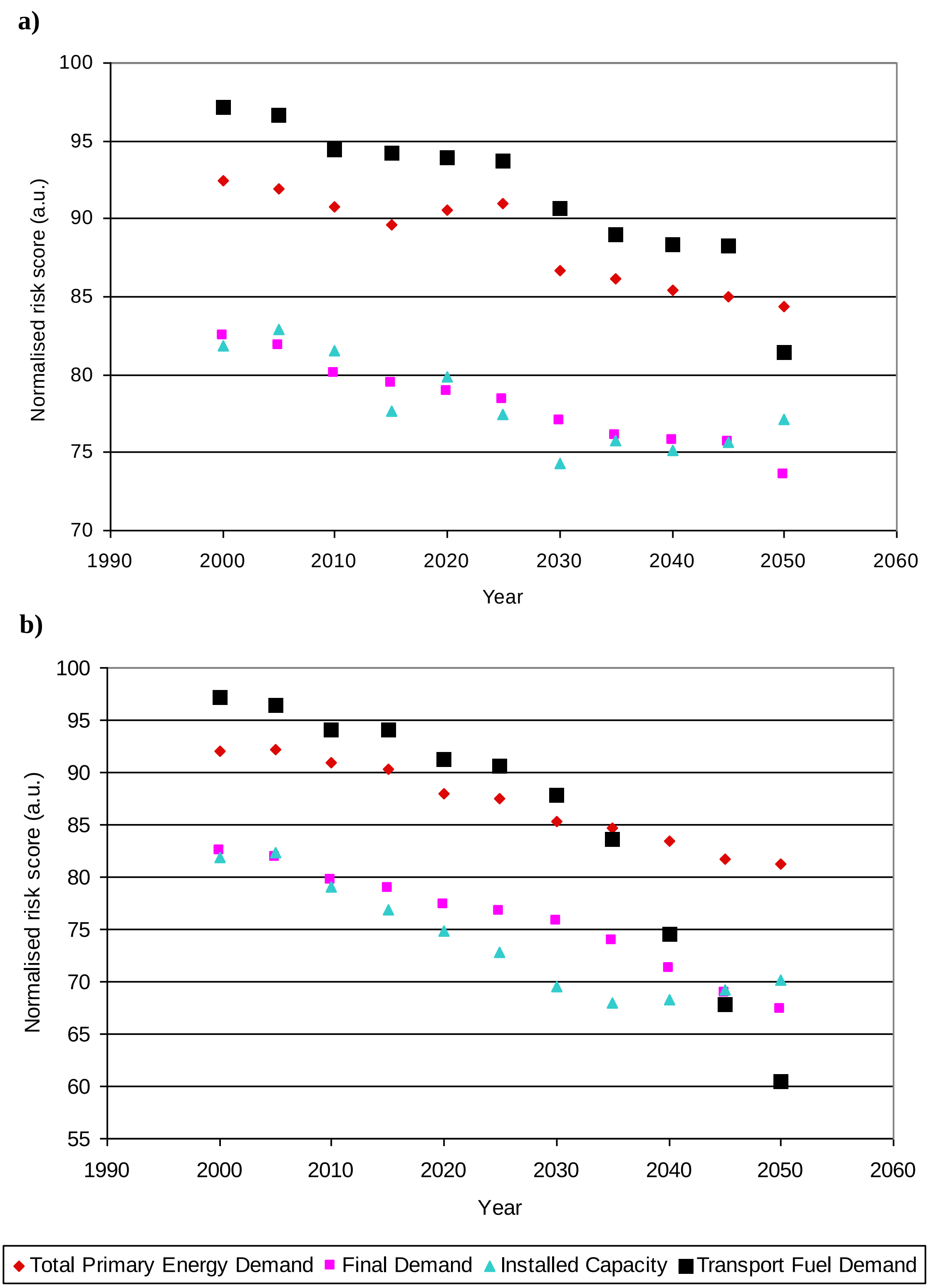


Figure 9.23 Summary of the risk profiles for total primary energy demand by fuel, final demand by fuel, installed electricity generating capacity, and transport fuel demand for a) the UKERC REF scenario, and b) the UKERC LC scenario.

The only measure allowing comparison of the UKERC scenarios with those created by NG is installed electricity generating capacity (Figure 9.24). For both UKERC and NG the more optimistic scenarios (LC and 2DEG, respectively) have lower risk scores than the more pessimistic (REF and CP, respectively), and this holds true for both 2030 and 2050. Also, in all cases, the NG scenarios have lower risk score than those of UKERC. Indeed, overall the NG CP scenario still scores considerably lower than any of the UKERC cases. These values are summarised in Table 9.15. This shows a systematic bias in the way the assumptions have been drawn-up and modelled. The NG assumptions are transparent and published, but the assumptions UKERC built into MARKAL are not transparent. We note too that the risk score for the UKERC scenarios are the same or higher for 2050 than 2030. This demonstrates that UKERC scenarios show that there is no ‘free lunch’ when it comes to decarbonisation of electricity generation – the trade-off is severe. It should be noted that risk arising in fuel supply chains was not part of their considerations when constructing their models; this is an emergent property of their results. We note that the NG scenarios contradict this view.

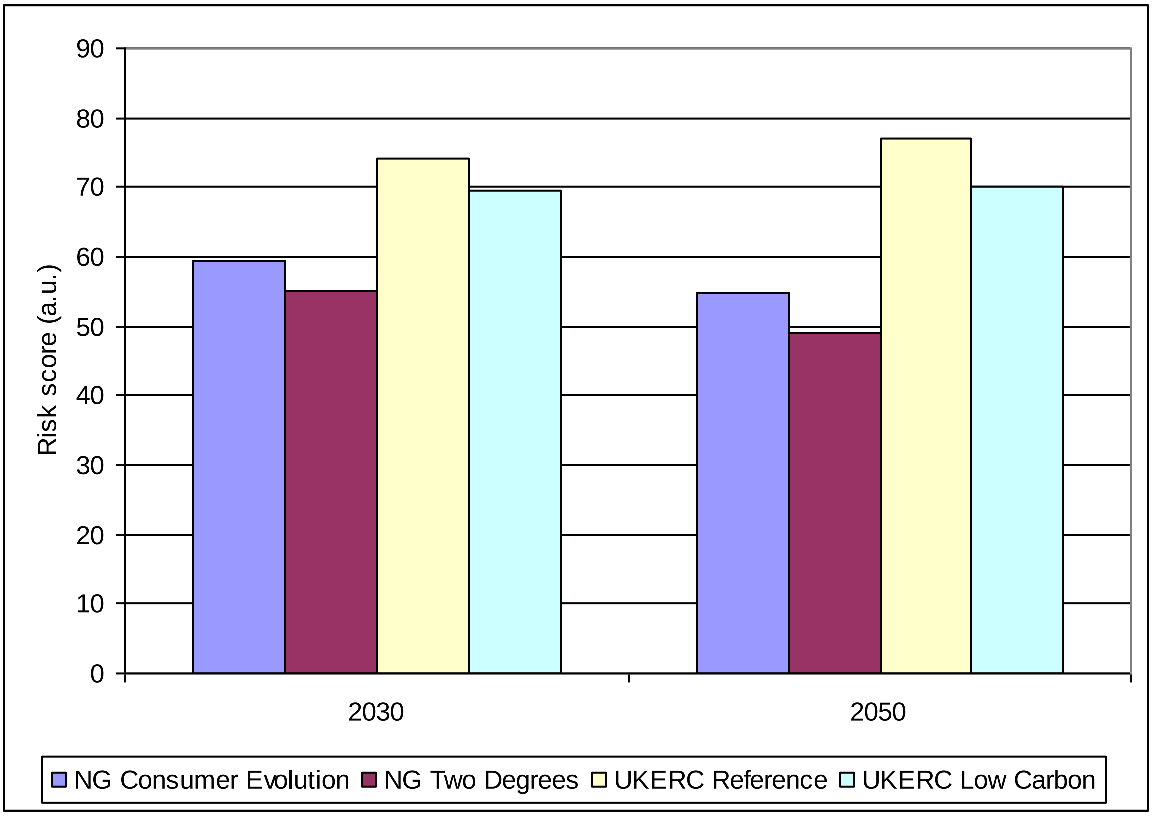


Figure 9.24 Comparing installed electricity generating capacity in 2030 and 2050 for the UKERC and NG scenarios. These represent the fastest and slowest rates of decarbonisation. The initial years in each set are different and therefore cannot be compared.

Scenario	Normalised Risk Score (a.u.)		Change in Risk Score (%)
	2030	2050	
NG 2DEG	55	49	-8%
NG CP	59	55	-11%
UKERC REF(2013)	74	77	4%
UKERC LC(2013)	69	70	1%

Table 9.15 Summary of the normalised risk scores for the comparison of the UKERC and NG scenarios for installed electricity generating capacity.

10 Expert Verification Workshop

In work requiring expert judgments, validation is an important stage. Usually, the approach is to convene a workshop to test methods or outcomes, or to offer specific input (Johansen and Rausand, 2014). The exact approach to take will depend on time available, scale of the project, maturity of the topic or method, or the type of information being sought (see for example Chang et al. (2014) or Eskandari Torbaghan et al. (2015)).

To test the results of our novel approach and assessment we convened a panel of experts to elicit opinions and implicit knowledge not commonly put into the public domain. The aim was to uncover why industry experts consider something to be important. Inevitably, statistics and the literature offer only part of the landscape for a research area such as ES. Academic studies may model sets of restricted or closely defined circumstances (scenarios) but cannot properly incorporate the professional experience of experts. Dagonneau et al. (2017) observed from their national-scale environmental policy workshops that compared with the literature, experts gave a narrower range for impact severity for environmental risks, a higher median severity for economic risks, and a wider spread of severity impact scores for societal risks. The energy industry is mostly in the private sector, but as a public utility it is strongly regulated with significant policy and legislative guidance. Therefore the interface between government and industry is interesting and pertinent to understanding how different sets of sector experts view the relevant risks, and according to Duijm (2015) any risk evaluation should reflect the common understanding of the stakeholders.

There are hurdles to running such an exercise. Participants need sufficient experience beyond entry level, but organisations can be reluctant to give time of senior people, there is little incentive to participate beyond meeting some new people, participants may be reticent about speaking freely in case important information is accidentally given away to rivals, and there are limits to what can be achieved in a short event and how much preparation participants are willing to undertake. There are actions which may be taken to mitigate some of these difficulties, with running the event under the Chatham House rule[3] is of primary importance. The most difficult mitigation task to

[3] Participants are free to use the information received, but neither the identity nor the affiliation of the speaker(s), nor that of any other participant, may be revealed.

execute is selecting invitees from different organisations with differing job functions, levels, or sectoral specialisation to ensure that potential clashes of interest are avoided. However, no matter how careful the planning, workshop organisers are at the whim of those who are prepared to attend. Furthermore, invitees sometimes offer substitute colleagues – sometimes less senior. These people may be unknown to the organisers, but courtesy dictates that the organisers trust the invitee's judgment that the substitute is appropriate.

10.1 Workshop Details

Our aim for the event was to consider the relative importance of causes of risk for a subset of fuels, and to suggest how policymakers can account better for risks when developing energy policy. We opted to hold a 2½ hour workshop with 15-18 participants. Although this number could not cover all of the possible combinations of technology or job function, we considered that it was a realistic number which would cover the main areas. As the literature on which we had relied was predominantly academic, we chose to invite mostly those with private sector experience. We took the criterion for expertise as ten or more years relevant experience and were chosen to reflect the categories of risk and/or process stages. We made 38 invitations of which 19 were accepted (four were substitutes suggested by the invitee). A further five people were unavailable and unable to offer a suitable alternative attendee. Sometime after the invitations had been made, the UK Prime Minister announced that a general election and this placed the civil service into purdah. Although this legally only prevents policy announcements from being made, government departments withdraw from even attending events, even as observers. This brought the final number of participants down to 16; one person did not attend on the day. We agreed to maintain the anonymity of the participants, but Table 10.1 gives a breakdown of their expertise in relation to our categories of risk and stages.

The subset of fuels that we used were selected using as they met one or more of the following criteria: 1) having importance in the current energy system, 2) considered as having priority in future energy systems, or 3) showing interesting properties in our initial analysis. If the invitees who agreed to participate had a lack of knowledge of one of the fuels we would have withdrawn that fuel from the discussion. The final list of fuels for discussion was: bioliquids, demand reduction, gas (unconventional), nuclear (fission), ocean (tidal), oil, solar (electric), and wind (offshore).

Job Title	Expertise	Stage(s)	Main Risk Categories
Partner	Investment	3, 4, 5	Economic
Consultant	Oil	1-5	Environmental
Manager	Nuclear fission	1-4	Innovation
Consultant	Renewables, investment	2-5	Manu, innovation
Research Fellow (academic)	Public acceptability	1-6	Political
Chief Executive	Demand	6	Political
Manager	Markets	1, 2	Economic
Senior Engineer	Nuclear fission	3, 4	Technical
Research Fellow	Demand	5	Environmental
Deputy Director	Shale gas	1, 2, 3	Economic
Director	Infrastructure	4, 5	Technical
Policy Analyst	Coal and renewables	4	Political
Research Fellow	Investment	3-6	Technical
Senior Lecturer	Heat	5, 6	Political
Advisor	Gas	2-4	Political
Company Director	Markets, investment	3-6	Economic

Table 10.1 Characteristics of the workshop participants.

Participants were split into three pre-ordained groups, each with a facilitator. Groups were formed based on specialist fuel knowledge and each group discussed three fuels. Membership of the groups (and facilitator) were kept constant. Although we had working definitions of the causes of risk, to give flexibility we allowed participants to interpret these or to add (or condense) them. Any deviations were recorded and explained. Participants were sent briefing notes on the project, the definitions of fuels, risks, and categories. All notes were written by the facilitators. We chose not to use audio recording devices as this can inhibit some people and inevitably some speech is lost if people speak over each other. There were three tasks as follows:

Task 1: The task for each group was to identify the most and least important causes of risk in each category for each fuel. The key point was to extract the reasoning why each expert had come to that conclusion. The discussion of differences in opinion was also important to record. Facilitators were instructed that if that proved too contentious or difficult then to prioritise the stages with which the group was most confident, though this did not prove necessary.

Task 2: In open session with all groups together, participants compared and contrasted these and prioritised the causes of risk across all eight fuels.

Task 3: Also in open session, participants discussed what policy measures or instruments BEIS (or other Government dept) could enact to mitigate the most important risks occurring. Originally this was to have input from the departmental representatives giving useful direct feedback as part of the discussion. Without the departmental representatives present this task was somewhat muted, but opinions were noted.

The open session also enabled facilitators to check whether a strong opinion was common or pertained only to an individual. We explicitly asked for criticism of our method of assessing risk in the open session.

10.2 Group One

This group was facilitated by Colin Axon (Department of Mechanical and Aerospace Engineering, Brunel University).

10.2.1 General Comments

One participant made a general point that the risk list does not sufficiently emphasise socio-technical issues, particularly elements which relate to civil society, for example, equity. This was about how perceived fairness is a risk when developing energy policy. [Clarification: This could relate to access to energy tariffs or financial fairness more generally, but really concerns any sort of energy policy. Social theory tells us of at least three different – but equally legitimate – views on fairness: parity (everyone is strictly equal), proportionality (those who are more deserving) and priority (everyone has equal opportunities). The risk is that energy policies are not 'fair' in plural senses of the word. This feeds into the broader point that causes of risk are rarely objective measures and that potentially any one of the categories could be perceived quite differently. For example, the risks of 'natural hazards' can equally plausibly be seen as catastrophes to avoid, uncertainties to manage or opportunities to exploit. Similarly, 'institutional governance' where discretion is given to firms is as equally legitimate as that where discretion is handed to regulators or where there is no discretion permitted at all. From any one of those perspectives, the others would be considered 'poor' governance. The point being decision makers need to account for different perceptions of risk in order to make energy policies more socially robust.] It was suggested that this could be encompassed as a new risk of 'lack of equity'.

10.2.2 Solar (Electric)

A general comment made was that the important issue for PV is a need for the storage of power to reduced (power) cost volatility. It was suggested that this could be interpreted as a new risk of 'lack of storage capacity'. However, this could be accommodated in the current fuel chain 'Grid-scale storage' if the definition is broadened to 'Distributed storage', say. The group chose to concentrate on innovation and political risks for stages 2-4 (exploit, condition, convert).

For the innovation category two participants considered optimism bias as a significant risk. One person considered it as a general risk, one specifically as price optimism i.e. the price of electricity generated from PV as not falling as fast or as low as expected. It was broadly accepted that power production in the wrong place at the wrong time, thus presenting a risk (the storage problem). We interpreted this as a technical risk, rather than innovation. Weak technology transfer was considered as not reducing costs of installation. This could be considered as a lack of capacity or capability in R&D to meet the challenge. Weak technology transfer was also considered in the context of building integrated systems, for example. There are many systems proposed or trialled, but relatively few types deployed as their cost is too great. This can be treated as a piece of evidence for weak technology transfer.

For the *Political* category, significant public concern ('NIMBYism') was considered by four participants as a key risk. In particular one participant suggested that public engagement with energy issues is too narrow in practice making it more of a risk than usually considered. One participant suggested that better public engagement with energy issues more broadly than solely price could drive policy change. However, this was challenged by another participant who suggested that this might imply that Government might change policy even more frequently with perhaps "*terrifying outcomes*". Standards and codes: one participant suggested that the development of appropriate standards and codes should be considered as a technical risk, whilst the enforcement a political risk. The role of the market and the Feed-in tariff (FiT) was discussed in the context of the risk of 'Changing policy or regulatory framework'. One participant suggested that the market as it is currently constituted was not important enough to have any significant effect as it manifests itself as only a small proportion of the energy price. There was agreement that the FiT was poorly thought out before implementation. Another participant observed that the key piece of evidence that the FiT was a risk is that a change in the FiT rate (payment) could easily "*make or kill PV*". Another participant noted that currently the cost of installation and operation of bi-directional meters far outweighed any financial and technical gains for exporting electricity generated by small-scale (residential) PV.

10.2.3 Demand Reduction (DR)

The inclusion of DR in the risk analysis was supported. But one participant raised the question of whether it might be better to consider DR at each and every stage of all the fuel supply chains. Meaning that every energy systems manufacturer, service provider, distributor, and user should consider a lack of DR activity as a risk. The main reason for proposing that DR be considered as a 'negafuel' is that it can be too easily subsumed and lost in a discussion. The point about every actor engaging in DR is well-made, but this analysis is at the national level. The aim is to prompt consideration of DR as an activity with significant value which requires specific policy instruments to given some level of coherence to such activities. But the point is taken and we will revisit our original method of including DR to see if improvements can be made to capture the micro-scale importance.

The first risk raised was that the discount rate of the future value of DR is very aggressive, meaning that the long-term value of DR is not recognised, thus not worth investing in. The risk of rebound effects is high. There a number of studies which can be used to estimate the level of this risk. It was suggested that this risk might occur in Stage 4 (conversion). Currently we had considered rebound effects as part of 'Optimism bias', but it was suggested that we examine whether rebound should be made an explicit risk. If DR were diffused through all stages, treating rebound explicitly would make the most sense. Lack of access to finance (capital) was identified as a cause of risk. The notion of equity raised in the discussion of PV may have relevance.

Addressing the issue of energy waste was raised as an important element of DR. It was suggested that 'lack of decreasing waste' as a risk or 'lack of increasing efficiency' might capture this explicitly. However, waste through technical losses is already covered by 'Operation failure'. Losses due to inefficiency are currently covered by 'Pollution event' i.e. an involuntary release of thermal energy (mostly) into the environment. We would expect to include efficiency improvement as an innovation risk. We will examine whether ‘waste’ or ‘lack of efficiency’ should be made an explicit cause of risk. Also raised as an element of ‘Operational failure’ as a cause of risk was poor installation quality e.g. the incorrect installation of cavity wall insulation in West facing walls. One participant linked this to skills.

At the exploitation stage, one participant highlighted incentives, and the recognition and spread of social norms. Incentives can be considered as an indicator of market failure, thus the cause of risk is the ‘lack of a well functioning market’. It was noted that the spread of social norms is more of a mechanism than a cause of risk.

A new cause of risk not previously categorised explicitly was described as a ‘lack of reputational loss for house builders’. Meaning that poor standards go unpunished. It was suggested that this could be included as a ‘lack of enforcement of standards and codes’. It was suggested that we examine whether ‘lack of reputational loss for house builders’ as a cause of risk should be made explicit.

10.2.4 Summary

One of the key risks is the changing policy or regulatory framework. For solar PV, the feed-in tariff was highlighted as an example. Timescale informs the role of demand reduction (perhaps via a market price), but in the end encourages more consumption. The value of demand reduction is underplayed generally. Generally, the lack of access to capital was considered to be important.

10.3 Group Two

These notes are adapted from those of the group facilitator, Dr. Barry Rawn (Department of Electronic and Computer Engineering, Brunel University).

10.3.1 Ocean (Tidal)

Several participants identified tidal stream type of technology versus the barrage type (as proposed for the Severn Estuary) or lagoon, as most likely. Stages 2-4 (exploit, condition, convert) were identified as the most critical stages, though one expert felt exploring was also significant. A special feature agreed upon was the unusual operating environment.

At Stages 2-4 (exploit, condition, convert) in the economic category of causes of risk the lack of access to capital was difficult not only because of high capital outlay, but also concern over competitiveness due to current levelised cost of electricity. The group considered that there may be limited remaining learning curve benefits for reducing cost (only marginal improvements likely) and that the industry lacks long-term history. The group noted that at any particular site the available resource is limited (an energy density issue). For the manufacturing category, a lack of specialist equipment and an insufficient capacity to construct sites were noted as a significant risks. For the environment category, it was that hazards for pilot checks on resource are different and daunting. Poor time of day match with demand i.e. unevenly distributed demand compared the tide times which although predictable, shift was noted as risk. For the innovation category, funding needed to achieve viable civil engineering designs was thought to be the key risk. This was interpreted as the lack of public subsidy and that the R&D capacity or capability does not match the challenge. In the environment category, the fouling of blades e.g. due to barnacles, and other deep-sea conditions (such as difficult physical access and natural hazards) were the most important risks. Finally, the lack of specialists in the local workforce was noted.

At Stage 5, (distribute), the high cost of connection due to distance and depth was the most significant issue, though economic impacts on other users of the area must be considered. For the environment category the group noted that exclusion zones imposed by environmental features could change.

10.3.2 Nuclear (Fission)

The group identified conversion (Stage 4) as most critical because the explore, exploit, and use stages all involved well understood commodities. Exploring in particular was viewed as not a problem, though it was mentioned that political aspects can harm both local exploration or imports, even from a large and stable market for uranium or other fissile materials. The cost was flagged as the most serious impediment. Perception of one participant: "*Lack of flexibility of production; more or less finished in future*". A participant stated that nuclear decommissioning costs are known, unless you account for removing the containment. The exception being Sellafield and Dounreay, which are uncertain. It is risky to use all the same reactor designs because if a design flaw emerges all reactors come off at the same time.

In the economic category, the greatest risks noted were associated with capital expenditure and uncertain cost forecasts. The lack of access to capital is a special problem because of extremely high absolute capex which has led to additions to the bill of consumers. Also noted was the treatment by the market due to lack of flexibility. Although decommissioning costs are put aside, some members of the group see these as small and relatively certain numbers, others saw these numbers as uncertain due to lack of certainty on whether it would be accepted by public or not.

In the political category, the group noted that waste treatment plans are not trusted by the public. Furthermore, they observed that the general public opposed nuclear (although one participant observed that this is side-stepped in UK). However, this has in part led to the Government changing policy towards nuclear over a long period of time. There is an interesting interaction with the risks associated with the innovation category i.e. know-how becomes political. For example, the Czech Republic indigenised its know how, compared with Bulgaria which suffered after loss of central support following the collapse of the USSR.

There was agreement that the nuclear sector was neither not innovating nor economic (always requiring subsidy). An interesting observation made was that negative learning rates demonstrated for projects in some countries arose because these are infrequent mega-projects, thus R&D capacity or capability may not match the challenge. Participants also noted that manufacturing of specialised components posed a risk to the industry.

The group observed that a pollution event brings risk of regulator shut-down. Also in the technical category, it was clear that it is not possible to neutralize waste at decommissioning. Other risks discussed by the group were that the risk of natural hazards (environmental category) results in small number of suitable approvable sites, even in the UK. This risk is not normally considered from this perspective. Finally, specialist skills (and maintaining the skills levels) was recognised widely as a significant risk for the nuclear industry in the UK.

10.3.3 Gas (Unconventional)

In general, the risks were concentrated in the first two stages. The political and environmental risk categories were linked to each other by the group, and economic risks were also noted. Participants had differing views on technical risks; some considered that innovation, technical, and manufacturing were of least concern, while some saw skills as a problem (however, it was judged to be low). Another general observation by the group was the future unaffordability of mining fossil fuels.

At Stage 1 (explore), the group noted four risks in the political category: public opposition to local exploration, that a lack of public engagement can lead to uncertainty or outright the denial of permission to access sites, explicit arrangements to share of economic benefit are key, as subsurface rights not present in the UK, and large-scale subsidies for shale decreasing at the expense of other unconventional fossil fuels.

At Stage 2 (exploit) the group identified a wider range of risks. In the Political category they discussed how infrastructure takes time to build during which period perceptions and support can change. Indeed changing policy or regulation was considered the main risk for shale gas and may take the form of pressure from carbon budgets which could change downstream usage and curtail demand. Linked to this was a suggestion from one participant that this uncertainty may lead to divestment, but other participants thought this to be unlikely. In the technical category it was noted that regulation is stronger in the UK i.e. the likelihood of a technical failure is lower. The group considered that there was some risk of skill sets not being available. A key risk noted by the group was whether or not a drilling site will yield commercial flow-rates (environmental category).

10.3.4 Summary

The system and processes themselves have effects which need to be discerned; the risk in failing to integrate "*enough*". The context could be political, technical, or innovation. Optimism bias was considered to be a more significant risk than usually considered. A general comment about political risk was that the interconnections (physical infrastructure and commercial) are on the rise in the energy sector. However, this tension, in part created by globalisation, is with energy independence.

10.4 Group Three

These notes are adapted from those of the group facilitator, Prof. Richard Darton (Department of Engineering Science, University of Oxford).

10.4.1 Oil

One participant considered that the main risks are economic and in particular [oil] price volatility for greenfield projects. This person suggested that the UK plays against international competition and US shale is an obvious competitor. Another participant agreed that global price volatility is a risk. A participant asked what time-scale should we consider? They suggested that electric vehicles will eventually (15-20 years) take over from the internal combustion engine, and that this will affect take-up of fossil fuel (a drop in consumer oil demand), but there is little appetite to drive this change at a faster rate still. Another participant was concerned that electric vehicles were already having effect and that work on efficiency in internal combustion engines is being dropped by car firms who see electric vehicles as the future. An associated risk to the viability of projects was identified as a reduction in demand – even the perception of it is a risk. However, another participant pointed out that there is demand for chemicals feedstocks. Another participant said that the political will is to *encourage* switch to EV rather than fiscal measures which will be politically unpalatable. But the will is scarcely sufficient to change [oil/gas demand] enough to meet the 1.5 °C target. So the 1.5 °C target can be seen as a risk to security because it will bear down on fossil fuels. [The risk is agreeing a target then not agreeing appropriate actions, leaving an uncertainty in future regulation/policy.]

A participant raised the issue of peak oil saying that the public domain data on reserves is very poor and perhaps unreliable, adding that we are in a time when oil is being used faster than it is being discovered. They continued by suggesting that peak conventional oil is about here because of the growth in the extraction of unconventional oil, but that the big question is how quickly its use will be expanded. Conventional was defined as all oil liquids except fracked, but not kerogen-based. The risk was stated as conventional oil not being available to meet demand. Another participant said that up to five years ago the risk was seen in terms of price because unconventional was more expensive, but unconventional is getting cheaper. There was some disagreement about non-availability. Historically, oil security is traditionally seen as producer-consumer balance. Another participant pointed out that political risk is changing because the US is now a competitive producer.

A participant raised the case of innovation risk stating that the trend is to phase out subsidies which could put projects at risk. Another participant doubted that this was a risk.

There was general agreement that the main risk for the UK is an uncertain regulatory framework. As an example of uncertainty in the policy/regulatory framework, a participant suggested that the 1.5 °C target was not matched by policy; the 1.5 °C is agreed, but not the routes to meet it. Frequent changes of UK Government policy means that companies now apply a risk premium to investment decisions.

Other risks mentioned were: revolution and war in Saudi, and maritime choke points (both of which can be interpreted as a risk of a lack of social stability). The risk posed by the deployment of carbon abatement to fossil fuel projects was raised. The participant suggested that it could lead to reductions or loss of market. The productive future looks very different for oil and gas in a world where carbon abatement is prioritised versus one where it isn't. It may also dictate the pace of CCS and other carbon-friendly technologies. That is, a project is developed on the basis of a certain production profile e.g. from a gas field, and then some future point abatement policy leads to extra costs or loss of demand (weaker market). Thus, abatement poses a project risk and at any time in the future the risk may be crystallised by policy and regulation to abate carbon, which would affect projects. Another participant suggested that this was perhaps indistinct and less important than the threat posed by mass EV take-up. Furthermore, EV take-up was seen as relatively close in time and could happen even faster were it not that governments are wary of driving this change too fast. It was suggested that the motor industry lobby were not keen on a fast EV take-up.

10.4.2 Offshore Wind

There was agreement that the main risk is the frequently changing policy and regulatory framework has been very undermining to the UK. A specific example raised was Scottish independence. There was agreement that the levelised cost of electricity is falling much faster for solar and onshore wind, than for offshore wind. One participant thought that offshore wind was not competitive, but others disagreed saying that offshore wind costs are reducing and that the German and Danish experience is good. A participant suggested that they would strongly prefer political consensus and cross-party support and considered a ‘lack of political consensus’ as a risk. They continued, Ed Milliband politicised the cost of energy. Whilst there is consensus on climate change, this consensus does not feed through into policy. So we have seen back-pedalling of political stances on energy policy because energy prices are now a political issue. Some other countries manage this differently and work harder to reach cross-party support for longer-term policies.

A question raised was if onshore wind and solar are more economic outside Europe, why would the UK benefit from pursuing technologies that are not globally competitive? If the market outside UK favours onshore/solar, said one participant, the UK should develop other skills. The risk as they saw it is that the UK develops skills that are not needed, however, there was some disagreement about this point.

Another point raised was whether there a risk from Brexit. Another participant suggested that it could be, but was doubtful as it was not seen as problem at the moment. It was noted that recently the UK slipped from number 3 or 4 on the Ernst and Young list of desirable places for renewables investment to number 12; with Germany or Denmark at the top. This was considered to be more damaging for attracting inward investment than Brexit. Another participant suggested that subsidies and regulations should not be changed overnight or without warning or consultation, with tapering is much preferred so as to create time for adjustment.

10.4.3 Bioliquids

Although not a risk as such, it was noted that the EROEI for all biofuels was very low [this could be seen as a risk in terms of environmental impact].

One participant stated that the main problem was in the politics and that oil is cheap. They continued by saying that uncertainties created by NGO campaigns on perceived problems, in particular the competition with land for food sources is over-exaggerated. This participant considered that there is no real issue as the feedstock is generally agriwaste or grown on unproductive land, and Most of the UK biofuel supply is imported (from South America). There was some disagreement about whether metrics to measure the environmental impacts are sufficiently disaggregated. A participant considered independent check of the biomass supply chain to be thorough and that the public perceptions on this are quite wrong. For example forest cover in the EU is increasing rapidly, and the track and trace programmes being used.

10.4.4 Summary

The greatest concern was the changing of the policy landscape, described as "*policy and regulatory meddling*" leading to a risk premium in the market price. Misconceptions drive policy and behaviour and is incompatible with stable future climate policy. Also noted as important was the innovation category, in particular the transition to EVs, and it was noted that there may be a slowing innovation optimism. The Skills category was thought to be of the least concern. In oil and gas, for example, it was thought that there was an oversupply of skilled people.

10.5 Conclusions of the Workshop

During the open discussion session, the participants agreed that a changing policy or regulatory framework was the most significant risk across all fuels and process stages.

They commented that it was one which the UK Government should treat with urgency and the highest priority (within BEIS). The participants agreed on a further seven risks which they considered to be more important than others, but not as significant as a changing policy or regulatory framework (Table 10.2).

Cause of Risk (unordered)	**Risk Category**
Changing policy or regulatory framework	Political
Lack of access to capital	Economic
Insufficient rate of infrastructure construction	Manufacturing
Optimism bias	Innovation
Significant public concern	Political
Lack of a well-functioning market	Economic
Lack of public subsidy	Innovation
Uncertain decommissioning costs	Economic

Table 10.2 Summary of the risks identified as most significant by the workshop participants.

10.5.1 Summary of Suggested Actions for Policy

The participants made three suggestions for discussion with the Department for Business, Energy, and Industrial Strategy. In no particular order:

1. Funding calls: the use of exploratory projects is the wrong approach because the public pays the development risk of the energy sector. This was considered as a form of privatising the profit whilst subsidising the risk.
2. BEIS should be more conscious of, or explicit about acknowledging, optimism bias.
3. Attempting to set up an open market is not working. The context for all energy policy is the supply-demand balance. Yet the simple use of £/MWh does not lead to a balance across the whole energy system because it is a poor metric for incorporating the requirements for flexibility and for multiple energy vectors. This means that a basket of relevant indicators is required to formulate, set, and judge policy instruments. It would be best not to use cost minimisation as a mechanism (or as a modelling tool).

One participant noted that the problem with ES, and energy issues in general, is that common perceptions are often very far from the truth.

10.5.2 Comments on the Methodology

We noted two criticisms of our methodology. The first that systemic risks are not being considered, only individual fuels. One participant noted that the EROEI for most fuels is getting worse e.g. PV never makes a contribution because it costs more energy to make than it generates (there was disagreement about this point). The second is that it appears to be about analysing the existing system – things as they are or are easily changed. Incorporating the risks goes some way to tackle this, but another participant thought that it is not a predictive tool as such. However, trends in data can be observed and used, though exogenous shocks cannot be accounted for without scenario analysis. Another question raised was how to account for risk interactions.

11 Conclusions

We can draw conclusions across three areas: 1) the performance of the method, 2) the numerical results which flowed from applying the method, and 3) recommendations to mitigate risks in UK energy policy and security. We then suggest some key next steps to carry this work forward.

11.1 The Performance of the Method

Using the principles of the PAM we have created a set of risks which work well with a wide range of current and fledgling fuels; we make four observations. First, that creating a risk register for ES is a tractable proposition. Secondly, that our method has been tested with an expert group. Thirdly, that sensitivity is readily incorporated to yield reasonable ranges for the overall risk scores. Fourthly, that our set of causes of risk is able to accommodate fuels and processes with a wide range of production and operating scales. These are aided by the transparency of our approach.

The six stages used give structure to the analysis, but are only one way in which the end-to-end process can be deconstructed. Using more stages gives greater detail, but increases the overhead of operating the method. In considering the limitations of this approach we need to appreciate that for complicated systems there is a balance to be struck between the level of detail of the analysis and the time required to obtain a useful set of causes of risk. The analysis can be neither too coarse nor too detailed. If we restricted our method to using the causes of risk without the six stages, then an intrinsically simpler analysis – albeit with a longer list of risk causes – could be screened against the fuel sources. By adding the process stages, the number of risk causes can be condensed by allowing (defined) interpretation of the causes of risk at each stage. In critically assessing the broad energy systems literature we estimated the levels of likelihood and impact for each cause of risk for each fuel and each process stage – creating the risk register.

Our approach offers the advantage of sufficient flexibility to make it readily applicable to a wider variety of nations or other situations related to energy systems. Furthermore, our analyst allows for the fact that not all of the fuel sources have a reliance on every stage in the same way. Wind and solar electric are two clear examples where the conditioning stage (stage 4) is not relevant. Our framework and methodology can be adapted for examining fuel-types from specific or single sites (or nations) as part of an assessment that might include detailed or specific international relations knowledge, say. A balanced judgment could be made about how important that source was to the ES at the system boundary.

A valid criticism of our method is that it is designed to analyse an existing system – things as they are or have been historically. However, well established trends can be projected forward in a defensible ways (Roberts et al., 2019). All methods for forward projections make assumptions – some more heroic than others. Frequently in energy scenario modelling assumptions are made about macroeconomic performance, energy prices, and technology improvement. In our case we assume that risk profiles for stages and fuels is unchanging with time which at first glance appears an unreasonable assumption. Public and expert understanding and appreciation of risk changes over time i.e. acceptability of the consequences; for example, health and safety at work or environmental pollution. But usually such changes are incremental and slow. Although public opinion can change dramatically in the aftermath of a major incident such as Chernobyl, Fukushima, or the 2007/08 financial crash, memories and concerns can also fade fast with a relatively quick return to business-as-usual. Moreover, we have 'priced' in extreme possibilities where the occurrence of a risk could lead to a catastrophic outcome i.e. shutdown a site, operation, or activity.

Incorporating risk adds a dimension to bridge the concepts of sustainability and security, but it is still not a predictive tool which can account for exogenous shocks. However, when used in conjunction with scenario analysis our method offers a powerful tool for assessing the value or barriers of competing proposed energy system configurations. Scenario analysis is complementary to our method. The error analysis (section 9.1.1) suggests that even quite sizable changes are not likely to change the groupings of the fuels in the rank order of risk. We suggest that this confirms that our approach is robust.

The purpose of holding a workshop with industry experts was to ascertain *why* some causes of risk were more important than others and to identify which were the most important. Whilst the workshop participants were not certain that we tackled risks arising from the structure of the energy system, it is not clear to us that this arises from disaggregating it into process stages prior to identifying risks. It is very difficult to judge what risks may be systemic without assessing either their prevalence within the supply chain or their potential to create a cascade through the supply chain, or across different fuel supply chains. It is possible that every risk may appear systemic (or grossly under-estimated) if the system is analysed as a single entity without structure. As systemic risks may occur as a result of interactions, the structure must play an explicit part. Coupled risks a ‘risk couplet’ (or even a ‘risk triplet’) will not necessarily lead to a systemic risk as that would need a cascading (amplification) mechanism and generate a contagion.

The practice of avoiding double-counting (when developing sustainability indicators) is a practice that highlights important overlaps in the system. For risk analysis double-counting means that some element of a risk is occurring in more than one place, which by definition means those entities are coupled in some way. The only way to understand interactions is to know something about the coupling strength i.e. have some data or hypothesis of how the risks are linked. For the UK, it is unlikely that many risks are strongly coupled because the supply of sources of fuel and final energy vectors is stable; the UK is not suffering from rationing or shortages, and electricity distribution outages are rare. This is the current state, but there is competition for scarce resources so the nature of the systemic risk may change.

We conceived the sharing of infrastructure as lowering risk, whereas the notion of ‘sharing’ in terms of systemic risk increases risk. Therefore we need always to be clear on the context. For example, the entry barrier for a new fuel source is lower (lower risk) if it generates an energy vector already in common use i.e. it shares the cost of the distribution infrastructure. This helps explain why it is hard for district heating, say, to gain a foothold because a new infrastructure is required. But this adds to the systemic risk of a shock or disruption to the means of distribution. However, disaggregating the distribution system leads to double-counting.

11.2 Application of the Method

The fuel ranking (Table 9.1) shows that non-renewables (fossil fuels and nuclear) confer the greatest levels of risk on an energy system. The only non-renewable in the bottom half of the table is DR. The broad split of renewables and non-renewables is not remarkable, but the exact position of some fuels and the detail of the importance of risks does warrant further comment.

Demand reduction appearing in the middle of the table goes some way to explaining why DR programmes have not achieved the impact expected – the risks involved have been under-estimated previously. The misaligned theoretical savings and field measurements suggests that the ‘quality of the fuel’ (reliability of behaviour) as a cause of risk in particular has been underestimated. A second point we note is that DR is not usually incorporated into future energy scenarios, and that the focus on primary energy supply misses the importance of DR. We suggest that by treating DR (or energy efficiency) as a 'negafuel' it can be automatically put on a par with fuel supply. We consider that finding a way – and preferably a simple way – to change attitudes towards energy efficiency is imperative. Declaring efficiency as the 'first fuel' is clearly not having the desired effect. Our work shows that it is not the first fuel. Although proponents of DR do not assume that it will occur without intervention or effort, many other actors in the energy sector appear to assume that it will. We propose that a holistic risk-based approach to DR – including treating it as a negafuel – will open-up a new fronts to understand how to create programmes of DR which may be more successful than previous programmes.

The relatively high risk-ranking of the biofuels is surprising at first sight. However, the amount of chemical processing required is costly and complicated which attracts risks at a high-level, such as the lack of access to capital. The risk assessment sheds light on why biofuels are not making inroads into the marketplace in the way proponents have been hoping. The same is true for geothermal energy sources. Assessing the detail of the risks, and their relative importance, for different fuels gives signals for the shaping of strategies to develop future energy systems portfolios.

Energy security, like sustainability, is multi-facetted and our analysis shows the variability in detailed indicators. From the UKERC and NG scenarios we see that a change in energy system configuration implies a transfer of risk from high carbon fuels to nuclear fission, demonstrating the importance of conducting a holistic analysis. For electricity generation the switch from non-renewables to renewables lowers risk, but for other final energy vectors, such as for heat and transport, this is not clear-cut. Our work shows that although various pathways and measures lead to lower annual carbon emissions, the risk profile may increase. This goes some way to explain why the market is finding difficulty in delivering a lower carbon energy system, even with subsidy and other support. The market may be better at assessing risks (by whatever methods) and its pricing is creating the barrier. A 'whole systems' approach to risk will assist in drilling down to find the key elements on which governments and companies should concentrate resources and expertise. The frequently changing policy and regulatory landscape suggests that the UK especially has not yet achieved a stable platform for energy (security) policy development. The power of this risk profiling technique allows analysts potentially to examine trade-offs between a more efficient technology using a fuel with a riskier upstream profile and a low risk fuel with an inefficient technology.

11.3 Policy Implications

The emphasis of policy support (including through the UK Energy Technologies Institute) has been on reducing the costs of deploying a particular technology or process, but progress has been patchy. In part this is explained by many renewables having similar risk scores i.e. there are no clear winners. These ‘good’ fuels sources are competing for the same investment capital, skilled labour, and other inputs. Our analysis shows that cost reduction alone is insufficient to deliver an efficient and more environmentally benign energy system. If a risk-based analysis had been carried out across the whole of the fuel supply chain earlier other important or competing factors would be been revealed. If this renewables log-jam had been foreseen actions to mitigate the situation could have been taken.

A possible and logical response of policy to the fuel rank is to support maximal use of each fuel starting from the bottom of the list, moving upwards, to fill the lowest ‘risk state’ of the energy system to meet demand requirements. However, our method is blind to the capacity of technologies to deliver the final energy vector, the abundance of each fuel, and the availability of sites to deploy the conversion technologies (stage 4). That is to say that we have not used any sort of resource weighting. For example, there is no point in using the solar technologies at sites which do not face South. And in the case of Solar (thermal), the panels can only deliver warm water which must be used locally. Furthermore, an issue arises in assigning abundance to fossil fuels, say, as some proportion of the total global resource.

Assumptions impact the risk profile and companies make investment decisions based on their assessment of risk. Therefore policymakers should scrutinise much more closely the assumptions made in scenarios produced by various energy systems models. The assumptions are frequently not transparent. With such differences between organisations which generate scenarios, how can a government make decisions based on energy systems modelling? The mis-modelling of schemes to support energy efficiency or particular technologies might have a lack of understanding of risk as the root cause. Private companies will make investment decisions incorporating a risk assessment; governments should do likewise.

The expert workshop participants identified policy and regulatory volatility as the key risk. By way of mitigation the participants made three suggestions for discussion with BEIS (in no particular order):

1. Stop the use of funded exploratory projects because the public pays the development risk of the energy sector. This was considered as a form of privatising the profit whilst subsidising the risk.
2. Greater consciousness of, or be explicit about acknowledging, optimism bias.
3. Attempting to set up an open market is not working. The context for all energy policy is the supply-demand balance. Yet the simple use of £/MWh does not lead to a balance across the whole energy system because it is a poor metric for incorporating the requirements for flexibility and for multiple energy vectors. This means that a basket of relevant indicators is required to formulate, set, and judge policy instruments. It would be best not to use cost minimisation as a mechanism (or as a modelling tool).

We make a fourth recommendation. As multi-partisan consensus in the UK is uncommon, we suggest to decouple energy policy from politics by creating an ‘Office for Energy Policy Responsibility’. Although not as limited as the Office for Budget Responsibility, it would have analogous functions for independent scrutiny. Such a body might assume the functions of the Climate Change Committee to give a comprehensive approach to long-term energy policy, including ES considerations.

11.4 Further Work

Developing our work from this point will take two principal directions. The first is incorporating risk analysis into the PAM for long-term ES, and the second is extending the risk analysis directly as a standalone method by improving, deepening, and applying it more widely .

11.4.1 The Process Analysis Method for ES

We outlined in chapter 1 the need to understand the role of risk before using the PAM to generate an indicator set for ES. Incorporating the causes of risk within the PAM output will create a hybrid method accounting for historically observed trends and important (but not yet occurring) risks. Past practice and historical decisions have created the topology and functionality of the present energy system(s). Current and future ES can only be built upon this system; the starting point is already defined. Some of the causes of risk identified can readily be broken down in the PAM, such as operational or infrastructure failure in the Technical category. Other causes of risk, such as the ‘lack of access to capital’, ‘changing policy or regulatory framework’, or ‘optimism bias’ could not be captured readily. In general, where a risk is observing an impact that has not yet occurred, a pure PAM approach will struggle to represent the impact adequately.

11.4.2 Improving the Risk Analysis Method

Aside from the mechanistic improvements already outlined we need to consider two additional concepts: the role of negotiation and the limitations of resource potential.

The first is whether to incorporate explicitly negotiation (section 8.3.3) and at which scale; the negotiation to mitigate which risk and for whom is another. Given that the case study system boundary was a sovereign nation state, inter-Government negotiations might be the only factor to consider. However, some of these manifest themselves in other causes of risk. For example, the results of climate change negotiations could be incorporated in ‘changing policy or regulatory framework’.

We have outlined the resource availability problem above. Since this characteristic of a fuel source might determine whether exploration is undertaken it is an important consideration. We suggest that it may be possible to normalise the risk profiles and scores with a measure of resource availability / potential.

The discussion of systemic risk in fuel supply chains for ES is an unresolved issue. We noted the prevalence of the causes of risk in this study, but this did not necessarily confirm them as systemic in nature. The strength of risk interaction is not revealed in our study, but must exist in some form e.g. skilled engineers trained and working in the nuclear industry can’t also work on improving solar PV systems (opportunity cost). Investigating the causes of risk from the perspective of a network may offer insight into the likelihood of a cascading failure.

11.4.3 Deepening the Risk Analysis Method

We can examine each fuel chain individually or as part of a specialist collection grouped by factors such as common processing elements, distribution mechanisms, end use types, or the purpose of the final energy vector.

There are narratives to be created for each individual supply chain. But for fuels of particular importance it will be interesting to see if analysing a very detailed set of sub-processes at each stage will yield a sophisticated view of how to better design and implement support mechanisms to mitigate risks. We will need to look at how the categories and causes might change or expand when drilling deeply into each stage. It will also be interesting to follow the profiles for individual causes of risk within and across fuels. We have only used renewable and non-renewable as broad categories to demonstrate the basic idea.

We will synthesise the elements relating to heat as a systems-level topic. Heat demand in the UK (300 GW peak) is approximately an order of magnitude greater than electricity (50 GW peak) at present. Despite these figures heat has been under-researched; although companies with high heat use have always had an incentive to reduce demand and improve efficiency. The implications of the different risks occurring in the electrical and thermal supply chains for heat warrant further investigation. From our analysis it is clear that the attendant risks for district heat distribution networks are substantially different from the onsite exploitation of surplus industrial heat, or a CHP unit for a commercial building, or a block of residential flats, say. The coarse scale of the process descriptions do not capture the duality of output of CHP whether using gas or biomass. Therefore a more detailed analysis of any supply chain with heat as a final use needs to split out these branches. Interest in heat decarbonisation is growing, thus our analysis will be timely.

Likewise, we suggest that there is merit in analysing transport energy resources. We judge that there are particular risks presented by the environment, to the environment (technical failures), political stability, and lack of innovation. The current development of electric and fuel cell vehicles, and biogenic liquid fuels will make this a topical study.

11.4.4 Further Applications of the Risk Analysis Method

The most obvious next step is to apply our method to one or more new nations. This can only conducted in collaboration as in-country expertise is required. Following recent talks given at international conferences (Axon and Darton, 2017, 2018) we have received interest from researchers in Australia and the USA. Although it is tempting to consider what might be the minimum risk portfolio of saleable fuels, we suggest that this may not be a useful question. The reason being that we do not have a clean sheet and would have to scale it using resource potential. The only exception might be in aiding the design of energy systems for a developing nation with almost no existing infrastructure.

Frequently, analysis methods will be applied to supra-national entities such as the European Union or the Gulf Co-operation Council, rather than aggregating studies of the individual nations which make up these bodies. We caution against this approach as the disparities between the member states can be significant; though we note that this might be less of a problem with the Gulf Co-operation Council member states.

Perhaps the most pressing of international energy and climate questions is how to reach the 1.5 °C global temperature rise target. This process is governed by the Nationally Determined Contributions (NDCs). Whilst each nation uses its own methodology to arrive at a figure for the Paris Agreement, these GHG reductions need to be implemented somehow. The UK uses carbon budgets modelled and monitored by the Climate Change Committee. The current period in the modelling phase is the fifth carbon budget (5CB) spanning 2028-2032. Assessing the risk for this and other carbon budgets will be a useful contribution to UK energy policy. We will also wish to compare the portfolios suggested by alternative 5CB models such as those generated by Roberts et al. (2018).

References

Abanades, J., Greaves, D., Iglesias, G., 2015. Wave farm impact on beach modal state. Marine Geology 361, 126–135. https://doi.org/10.1016/j.margeo.2015.01.008

Abbott, D.J., Bowers, J.P., James, S.R., 2012. The impact of natural gas composition variations on the operation of gas turbines for power generation. 6th International Gas Turbine Conference 17–18 Octbober, Brussels, Belgium.

Acquaye, A.A., Sherwen, T., Genovese, A., Kuylenstierna, J., Lenny Koh, S., McQueen-Mason, S., 2012. Biofuels and their potential to aid the UK towards achieving emissions reduction policy targets. Renewable and Sustainable Energy Reviews 16, 5414–5422. https://doi.org/10.1016/j.rser.2012.04.046

Adams, P.W., Hammond, G.P., McManus, M.C., Mezzullo, W.G., 2011. Barriers to and drivers for UK bioenergy development. Renewable and Sustainable Energy Reviews 15, 1217–1227. https://doi.org/10.1016/j.rser.2010.09.039

Adams, P.W.R., Lindegaard, K., 2016. A critical appraisal of the effectiveness of UK perennial energy crops policy since 1990. Renewable and Sustainable Energy Reviews 55, 188–202. https://doi.org/10.1016/j.rser.2015.10.126

Adams, P.W.R., Mezzullo, W.G., McManus, M.C., 2015. Biomass sustainability criteria: Greenhouse gas accounting issues for biogas and biomethane facilities. Energy Policy 87, 95–109. https://doi.org/10.1016/j.enpol.2015.08.031

Ahmadi, M., John, K., 2015. Statistical evaluation of the impact of shale gas activities on ozone pollution in North Texas. Science of The Total Environment 536, 457–467. https://doi.org/10.1016/j.scitotenv.2015.06.114

Ahmadian, R., Olbert, A.I., Hartnett, M., Falconer, R.A., 2014. Sea level rise in the Severn Estuary and Bristol Channel and impacts of a Severn Barrage. Computers & Geosciences 66, 94–105. https://doi.org/10.1016/j.cageo.2013.12.011

Alberola-Borràs, J.-A., Vidal, R., Juárez-Pérez, E.J., Mas-Marzá, E., Guerrero, A., Mora-Seró, I., 2018. Relative impacts of methylammonium lead triiodide perovskite solar cells based on life cycle assessment. Solar Energy Materials and Solar Cells 179, 169–177. https://doi.org/10.1016/j.solmat.2017.11.008

Al-Douri, A., Sengupta, D., El-Halwagi, M.M., 2017. Shale gas monetization – A review of downstream processing to chemicals and fuels. Journal of Natural Gas Science and Engineering 45, 436–455. https://doi.org/10.1016/j.jngse.2017.05.016

Al-Habaibeh, A., Athresh, A.P., Parker, K., 2018. Performance analysis of using mine water from an abandoned coal mine for heating of buildings using an open loop based single shaft GSHP system. Applied Energy 211, 393–402. https://doi.org/10.1016/j.apenergy.2017.11.025

Allan, G., Eromenko, I., Gilmartin, M., Kockar, I., McGregor, P., 2015. The economics of distributed energy generation: A literature review. Renewable and Sustainable Energy Reviews 42, 543–556. https://doi.org/10.1016/j.rser.2014.07.064

Allan, N., Yin, Y., 2011. Development of a Methodology for Understanding the Potency of Risk Connectivity. Journal of Management in Engineering 27, 75–79. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000036

Allen, P., Chatterton, T., 2013. Carbon reduction scenarios for 2050: An explorative analysis of public preferences. En. Policy 63, 796–808. https://doi.org/10.1016/j.enpol.2013.08.079

Allen, S.R., Hammond, G.P., Harajli, H.A., McManus, M.C., Winnett, A.B., 2010. Integrated appraisal of a Solar Hot Water system. Energy 35, 1351–1362. https://doi.org/10.1016/j.energy.2009.11.018

Almond, S., Clancy, S.A., Davies, R.J., Worrall, F., 2014. The flux of radionuclides in flowback fluid from shale gas exploitation. Environmental Science and Pollution Research 21, 12316–12324. https://doi.org/10.1007/s11356-014-3118-y

Al-Shemmeri, T.T., Yedla, R., Wardle, D., 2015. Thermal characteristics of various biomass fuels in a small-scale biomass combustor. Applied Thermal Engineering 85, 243–251. https://doi.org/10.1016/j.applthermaleng.2015.03.055

Amundrud, Ø., Aven, T., 2015. On how to understand and acknowledge risk. Reliability Engineering & System Safety 142, 42–47. https://doi.org/10.1016/j.ress.2015.04.021
Anable, J., Brand, C., Tran, M., Eyre, N., 2012. Modelling transport energy demand: A socio-technical approach. Energy Policy, Modeling Transport (Energy) Demand and Policies 41, 125–138. https://doi.org/10.1016/j.enpol.2010.08.020
Andersson-Hudson, J., Knight, W., Humphrey, M., O'Hara, S., 2016. Exploring support for shale gas extraction in the United Kingdom. Energy Policy 98, 582–589. https://doi.org/10.1016/j.enpol.2016.09.042
Ang, B.W., Choong, W.L., Ng, T.S., 2015. Energy security: Definitions, dimensions and indexes. Renewable & Sustainable Egy Rev 42, 1077–1093. https://doi.org/10.1016/j.rser.2014.10.064
Angeloudis, A., Kramer, S.C., Avdis, A., Piggott, M.D., 2018. Optimising tidal range power plant operation. Applied Energy 212, 680–690. https://doi.org/10.1016/j.apenergy.2017.12.052
Anifowose, B., Lawler, D.M., van der Horst, D., Chapman, L., 2016. A systematic quality assessment of Environmental Impact Statements in the oil and gas industry. Science of The Total Environment 572, 570–585. https://doi.org/10.1016/j.scitotenv.2016.07.083
Anifowose, B., Lawler, D.M., van der Horst, D., Chapman, L., 2012. Attacks on oil transport pipelines in Nigeria: A quantitative exploration and possible explanation of observed patterns. Applied Geography 32, 636–651. https://doi.org/10.1016/j.apgeog.2011.07.012
Ansar, A., Flyvbjerg, B., 2016. Big isfragile. Energy World 20–21.
Ansar, A., Flyvbjerg, B., Budzier, A., Lunn, D., 2014. Should we build more large dams? The actual costs of hydropower megaproject development. Energy Policy 69, 43–56. https://doi.org/10.1016/j.enpol.2013.10.069
APERC, 2007. A quest for energy security in the 21st century: resources and constraints (No. APEC # 207-RE-01.2). Asia Pacific Energy Research Centre, Institute of Energy Economics, Tokyo, Japan.
Arapostathis, S., Carlsson-Hyslop, A., Pearson, P.J.G., Thornton, J., Gradillas, M., Laczay, S., Wallis, S., 2013. Governing transitions: Cases and insights from two periods in the history of the UK gas industry. En. Policy 52, 25–44. https://doi.org/10.1016/j.enpol.2012.08.016
Arup, 2019. SPeAR® (Sustainable Project Appraisal Routine). URL https://www.arup.com/projects/spear (accessed 29/12/19).
Atkins, M.J., Walmsley, M.R.W., Morrison, A.S., 2010. Integration of solar thermal for improved energy efficiency in low-temperature-pinch industrial processes. Energy 35, 1867–1873. https://doi.org/10.1016/j.energy.2009.06.039
Augustine, C., Tester, J.W., Anderson, B., Petty, S., Livesay, B., 2006. A Comparison of Geothermal with Oil and Gas Well Drilling Costs, in: Proceedings. 31st Workshop on Geothermal Reservoir Eng, 30 Jan - 1 Feb, SGP-TR-179, Stanford, California, USA, p. 15.
Ault, T., Gosen, B.V., Krahn, S., Croff, A., 2016. Natural Thorium Resources and Recovery: Options and Impacts. Nuclear Tech. 194, 136–151. https://doi.org/10.13182/NT15-83
Aven, T., 2016. Risk assessment and risk management: Review of recent advances on their foundation. Eur J. Operational Res. 253, 1–13. https://doi.org/10.1016/j.ejor.2015.12.023
Aven, T., 2017. Improving risk characterisations in practical situations by highlighting knowledge aspects, with applications to risk matrices. Reliability Engineering & System Safety, Special Section: Applications of Probabilistic Graphical Models in Dependability, Diagnosis and Prognosis 167, 42–48. https://doi.org/10.1016/j.ress.2017.05.006
Aven, T., Cox, L.A., 2016. National and Global Risk Studies: How Can the Field of Risk Analysis Contribute? Risk Analysis 36, 186–190. https://doi.org/10.1111/risa.12584
Aven, T., Renn, O., 2009. The Role of Quantitative Risk Assessments for Characterizing Risk and Uncertainty and Delineating Appropriate Risk Management Options, with Special Emphasis on Terrorism Risk. Risk Analysis 29, 587–600. https://doi.org/10.1111/j.1539-6924.2008.01175.x
Aven, T., Renn, O., 2018. Improving government policy on risk: Eight key principles. Reliability Engineering & System Safety 176, 230–241. https://doi.org/10.1016/j.ress.2018.04.018
Awudu, I., Zhang, J., 2012. Uncertainties and sustainability concepts in biofuel supply chain management: A review. Renewable and Sustainable Energy Reviews 16, 1359–1368. https://doi.org/10.1016/j.rser.2011.10.016

Axelsson, G., Stefánsson, V., Björnsson, G., Liu, J., 2005. Sustainable Management of Geothermal Resources and Utilization for 100-300 Years. World Geothermal Congress, 24-29 April, International Geothermal Association, Antalya, Turkey, pp. 1–8.

Axon, C.J., Bright, S.J., Dixon, T.J., Janda, K.B., Kolokotroni, M., 2012. Building communities: reducing energy use in tenanted commercial property. Build. Res. Informat. 40, 461–472. https://doi.org/10.1080/09613218.2012.680701

Axon, C.J., Darton, R.C., 2017. Transitioning to sustainability: energy security and risk. World Congress of Chemical Engineering & 6th International Congress on Sustainability Science & Engineering Oct 1-5, 2017, Barcelona, Spain.

Axon, C.J., Darton, R.C., 2018. Measuring Energy Security from a comprehensive assessment of risk in fuel supply chains. AIChE Annual Meeting, 28 Oct-2 Nov, Pittsburgh, USA.

Axon, C.J., Darton, R.C., Winzer, C., 2013. Measuring Energy Security, in: Mitchell, C.H.C., Watson, J., Whiting, J. (Eds.), New Challenges in Energy Security: The UK in a Multipolar World. Palgrave Macmillan, London, UK, pp. 208–237. https://doi.org/10.1057/9781137298850

Axon, S., 2017. "Keeping the ball rolling": Addressing the enablers of, and barriers to, sustainable lifestyles. J. Env. Psychology 52, 11–25. https://doi.org/10.1016/j.jenvp.2017.05.002

Axon, S., Morrissey, J., Aiesha, R., Hillman, J., Revez, A., Lennon, B., Salel, M., Dunphy, N., Boo, E., 2018. The human factor: Classification of European community-based behaviour change initiatives. J Cleaner Production 182, 567–586. https://doi.org/10.1016/j.jclepro.2018.01.232

Azzuni, A., Breyer, C., 2018. Definitions and dimensions of energy security: a literature review: Definitions and dimensions of energy security. Wiley Interdisciplinary Reviews: Energy and Environment 7, e268. https://doi.org/10.1002/wene.268

Baborska-Narozny, M., Grudzinska, M., 2017. Overheating in a UK High-rise Retrofit Apartment Block – Ranking of Measures Available to Case Study Occupants Based on Modelling. Energy Procedia 111, 568–577. https://doi.org/10.1016/j.egypro.2017.03.219

Baborska-Narozny, M., Stevenson, F., Ziyad, F.J., 2016. User learning and emerging practices in relation to innovative technologies: A case study of domestic photovoltaic systems in the UK. Energy Research & Social Science, Energy Transitions in Europe: Emerging Challenges, Innovative Approaches, and Possible Solutions 13, 24–37. https://doi.org/10.1016/j.erss.2015.12.002

Badcock, J., Lenzen, M., 2010. Subsidies for electricity-generating technologies: A review. Energy Policy 38, 5038–5047. https://doi.org/10.1016/j.enpol.2010.04.031

Bahaj, A.S., 2011. Generating electricity from the oceans. Renewable and Sustainable Energy Reviews 15, 3399–3416. https://doi.org/10.1016/j.rser.2011.04.032

Bailey, I., West, J., Whitehead, I., 2011. Out of Sight but Not out of Mind? Public Perceptions of Wave Energy. Journal of Environmental Policy & Planning 13, 139–157. https://doi.org/10.1080/1523908X.2011.573632

Bailey, M.T., Gandy, C.J., Watson, I.A., Wyatt, L.M., Jarvis, A.P., 2016. Heat recovery potential of mine water treatment systems in Great Britain. International Journal of Coal Geology, Abandoned Coal Mines: From Environmental Liabilities to Low-Carbon Energy Assets 164, 77–84. https://doi.org/10.1016/j.coal.2016.03.007

Bailey, R., 2013. The Trouble with Biofuels: Costs and Consequences of Expanding Biofuel Use in the United Kingdom (No. ER PP 2013/01), Energy, Environment and Resources. The Royal Institute of International Affairs, Chatham House, London, UK.

Baker, C., 1991. Tidal power. Energy Policy 19, 792–797. https://doi.org/10.1016/0301-4215(91)90049-T

Balcombe, P., Rigby, D., Azapagic, A., 2014. Investigating the importance of motivations and barriers related to microgeneration uptake in the UK. Applied Energy 130, 403–418. https://doi.org/10.1016/j.apenergy.2014.05.047

Balta-Ozkan, N., Watson, T., Connor, P., Axon, C., Whitmarsh, L.E., Davidson, R., Spence, A., Baker, P., Xenias, D., Cipcigan, L.M., 2014. Scenarios for the Development of Smart Grids in the UK: synthesis report (No. UKERC/RR/ES/2014/002). UKERC, London.

Balta-Ozkan, N., Yildirim, J., Connor, P.M., 2015. Regional distribution of photovoltaic deployment in the UK and its determinants: A spatial econometric approach. Energy Economics 51, 417–429. https://doi.org/10.1016/j.eneco.2015.08.003
Banister, D., Hickman, R., 2013. Transport futures: Thinking the unthinkable. Transport Policy 29, 283–293. https://doi.org/10.1016/j.tranpol.2012.07.005
Banks, A.N., Sanderson, W.G., Hughes, B., Cranswick, P.A., Smith, L.E., Whitehead, S., Musgrove, A.J., Haycock, B., Fairney, N.P., 2008. The Sea Empress oil spill (Wales, UK): Effects on Common Scoter Melanitta nigra in Carmarthen Bay and status ten years later. Marine Pollution Bulletin 56, 895–902. https://doi.org/10.1016/j.marpolbul.2008.01.032
Banks, D., 2016. Scottish Pioneers of Tools for Low Temperature Geothermal Applications: William Cullen, the Stirling Brothers and William Rankine. The Int J. for the History of Engineering & Technology 86, 147–160. https://doi.org/10.1080/17581206.2016.1223936
Bao, C., Li, J., Wu, D., 2018. A fuzzy mapping framework for risk aggregation based on risk matrices. J. Risk Research 21, 539–561. https://doi.org/10.1080/13669877.2016.1223161
Barker, J.A., Downing, R.A., Gray, D.A., Findlay, J., Kellaway, G.A., Parker, R.H., Rollin, K.E., 2000. Hydrogeothermal studies in the United Kingdom. Quarterly Journal of Engineering Geology and Hydrogeology 33, 41–58. https://doi.org/10.1144/qjegh.33.1.41
Barrett, M., Bradshaw, M., Froggatt, A., Mitchell, C., Parag, Y., Stirling, A., Watson, J., Winzer, C., n.d. Energy Security in a Multi-polar World (Discussion Paper). Exeter, UK.
Bartle, A., Hallowes, G., 2005. Hydroelectric power: present role and future prospects. Proc. Inst. Civil Engineers - Civil Engineering 158, 28–31. https://doi.org/10.1680/cien.2005.158.6.28
Barton, J., Davies, L., Dooley, B., Foxon, T.J., Galloway, S., Hammond, G.P., O'Grady, Á., Robertson, E., Thomson, M., 2018. Transition pathways for a UK low-carbon electricity system: Comparing scenarios and technology implications. Renewable and Sustainable Energy Reviews 82, 2779–2790. https://doi.org/10.1016/j.rser.2017.10.007
Barua, S., Gao, X., Mannan, M.S., 2016. Comparison of prescriptive and performance-based regulatory regimes in the U.S.A and the U.K. Journal of Loss Prevention in the Process Industries 44, 764–769. https://doi.org/10.1016/j.jlp.2016.10.009
Bassi, S., Boyd, R., Buckle, S., Fennell, P., Mac Dowell, N., Makuch, Z., Staffell, I., 2015. Bridging the gap: improving the economic and policy framework for carbon capture and storage in the European Union. Policy brief: Centre for Climate Change Economics and Policy, Grantham Research Institute on Climate Change and the Env., London, UK.
Bast, E., Doukas, A., Pickard, S., van der Burg, L., Whitley, S., 2015. Empty promises: G20 subsidies to oil, gas and coal production. Overseas Development Institute, London, UK.
Batchelor, A.S., 1987. Development of hot-dry-rock geothermal systems in the UK. IEE Proceedings A - Physical Science, Measurement and Instrumentation, Management and Education - Reviews 134, 371–380. https://doi.org/10.1049/ip-a-1:19870058
Batey, M., Mourik, R., 2016. From calculated to real energy savings performance evaluation: an ICT-based methodology to enable meaningful do-it-yourself data collection. Energy Efficiency 9, 939–950. https://doi.org/10.1007/s12053-015-9415-6
Battiston, S., Caldarelli, G., May, R.M., Roukny, T., Stiglitz, J.E., 2016. The price of complexity in financial networks. Proc National Academy of Sciences USA 113, 10031–10036. https://doi.org/10.1073/pnas.1521573113
Baumann, H., Tillman, A.-M., 2004. The Hitch Hiker's Guide to LCA: An Orientation in Life Cycle Assessment Methodology and Applications. Studentlitteratur AB, Lund, Sweden.
Baumuller, H., Donnelly, E., Vines, A., Weimer, M., 2011. The Effects of Oil Companies' Activities on the Environment, Health and Development in Africa (No. EXPO/B/DEVE/FWC/2009-01/Lot5/11 PE 433.768). DG External Policies of the Union, Brussels, Belgium.
Baxter, T., Bebbington, J., Cutteridge, D., 2002. The Sustainability Assessment Model (SAM). SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production, Kuala Lumpur, Malaysia 20-22 March, Society of Petroleum Engineers. https://doi.org/10.2118/73968-MS
Baxter, X.C., Darvell, L.I., Jones, J.M., Barraclough, T., Yates, N.E., Shield, I., 2014. Miscanthus combustion properties and variations with Miscanthus agronomy. Fuel 117, 851–869. https://doi.org/10.1016/j.fuel.2013.09.003

Baybutt, P., 2016. Designing risk matrices to avoid risk ranking reversal errors. Process Safety Progress 35, 41–46. https://doi.org/10.1002/prs.11768
Baybutt, P., 2018. Guidelines for designing risk matrices. Process Safety Progress 37, 49–55. https://doi.org/10.1002/prs.11905
BBC News, 2012. Sizewell B nuclear reactor has unplanned shutdown. URL http://www.bbc.co.uk/news/uk-england-suffolk-18899367 (accessed 12/6/16).
Beaudoin, Y.C., Dallimore, S.R., Boswell, R. (Eds.), 2014a. Frozen heat: a global outlook on methane gas hydrates. Volume 2. United Nations Environment Programme, Arendal, Norway.
Beaudoin, Y.C., Waite, W., Boswell, R., Dallimore, S.R. (Eds.), 2014b. Frozen heat: a global outlook on methane gas hydrates. Volume 1. United Nations Environment Programme, Arendal, Norway.
Beerten, J., Laes, E., Meskens, G., D'haeseleer, W., 2009. Greenhouse gas emissions in the nuclear life cycle: A balanced appraisal. Energy Policy 37, 5056–5068. https://doi.org/10.1016/j.enpol.2009.06.073
BEIS, 2016a. UK risk assessment on security of gas supply: Report completed for EU regulation 994/2010. Department for Business, Energy and Industrial Strategy, London, UK.
BEIS, 2016b. Physical gas flows across Europe and diversity of gas supply in 2015, in: Energy Trends. Department for Business, Energy and Industrial Strategy, London, UK, pp. 77–88.
BEIS, 2016c. Rise Up Against Gas Storage, London, UK.
BEIS, 2017a. Clean Growth Strategy. Department for Business, Energy and Industrial Strategy, London, UK.
BEIS, 2017b. Digest of United Kingdom energy statistics 2017. Department for Business, Energy and Industrial Strategy, London, UK.
BEIS, 2017c. Digest of United Kingdom energy statistics 2017. Department for Business, Energy and Industrial Strategy, London, UK.
BEIS, 2017d. UK Energy in Brief. Department for Business, Energy and Industrial Strategy, London, UK.
BEIS, 2019. Contracts for Difference. Department for Energy and Industrial Strategy. URL https://www.gov.uk/government/publications/contracts-for-difference/contract-for-difference (accessed 22/12/19).
Beizaee, A., Allinson, D., Lomas, K.J., Foda, E., Loveday, D.L., 2015. Measuring the potential of zonal space heating controls to reduce energy use in UK homes: The case of un-furbished 1930s dwellings. Energy and Buildings 92, 29–44. https://doi.org/10.1016/j.enbuild.2015.01.040
Bell, R.A., Darling, W.G., Ward, R.S., Basava-Reddi, L., Halwa, L., Manamsa, K., Ó Dochartaigh, B.E., 2017. A baseline survey of dissolved methane in aquifers of Great Britain. Science of The Total Env. 601–602, 1803–1813. https://doi.org/10.1016/j.scitotenv.2017.05.191
Bellos, E., 2018. Sustainable energy development: How can the tension between energy security and energy transition be measured and managed in South Africa? Journal of Cleaner Production 205, 738–753. https://doi.org/10.1016/j.jclepro.2018.08.196
Bennett, S.J., Pearson, P.J.G., 2009. From petrochemical complexes to biorefineries? The past and prospective co-evolution of liquid fuels and chemicals production in the UK. Chemical Engineering Research and Design, Special Issue on Biorefinery Integration 87, 1120–1139. https://doi.org/10.1016/j.cherd.2009.02.008
Bentley, R., Bentley, Y., 2015. Explaining the price of oil 1971–2014 : The need to use reliable data on oil discovery and to account for 'mid-point' peak. Energy Policy 86, 880–890. https://doi.org/10.1016/j.enpol.2015.04.028
Bentley, R.W., 2002. Global oil & gas depletion: an overview. Energy Policy 30, 189–205. https://doi.org/10.1016/S0301-4215(01)00144-6
Bergman, N., Eyre, N., 2011. What role for microgeneration in a shift to a low carbon domestic energy sector in the UK? Energy Eff 4, 335–353. https://doi.org/10.1007/s12053-011-9107-9
Bergthorson, J.M., Thomson, M.J., 2015. A review of the combustion and emissions properties of advanced transportation biofuels and their impact on existing and future engines. Renewable and Sustainable Energy Reviews 42, 1393–1417. https://doi.org/10.1016/j.rser.2014.10.034

Berti, P., Levidow, L., 2014. Fuelling expectations: A policy-promise lock-in of UK biofuel policy. Energy Policy 66, 135–143. https://doi.org/10.1016/j.enpol.2013.09.044
Bertoldi, P., Boza-Kiss, B., 2017. Analysis of barriers and drivers for the development of the ESCO markets in Europe. Energy Policy 107, 345–355. https://doi.org/10.1016/j.enpol.2017.04.023
Bing, L., Akintoye, A., Edwards, P.J., Hardcastle, C., 2005. The allocation of risk in PPP/PFI construction projects in the UK. International Journal of Project Management 23, 25–35. https://doi.org/10.1016/j.ijproman.2004.04.006
Binnie, C., 2016. Tidal energy from the Severn estuary, UK. Proceedings of the Institution of Civil Engineers - Energy 169, 3–17. https://doi.org/10.1680/jener.14.00025
Bishop, J.D.K., Axon, C.J., Tran, M., Bonilla, D., Banister, D., McCulloch, M.D., 2012. Identifying the fuels and energy conversion technologies necessary to meet European passenger car emissions legislation to 2020. Fuel 99, 88–105. https://doi.org/10.1016/j.fuel.2012.04.045
Bithas, K., Kalimeris, P., 2013. Re-estimating the decoupling effect: Is there an actual transition towards a less energy-intensive economy? Energy 51, 78–84. https://doi.org/10.1016/j.energy.2012.11.033
Bjerga, T., Aven, T., 2016. Some perspectives on risk management: A security case study from the oil and gas industry. Proceedings of the IMechE 230, 512–520. https://doi.org/10.1177/1748006X16654589
Bjørgum, Ø., Sørheim, R., 2015. The funding of new technology firms in a pre-commercial industry – the role of smart capital. Technology Analysis & Strategic Management 27, 249–266. https://doi.org/10.1080/09537325.2014.971002
Boait, P.J., Dixon, D., Fan, D., Stafford, A., 2012. Production efficiency of hot water for domestic use. Energy and Buildings 54, 160–168. https://doi.org/10.1016/j.enbuild.2012.07.011
Boait, P.J., Fan, D., Stafford, A., 2011. Performance and control of domestic ground-source heat pumps in retrofit installations. Energy and Buildings 43, 1968–1976. https://doi.org/10.1016/j.enbuild.2011.04.003
Boardman, B., 2004. Achieving energy efficiency through product policy: the UK experience. Environmental Science & Policy 7, 165–176. https://doi.org/10.1016/j.envsci.2004.03.002
Boardman, B., 2007a. Examining the carbon agenda via the 40% House scenario. Building Research & Information 35, 363–378. https://doi.org/10.1080/09613210701238276
Boardman, B., 2007b. Home truths: a low-carbon strategy to reduce UK housing emissions by 80% by 2050. Environmental Change Institute, University of Oxford, Oxford.
Boardman, B., Darby, S., Killip, G., Hinnells, M., Jardine, C.N., Palmer, J., Sinden, G., 2005. 40% House. Environmental Change Institute, University of Oxford, Oxford, UK.
Bogacka, M., Pikoń, K., Landrat, M., 2017. Environmental impact of PV cell waste scenario. Waste Management 70, 198–203. https://doi.org/10.1016/j.wasman.2017.09.007
Bogush, A., Stegemann, J.A., Wood, I., Roy, A., 2015. Element composition and mineralogical characterisation of air pollution control residue from UK energy-from-waste facilities. Waste Management 36, 119–129. https://doi.org/10.1016/j.wasman.2014.11.017
Boholm, Å., Prutzer, M., 2017. Experts' understandings of drinking water risk management in a climate change scenario. Climate Risk Management 16, 133–144. https://doi.org/10.1016/j.crm.2017.01.003
Bolton, R., Foxon, T.J., 2015. Infrastructure transformation as a socio-technical process — Implications for the governance of energy distribution networks in the UK. Technological Forecasting & Social Change 90, 538–550. https://doi.org/10.1016/j.techfore.2014.02.017
Bomberg, E., 2017. Shale We Drill? Discourse Dynamics in UK Fracking Debates. J. Env. Policy & Planning 19, 72–88. https://doi.org/10.1080/1523908X.2015.1053111
Bonilla, D., Bishop, J.D.K., Axon, C.J., Banister, D., 2014. Innovation, the diesel engine and vehicle markets: Evidence from OECD engine patents. Transport. Res. Part D-Transport. Environ. 27, 51–58. https://doi.org/10.1016/j.trd.2013.12.012
Booth, A.T., Choudhary, R., 2013. Decision making under uncertainty in the retrofit analysis of the UK housing stock: Implications for the Green Deal. Energy and Buildings 64, 292–308. https://doi.org/10.1016/j.enbuild.2013.05.014

Boot-Handford, M.E., Abanades, J.C., Anthony, E.J., Blunt, M.J., Brandani, S., Dowell, N.M., Fernández, J.R., Ferrari, M.-C., Gross, R., Hallett, J.P., Haszeldine, R.S., Heptonstall, P., Lyngfelt, A., Makuch, Z., Mangano, E., Porter, R.T.J., Pourkashanian, M., Rochelle, G.T., Shah, N., Yao, J.G., Fennell, P.S., 2013. Carbon capture and storage update. Energy Environ. Sci. 7, 130–189. https://doi.org/10.1039/C3EE42350F

Boothroyd, I.M., Almond, S., Qassim, S.M., Worrall, F., Davies, R.J., 2016. Fugitive emissions of methane from abandoned, decommissioned oil and gas wells. Science of The Total Environment 547, 461–469. https://doi.org/10.1016/j.scitotenv.2015.12.096

Boothroyd, I.M., Almond, S., Worrall, F., Davies, R.J., 2017. Assessing the fugitive emission of CH4 via migration along fault zones – Comparing potential shale gas basins to non-shale basins in the UK. Science of The Total Environment 580, 412–424. https://doi.org/10.1016/j.scitotenv.2016.09.052

Boucher, P., 2012. The role of controversy, regulation and engineering in UK biofuel development. Energy Policy 42, 148–154. https://doi.org/10.1016/j.enpol.2011.11.058

Boussena, S., Locatelli, C., 2013. Energy institutional and organisational changes in EU and Russia: Revisiting gas relations. Energy Policy 55, 180–189. https://doi.org/10.1016/j.enpol.2012.11.052

Bouzarovski, S., Bradshaw, M., Wochnik, A., 2015. Making territory through infrastructure: The governance of natural gas transit in Europe. Geoforum 64, 217–228. https://doi.org/10.1016/j.geoforum.2015.06.022

BP, 2018. BP Statistical Review of World Energy, 67th ed. BP, London, UK.

Brack, D., 2017. Woody Biomass for Power and Heat: Impacts on the Global Climate (Research Paper). The Royal Institute of International Affairs, Chatham House, London, UK.

Bradford, P.A., 2013. How to close the US nuclear industry: Do nothing. Bulletin of the Atomic Scientists 69, 12–21. https://doi.org/10.1177/0096340213477996

Bradshaw, M., Solman, N., 2018. A New Approach to Assessing UK Gas Security (Briefing Paper). Warwick Business School and UKERC, Coventry, UK.

Bradshaw, M., Waite, C., 2017. Learning from Lancashire: Exploring the contours of the shale gas conflict in England. Global Environmental Change 47, 28–36. https://doi.org/10.1016/j.gloenvcha.2017.08.005

Brand, C., 2016. Beyond 'Dieselgate': Implications of unaccounted and future air pollutant emissions and energy use for cars in the United Kingdom. Energy Policy 97, 1–12. https://doi.org/10.1016/j.enpol.2016.06.036

Brand, C., Anable, J., Tran, M., 2013. Accelerating the transformation to a low carbon passenger transport system: The role of car purchase taxes, feebates, road taxes and scrappage incentives in the UK. Transportation Research Part A: Policy and Practice 49, 132–148. https://doi.org/10.1016/j.tra.2013.01.010

Brand, C., Goodman, A., Ogilvie, D., 2014. Evaluating the impacts of new walking and cycling infrastructure on carbon dioxide emissions from motorized travel: A controlled longitudinal study. App. En 128, 284–295. https://doi.org/10.1016/j.apenergy.2014.04.072

BRE, University of Edinburgh, Centre for, Centre for Sustainable Energy, 2013. Research into barriers to deployment of district heating networks (No. URN 13D/073). Department of Energy and Climate Change, London, UK.

Brecha, R.J., 2012. Logistic curves, extraction costs and effective peak oil. Energy Policy, Renewable Energy in China 51, 586–597. https://doi.org/10.1016/j.enpol.2012.09.016

Breukers, S., Wolsink, M., 2007. Wind power implementation in changing institutional landscapes: An international comparison. Energy Policy 35, 2737–2750. https://doi.org/10.1016/j.enpol.2006.12.004

Bridge, G., Bradshaw, M., 2017. Making a Global Gas Market: Territoriality and Production Networks in Liquefied Natural Gas. Economic Geography 93, 215–240. https://doi.org/10.1080/00130095.2017.1283212

Bright, S., Weatherall, D., Willis, R., 2018. Exploring the complexities of energy retrofit in mixed tenure social housing: a case study from England, UK. Energy Efficiency 1–18. https://doi.org/10.1007/s12053-018-9676-y

British Geological Survey, 2014. The unconventional hydrocarbon resources of britain's onshore basins – shale gas. Department of Energy and Climate Change, London, UK.
Broadribb, M.P., 2015. What have we really learned? Twenty five years after Piper Alpha. Proc. Safety Prog. 34, 16–23. https://doi.org/10.1002/prs.11691
Bromley, C., Goldstein, B., Hiriart, G., Bertani, R., Huenges, E., Muraoka, H., Ragnarsson, A., Tester, J., Zui, V., 2010. Contribution of Geothermal Energy to Climate Change Mitigation: the IPCC Renewable Energy Report. World Geothermal Congress, 25-29 April, International Geothermal Association, Bali, Indonesia, pp. 1–5.
Brook Lyndhurst, 2012. Domestic energy use study: to understand why comparable households use different amounts of energy (No. 12D/424). Department of Energy and Climate Change, London, UK.
Brown, K.A., Maunder, D.H., 1994. Using landfill gas: A UK perspective. Renewable Energy, Climate change Energy and the environment 5, 774–781. https://doi.org/10.1016/0960-1481(94)90086-8
Brown, M.A., Wang, Y., Sovacool, B.K., D'Agostino, A.L., 2014. Forty years of energy security trends: A comparative assessment of 22 industrialized countries. Energy Research & Social Science 4, 64–77. https://doi.org/10.1016/j.erss.2014.08.008
Bryden, I.G., 2006. The marine energy resource, constraints and opportunities. Proc. Inst. Civil Engineers - Maritime Engineering 159, 55–65. https://doi.org/10.1680/maen.2006.159.2.55
Buchanan, K., Banks, N., Preston, I., Russo, R., 2016. The British public's perception of the UK smart metering initiative: Threats and opportunities. Energy Policy 91, 87–97. https://doi.org/10.1016/j.enpol.2016.01.003
Buchanan, K., Russo, R., Anderson, B., 2015. The question of energy reduction: The problem(s) with feedback. Energy Policy 77, 89–96. https://doi.org/10.1016/j.enpol.2014.12.008
Buckley, T., 2015. Galilee Coal Basin: Carmichael – A Stranded Asset? Institute of Energy Economics and Financial Analysi, Cleveland OH, USA.
Buker, M.S., Mempouo, B., Riffat, S.B., 2014. Performance evaluation and techno-economic analysis of a novel building integrated PV/T roof collector: An experimental validation. Energy and Buildings 76, 164–175. https://doi.org/10.1016/j.enbuild.2014.02.078
Bull, R., Petts, J., Evans, J., 2010. The importance of context for effective public engagement: learning from the governance of waste. Journal of Environmental Planning and Management 53, 991–1009. https://doi.org/10.1080/09640568.2010.495503
Bunn, D., Yusupov, T., 2015. The progressive inefficiency of replacing renewable obligation certificates with contracts-for-differences in the UK electricity market. Energy Policy 82, 298–309. https://doi.org/10.1016/j.enpol.2015.01.002
Burgherr, P., 2007. In-depth analysis of accidental oil spills from tankers in the context of global spill trends from all sources. Journal of Hazardous Materials 140, 245–256. https://doi.org/10.1016/j.jhazmat.2006.07.030
Burgherr, P., Hirschberg, S., 2014. Comparative risk assessment of severe accidents in the energy sector. Energy Policy, Nuclear Energy and Sustainable Development: Selected Topics 74, Supplement 1, S45–S56. https://doi.org/10.1016/j.enpol.2014.01.035
Burkholz, R., Garas, A., Schweitzer, F., 2016. How damage diversification can reduce systemic risk. Phys. Rev. E 93, 042313. https://doi.org/10.1103/PhysRevE.93.042313
Burnett, D., Barbour, E., Harrison, G.P., 2014. The UK solar energy resource and the impact of climate change. Renewable En. 71, 333–343. https://doi.org/10.1016/j.renene.2014.05.034
Burns, M., Reid, C., Bremen, J., 2016. UK shale gas – a policy tug of war. Journal of Energy & Natural Resources Law 34, 247–260. https://doi.org/10.1080/02646811.2016.1131521
Burrows, R., Yates, N.C., Hedges, T.S., Li, M., Zhou, J.G., Chen, D.Y., Walkington, I.A., Wolf, J., Holt, J., Proctor, R., 2009. Tidal energy potential in UK waters. Proc. Inst. Civil Engineers - Maritime Engineering 162, 155–164. https://doi.org/10.1680/maen.2009.162.4.155

Burruss, R.C., Ryder, R.T., 2014. Composition of Natural Gas and Crude Oil Produced From 14 Wells in the Lower Silurian “Clinton” Sandstone and Medina Group Sandstones, Northeastern Ohio and Northwestern Pennsylvania, in: Ruppert, L.F., Ryder, R.T. (Eds.), Coal and Petroleum Resources in the Appalachian Basin: Distribution, Geologic Framework, and Geochemical Character, Chapter G.6, Professional Paper 1708. U.S. Geological Survey, Reston, Virginia, USA.
Burt, G., 2011. Towards the integration of system modelling with scenario planning to support strategy: the case of the UK energy industry. Journal of the Operational Research Society 62, 830–839. https://doi.org/10.1057/jors.2010.47
Burzynski, R., Crane, M., Yao, R., Becerra, V.M., 2012. Space heating and hot water demand analysis of dwellings connected to district heating scheme in UK. Journal of Central South University 19, 1629–1638. https://doi.org/10.1007/s11771-012-1186-z
Busby, J., 2014. Geothermal energy in sedimentary basins in the UK. Hydrogeol J 22, 129–141. https://doi.org/10.1007/s10040-013-1054-4
Busby, J., 2015. UK shallow ground temperatures for ground coupled heat exchangers. Quarterly J of Eng Geology and Hydrogeology 48, 248–260. https://doi.org/10.1144/qjegh2015-077
Busby, J., Gillespie, M., Kender, S., 2015. How hot are the Cairngorms? Scottish Journal of Geology 51, 105–115. https://doi.org/10.1144/sjg2014-027
Busby, J., Kingdon, A., Williams, J., 2011. The measured shallow temperature field in Britain. Qy J Eng Geology and Hydrogeology 44, 373–387. https://doi.org/10.1144/1470-9236/10-049
Busby, J., Terrington, R., 2017. Assessment of the resource base for engineered geothermal systems in Great Britain. Geothermal Energy 5, 7. https://doi.org/10.1186/s40517-017-0066-z
Bush, R.E., Bale, C.S.E., Powell, M., Gouldson, A., Taylor, P.G., Gale, W.F., 2017. The role of intermediaries in low carbon transitions – Empowering innovations to unlock district heating in the UK. J Cleaner Production 148, 137–147. https://doi.org/10.1016/j.jclepro.2017.01.129
Busic-Sontic, A., Czap, N.V., Fuerst, F., 2017. The role of personality traits in green decision-making. J Economic Psychology 62, 313–328. https://doi.org/10.1016/j.joep.2017.06.012
Butcher, J.G., 2013. The International Court of Justice and the Territorial Dispute between Indonesia and Malaysia in the Sulawesi Sea. Contemporary Southeast Asia: A Journal of International & Strategic Affairs 35, 235–257. https://doi.org/10.1355/cs35-2e
Butler, C., Parkhill, K.A., Pidgeon, N.F., 2016. Energy consumption and everyday life: Choice, values and agency through a practice theoretical lens. Journal of Consumer Culture 16, 887–907. https://doi.org/10.1177/1469540514553691
BVG Associates, 2015. Wave and Tidal Supply Chain Development Plan: Supply chain capability and enabling action recommendations. RenewableUK and Scottish Renewables., Fife, UK.
BVG Associates, 2016. Strategic review of UK east coast staging and construction facilities. Offshore Wind Industry Council, London, UK.
Cabalu, H., 2010. Indicators of security of natural gas supply in Asia. Energy Policy 38, 218–225. https://doi.org/10.1016/j.enpol.2009.09.008
Cabinet Office, 2017. National Risk Register of Civil Emergencies. Cabinet Office, London, UK.
Cain, N.L., Nelson, H.T., 2013. What drives opposition to high-voltage transmission lines? Land Use Policy 33, 204–213. https://doi.org/10.1016/j.landusepol.2013.01.003
Caird, S., Roy, R., Herring, H., 2008. Improving the energy performance of UK households: Results from surveys of consumer adoption and use of low- and zero-carbon technologies. Energy Efficiency 1, 149. https://doi.org/10.1007/s12053-008-9013-y
Caird, S., Roy, R., Potter, S., 2012. Domestic heat pumps in the UK: user behaviour, satisfaction and performance. Energy Eff. 5, 283–301. https://doi.org/10.1007/s12053-012-9146-x
Cairney, P., McHarg, A., McEwen, N., Turner, K., 2019. How to conceptualise energy law and policy for an interdisciplinary audience: The case of post-Brexit UK. Energy Policy 129, 459–466. https://doi.org/10.1016/j.enpol.2019.02.022
Candelise, C., Gross, R., Leach, M.A., 2010. Conditions for photovoltaics deployment in the UK: The role of policy and technical developments. Proc Inst Mechanical Engineers, Part A: Journal of Power and Energy 224, 153–166. https://doi.org/10.1243/09576509JPE768

Candelise, C., Speirs, J.F., Gross, R.J.K., 2011. Materials availability for thin film (TF) PV technologies development: A real concern? Renewable and Sustainable Energy Reviews 15, 4972–4981. https://doi.org/10.1016/j.rser.2011.06.012

Cárdenas-Fernández, M., Bawn, M., Hamley-Bennett, C., Bharat, P.K.V., Subrizi, F., Suhaili, N., Ward, D.P., Bourdin, S., Dalby, P.A., Hailes, H.C., Hewitson, P., Ignatova, S., Kontoravdi, C., Leak, D.J., Shah, N., Sheppard, T.D., Ward, J.M., Lye, G.J., 2017. An integrated biorefinery concept for conversion of sugar beet pulp into value-added chemicals and pharmaceutical intermediates. Faraday Discussions 202, 415–431. https://doi.org/10.1039/C7FD00094D

Carless, D., Whitehead, P.G., 2013. The potential impacts of climate change on hydropower generation in Mid Wales. Hydrology Res 44, 495–505. https://doi.org/10.2166/nh.2012.012

Carrere, H., Antonopoulou, G., Affes, R., Passos, F., Battimelli, A., Lyberatos, G., Ferrer, I., 2016. Review of feedstock pretreatment strategies for improved anaerobic digestion: From lab-scale research to full-scale application. Bioresource Technology 199, 386–397. https://doi.org/10.1016/j.biortech.2015.09.007

Carruth, A., Dickerson, A., Henley, A., 2000. What do We Know About Investment Under Uncertainty? J Economic Surveys 14, 119–154. https://doi.org/10.1111/1467-6419.00107

CCC, 2013. Reducing the UK's carbon footprint. Committee on Climate Change, London, UK.

CCC, 2015a. Sectoral scenarios for the Fifth Carbon Budget (Technical Report). Committee on Climate Change, London, UK.

CCC, 2015b. Reducing emissions and preparing for climate change: 2015 Progress Report to Parliament. Committee on Climate Change, London, UK.

CCC, 2016. Next steps for UK heat policy. Committee on Climate Change, London, UK.

CCC, 2017. Meeting Carbon Budgets - 2017. Progress Report to Parliament. Committee on Climate Change, London, UK.

CCSCRTF, 2013. CCS Cost Reduction Taskforce: Final Report. CCS Cost Reduction Task Force, London, UK.

Challis, C., Tierney, M., Todd, A., Wilson, E., 2017. Human factors in dairy industry process control for energy reduction. Journal of Cleaner Production 168, 1319–1334. https://doi.org/10.1016/j.jclepro.2017.09.121

Chang, S.E., McDaniels, T., Fox, J., Dhariwal, R., Longstaff, H., 2014. Toward Disaster-Resilient Cities: Characterizing Resilience of Infrastructure Systems with Expert Judgments. Risk Analysis 34, 416–434. https://doi.org/10.1111/risa.12133

Chapman, B., 2017. Skills shortage for UK services firms at worst in almost two decades, 29 August. The Independent. URL http://www.independent.co.uk/news/business/news/skills-shortage-among-uk-services-firms-at-its-worst-in-almost-two-decades-finds-survey-a7913001.html (accessed 25/7/18).

Chatham House, 2016. Guidelines for Good Governance in Emerging Oil and Gas Producers. The Royal Institute of International Affairs, Chatham House, London, UK.

Chaudry, M., Abeysekera, M., Hosseini, S.H.R., Jenkins, N., Wu, J., 2015. Uncertainties in decarbonising heat in the UK. Energy Policy 87, 623–640. https://doi.org/10.1016/j.enpol.2015.07.019

Checchi, A., Behrens, A., Egenhofer, C., 2009. Long-Term Energy Security Risks for Europe: A Sector-Specific Approach (Working Document No. 309). Centre for European Policy Studies, Brussels, Belgium.

Chee Tahir, A., Darton, R.C., 2010. The Process Analysis Method of selecting indicators to quantify the sustainability performance of a business operation. Journal of Cleaner Production 18, 1598–1607. https://doi.org/10.1016/j.jclepro.2010.07.012

Chen, C., Iyengar, G., Moallemi, C.C., 2013. An Axiomatic Approach to Systemic Risk. Management Science 59, 1373–1388. https://doi.org/10.1287/mnsc.1120.1631

Cherp, A., Adenikinju, A., Goldthau, A., Hernandez, F., Hughes, L., Jansen, J.C., Jewell, J., Olshanskaya, M., de Oliveira, R., Sovacool, B.K., Vakulenko, S., Fisk, D.J., Pal, S., 2012. Chapter 5 - Energy and Security, in: Global Energy Assessment - Toward a Sustainable Future. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 325–384.

Cherrington, R., Goodship, V., Longfield, A., Kirwan, K., 2013. The feed-in tariff in the UK: A case study focus on domestic photovoltaic systems. Renewable Energy 50, 421–426. https://doi.org/10.1016/j.renene.2012.06.055

Chilvers, J., Foxon, T.J., Galloway, S., Hammond, G.P., Infield, D., Leach, M., Pearson, P.J., Strachan, N., Strbac, G., Thomson, M., 2017. Realising transition pathways for a more electric, low-carbon energy system in the United Kingdom: Challenges, insights and opportunities. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 231, 440–477. https://doi.org/10.1177/0957650917695448

Chitnis, M., Sorrell, S., 2015. Living up to expectations: Estimating direct and indirect rebound effects for UK households. Energy Economics 52, S100–S116. https://doi.org/10.1016/j.eneco.2015.08.026

Chitnis, M., Sorrell, S., Druckman, A., Firth, S.K., Jackson, T., 2013. Turning lights into flights: Estimating direct and indirect rebound effects for UK households. Energy Policy 55, 234–250. https://doi.org/10.1016/j.enpol.2012.12.008

Christopherson, S., Rightor, N., 2012. How shale gas extraction affects drilling localities: Lessons for regional and city policy makers. Journal of Town and City Management 2, 1–20.

Christophorou, L.G., Olthoff, J.K., Brunt, R.J.V., 1997. Sulfur hexafluoride and the electric power industry. IEEE Electrical Insulation Magazine 13, 20–24. https://doi.org/10.1109/57.620514

Clancy, S.A., Worrall, F., Davies, R.J., Gluyas, J.G., 2018. The potential for spills and leaks of contaminated liquids from shale gas developments. Science of The Total Environment 626, 1463–1473. https://doi.org/10.1016/j.scitotenv.2018.01.177

Clark, A.J., Roddy, D.J., 2012. Community-level renewable energy planning in sensitive areas. Proceedings of the Institution of Civil Engineers - Energy 165, 33–42. https://doi.org/10.1680/ener.2012.165.1.33

Clarke, H., Eisner, L., Styles, P., Turner, P., 2014. Felt seismicity associated with shale gas hydraulic fracturing: The first documented example in Europe: Hydraulic fracturing, induced seismicity. Geophysical Research Letters 41, 8308–8314. https://doi.org/10.1002/2014GL062047

CMA, 2016. Energy market investigation: Final report. Competition and Markets Authority, London, UK.

CMA, 2017. Rough gas storage undertakings review: Final decision. Competition and Markets Authority, London, UK.

Cogent, 2010a. Power People: The Civil Nuclear Workforce 2009-2025, Renaissance Nuclear Skills series: 1. The National Skills Academy for Nuclear, Warrington, UK.

Cogent, 2010b. Next Generation: Skills for New Build Nuclear, Renaissance Nuclear Skills series: 2. The National Skills Academy for Nuclear, Warrington, UK.

Cogent, 2010c. Illuminations: Future Skills fNuclear, Renaissance Nuclear Skills series: 4. The National Skills Academy for Nuclear, Warrington, UK.

Cohen, J., Moeltner, K., Reichl, J., Schmidthaler, M., 2016. An Empirical Analysis of Local Opposition to New Transmission Lines Across the EU-27. The Energy Journal 37. https://doi.org/10.5547/01956574.37.3.jcoh

Cohen, J.J., Reichl, J., Schmidthaler, M., 2014. Re-focussing research efforts on the public acceptance of energy infrastructure: A critical review. Energy 76, 4–9. https://doi.org/10.1016/j.energy.2013.12.056

Coker, P., Barlow, J., Cockerill, T., Shipworth, D., 2013. Measuring significant variability characteristics: An assessment of three UK renewables. Renewable Energy 53, 111–120. https://doi.org/10.1016/j.renene.2012.11.013

Colantuono, G., Everard, A., Hall, L.M.H., Buckley, A.R., 2014. Monitoring nationwide ensembles of PV generators: Limitations and uncertainties. The case of the UK. Solar Energy 108, 252–263. https://doi.org/10.1016/j.solener.2014.06.030

Coleman, M., Brown, N., Wright, A., Firth, S.K., 2012. Information, communication and entertainment appliance use—Insights from a UK household study. Energy and Buildings 54, 61–72. https://doi.org/10.1016/j.enbuild.2012.06.008

Connor, P.M., 2003. UK renewable energy policy: a review. Renewable and Sustainable Energy Reviews 7, 65–82. https://doi.org/10.1016/S1364-0321(02)00054-0

Connor, P.M., Axon, C.J., Xenias, D., Balta-Ozkan, N., 2018. Sources of risk and uncertainty in UK smart grid deployment: An expert stakeholder analysis. Energy 161, 1–9. https://doi.org/10.1016/j.energy.2018.07.115
Connor, P.M., Baker, P.E., Xenias, D., Balta-Ozkan, N., Axon, C.J., Cipcigan, L., 2014. Policy and regulation for smart grids in the United Kingdom. Renew. Sust. Energ. Rev. 40, 269–286. https://doi.org/10.1016/j.rser.2014.07.065
Connor, P.M., Xie, L., Lowes, R., Britton, J., Richardson, T., 2015. The development of renewable heating policy in the United Kingdom. Renewable Energy 75, 733–744. https://doi.org/10.1016/j.renene.2014.10.056
Convertino, M., Annis, A., Nardi, F., 2019. Information-theoretic portfolio decision model for optimal flood management. Environmental Modelling & Software 119, 258–274. https://doi.org/10.1016/j.envsoft.2019.06.013
Convertino, M., Valverde, L.J., 2019. Toward a pluralistic conception of resilience. Ecological Indicators 107, 105510. https://doi.org/10.1016/j.ecolind.2019.105510
Cooper, J., Stamford, L., Azapagic, A., 2018. Economic viability of UK shale gas and potential impacts on the energy market up to 2030. Applied Energy 215, 577–590. https://doi.org/10.1016/j.apenergy.2018.02.051
Cooper, J., Stamford, L., Azapagic, A., 2016. Shale Gas: A Review of the Economic, Environmental, and Social Sustainability. Energy Technology 4, 772–792. https://doi.org/10.1002/ente.201500464
Cooper, J., Stamford, L., Azapagic, A., 2014. Environmental Impacts of Shale Gas in the UK: Current Situation and Future Scenarios. Energy Technology 2, 1012–1026. https://doi.org/10.1002/ente.201402097
Cooper, S.J.G., Hammond, G.P., Norman, J.B., 2016. Potential for use of heat rejected from industry in district heating networks, GB perspective. Journal of the Energy Institute 89, 57–69. https://doi.org/10.1016/j.joei.2015.01.010
Cordell, R.L., Mazet, M., Dechoux, C., Hama, S.M.L., Staelens, J., Hofman, J., Stroobants, C., Roekens, E., Kos, G.P.A., Weijers, E.P., Frumau, K.F.A., Panteliadis, P., Delaunay, T., Wyche, K.P., Monks, P.S., 2016. Evaluation of biomass burning across North West Europe and its impact on air quality. Atm Env 141, 276–286. https://doi.org/10.1016/j.atmosenv.2016.06.065
Corner, A., Venables, D., Spence, A., Poortinga, W., Demski, C., Pidgeon, N., 2011. Nuclear power, climate change and energy security: Exploring British public attitudes. Energy Policy 39, 4823–4833. https://doi.org/10.1016/j.enpol.2011.06.037
Cornwall and Isles of Scilly Growth Programme, 2016. European funding secures geothermal energy for Penzance’s Jubilee Pool. URL http://www.cornwallislesofscillygrowthprogramme.org.uk/european-funding-secures-geothermal-energy-penzances-jubilee-pool/ (accessed 22/4/18).
Corsatea, T.D., 2014. Increasing synergies between institutions and technology developers: Lessons from marine energy. Energy Policy 74, 682–696. https://doi.org/10.1016/j.enpol.2014.07.006
Costa-Campi, M.T., Duch-Brown, N., García-Quevedo, J., 2014. R&D drivers and obstacles to innovation in the energy industry. Energy Economics 46, 20–30. https://doi.org/10.1016/j.eneco.2014.09.003
Cotton, D., Miller, W., Winter, J., Bailey, I., Sterling, S., 2016. Knowledge, agency and collective action as barriers to energy-saving behaviour. Local Environment 21, 883–897. https://doi.org/10.1080/13549839.2015.1038986
Cotton, M., 2015. Stakeholder perspectives on shale gas fracking: a Q-method study of environmental discourses. Environment and Planning A 47, 1944–1962. https://doi.org/10.1177/0308518X15597134
Cotton, M., Rattle, I., Van Alstine, J., 2014. Shale gas policy in the United Kingdom: An argumentative discourse analysis. Energy Policy 73, 427–438. https://doi.org/10.1016/j.enpol.2014.05.031
Court, R., 2017. The role for alternative, low carbon gases for heating. Energy World, April 14–16.
Cox, E., 2016. Opening the black box of energy security: A study of conceptions of electricity security in the United Kingdom. Energy Research & Social Science 21, 1–11. https://doi.org/10.1016/j.erss.2016.06.020

Cox, E., 2018. Assessing long-term energy security: The case of electricity in the United Kingdom. Renewable and Sustainable Energy Reviews 82, 2287–2299. https://doi.org/10.1016/j.rser.2017.08.084

Cox, L.A., 2008. What's Wrong with Risk Matrices? Risk Analysis 28, 497–512. https://doi.org/10.1111/j.1539-6924.2008.01030.x

Craig, M.P.A., 2020. 'Treasury Control' and the British Environmental State: The Political Economy of Green Development Strategy in UK Central Government. New Political Economy 25, 30–45. https://doi.org/10.1080/13563467.2018.1526269

Creedy, D., Tilley, H., 2003. Coalbed methane extraction and utilization. Proc. Instn Mech. Engrs: Part A: J. Power and Energy 217, 19–25.

Creti, A., Fabra, N., 2007. Supply security and short-run capacity markets for electricity. Energy Economics 29, 259–276. https://doi.org/10.1016/j.eneco.2006.04.007

Criscuolo, C., Menon, C., 2015. Environmental policies and risk finance in the green sector: Cross-country evidence. Energy Policy 83, 38–56. https://doi.org/10.1016/j.enpol.2015.03.023

Crompton, D., 2002. Cardiff Bay Barrage. Proceedings of the Institution of Civil Engineers: Water & Maritime Engineering 154, 81–88.

Cross, J., 2017. ISO 31010 Risk assessment techniques and open systems, in: Tokoro, M., Bloomfield, R., Kinoshita, Y. (Eds.), Sixth Workshop on Open Systems Dependability. Association of Dependability Engineering for Open Systems, Tokyo, Japan, pp. 15–18.

Cruz, A.M., Krausmann, E., 2013. Vulnerability of the oil and gas sector to climate change and extreme weather events. Climatic Ch 121, 41–53. https://doi.org/10.1007/s10584-013-0891-4

Csereklyei, Z., Stern, D.I., 2015. Global energy use: Decoupling or convergence? Energy Economics 51, 633–641. https://doi.org/10.1016/j.eneco.2015.08.029

Curtin, J., McInerney, C., Johannsdottir, L., 2018. How can financial incentives promote local ownership of onshore wind and solar projects? Case study evidence from Germany, Denmark, the UK and Ontario. Local Economy: The Journal of the Local Economy Policy Unit 33, 40–62. https://doi.org/10.1177/0269094217751868

Dagonneau, J., Rocks, S.A., Prpich, G., Garnett, K., Black, E., Pollard, S.J.T., 2017. Strategic risk appraisal. Comparing expert- and literature-informed consequence assessments for environmental policy risks receiving national attention. Science of The Total Environment 595, 537–546. https://doi.org/10.1016/j.scitotenv.2017.03.293

Dalal-Clayton, B., Sadler, B., 2014. Sustainability Appraisal: A Sourcebook and Reference Guide to International Experience. Routledge, Abingdon, UK.

Dannreuther, R., 2015. Energy security and shifting modes of governance. Int Polit 52, 466–483. https://doi.org/10.1057/ip.2015.4

Daraktchieva, Z., Wasikiewicz, J.M., Howarth, C.B., Bradley, E.J., 2017. Radon baseline monitoring around a potential shale gas development site in Yorkshire, England. Radiation Protection Dosimetry 177, 140–143. https://doi.org/10.1093/rpd/ncx134

Darby, S.J., 2018. Smart technology in the home: time for more clarity. Building Research & Information 46, 140–147. https://doi.org/10.1080/09613218.2017.1301707

Darby, S.J., Pisica, I., 2013. Focus on electricity tariffs: experience and exploration of different charging schemes. ECEEE Summer Study, June 3-7, Hyères, France, pp. 2321–2331.

Darton, R.C., 2017. Metrics-Based Measurement: The Process Analysis Method, in: Abraham, M.A. (Ed.), Encyclopedia of Sustainable Technologies. Elsevier, pp. 51–61. https://doi.org/10.1016/B978-0-12-409548-9.10047-8

Dato, P., 2018. Investment in Energy Efficiency, Adoption of Renewable Energy and Household Behavior: Evidence from OECD Countries. The Energy Journal 39. https://doi.org/10.5547/01956574.39.3.pdat

Davidsson, S., Höök, M., 2017. Material requirements and availability for multi-terawatt deployment of photovoltaics. Energy Policy 108, 574–582. https://doi.org/10.1016/j.enpol.2017.06.028

Davies, R.J., Almond, S., Ward, R.S., Jackson, R.B., Adams, C., Worrall, F., Herringshaw, L.G., Gluyas, J.G., Whitehead, M.A., 2014. Oil and gas wells and their integrity: Implications for shale and unconventional resource exploitation. Marine and Petroleum Geology 56, 239–254. https://doi.org/10.1016/j.marpetgeo.2014.03.001

DBIS, 2013. A Review of the Civil Nuclear R&D Landscape in the UK (No. BIS/13/631). Department for Business, Innovation and Skills, London, UK.
DCLG, 2017. Housing supply: net additional dwellings, England: 2016 to 2017. Department for Communities and Local Government, London, UK.
de Amorim, W.S., Valduga, I.B., Ribeiro, J.M.P., Williamson, V.G., Krauser, G.E., Magtoto, M.K., de Andrade Guerra, J.B.S.O., 2018. The nexus between water, energy, and food in the context of the global risks: An analysis of the interactions between food, water, and energy security. Environmental Impact Assessment Review 72, 1–11. https://doi.org/10.1016/j.eiar.2018.05.002
De Dominicis, M., O'Hara Murray, R., Wolf, J., 2017. Multi-scale ocean response to a large tidal stream turbine array. Renewable Energy 114, 1160–1179. https://doi.org/10.1016/j.renene.2017.07.058
de Groot, J., Bailey, I., 2016. What drives attitudes towards marine renewable energy development in island communities in the UK? International Journal of Marine Energy 13, 80–95. https://doi.org/10.1016/j.ijome.2016.01.007
de Joode, J., Kingma, D., Lijesen, M., Mulder, M., Shestalova, V., 2004. Energy Policies and Risks on Energy Markets: A cost-benefit analysis. Netherlands Bureau for Economic Policy Analysis, The Hague, Netherlands.
De Laurentis, C., Eames, M., Hunt, M., 2017. Retrofitting the built environment 'to save' energy: Arbed, the emergence of a distinctive sustainability transition pathway in Wales. Env and Planning C: Politics and Space 35, 1156–1175. https://doi.org/10.1177/0263774X16648332
DECC, 2010a. 2050 Pathway Analysis. Department of Energy and Climate Change, London, UK.
DECC, 2010b. Severn Tidal Power: Feasibility Study Conclusions and Summary Report. Department of Energy and Climate Change, London, UK.
DECC, 2010c. Consultation on an updated Waste Transfer Pricing Methodology for the disposal of higher activity waste from new nuclear power stations (URN: 10D/994). Department of Energy and Climate Change, London, UK.
DECC, 2012. Energy security strategy (URN: 12D/349). Department of Energy and Climate Change, London, UK.
DECC, 2013a. UK Solar PV Strategy Part 1: Roadmap to a Brighter Future (URN 13D/251). Department of Energy and Climate Change, London, UK.
DECC, 2013b. The Future of Heating::Meeting the challenge (URN: 13D/033). Department of Energy and Climate Change, London, UK.
DECC, 2013c. The Future of Heating:Meeting the challenge (Evidence Annex). Department of Energy and Climate Change, London, UK.
DECC, 2014. Community Energy Strategy: Full Report (URN 14D/019). Department of Energy and Climate Change, London, UK.
DECC, 2015a. Community Energy Strategy Update (URN 15D/133). Department of Energy and Climate Change, London, UK.
DECC, 2015b. Changes to onshore wind subsidies protect investment and get the best deal for bill payers. URL https://www.gov.uk/government/news/changes-to-onshore-wind-subsidies-protect-investment-and-get-the-best-deal-for-bill-payers (accessed 5/1/7).
DECC, 2015c. Sustaining Our Nuclear Skills (URN 15 D/ 106). Department of Energy and Climate Change, London, UK.
Decourt, B., Alias, S., Debarre, R., 2015. Gas Hydrates: Taking the heat out of the burning-ice debate. Potential and Future of Gas Hydrates., Natural Gas Factbook. SBC Energy Institute, Gravenhage, Netherlands.
DEFRA, 2013. Incineration of Municipal Solid Waste (URN: PB13889). Department for Environment, Food, and Rural Affairs, London, UK.
DEFRA, 2018. UK Statistics on Waste. Department for Environment, Food, and Rural Affairs, York, UK.
DEFRA, DECC, 2014. Energy from waste: a guide to the debate (URN: PB14130). Department for Environment, Food, and Rural Affairs, London, UK.
de-Llano Paz, F., Antelo, S.I., Calvo Silvosa, A., Soares, I., 2014. The technological and environmental efficiency of the EU-27 power mix: An evaluation based on MPT. Energy 69, 67–81. https://doi.org/10.1016/j.energy.2014.02.036

Deloitte, 2013. Oil and gas taxation in the UK, London, UK.
Delta Energy & Environment, 2012. 2050 Pathways for Domestic Heat. Energy Networks Association, Edinburgh, UK.
Demski, C., Spence, A., Pidgeon, N., 2017. Effects of exemplar scenarios on public preferences for energy futures using the my2050 scenario-building tool. Nature Energy 2, 17027. https://doi.org/10.1038/nenergy.2017.27
Devine-Wright, P., 2011. Enhancing local distinctiveness fosters public acceptance of tidal energy: A UK case study. Energy Policy 39, 83–93. https://doi.org/10.1016/j.enpol.2010.09.012
DfT, 2018. Analyses from the National Travel Survey. Department for Transport, London, UK.
DfT, 2017. Transport Statistics for Great Britain. Department for Transport, London, UK.
Distefano, T., Riccaboni, M., Marin, G., 2018. Systemic risk in the global water input-output network. Water Resources and Econ. 23, 28–52. https://doi.org/10.1016/j.wre.2018.01.004
Divya, D., Gopinath, L.R., Merlin Christy, P., 2015. A review on current aspects and diverse prospects for enhancing biogas production in sustainable means. Renewable and Sustainable Energy Reviews 42, 690–699. https://doi.org/10.1016/j.rser.2014.10.055
DNV GL, 2016. Study on UK Offshore Wind Variability (No. L2C124303-UKBR-R-01 Issue B). The Crown Estate, London, UK.
Dockerty, Tim, Lovett, A., Dockerty, Trudie, Papathanasopoulou, E., Beaumont, N., Wang, S., Smith, P., 2014. Interactions between the Energy System, Ecosystem Services and Natural Capital (Working Paper No. UKERC/WP/FG/2014/010). UK Energy Research Centre, London, UK.
Dodds, P.E., McDowall, W., 2013. The future of the UK gas network. Energy Policy 60, 305–316. https://doi.org/10.1016/j.enpol.2013.05.030
Dolman, S., Simmonds, M., 2010. Towards best environmental practice for cetacean conservation in developing Scotland's marine renewable energy. Marine Policy 34, 1021–1027. https://doi.org/10.1016/j.marpol.2010.02.009
Dommett, L., 2009. Assessing biomass availability in the UK. Biofuels, Bioproducts and Biorefining 3, 496–499.
Douglas, H., 2011. Gulf of Mexico Oil Spill: Likely Impact on UK Regulation and Contractual Arrangements. Energy and Environment 22, 241–246. https://doi.org/10.1260/0958-305X.22.3.241
Downing, R.A., Gray, D.A., 1986. Geothermal resources of the United Kingdom. Journal of the Geological Society 143, 499–507. https://doi.org/10.1144/gsjgs.143.3.0499
Dowson, M., Poole, A., Harrison, D., Susman, G., 2012. Domestic UK retrofit challenge: Barriers, incentives and current performance leading into the Green Deal. Energy Policy, Special Section: Past and Prospective Energy Transitions - Insights from History 50, 294–305. https://doi.org/10.1016/j.enpol.2012.07.019
Drewer, J., Yamulki, S., Leeson, S.R., Anderson, M., Perks, M.P., Skiba, U.M., McNamara, N.P., 2017. Difference in Soil Methane (CH<Subscript>4</Subscript>) and Nitrous Oxide (N<Subscript>2</Subscript>O) Fluxes from Bioenergy Crops SRC Willow and SRF Scots Pine Compared with Adjacent Arable and Fallow in a Temperate Climate. Bioenerg. Res. 10, 575–582. https://doi.org/10.1007/s12155-017-9824-9
Du, Y., Parsons, J.E., 2009. Update on the cost of nuclear power (No. 09–004). Center for Energy and Environmental Policy Research, MIT, Cambridge, USA.
Duch-Brown, N., Costa-Campi, M.T., 2015. The diffusion of patented oil and gas technology with environmental uses: A forward patent citation analysis. Energy Policy 83, 267–276. https://doi.org/10.1016/j.enpol.2015.03.001
Duijm, N.J., 2015. Recommendations on the use and design of risk matrices. Safety Science 76, 21–31. https://doi.org/10.1016/j.ssci.2015.02.014
Dyer, C.H., Hammond, G.P., Jones, C.I., McKenna, R.C., 2008. Enabling technologies for industrial energy demand management. Energy Policy, Foresight Sustainable Energy Management and the Built Environment Project 36, 4434–4443. https://doi.org/10.1016/j.enpol.2008.09.028

EDF, 2016. Events reported to ONR by EDF Energy (01 Apr 2012 to 19 Jan 2016). URL https://www.edfenergy.com/sites/default/files/onr_extract_for_comms_150202_apr12_jan16v3.pdf (accessed 12/6/16).
Edwards, J., Othman, M., Burn, S., 2015. A review of policy drivers and barriers for the use of anaerobic digestion in Europe, the United States and Australia. Renewable and Sustainable Energy Reviews 52, 815–828. https://doi.org/10.1016/j.rser.2015.07.112
Eiholzer, T., Olsen, D., Hoffmann, S., Sturm, B., Wellig, B., 2017. Integration of a solar thermal system in a medium-sized brewery using pinch analysis: Methodology and case study. App. Thermal Eng. 113, 1558–1568. https://doi.org/10.1016/j.applthermaleng.2016.09.124
Eke, S.J., 2014. No pay, no peace: political settlement and post-amnesty violence in the Niger Delta, Nigeria. Journal of Asian and African Studies 50, 750–764. https://doi.org/10.1177/0021909614541085
Ekins, P., Anandarajah, G., Strachan, N., 2011. Towards a low-carbon economy: scenarios and policies for the UK. Climate Policy 11, 865–882. https://doi.org/10.3763/cpol.2010.0126
Ekins, P., Keppo, I., Skea, J., Strachan, N., Usher, W., Anandarajah, G., 2013. The UK energy system in 2050: comparing low-carbon, resilient scenarios. UKERC, London, UK.
Ekins, P., Vanner, R., Firebrace, J., 2006. Decommissioning of offshore oil and gas facilities: A comparative assessment of different scenarios. Journal of Environmental Management 79, 420–438. https://doi.org/10.1016/j.jenvman.2005.08.023
Elahidoost, A., Tedeschi, E., 2017. Expansion of offshore HVDC grids: An overview of contributions, status, challenges and perspectives, in: RTUCON. 58th International Scientific Conference on Power and Electrical Engineering, IEEE, 12-13 October, Riga, Latvia. https://doi.org/10.1109/RTUCON.2017.8124767
El-Katiri, L., Fattouh, B., Mallinson, R., 2014. The Arab Uprisings and MENA Political Instability: Implications for Oil & Gas Markets (No. MEP 8), OIES Paper. Oxford Institute for Energy Studies, Oxford, UK.
Elliott, B., Bull, R., Mallaburn, P., 2015. A new lease of life? Investigating UK property investor attitudes to low carbon investment decisions in commercial buildings. Energy Efficiency 8, 667–680. https://doi.org/10.1007/s12053-014-9314-2
Elliott, D., 2003. Energy, Society and Environment, 2nd ed. Routledge, London, UK.
Elliott, D., 2009. Marine renewables: a new innovation frontier. Technology Analysis & Strategic Management 21, 267–275. https://doi.org/10.1080/09537320802625348
Ellsworth-Krebs, K., Reid, L., 2016. Conceptualising energy prosumption: Exploring energy production, consumption and microgeneration in Scotland, UK. Environment and Planning A: Economy and Space 48, 1988–2005. https://doi.org/10.1177/0308518X16649182
Energy Institute, Deloitte, Norman Broadbent, 2008. Skills needs in the energy industry. Energy Institute, London, UK.
Engineering UK, 2018. Engineering UK 2018: Synopsis and recommendations. Engineering UK, London, UK.
Engle, R.F., Ruan, T., 2019. Measuring the probability of a financial crisis. Proc. Natl. Acad. Sci. USA. 116, 18341–18346. https://doi.org/10.1073/pnas.1903879116
EPRI, 2003. A Survey of Water Use and Sustainability in the United States With a Focus on Power Generation (Technical Report No. 1005474). Electric Power Research Institute, Palo Alto, California, USA.
Erickson, W.P., Johnson, G.D., Young Jr, D.P., 2005. A summary and comparison of bird mortality from anthropogenic causes with an emphasis on collisions, in: Ralph, C.J., Rich, T.D. (Eds.), Bird Conservation Implementation and Integration in the Americas. Third International Partners in Flight Conference, March 20-24, 2002, U.S. Department of Agriculture, Asilomar, USA, pp. 1029–1042.
Ermolieva, T., Havlík, P., Ermoliev, Y., Mosnier, A., Obersteiner, M., Leclère, D., Khabarov, N., Valin, H., Reuter, W., 2016. Integrated Management of Land Use Systems under Systemic Risks and Security Targets: A Stochastic Global Biosphere Management Model. Journal of Agricultural Economics 67, 584–601. https://doi.org/10.1111/1477-9552.12173

Escribano Francés, G., Marín-Quemada, J.M., San Martín González, E., 2013. RES and risk: Renewable energy's contribution to energy security. A portfolio-based approach. Renewable and Sustainable Energy Reviews 26, 549–559. https://doi.org/10.1016/j.rser.2013.06.015
Eskandari Torbaghan, M., Burrow, M.P.N., Hunt, D.V.L., 2015. Risk assessment for a UK pan-European Supergrid: Risk assessment for a UK Pan-European Supergrid. International Journal of Energy Research 39, 1564–1578. https://doi.org/10.1002/er.3365
Espiner, R., Kaye, D., Goodfellow, G., Hopkins, P., 2008. Inspection & assessment of damaged subsea pipelines: A case study. 7th International Pipeline Conference, 29 September–3 October, American Society of Mechanical Engineers, Calgary, Canada.
Esteban, M.D., Diez, J.J., López, J.S., Negro, V., 2011. Why offshore wind energy? Renewable Energy 36, 444–450. https://doi.org/10.1016/j.renene.2010.07.009
Etmannski, T.R., Darton, R.C., 2014. A methodology for the sustainability assessment of arsenic mitigation technology for drinking water. Science of The Total Environment 488–489, 505–511. https://doi.org/10.1016/j.scitotenv.2013.10.112
Evangelisti, S., Lettieri, P., Borello, D., Clift, R., 2014. Life cycle assessment of energy from waste via anaerobic digestion: A UK case study. Waste Management 34, 226–237. https://doi.org/10.1016/j.wasman.2013.09.013
Evans, P., Mason-Jones, A., Wilson, C., Wooldridge, C., O'Doherty, T., O'Doherty, D., 2015. Constraints on extractable power from energetic tidal straits. Renewable Energy 81, 707–722. https://doi.org/10.1016/j.renene.2015.03.085
Evensen, D., Stedman, R., O'Hara, S., Humphrey, M., Andersson-Hudson, J., 2017. Variation in beliefs about 'fracking' between the UK and US. Environ. Res. Lett. 12, 124004. https://doi.org/10.1088/1748-9326/aa8f7e
EY, 2013. Oil and gas report (No. AU1754), Business Pulse: Exploring dual perspectives on the top 10 risks and opportunities in 2013 and beyond. Ernst and Young.
Eyre, N., 2011. Efficiency, Demand Reduction or Electrification?, in: Energy Efficiency First: The Foundation of a Low-Carbon Society. ECEEE, Summer Study. Belambra Les Criques, France, pp. 1391–1399.
Eyre, N., 2013. Energy saving in energy market reform—The feed-in tariffs option. Energy Policy, Special Section: Transition Pathways to a Low Carbon Economy 52, 190–198. https://doi.org/10.1016/j.enpol.2012.07.042
Faaij, A., van Ree, R., Waldheim, L., Olsson, E., Oudhuis, A., van Wijk, A., Daey-Ouwens, C., Turkenburg, W., 1997. Gasification of biomass wastes and residues for electricity production. Biomass and Bioenergy 12, 387–407. https://doi.org/10.1016/S0961-9534(97)00010-X
Faiers, A., Neame, C., 2006. Consumer attitudes towards domestic solar power systems. Energy Policy 34, 1797–1806. https://doi.org/10.1016/j.enpol.2005.01.001
Fairley, I., Evans, P., Wooldridge, C., Willis, M., Masters, I., 2013. Evaluation of tidal stream resource in a potential array area via direct measurements. Renewable Energy 57, 70–78. https://doi.org/10.1016/j.renene.2013.01.024
Fais, B., Sabio, N., Strachan, N., 2016. The critical role of the industrial sector in reaching long-term emission reduction, energy efficiency and renewable targets. Applied Energy 162, 699–712. https://doi.org/10.1016/j.apenergy.2015.10.112
Farooq, M.U., Thaheem, M.J., Arshad, H., 2018. Improving the risk quantification under behavioural tendencies: A tale of construction projects. International Journal of Project Management 36, 414–428. https://doi.org/10.1016/j.ijproman.2017.12.004
Farr, G.J., Patton, A.M., Boon, D.P., James, D.R., Williams, B., Schofield, D.I., 2017. Mapping shallow urban groundwater temperatures, a case study from Cardiff, UK. Q. J. Engineering Geology and Hydrogeology 50, 187–198. https://doi.org/10.1144/qjegh2016-058
Fawkes, S., 2015. Increasing the flow of investment into energy efficiency. Energy World, Oct, 3.
Fernandes, L.J., Barbosa-Povoa, A.P., Relvas, S., 2010. Risk Management Framework for the Petroleum Supply Chain, in: Pierucci, S., Ferraris, B.G. (Eds.), 20th European Symposium on Computer Aided Process Engineering, 6-9 June. European Symp. Computer Aided Process Eng-20 (ESCAPE-20), 6-9 June, Elsevier Science Bv, Ischia, Italy, pp. 157–162.

Fiaschi, D., Manfrida, G., Rogai, E., Talluri, L., 2017. Exergoeconomic analysis and comparison between ORC and Kalina cycles to exploit low and medium-high temperature heat from two different geothermal sites. Energy Conversion and Management 154, 503–516. https://doi.org/10.1016/j.enconman.2017.11.034
Figus, G., Swales, J.K., Turner, K., 2018. Can Private Vehicle-augmenting Technical Progress Reduce Household and Total Fuel Use? Ecological Economics 146, 136–147. https://doi.org/10.1016/j.ecolecon.2017.10.005
Figus, G., Turner, K., McGregor, P., Katris, A., 2017. Making the case for supporting broad energy efficiency programmes: Impacts on household incomes and other economic benefits. Energy Policy 111, 157–165. https://doi.org/10.1016/j.enpol.2017.09.028
Filimonau, V., Högström, M., 2017. The attitudes of UK tourists to the use of biofuels in civil aviation: An exploratory study. Journal of Air Transport Management 63, 84–94. https://doi.org/10.1016/j.jairtraman.2017.06.002
Finney, K.N., Sharifi, V.N., Swithenbank, J., Nolan, A., White, S., Ogden, S., 2012. Developments to an existing city-wide district energy network – Part I: Identification of potential expansions using heat mapping. Energy Conversion and Management 62, 165–175. https://doi.org/10.1016/j.enconman.2012.03.006
Firrisa, M.T., Duren, I. van, Voinov, A., 2014. Energy efficiency for rapeseed biodiesel production in different farming systems. Energy Eff 7, 79–95. https://doi.org/10.1007/s12053-013-9201-2
Firth, S., Hildenbrand, B., Morgan, P., 2014. Ethanol effects on the fate and transport of gasoline constituents in the UK. Science of The Total Environment 485–486, 705–710. https://doi.org/10.1016/j.scitotenv.2014.02.119
Fleiß, E., Hatzl, S., Seebauer, S., Posch, A., 2017. Money, not morale: The impact of desires and beliefs on private investment in photovoltaic citizen participation initiatives. Journal of Cleaner Production 141, 920–927. https://doi.org/10.1016/j.jclepro.2016.09.123
Flynn, B., 2015. Ecological modernisation of a ‘Cinderella renewable’? The emerging politics of global ocean energy. Environmental Politics 24, 249–269. https://doi.org/10.1080/09644016.2014.1000638
Forbes, E.G.A., Easson, D.L., Lyons, G.A., McRoberts, W.C., 2014. Physico-chemical characteristics of eight different biomass fuels and comparison of combustion and emission results in a small scale multi-fuel boiler. Energy Conversion and Management 87, 1162–1169. https://doi.org/10.1016/j.enconman.2014.06.063
Foxon, T.J., Gross, R., Chase, A., Howes, J., Arnall, A., Anderson, D., 2005. UK innovation systems for new and renewable energy technologies: drivers, barriers and systems failures. Energy Policy 33, 2123–2137. https://doi.org/10.1016/j.enpol.2004.04.011
Frank, R.R., Cipullo, S., Garcia, J., Davies, S., Wagland, S.T., Villa, R., Trois, C., Coulon, F., 2017. Compositional and physicochemical changes in waste materials and biogas production across 7 landfill sites in UK. Waste Management, Special Thematic Issue: Sanitary Landfilling 63, 11–17. https://doi.org/10.1016/j.wasman.2016.08.026
Fransway, A., Fransway, P., Belsito, D., Yiannias, J., 2019. Paraben Toxicology. Dermatitis 30, 32–45. https://doi.org/10.1097/DER.0000000000000428
Freeman, M.C., Groom, B., Panopoulou, E., Pantelidis, T., 2015. Declining discount rates and the Fisher Effect: Inflated past, discounted future? Journal of Environmental Economics and Management 73, 32–49. https://doi.org/10.1016/j.jeem.2015.06.003
Frondel, M., Schmidt, C.M., 2008. Measuring Energy Security – A Conceptual Note (No. 52), Ruhr Economic Papers. RWI, Essen, Germany.
Frynas, J., 2012. Corporate Social Responsibility or Government Regulation? Evidence on Oil Spill Prevention. Ecology and Society 17. https://doi.org/10.5751/ES-05073-170404
Fubara, T., Cecelja, F., Yang, A., 2018. Techno-economic assessment of natural gas displacement potential of biomethane: A case study on domestic energy supply in the UK. Chemical Engineering Research and Design, Energy Systems Engineering 131, 193–213. https://doi.org/10.1016/j.cherd.2017.12.022

Fylan, F., Glew, D., Smith, M., Johnston, D., Brooke-Peat, M., Miles-Shenton, D., Fletcher, M., Aloise-Young, P., Gorse, C., 2016. Reflections on retrofits: Overcoming barriers to energy efficiency among the fuel poor in the United Kingdom. Energy Research & Social Science 21, 190–198. https://doi.org/10.1016/j.erss.2016.08.002

Gage, J.D., Gordon, J.D.M., 1995. Sound bites, science and the Brent Spar: Environmental considerations relevant to the deep-sea disposal option. Marine Pollution Bulletin 30, 772–779. https://doi.org/10.1016/0025-326X(96)81924-2

Gao, G., Falconer, R.A., Lin, B., 2013. Modeling effects of a tidal barrage on water quality indicator distribution in the Severn Estuary. Front. Environ. Sci. Eng. 7, 211–218. https://doi.org/10.1007/s11783-012-0464-1

Gao, J., You, F., 2017. Design and optimization of shale gas energy systems: Overview, research challenges, and future directions. Computers & Chemical Engineering, ESCAPE-26 106, 699–718. https://doi.org/10.1016/j.compchemeng.2017.01.032

Garber, D., Choudhary, R., Soga, K., 2013. Risk based lifetime costs assessment of a ground source heat pump (GSHP) system design: Methodology and case study. Building and Environment 60, 66–80. https://doi.org/10.1016/j.buildenv.2012.11.011

García-Oliva, M., Djordjević, S., Tabor, G.R., 2017. The impacts of tidal turbines on water levels in a shallow estuary. Int J Marine Egy 19, 177–197. https://doi.org/10.1016/j.ijome.2017.07.006

Garcia-Oliva, M., Hooper, T., Djordjević, S., Belmont, M., 2017. Exploring the implications of tidal farms deployment for wetland-birds habitats in a highly protected estuary. Marine Policy 81, 359–367. https://doi.org/10.1016/j.marpol.2017.04.011

Gardoni, P., Murphy, C., 2014. A Scale of Risk. Risk Analysis 34, 1208–1227. https://doi.org/10.1111/risa.12150

Garg, A., Smith, R., Hill, D., Longhurst, P.J., Pollard, S.J.T., Simms, N.J., 2009. An integrated appraisal of energy recovery options in the United Kingdom using solid recovered fuel derived from municipal solid waste. Waste Management 29, 2289–2297. https://doi.org/10.1016/j.wasman.2009.03.031

Garner, J., Cairns, J., Read, D., 2015. NORM in the East Midlands' oil and gas producing region of the UK. J. Env. Radioactivity 150, 49–56. https://doi.org/10.1016/j.jenvrad.2015.07.016

Gegg, P., Wells, V., 2017. UK Macro-Algae Biofuels: A Strategic Management Review and Future Research Agenda. Journal of Marine Science and Engineering 5, 32. https://doi.org/10.3390/jmse5030032

Gentvilaite, R., Kander, A., Warde, P., 2014. The Role of Energy Quality in Shaping Long-Term Energy Intensity in Europe. Energies 8, 133–153. https://doi.org/10.3390/en8010133

Georgitsioti, T., Pearsall, N., Forbes, I., 2014. Simplified levelised cost of the domestic photovoltaic energy in the UK: the importance of the feed-in tariff scheme. IET Renewable Power Generation 8, 451–458. https://doi.org/10.1049/iet-rpg.2013.0241

Ghazi, S., Ip, K., 2014. The effect of weather conditions on the efficiency of PV panels in the southeast of UK. Renewable En. 69, 50–59. https://doi.org/10.1016/j.renene.2014.03.018

Gibbons, S., 2015. Gone with the wind: Valuing the visual impacts of wind turbines through house prices. Journal of Environmental Economics and Management 72, 177–196. https://doi.org/10.1016/j.jeem.2015.04.006

Gilbert, R., Perl, A., 2010. Transport Revolutions: Moving People and Freight Without Oil, Second edition. ed. New Society Publishers, Gabriola Island, BC, Canada.

Gill, Z.M., Tierney, M.J., Pegg, I.M., Allan, N., 2011. Measured energy and water performance of an aspiring low energy/carbon affordable housing site in the UK. Energy and Buildings 43, 117–125. https://doi.org/10.1016/j.enbuild.2010.08.025

Glass, J., Dainty, A.R.J., Gibb, A.G.F., 2008. New build: Materials, techniques, skills and innovation. Energy Policy, Foresight Sustainable Energy Management and the Built Environment Project 36, 4534–4538. https://doi.org/10.1016/j.enpol.2008.09.016

Glithero, N.J., Wilson, P., Ramsden, S.J., 2013a. Straw use and availability for second generation biofuels in England. Biomass and Bioenergy 55, 311–321. https://doi.org/10.1016/j.biombioe.2013.02.033

Glithero, N.J., Wilson, P., Ramsden, S.J., 2013b. Prospects for arable farm uptake of Short Rotation Coppice willow and miscanthus in England. Applied Energy 107, 209–218. https://doi.org/10.1016/j.apenergy.2013.02.032
Global Energy Institute, 2018. International Index of Energy Security Risk. U.S. Chamber of Commerce, Washington, D.C. USA.
Gluyas, J.G., Adams, C.A., Busby, J.P., Craig, J., Hirst, C., Manning, D.A.C., McCay, A., Narayan, N.S., Robinson, H.L., Watson, S.M., Westaway, R., Younger, P.L., 2018. Keeping warm: a review of deep geothermal potential of the UK. Proc Inst Mechanical Engineers, Part A: Journal of Power and Energy 232, 115–126. https://doi.org/10.1177/0957650917749693
Goerlandt, F., Goite, H., Valdez Banda, O.A., Höglund, A., Ahonen-Rainio, P., Lensu, M., 2017. An analysis of wintertime navigational accidents in the Northern Baltic Sea. Safety Science 92, 66–84. https://doi.org/10.1016/j.ssci.2016.09.011
Goerlandt, F., Reniers, G., 2016. On the assessment of uncertainty in risk diagrams. Safety Science 84, 67–77. https://doi.org/10.1016/j.ssci.2015.12.001
Goldin, I., Mariathasan, M., 2014. The Butterfly Defect: How Globalization Creates Systemic Risks, and What to Do about It. Princeton University Press, Princeton, USA.
Goodier, C.I., Chmutina, K., Poulter, E., Stoelinga, P., 2013. Potential for seawater district heating and cooling in the UK. Proceedings of the Institution of Civil Engineers - Energy 166, 102–106. https://doi.org/10.1680/ener.12.00016
Gooding, L., Gul, M.S., 2017. Enabling a self-sufficient energy efficient retrofit services sector future: A qualitative study. Energy and Buildings 156, 306–314. https://doi.org/10.1016/j.enbuild.2017.09.072
Goulden, M., Ryley, T., Dingwall, R., 2014. Beyond 'predict and provide': UK transport, the growth paradigm and climate change. Transport Policy 32, 139–147. https://doi.org/10.1016/j.tranpol.2014.01.006
Gouldson, A., Carpenter, A., Afionis, S., 2014. An international comparison of the outcomes of environmental regulation. Env Res Lett 9, 074019. https://doi.org/10.1088/1748-9326/9/7/074019
Gove, B., Williams, L.J., Beresford, A.E., Roddis, P., Campbell, C., Teuten, E., Langston, R.H.W., Bradbury, R.B., 2016. Reconciling Biodiversity Conservation and Widespread Deployment of Renewable Energy Technologies in the UK. PLOS ONE 11, e0150956. https://doi.org/10.1371/journal.pone.0150956
Gowreesunker, B., Tassou, S., 2016. The Impact of Renewable Energy Policies on the Adoption of Anaerobic Digesters with Farm-Fed Wastes in Great Britain. Energies 9, 1038. https://doi.org/10.3390/en9121038
Gray, A., Dickens, B., Bruce, T., Ashton, I., Johanning, L., 2017. Reliability and O&M sensitivity analysis as a consequence of site specific characteristics for wave energy converters. Ocean Engineering 141, 493–511. https://doi.org/10.1016/j.oceaneng.2017.06.043
Greaves, D., Attrill, M., Chadwick, A., Conley, D., Eccleston, A., Hosegood, P., Pan, S., Reeve, D., Williams, J., Wolfram, J., Xu, J., Zou, Q., Smith, G., Godley, B., Hor, C.L., Johanning, L., Millar, D., Wolfram, J., Zobaa, A., Belmont, M., Harrington, N., 2009. Marine renewable energy development – research, design, install. Proc. Inst. Civil Engineers - Maritime Engineering 162, 187–196. https://doi.org/10.1680/maen.2009.162.4.187
Green, R., Staffell, I., 2013. The Impact of Government Interventions on Investment in the GB Electricity Market. Imperial College London, London, UK.
Green, R.E., Langston, R.H.W., McCluskie, A., Sutherland, R., Wilson, J.D., 2016. Lack of sound science in assessing wind farm impacts on seabirds. J Appl Ecol 53, 1635–1641. https://doi.org/10.1111/1365-2664.12731
Greenhalgh, C., Azapagic, A., 2009. Review of drivers and barriers for nuclear power in the UK. Env. Science & Policy 12, 1052–1067. https://doi.org/10.1016/j.envsci.2009.07.006
Greening, B., Azapagic, A., 2014. Domestic solar thermal water heating: A sustainable option for the UK? Renewable Energy 63, 23–36. https://doi.org/10.1016/j.renene.2013.07.048
Griffin, P.W., Hammond, G.P., Ng, K.R., Norman, J.B., 2012. Impact review of past UK public industrial energy efficiency RD&D programmes. Energy Conversion and Management 60, 243–250. https://doi.org/10.1016/j.enconman.2012.02.013

Griffin, P.W., Hammond, G.P., Norman, J.B., 2016. Industrial energy use and carbon emissions reduction: a UK perspective: Industrial energy use and carbon emissions reduction. Wiley Interdisciplinary Reviews: Energy and Environment 5, 684–714. https://doi.org/10.1002/wene.212
Griffin, P.W., Hammond, G.P., Norman, J.B., 2017. Opportunities for Energy Demand and Carbon Emissions Reduction in the Chemicals Sector. Energy Procedia, 8th International Conference on Applied Energy, ICAE2016, 8-11 October 2016, Beijing, China 105, 4347–4356. https://doi.org/10.1016/j.egypro.2017.03.913
Griffin, P.W., Hammond, G.P., Norman, J.B., 2018. Industrial decarbonisation of the pulp and paper sector: A UK perspective. Applied Thermal Engineering 134, 152–162. https://doi.org/10.1016/j.applthermaleng.2018.01.126
Grimston, M., Nuttall, W.J., Vaughan, G., 2014. The siting of UK nuclear reactors. J. Radiol. Prot. 34, R1. https://doi.org/10.1088/0952-4746/34/2/R1
Gross, R., Watson, J., 2015. Driving innovation through continuity in UK energy policy: Four simple steps to maintain investor confidence, boost innovation and reduce costs in the UK power sector (UKERC Working Paper). UKERC, London.
Groves, C., 2015. The bomb in my backyard, the serpent in my house: environmental justice, risk, and the colonisation of attachment. Environmental Politics 24, 853–873. https://doi.org/10.1080/09644016.2015.1067348
Groves, C., Munday, M., Yakovleva, N., 2013. Fighting the pipe: neoliberal governance and barriers to effective community participation in energy infrastructure planning. Environment and Planning C: Government and Policy 31, 340–356. https://doi.org/10.1068/c11331r
Grubb, M., Butler, L., Twomey, P., 2006. Diversity and security in UK electricity generation: The influence of low-carbon objectives. Energy Policy 34, 4050–4062. https://doi.org/10.1016/j.enpol.2005.09.004
Grubb, M., Newbery, D., 2018. UK Electricity Market Reform and the Energy Transition: Emerging Lessons. EJ 39. https://doi.org/10.5547/01956574.39.6.mgru
Guertler, P., 2016. The UK - still the cold man of Europe. Energy World, January, 34–35.
Gul, M., Kotak, Y., Muneer, T., 2016. Review on recent trend of solar photovoltaic technology. En. Exploration & Exploitation 34, 485–526. https://doi.org/10.1177/0144598716650552
Guo, M., Song, W., Buhain, J., 2015. Bioenergy and biofuels: History, status, and perspective. Renewable & Sustainable Energy Rev 42, 712–725. https://doi.org/10.1016/j.rser.2014.10.013
Gupta, R., Gregg, M., 2012. Appraisal of UK funding frameworks for energy research in housing. Building Res & Information 40, 446–460. https://doi.org/10.1080/09613218.2012.683240
Gupta, R., Gregg, M., 2018. Targeting and modelling urban energy retrofits using a city-scale energy mapping approach. Journal of Cleaner Production 174, 401–412. https://doi.org/10.1016/j.jclepro.2017.10.262
Gupta, R., Gregg, M., Williams, K., 2015. Cooling the UK housing stock post-2050s. Building Services Engineering Res & Tech 36, 196–220. https://doi.org/10.1177/0143624414566242
Haggett, C., 2011. Understanding public responses to offshore wind power. Energy Policy, Special Section on Offshore wind power planning, economics and environment 39, 503–510. https://doi.org/10.1016/j.enpol.2010.10.014
Hagmann, J., Cavelty, M.D., 2012. National risk registers: Security scientism and the propagation of permanent insecurity. Security Dialogue 43, 79–96. https://doi.org/10.1177/0967010611430436
Haldane, A.G., May, R.M., 2011. Systemic risk in banking ecosystems. Nature 469, 351–355. https://doi.org/10.1038/nature09659
Hall, D.O., Scrase, J.I., 1998. Will biomass be the environmentally friendly fuel of the future? Biomass and Bioenergy 15, 357–367. https://doi.org/10.1016/S0961-9534(98)00030-0
Hamilton, I., Summerfield, A., Oreszczyn, T., Ruyssevelt, P., 2017. Using epidemiological methods in energy and buildings research to achieve carbon emission targets. Energy and Buildings 154, 188–197. https://doi.org/10.1016/j.enbuild.2017.08.079
Hamilton, I.G., Shipworth, D., Summerfield, A.J., Steadman, P., Oreszczyn, T., Lowe, R., 2014. Uptake of energy efficiency interventions in English dwellings. Building Research & Information 42, 255–275. https://doi.org/10.1080/09613218.2014.867643

Hammes, U., Krause, M., Mutti, M., 2013. Unconventional reservoir potential of the upper Permian Zechstein Group: a slope to basin sequence stratigraphic and sedimentological evaluation of carbonates and organic-rich mudrocks, Northern Germany. Environ Earth Sci 70, 3797–3816. https://doi.org/10.1007/s12665-013-2724-1
Hammond, G., Harajli, H.A., Jones, C.I., Winnett, A.B., 2012. Whole systems appraisal of a UK Building Integrated Photovoltaic (BIPV) system: Energy, environmental, and economic evaluations. Energy Policy, Strategic Choices for Renewable Energy Investment 40, 219–230. https://doi.org/10.1016/j.enpol.2011.09.048
Hammond, G.P., 2004. Engineering sustainability: thermodynamics, energy systems, and the environment. Int. J. Energy Res. 28, 613–639. https://doi.org/10.1002/er.988
Hammond, G.P., Howard, H.R., Tuck, A., 2012. Risk assessment of UK biofuel developments within the rapidly evolving energy and transport sectors. Proceedings of the IMechE 226, 526–548. https://doi.org/10.1177/1748006X12448147
Hammond, G.P., Li, B., 2016. Environmental and resource burdens associated with world biofuel production out to 2050: footprint components from carbon emissions and land use to waste arisings and water consumption. GCB Bioenergy 8, 894–908. https://doi.org/10.1111/gcbb.12300
Hammond, G.P., Norman, J.B., 2012. Decomposition analysis of energy-related carbon emissions from UK manufacturing. Energy 41, 220–227. https://doi.org/10.1016/j.energy.2011.06.035
Hammond, G.P., Norman, J.B., 2014. Heat recovery opportunities in UK industry. Applied Energy 116, 387–397. https://doi.org/10.1016/j.apenergy.2013.11.008
Hammond, G.P., O'Grady, Á., 2017. Indicative energy technology assessment of UK shale gas extraction. Applied Energy, Clean, Efficient and Affordable Energy for a Sustainable Future 185, 1907–1918. https://doi.org/10.1016/j.apenergy.2016.02.024
Hammond, G.P., Waldron, R., 2008. Risk assessment of UK electricity supply in a rapidly evolving energy sector. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 222, 623–642. https://doi.org/10.1243/09576509JPE543
Haney, J.C., Geiger, H.J., Short, J.W., 2014. Bird mortality from the Deepwater Horizon oil spill. I. Exposure probability in the offshore Gulf of Mexico. Marine Ecology Progress Series 513, 225–237. https://doi.org/10.3354/meps10991
Hanmer, C., Abram, S., 2017a. Actors, networks, and translation hubs: Gas central heating as a rapid socio-technical transition in the United Kingdom. Energy Research & Social Science 34, 176–183. https://doi.org/10.1016/j.erss.2017.03.017
Hanmer, C., Abram, S., 2017b. Actors, networks, and translation hubs: Gas central heating as a rapid socio-technical transition in the United Kingdom. Energy Research & Social Science 34, 176–183. https://doi.org/10.1016/j.erss.2017.03.017
Hanna, R., Gross, R., Speirs, J., Heptonstall, P., Gambhir, A., 2015. Innovation timelines from invention to maturity. UKERC, London, UK.
Hanna, R., Leach, M., Torriti, J., 2018. Microgeneration: The installer perspective. Renewable Energy 116, 458–469. https://doi.org/10.1016/j.renene.2017.09.023
Hanna, R., Parrish, B., Gross, R., 2016. Best practice in heat decarbonisation policy: A review of the international experience of policies to promote the uptake of low-carbon heat supply (Working Paper). UK Energy Research Centre, London, UK.
Hannon, M., Skea, J., 2014. UK innovation support for energy demand reduction. Proc. Inst. Civil Engineers - Energy 167, 171–180. https://doi.org/10.1680/ener.14.00009
Hanumante, N.C., Shastri, Y., Hoadley, A., 2019. Assessment of circular economy for global sustainability using an integrated model. Resources, Conservation and Recycling 151, 104460. https://doi.org/10.1016/j.resconrec.2019.104460
Hards, S.K., 2013. Status, stigma and energy practices in the home. Local Environment 18, 438–454. https://doi.org/10.1080/13549839.2012.748731
Harleman, M., Weber, J.G., 2017. Natural resource ownership, financial gains, and governance: The case of unconventional gas development in the UK and the US. Energy Policy 111, 281–296. https://doi.org/10.1016/j.enpol.2017.09.036
Harris, G., Heptonstall, P., Gross, R., Handley, D., 2013. Cost estimates for nuclear power in the UK. Energy Policy 62, 431–442. https://doi.org/10.1016/j.enpol.2013.07.116

Harrison, S., Jiang, L., 2018. An investigation into the energy performance gap between the predicted and measured output of photovoltaic systems using dynamic simulation modelling software—a case study. International Journal of Low-Carbon Technologies 13, 23–29. https://doi.org/10.1093/ijlct/ctx016

Harvey, L.D.D., 2010. Energy and the New Reality 2: Carbon-free Energy Supply. Routledge, London, UK.

Hashemi, M.R., Grilli, S.T., Neill, S.P., 2016. A simplified method to estimate tidal current effects on the ocean wave power resource. Renewable Energy 96, 257–269. https://doi.org/10.1016/j.renene.2016.04.073

Hassani, H., Silva, E.S., Al Kaabi, A.M., 2017. The role of innovation and technology in sustaining the petroleum and petrochemical industry. Technological Forecasting and Social Change 119, 1–17. https://doi.org/10.1016/j.techfore.2017.03.003

Hawkey, D., Webb, J., 2014. District energy development in liberalised markets: situating UK heat network development in comparison with Dutch and Norwegian case studies. Technology Analysis & Strategic Mgt 26, 1228–1241. https://doi.org/10.1080/09537325.2014.971001

Hawkey, D., Webb, J., Winskel, M., 2013. Organisation and governance of urban energy systems: district heating and cooling in the UK. Journal of Cleaner Production 50, 22–31. https://doi.org/10.1016/j.jclepro.2012.11.018

Hawkey, D.J.C., 2012. District heating in the UK: A Technological Innovation Systems analysis. Env Innovation & Societal Trans 5, 19–32. https://doi.org/10.1016/j.eist.2012.10.005

Hays, J., Finkel, M.L., Depledge, M., Law, A., Shonkoff, S.B.C., 2015. Considerations for the development of shale gas in the United Kingdom. Science of The Total Environment 512–513, 36–42. https://doi.org/10.1016/j.scitotenv.2015.01.004

HCECCC, 2016. Future of carbon capture and storage in the UK (No. HC 692). House of Commons Energy and Climate Change Committee, London, UK.

Hdidouan, D., Staffell, I., 2017. The impact of climate change on the levelised cost of wind energy. Renewable Energy 101, 575–592. https://doi.org/10.1016/j.renene.2016.09.003

He, Z., Krishnamurthy, A., 2019. A Macroeconomic Framework for Quantifying Systemic Risk. American Economic J: Macroeconomics 11, 1–37. https://doi.org/10.1257/mac.20180011

Heckmann, I., Comes, T., Nickel, S., 2015. A critical review on supply chain risk – Definition, measure and modeling. Omega 52, 119–132. https://doi.org/10.1016/j.omega.2014.10.004

Heede, R., Oreskes, N., 2016. Potential emissions of CO2 and methane from proved reserves of fossil fuels: An alternative analysis. Global Environmental Change 36, 12–20. https://doi.org/10.1016/j.gloenvcha.2015.10.005

Heffernan, E., Pan, W., Liang, X., de Wilde, P., 2015. Zero carbon homes: Perceptions from the UK construction industry. Energy Policy 79, 23–36. https://doi.org/10.1016/j.enpol.2015.01.005

Heiskanen, E., Matschoss, K., 2017. Understanding the uneven diffusion of building-scale renewable energy systems: A review of household, local and country level factors in diverse European countries. Renewable and Sustainable Energy Reviews 75, 580–591. https://doi.org/10.1016/j.rser.2016.11.027

Helbing, D., 2013. Globally networked risks and how to respond. Nature 497, 51–59. https://doi.org/10.1038/nature12047

Henderson, J., Loe, J., 2014. The prospects and challenges for Arctic oil development. (No. WPM 54), OIES Paper. Oxford Institute for Energy Studies, Oxford, UK.

Hendryx, M., 2015. The public health impacts of surface coal mining. The Extractive Industries and Society 2, 820–826. https://doi.org/10.1016/j.exis.2015.08.006

Hennissen, J.A.I., Hough, E., Vane, C.H., Leng, M.J., Kemp, S.J., Stephenson, M.H., 2017. The prospectivity of a potential shale gas play: An example from the southern Pennine Basin (central England, UK). Marine and Petroleum Geology 86, 1047–1066. https://doi.org/10.1016/j.marpetgeo.2017.06.033

Henselwood, F., Phillips, G., 2006. A matrix-based risk assessment approach for addressing linear hazards such as pipelines. Journal of Loss Prevention in the Process Industries 19, 433–441. https://doi.org/10.1016/j.jlp.2005.10.005

Herbert, A., Arthur, S., Chillingworth, G., 2013. Thermal modelling of large scale exploitation of ground source energy in urban aquifers as a resource management tool. Applied Energy 109, 94–103. https://doi.org/10.1016/j.apenergy.2013.03.005

Herrando, M., Markides, C.N., 2016. Hybrid PV and solar-thermal systems for domestic heat and power provision in the UK: Techno-economic considerations. Applied Energy 161, 512–532. https://doi.org/10.1016/j.apenergy.2015.09.025

Hewett, C.J.M., Quinn, P.F., Whitehead, P.G., Heathwaite, A.L., Flynn, N.J., 2004. Towards a nutrient export risk matrix approach to managing agricultural pollution at source. Hydrology and Earth System Sciences 8, 834–845. https://doi.org/10.5194/hess-8-834-2004

Hillson, D., Simon, P., 2007. Practical Project Risk Management: The ATOM Methodology. Kogan Page, Vienna, USA.

Hilton, A.C.E., 1992. Oil, energy and capital. Energy Policy, The petroleum industry: entering the 21st century 20, 963–972. https://doi.org/10.1016/0301-4215(92)90184-4

Hines, L., 2017. The UK’s energy skills challenge. Energy World, January, 24–25.

Hinnells, M., 2008. Technologies to achieve demand reduction and microgeneration in buildings. Energy Policy, Foresight Sustainable Energy Management and the Built Environment Project 36, 4427–4433. https://doi.org/10.1016/j.enpol.2008.09.029

HLSCST, 2011. Nuclear Research and Development Capabilities (HL Paper 221). House of Lords Select Committee on Science and Technology, London, UK.

HM Government, 2008. Climate Change Act. HMSO, London, UK.

HM Treasury, 2013. National Infrastructure Plan 2013 (No. PU1576). London, UK.

HM Treasury, 2014. Driving investment: a plan to reform the oil and gas fiscal regime (No. PU1721). London, UK.

Hochrainer-Stigler, S., Colon, C., Boza, G., Brännström, Å., Linnerooth-Bayer, J., Pflug, G., Poledna, S., Rovenskaya, E., Dieckmann, U., 2019. Measuring, modeling, and managing systemic risk: the missing aspect of human agency. Journal of Risk Research 1–17. https://doi.org/10.1080/13669877.2019.1646312

Hodgson, E., Ruiz-Molina, M.-E., Marazza, D., Pogrebnyakova, E., Burns, C., Higson, A., Rehberger, M., Hiete, M., Gyalai-Korpos, M., Lucia, L.D., Noël, Y., Woods, J., Gallagher, J., 2016. Horizon scanning the European bio-based economy: a novel approach to the identification of barriers and key policy interventions from stakeholders in multiple sectors and regions: Biohorizons: Horizon scanning the European bio-based economy. Biofuels, Bioproducts and Biorefining 10, 508–522. https://doi.org/10.1002/bbb.1665

Holland, R., Ketsopoulou, I., Beaumont, N., Austen, M., Hooper, T., Gross, R., Heptonstall, P., Watson, J., Taylor, G., 2016. How consistent and comparable are ecosystem services and energy system scenarios? (Working Paper). UKERC, London, UK.

Hoogeveen, F., Perlot, W., 2007. The EU’s Policies of Security of Energy Supply Towards the Middle East and Caspian Region: Major Power Politics? Perspectives on Global Development and Technology 6, 485–507. https://doi.org/10.1163/156914907X207847

Hooper, T., Ashley, M., Austen, M., 2015. Perceptions of fishers and developers on the co-location of offshore wind farms and decapod fisheries in the UK. Marine Policy 61, 16–22. https://doi.org/10.1016/j.marpol.2015.06.031

Hooper, T., Austen, M., 2013. Tidal barrages in the UK: Ecological and social impacts, potential mitigation, and tools to support barrage planning. Renew. Sust. Energ. Rev. 23, 289–298. https://doi.org/10.1016/j.rser.2013.03.001

Hoover, J., Gonzales, M., Shuey, C., Barney, Y., Lewis, J., 2017. Elevated Arsenic and Uranium Concentrations in Unregulated Water Sources on the Navajo Nation, USA. Exposure and Health 9, 113–124. https://doi.org/10.1007/s12403-016-0226-6

Hope, A.J., Booth, A., 2014. Attitudes and behaviours of private sector landlords towards the energy efficiency of tenanted homes. Energy Policy 75, 369–378. https://doi.org/10.1016/j.enpol.2014.09.018

Howell, R.A., 2018. UK public beliefs about fracking and effects of knowledge on beliefs and support: A problem for shale gas policy. Energy Policy 113, 721–730. https://doi.org/10.1016/j.enpol.2017.11.061

HSE, 2006. Offshore Installations (Safety Case) Regulations 2005 Regulation 12 Demonstrating compliance with the relevant statutory provisions (No. 2/2006), Offshore Information Sheet. Health and Safety Executive, London, UK.
HSE, 2016. Offshore Statistics and Regulatory Activity Report 2015. Health and Safety Executive, London, UK.
Hsu, W.-K., Lian, S.-J., Huang, S.-H., 2017. Risk Assessment of Operational Safety for Oil Tankers - A Revised Risk Matrix. The Journal of Navigation 70, 775–788. https://doi.org/10.1017/S0373463316000941
Huang, Y., Wang, Y.D., Chen, H., Zhang, X., Mondol, J., Shah, N., Hewitt, N.J., 2017. Performance analysis of biofuel fired trigeneration systems with energy storage for remote households. Applied Energy, Sustainable Thermal Energy Management (SusTEM2015) 186, 530–538. https://doi.org/10.1016/j.apenergy.2016.03.028
Hubbard, D., Evans, D., 2010. Problems with scoring methods and ordinal scales in risk assessment. IBM J. Res & Dev. 54, 2:1-2:10. https://doi.org/10.1147/JRD.2010.2042914
Hubbert, M.K., 1956. Nuclear Energy and Fossil Fuels, in: Drilling and Production Practice. Spring Meeting of the Southern District, American Petroleum Institute, The American Petroleum Institute, San Antonio, Texas, USA, pp. 7–25.
Hubbert, M.K., 1981. The Worlds Evolving Energy System. Am. J. Phys. 49, 1007–1029. https://doi.org/10.1119/1.12656
Hudson, L., Winskel, M., Allen, S., 2011. The hesitant emergence of low carbon technologies in the UK: the micro-CHP innovation system. Technology Analysis & Strategic Management 23, 297–312. https://doi.org/10.1080/09537325.2011.550396
Huebner, G.M., McMichael, M., Shipworth, D., Shipworth, M., Durand-Daubin, M., Summerfield, A., 2013a. The reality of English living rooms – A comparison of internal temperatures against common model assumptions. Energy and Buildings 66, 688–696. https://doi.org/10.1016/j.enbuild.2013.07.025
Huebner, G.M., McMichael, M., Shipworth, D., Shipworth, M., Durand-Daubin, M., Summerfield, A., 2013b. Heating patterns in English homes: Comparing results from a national survey against common model assumptions. Building and Environment 70, 298–305. https://doi.org/10.1016/j.buildenv.2013.08.028
Huebner, G.M., McMichael, M., Shipworth, D., Shipworth, M., Durand-Daubin, M., Summerfield, A.J., 2015. The shape of warmth: temperature profiles in living rooms. Building Research & Information 43, 185–196. https://doi.org/10.1080/09613218.2014.922339
Hughes, I., Hase, T., 2010. Measurements And Their Uncertainties: A practical guide to modern error analysis. Oxford University Press, Oxford.
Hughes, L., de Jong, M., Wang, X.Q., 2016. A generic method for analyzing the risks to energy systems. Applied Energy 180, 895–908. https://doi.org/10.1016/j.apenergy.2016.07.133
Hughes, N., Strachan, N., 2010. Methodological review of UK and international low carbon scenarios. Energy Policy 38, 6056–6065. https://doi.org/10.1016/j.enpol.2010.05.061
Humphries, M.E., 1995. The competitive environment for oil and gas financing. Energy Policy, Financing the energy sector in developing countries 23, 991–1000. https://doi.org/10.1016/0301-4215(95)00103-4
Hyder, Z., Ripepi, N.S., Karmis, M.E., 2016. A life cycle comparison of greenhouse emissions for power generation from coal mining and underground coal gasification. Mit & Adaptation Strat for Global Change 21, 515–546. https://doi.org/10.1007/s11027-014-9561-8
IAEA, 2012. Efficient water management in water cooled reactors. (No. NP-T-2.6), Nuclear Energy Series. International Atomic Energy Agency, Vienna, Austria.
IEA, 2017. Energy Efficiency 2017, Market Report. International Energy Agency, Paris, France.
IET, 2018. Power Academy. Institute of Engineering and Technology. URL https://conferences.theiet.org/power-academy/about/index.cfm (accessed 28/7/18).
Iglesias, G., Carballo, R., 2014. Wave farm impact: The role of farm-to-coast distance. Renewable Energy 69, 375–385. https://doi.org/10.1016/j.renene.2014.03.059
IHA, 2018. Hydropower Sustainability Assessment Protocol: background document. International Hydropower Association, London, UK.

IMO, 2013. Revised Guidelines for Formal Safety Assessment (FSA) for Use in the IMO Rule-making Process (No. MSC-MEPC.2/Circ.12). International Maritime Org, London, UK.
IOD, 2013. Getting shale gas working (No. 6), Infrastructure for Business. Institute of Directors, London, UK.
IPCC, 2015. Climate change 2014: synthesis report. Intergovernmental Panel on Climate Change, Geneva, Switzerland.
IPIECA, IOGP, 2013. Oil spill risk assessment and response planning for offshore installations. International Petroleum Industry Environmental Conservation Association and International Association of Oil and Gas Producers, London, UK.
Ipsos MORI, Energy Saving Trust, 2013. Homeowners' Willingness To Take Up More Efficient Heating Systems (No. URN 13D/078). Dept of Energy and Climate Change, London, UK.
Iqbal, J., Vähämaa, S., 2019. Managerial risk-taking incentives and the systemic risk of financial institutions. Rev Quant Finan Acc 53, 1229–1258. https://doi.org/10.1007/s11156-018-0780-z
IRENA, 2012. 30 Years of Policies for Wind Energy: Lessons from 12 Wind Energy Markets. International Renewable Energy Agency, Dubai, UAE.
IRM, 2013. Managing Cost Risk & Uncertainty In Infrastructure Projects. Leading Practice and Improvement: Report from the Infrastructure Risk Group. The Institute of Risk Management, London, UK.
Iskandarova, M., 2017. From the idea of scale to the idea of agency: An actor-network theory perspective on policy development for renewable energy. Sci Public Policy 44, 476–485. https://doi.org/10.1093/scipol/scw075
ISO, 2009. IEC 31010 Risk management -- Risk assessment techniques. International Standardization Organization, Geneva, Switzerland.
ITPOES, 2010. The oil crunch: a wake-up call for the UK economy. UK Industry Taskforce on Peak Oil and Energy Security, London.
Iyer, S.S.R., Regan, K.A., Burnham, J.M., Chen, C.J., 2019. Surgical management of diabetic tractional retinal detachments. Survey of Ophthalmology 64, 780–809. https://doi.org/10.1016/j.survophthal.2019.04.008
Jaccard, M., Agbenmabiese, L., Azar, C., De, O., Fischer, C., Fisher, B., Hughes, A., Ohadi, M., Kenji, Y., Zhang, X., 2012. Chapter 22 - Policies for Energy System Transformations: Objectives and Instruments, in: Global Energy Assessment - Toward A Sustainable Future. Cambridge University Press, Cambridge, UK, pp. 1549–1602.
Jackson, A.L.R., 2011. Renewable energy vs. biodiversity: Policy conflicts and the future of nature conservation. Global Environmental Change 21, 1195–1208. https://doi.org/10.1016/j.gloenvcha.2011.07.001
Jagger, N., Foxon, T., Gouldson, A., 2013. Skills constraints and the low carbon transition. Climate Policy 13, 43–57. https://doi.org/10.1080/14693062.2012.709079
Jain, P., Reese, A.M., Chaudhari, D., Mentzer, R.A., Mannan, M.S., 2017. Regulatory approaches - Safety case vs US approach: Is there a best solution today? Journal of Loss Prevention in the Process Industries 46, 154–162. https://doi.org/10.1016/j.jlp.2017.02.001
Jamasb, T., Nepal, R., 2010. Issues and options in waste management: A social cost–benefit analysis of waste-to-energy in the UK. Resources, Conservation and Recycling 54, 1341–1352. https://doi.org/10.1016/j.resconrec.2010.05.004
Jamasb, T., Pollitt, M., 2008a. Security of supply and regulation of energy networks. Energy Policy, Foresight Sustainable Energy Management and the Built Environment Project 36, 4584–4589. https://doi.org/10.1016/j.enpol.2008.09.007
Jamasb, T., Pollitt, M., 2008b. Liberalisation and R&D in network industries: The case of the electricity industry. Res Policy 37, 995–1008. https://doi.org/10.1016/j.respol.2008.04.010
Jamasb, T., Pollitt, M.G., 2015. Why and how to subsidise energy R+D: Lessons from the collapse and recovery of electricity innovation in the UK. Energy Policy 83, 197–205. https://doi.org/10.1016/j.enpol.2015.01.041
Jansen, J.C., Seebregts, A.J., 2010. Long-term energy services security: What is it and how can it be measured and valued? Energy Policy, Energy Security - Concepts and Indicators with regular papers 38, 1654–1664. https://doi.org/10.1016/j.enpol.2009.02.047

Jansen, J.C., van Arkel, W.G., Boots, M.G., 2004. Designing indicators of long-term energy supply security (No. ECN-C--04-007). Energy Research Centre of the Netherlands, Petten, The Netherlands.
Jaruzelski, B., Hirsh, E., 2016. The 2015 Global Innovation 1000: Automotive industry findings. PwC, Florham Park, New Jersey, USA.
Jaspal, R., Nerlich, B., 2014. Fracking in the UK press: Threat dynamics in an unfolding debate. Public Understanding of Science 23, 348–363. https://doi.org/10.1177/0963662513498835
Jeffrey, H., Jay, B., Winskel, M., 2013. Accelerating the development of marine energy: Exploring the prospects, benefits and challenges. Technological Forecasting and Social Change 80, 1306–1316. https://doi.org/10.1016/j.techfore.2012.03.004
Jeffrey, H., Sedgwick, J., Gerrard, G., 2014. Public funding for ocean energy: A comparison of the UK and U.S. Technological Forecasting and Social Change 84, 155–170. https://doi.org/10.1016/j.techfore.2013.08.006
Jeswani, H.K., Azapagic, A., 2016. Assessing the environmental sustainability of energy recovery from municipal solid waste in the UK. Waste Management 50, 346–363. https://doi.org/10.1016/j.wasman.2016.02.010
Jewell, J., 2011. The IEA Model of Short-term Energy Security (Working Paper). International Energy Agency, Paris, France.
Jewell, J., Cherp, A., Riahi, K., 2014. Energy security under de-carbonization scenarios: An assessment framework and evaluation under different technology and policy choices. Energy Policy 65, 743–760. https://doi.org/10.1016/j.enpol.2013.10.051
Johannsdottir, L., Cook, D., 2019. Systemic risk of maritime-related oil spills viewed from an Arctic and insurance perspective. Ocean & Coastal Management 179, 104853. https://doi.org/10.1016/j.ocecoaman.2019.104853
Johansen, I.L., Rausand, M., 2014. Foundations and choice of risk metrics. Safety Science 62, 386–399. https://doi.org/10.1016/j.ssci.2013.09.011
Johansson, B., 2013. A broadened typology on energy and security. Energy 53, 199–205. https://doi.org/10.1016/j.energy.2013.03.012
Johansson, B., Jonsson, D.K., Veibäck, E., Sonnsjö, H., 2016. Assessing the capabilites to manage risks in energy systems–analytical perspectives and frameworks with a starting point in Swedish experiences. Energy 116, 429–435. https://doi.org/10.1016/j.energy.2016.09.122
Johnston, D., Farmer, D., Brooke-Peat, M., Miles-Shenton, D., 2016. Bridging the domestic building fabric performance gap. Building Research & Information 44, 147–159. https://doi.org/10.1080/09613218.2014.979093
Johnston, D., Miles-Shenton, D., Farmer, D., 2015. Quantifying the domestic building fabric 'performance gap.' Building Services Engineering Research and Technology 36, 614–627. https://doi.org/10.1177/0143624415570344
Johnston, D., Siddall, M., 2016. The Building Fabric Thermal Performance of Passivhaus Dwellings—Does It Do What It Says on the Tin? Sustainability 8, 97. https://doi.org/10.3390/su8010097
Jones, C.R., Eiser, J.R., 2010. Understanding 'local' opposition to wind development in the UK: How big is a backyard? Energy Policy, The Role of Trust in Managing Uncertainties in the Transition to a Sustainable Energy Economy, Special Section with Regular Papers 38, 3106–3117. https://doi.org/10.1016/j.enpol.2010.01.051
Jones, O., Dodds, P.E., 2017. Definitions of Energy Security, in: Steinberger-Wilckens, R., Dodds, P.E., Kurban, Z., Velazquez Abad, A., Radcliffe, J. (Eds.), The Role of Hydrogen and Fuel Cells in Delivering Energy Security for the UK. H2FC SUPERGEN, Bham, UK, pp. 21–34.
Jones, R.V., Fuertes, A., Boomsma, C., Pahl, S., 2016. Space heating preferences in UK social housing: A socio-technical household survey combined with building audits. Energy and Buildings 127, 382–398. https://doi.org/10.1016/j.enbuild.2016.06.006
Jordan, S., Mitterhofer, H., Jørgensen, L., 2018. The interdiscursive appeal of risk matrices: Collective symbols, flexibility normalism and the interplay of 'risk' and 'uncertainty.' Accounting, Organizations and Soc 67, 34–55. https://doi.org/10.1016/j.aos.2016.04.003

JRC, 2014. Strategic Energy Technology (SET) plan European energy education and training initiative (No. JRC90300). Joint Research Centre, European Commission, Westerduinweg, The Netherlands.
Judge, A., Maltby, T., 2017. European Energy Union? Caught between securitisation and ‘riskification.’ Eur J International Security 2, 179–202. https://doi.org/10.1017/eis.2017.3
Jüttner, U., 2005. Supply chain risk management: Understanding the business requirements from a practitioner perspective. International Journal Logistics Management 16, 120–141. https://doi.org/10.1108/09574090510617385
Kadiri, M., Ahmadian, R., Bockelmann-Evans, B., Falconer, R.A., Kay, D., 2014. An assessment of the impacts of a tidal renewable energy scheme on the eutrophication potential of the Severn Estuary, UK. Computers & Geosciences, Marine Renewable Energy 71, 3–10. https://doi.org/10.1016/j.cageo.2014.07.018
Kadiri, M., Ahmadian, R., Bockelmann-Evans, B., Rauen, W., Falconer, R., 2012. A review of the potential water quality impacts of tidal renewable energy systems. Renewable and Sustainable Energy Reviews 16, 329–341. https://doi.org/10.1016/j.rser.2011.07.160
Kaiser, M.J., 2015. Hurricane clean-up activity in the Gulf of Mexico, 2004–2013. Marine Policy 51, 512–526. https://doi.org/10.1016/j.marpol.2014.09.001
Kaiser, M.J., Snyder, B., 2012. Modeling the decommissioning cost of offshore wind development on the U.S. Outer Continental Shelf. Marine Policy 36, 153–164. https://doi.org/10.1016/j.marpol.2011.04.008
Kane, T., Firth, S.K., Lomas, K.J., 2015. How are UK homes heated? A city-wide, socio-technical survey and implications for energy modelling. Energy and Buildings 86, 817–832. https://doi.org/10.1016/j.enbuild.2014.10.011
Katsouris, C., Sayne, A., 2013. Nigeria’s criminal crude: international options to combat the export of stolen oil. The Royal Institute of International Affairs, Chatham House, London, UK.
Ke, Y., Wang, S., Chan, A.P., 2010. Risk allocation in public-private partnership infrastructure projects: comparative study. Journal of Infrastructure Systems 16, 343–351.
Keairns, D. l., Darton, R. c., Irabien, A., 2016. The Energy-Water-Food Nexus. Annu. Rev. Chem. Biomol. Eng. 7, 239–262. https://doi.org/10.1146/annurev-chembioeng-080615-033539
Keirstead, J., 2007. Behavioural responses to photovoltaic systems in the UK domestic sector. Energy Policy 35, 4128–4141. https://doi.org/10.1016/j.enpol.2007.02.019
Kelly, K.A., McManus, M.C., Hammond, G.P., 2012. An energy and carbon life cycle assessment of tidal power case study: The proposed Cardiff–Weston severn barrage scheme. Energy, Integration and Energy System Engineering, European Symposium on Computer-Aided Process Engineering 2011 44, 692–701. https://doi.org/10.1016/j.energy.2012.05.023
Kelly, S., Pollitt, M., 2010. An assessment of the present and future opportunities for combined heat and power with district heating (CHP-DH) in the United Kingdom. Energy Policy 38, 6936–6945. https://doi.org/10.1016/j.enpol.2010.07.010
Keppler, J.H., 2007. International Relations and Security of Energy Supply: Risks to Continuity and Geopolitical Risks (No. EP/EXPO/B/AFET/2006/43). European Parliament, Brussels, Belgium.
Kerkvliet, H., Polatidis, H., 2016. Offshore wind farms’ decommissioning: a semi quantitative Multi-Criteria Decision Aid framework. Sustainable Energy Technologies and Assessments 18, 69–79. https://doi.org/10.1016/j.seta.2016.09.008
Kern, F., Kuzemko, C., Mitchell, C., 2014. Measuring and explaining policy paradigm change: the case of UK energy policy. Policy & Politics 42, 513–530. https://doi.org/10.1332/030557312X655765
Kerr, D., 2007. Marine energy. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 365, 971–992. https://doi.org/10.1098/rsta.2006.1959
Kerr, D., 2005. Marine energy: getting power from tides and waves. Proc. Inst. Civil Engineers - Civil Engineering 158, 32–39. https://doi.org/10.1680/cien.2005.158.6.32
Keys, P.W., Galaz, V., Dyer, M., Matthews, N., Folke, C., Nyström, M., Cornell, S.E., 2019. Anthropocene risk. Nat Sustain 2, 667–673. https://doi.org/10.1038/s41893-019-0327-x

Khan, N., Kalair, A., Abas, N., Haider, A., 2017. Review of ocean tidal, wave and thermal energy technologies. Renewable and Sustainable Energy Reviews 72, 590–604. https://doi.org/10.1016/j.rser.2017.01.079

Khatib, H., 2014. Oil and natural gas prospects: Middle East and North Africa. Energy Policy 64, 71–77. https://doi.org/10.1016/j.enpol.2013.07.091

Kikuchi, R., 2010. Risk formulation for the sonic effects of offshore wind farms on fish in the EU region. Marine Pollution Bul 60, 172–177. https://doi.org/10.1016/j.marpolbul.2009.09.023

Killip, G., 2013. Transition Management Using a Market Transformation Approach: Lessons for Theory, Research, and Practice from the Case of Low-Carbon Housing Refurbishment in the UK. Environ Plann C Gov Policy 31, 876–892. https://doi.org/10.1068/c11336

Killip, G., Fawcett, T., Janda, K.B., 2014. Innovation in low-energy residential renovation: UK and France. Proc. Inst. Civil Eng - Energy 167, 117–124. https://doi.org/10.1680/ener.14.00011

Killip, G., Owen, A., Morgan, E., Topouzi, M., 2018. A co-evolutionary approach to understanding construction industry innovation in renovation practices for low-carbon outcomes. The International Journal of Entrepreneurship and Innovation 19, 9–20. https://doi.org/10.1177/1465750317753933

Kim, I.S., Binfield, J., Patton, M., Zhang, L., Moss, J., 2013. Impact of increasing liquid biofuel usage on EU and UK agriculture. Food Policy 38, 59–69. https://doi.org/10.1016/j.foodpol.2012.10.006

Kim, J., Guillaume, B., Chung, J., Hwang, Y., 2015. Critical and precious materials consumption and requirement in wind energy system in the EU 27. Applied Energy 139, 327–334. https://doi.org/10.1016/j.apenergy.2014.11.003

Kirby, M.F., Law, R.J., 2010. Accidental spills at sea – Risk, impact, mitigation and the need for co-ordinated post-incident monitoring. Marine Pollution Bulletin 60, 797–803. https://doi.org/10.1016/j.marpolbul.2010.03.015

Kleindorfer, P.R., Saad, G.H., 2005. Managing Disruption Risks in Supply Chains. Production and Operations Management 14, 53–68. https://doi.org/10.1111/j.1937-5956.2005.tb00009.x

Knopper, L.D., Ollson, C.A., 2011. Health effects and wind turbines: A review of the literature. Environmental Health 10, 78. https://doi.org/10.1186/1476-069X-10-78

Kolios, A., Read, G., Ioannou, A., 2016. Application of multi-criteria decision-making to risk prioritisation in tidal energy developments. International Journal of Sustainable Energy 35, 59–74. https://doi.org/10.1080/14786451.2014.880438

Komnenic, A., 2014. Paladin Energy suspends production at Malawi uranium mine, 7 February. URL http://www.mining.com/paladin-suspends-malawi-mine-66181/ (accessed 17/4/14).

Kontovas, C.A., Psaraftis, H.N., Ventikos, N.P., 2010. An empirical analysis of IOPCF oil spill cost data. Marine Poll Bul 60, 1455–1466. https://doi.org/10.1016/j.marpolbul.2010.05.010

Koomey, J., Hultman, N.E., 2007. A reactor-level analysis of busbar costs for US nuclear plants, 1970-2005. Energy Policy 35, 5630–5642. https://doi.org/10.1016/j.enpol.2007.06.005

Krausmann, E., Renni, E., Campedel, M., Cozzani, V., 2011. Industrial accidents triggered by earthquakes, floods and lightning: lessons learned from a database analysis. Nat Hazards 59, 285–300. https://doi.org/10.1007/s11069-011-9754-3

Kretzer, U.M.H., 1993. Allocating oil leases. Resources Policy 19, 299–311. https://doi.org/10.1016/0301-4207(93)90042-L

Krewitt, W., Simon, S., Graus, W., Teske, S., Zervos, A., Schäfer, O., 2007. The 2°C scenario—A sustainable world energy perspective. Energy Policy 35, 4969–4980. https://doi.org/10.1016/j.enpol.2007.04.034

Krishnan, R., 2016. Energy security through a framework of country risks and vulnerabilities. Energy Sources, Part B: Economics, Planning, and Policy 11, 32–37. https://doi.org/10.1080/15567249.2011.563260

Kristensen, V., Aven, T., Ford, D., 2006. A new perspective on Renn and Klinke's approach to risk evaluation and management. Reliability Engineering & System Safety 91, 421–432. https://doi.org/10.1016/j.ress.2005.02.006

Krohn, S., Damborg, S., 1999. On public attitudes towards wind power. Renewable Energy, Renewable Energy Energy Efficiency, Policy and the Environment 16, 954–960. https://doi.org/10.1016/S0960-1481(98)00339-5

Kruyt, B., van Vuuren, D.P., de Vries, H.J.M., Groenenberg, H., 2009. Indicators for energy security. Energy Policy, China Energy Efficiency 37, 2166–2181. https://doi.org/10.1016/j.enpol.2009.02.006
Kucharski, J., Unesaki, H., 2015. A Policy-oriented Approach to Energy Security. Procedia Environmental Sciences, The 5th Sustainable Future for Human Security (SustaiN 2014) 28, 27–36. https://doi.org/10.1016/j.proenv.2015.07.005
Kula, E., 2015. Future generations and nuclear power—A pluralistic economic appraisal. Futures 73, 37–47. https://doi.org/10.1016/j.futures.2015.08.001
Kyllonen, S., 2014. Civil Disobedience, Climate Protests and a Rawlsian Argument for “Atmospheric” Fairness. Environ. Values 23, 593–613. https://doi.org/10.3197/096327114X13947900181671
Lago, C., Prades, A., Lechon, Y., Oltra, C., Pullen, A., Auer, H., 2015. Environmental issues, in: European Wind Energy Association (Ed.), Wind Energy - The Facts: A Guide to the Technology, Economics and Future of Wind Power. Earthscan, London, UK, pp. 307–411.
Lange, I., Moro, M., Traynor, L., 2014. Green hypocrisy?: Environmental attitudes and residential space heating expenditure. Ecological Economics 107, 76–83. https://doi.org/10.1016/j.ecolecon.2014.07.021
Langsam, J.A., Fouque, J.-P. (Eds.), 2013. Handbook on Systemic Risk. Cambridge University Press, New York, USA.
Langston, R.H.W., 2013. Birds and wind projects across the pond: A UK perspective. Wildlife Society Bulletin 37, 5–18. https://doi.org/10.1002/wsb.262
Larson, E.D., Li, Z., Williams, R.H., 2012. Chapter 12 - Fossil Energy, in: Global Energy Assessment - Toward a Sustainable Future. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 901–992.
Last, M., Finn, A., 2015a. UK Shale Processing: Part 1. Hydrocarbon Engineering 56–60.
Last, M., Finn, A., 2015b. UK Shale Processing: Part 2. Hydrocarbon Engineering 26–30.
Lawrence, J., Sedgwick, J., Jeffrey, H., Bryden, I., 2013. An Overview of the U.K. Marine Energy Sector. Proc.IEEE 101, 876–890. https://doi.org/10.1109/JPROC.2012.2235055
Lazarevic, D., 2018. The legitimacy of life cycle assessment in the waste management sector. Int J Life Cycle Assess 23, 1415–1428. https://doi.org/10.1007/s11367-015-0884-9
LCICG, 2012a. Technology Innovation Needs Assessment: Marine Energy. Low Carbon Innovation Coordination Group.
LCICG, 2012b. Technology Innovation Needs Assessment: Bio-energy. Low Carbon Innovation Coordination Group.
LCICG, 2012c. Technology Innovation Needs Assessment: Industrial Sector. Low Carbon Innovation Coordination Group.
LCICG, 2012d. Technology Innovation Needs Assessment: Electricity Networks & Storage. Low Carbon Innovation Coordination Group.
LCICG, 2016a. Technology Innovation Needs Assessment: Solar Photovoltaic and Thermal Technologies. Low Carbon Innovation Coordination Group.
LCICG, 2016b. Technology Innovation Needs Assessment: Heat. Low Carbon Innovation Coordination Group.
LCICG, 2016c. Technology Innovation Needs Assessment: Domestic Buildings. Low Carbon Innovation Coordination Group.
LCICG, 2016d. Technology Innovation Needs Assessment: Non-Domestic Buildings. Low Carbon Innovation Coordination Group.
LCICG, 2016e. Technology Innovation Needs Assessment: Nuclear Fission. Low Carbon Innovation Coordination Group.
Le Coq, C., Paltseva, E., 2009. Measuring the security of external energy supply in the European Union. Energy Policy 37, 4474–4481. https://doi.org/10.1016/j.enpol.2009.05.069
Le Fevre, C., 2013. Gas storage in Great Britain (No. NG 72). Oxford Institute for Energy Studies, Oxford, UK.

Leal-Arcas, R., Lasniewska, F., Proedrou, F., 2017. Smart grids in the European Union: Assessing energy security, regulation and social and ethical considerations (Legal Studies Research Paper No. 263/2017), School of Law. Queen Mary University of London, London, UK.
Lecompte, S., Huisseune, H., van den Broek, M., Vanslambrouck, B., De Paepe, M., 2015. Review of organic Rankine cycle (ORC) architectures for waste heat recovery. Renewable and Sustainable Energy Reviews 47, 448–461. https://doi.org/10.1016/j.rser.2015.03.089
Ledwoch, A., Brintrup, A., Mehnen, J., Tiwari, A., 2018. Systemic Risk Assessment in Complex Supply Networks. IEEE Systems Journal 12, 1826–1837. https://doi.org/10.1109/JSYST.2016.2596999
Leete, S., Xu, J., Wheeler, D., 2013. Investment barriers and incentives for marine renewable energy in the UK: An analysis of investor preferences. Energy Policy 60, 866–875. https://doi.org/10.1016/j.enpol.2013.05.011
Lefèvre, N., 2010. Measuring the energy security implications of fossil fuel resource concentration. Energy Policy, Energy Security - Concepts and Indicators with regular papers 38, 1635–1644. https://doi.org/10.1016/j.enpol.2009.02.003
Lekka, C., Sugden, C., 2011. The successes and challenges of implementing high reliability principles: A case study of a UK oil refinery. Process Safety and Environmental Protection, Special Issue: Centenary of the Health and Safety Issue 89, 443–451. https://doi.org/10.1016/j.psep.2011.07.003
Lenzen, M., Malik, A., Foran, B., 2016. Decoupling global environmental pressure and economic growth: scenarios for energy use, materials use and carbon emissions. Journal of Cleaner Production 132, 45–56. https://doi.org/10.1016/j.jclepro.2015.06.100
Lesbirel, S.H., 2004. Diversification and Energy Security Risks: The Japanese Case. Japanese Journal of Political Science 5, 1–22. https://doi.org/10.1017/S146810990400129X
Levi, P.G., Pollitt, M.G., 2015. Cost trajectories of low carbon electricity generation technologies in the UK: A study of cost uncertainty. Energy Policy 87, 48–59. https://doi.org/10.1016/j.enpol.2015.08.003
Levidow, L., Papaioannou, T., 2016. Policy-driven, narrative-based evidence gathering: UK priorities for decarbonisation through biomass. Science and Public Policy 43, 46–61. https://doi.org/10.1093/scipol/scv016
Levidow, L., Papaioannou, T., 2014. UK Biofuel Policy: Envisaging Sustainable Biofuels, Shaping Institutions and Futures. Environment and Planning A 46, 280–298. https://doi.org/10.1068/a45711
Levidow, L., Papaioannou, T., 2013. State imaginaries of the public good: shaping UK innovation priorities for bioenergy. Environmental Science & Policy, SI: Environmental and Developmental Discourses: Technical knowledge, discursive spaces and politics 30, 36–49. https://doi.org/10.1016/j.envsci.2012.10.008
Levidow, L., Upham, P., 2017. Linking the multi-level perspective with social representations theory: Gasifiers as a niche innovation reinforcing the energy-from-waste (EfW) regime. Tech Forecasting and Social Change 120, 1–13. https://doi.org/10.1016/j.techfore.2017.03.028
Levine, E.S., 2012. Improving risk matrices: the advantages of logarithmically scaled axes. Journal of Risk Research 15, 209–222. https://doi.org/10.1080/13669877.2011.634514
Lewis, C., Speirs, J., MacSweeney, R., 2014. Getting ready for UK shale gas: Supply chain and skills requirements and opportunities. Ernst and Young, London, UK.
Lewis, M.J., Angeloudis, A., Robins, P.E., Evans, P.S., Neill, S.P., 2017. Influence of storm surge on tidal range energy. Energy 122, 25–36. https://doi.org/10.1016/j.energy.2017.01.068
Li, F.G.N., 2017. Actors behaving badly: Exploring the modelling of non-optimal behaviour in energy transitions. Energy Strat Rev 15, 57–71. https://doi.org/10.1016/j.esr.2017.01.002
Li, F.G.N., Trutnevyte, E., 2017. Investment appraisal of cost-optimal and near-optimal pathways for the UK electricity sector transition to 2050. Applied Energy 189, 89–109. https://doi.org/10.1016/j.apenergy.2016.12.047
Lieb-Dóczy, E., Börner, A.-R., MacKerron, G., 2003. Who Secures the Security of Supply? European Perspectives on Security, Competition, and Liability. The Electricity Journal 16, 10–19. https://doi.org/10.1016/j.tej.2003.10.008

Linares, P., Conchado, A., 2013. The economics of new nuclear power plants in liberalized electricity markets. Egy Econ 40, S119–S125. https://doi.org/10.1016/j.eneco.2013.09.007

Liotta, P.H., Shearer, A.W., 2008. Zombie Concepts and Boomerang Effects, in: Liotta, P.H., Mouat, D.A., Kepner, W.G., Lancaster, J.M. (Eds.), Environmental Change and Human Security: Recognizing and Acting on Hazard Impacts, NATO Science for Peace and Security Series C: Environmental Security. Springer, Dordrecht, Netherlands, pp. 9–33. https://doi.org/10.1007/978-1-4020-8551-2_2

Liss, C., 2011. Indicators for Energy Security, in: Sovacool, B.K. (Ed.), The Routledge Handbook of Energy Security. Routledge, Abingdon, UK, pp. 113–128.

Lister, J., Poulsen, R.T., Ponte, S., 2015. Orchestrating transnational environmental governance in maritime shipping. Global Environmental Change 34, 185–195. https://doi.org/10.1016/j.gloenvcha.2015.06.011

Littlewood, J., Murphy, R.J., Wang, L., 2013. Importance of policy support and feedstock prices on economic feasibility of bioethanol production from wheat straw in the UK. Renewable and Sustainable Energy Reviews 17, 291–300. https://doi.org/10.1016/j.rser.2012.10.002

Liu, Y., 2018. Role of a forward-capacity market to promote electricity use reduction in the residential sector—a case study of the potential of social housing participation in the Electricity Demand Reduction Pilot in the UK. Energy Efficiency 11, 799–822. https://doi.org/10.1007/s12053-017-9607-3

Löfstedt, R.E., Renn, O., 1997. The Brent Spar Controversy: An Example of Risk Communication Gone Wrong. Risk Analysis 17, 131–136. https://doi.org/10.1111/j.1539-6924.1997.tb00852.x

Long, D., 2001. The Western Frontiers Association — Evaluating seabed conditions west of the UK. Continental Shelf Research, The Marine Environment of the North East Atlantic Margin 21, 811–824. https://doi.org/10.1016/S0278-4343(00)00114-X

Long, T.B., Young, W., Webber, P., Gouldson, A., Harwatt, H., 2015. The impact of domestic energy efficiency retrofit schemes on householder attitudes and behaviours. J. Env Planning and Management 58, 1853–1876. https://doi.org/10.1080/09640568.2014.965299

Lordan, R., Spada, M., Burgherr, P., 2015. Import-adjusted fatality rates for individual Organization for Economic Cooperation and Development (OECD) countries caused by accidents in the oil energy chain. Journal of Cleaner Production 108, Part A, 1203–1212. https://doi.org/10.1016/j.jclepro.2015.08.097

Löschel, A., Moslener, U., Rübbelke, D.T.G., 2010. Indicators of energy security in industrialised countries. Energy Policy, Energy Security - Concepts and Indicators with regular papers 38, 1665–1671. https://doi.org/10.1016/j.enpol.2009.03.061

Loucari, C., Taylor, J., Raslan, R., Oikonomou, E., Mavrogianni, A., 2016. Retrofit solutions for solid wall dwellings in England: The impact of uncertainty upon the energy performance gap. Building Serv Eng Res & Tech 37, 614–634. https://doi.org/10.1177/0143624416647758

Love, J., Smith, A.Z.P., Watson, S., Oikonomou, E., Summerfield, A., Gleeson, C., Biddulph, P., Chiu, L.F., Wingfield, J., Martin, C., Stone, A., Lowe, R., 2017. The addition of heat pump electricity load profiles to GB electricity demand: Evidence from a heat pump field trial. Applied Energy 204, 332–342. https://doi.org/10.1016/j.apenergy.2017.07.026

Lovelace, R., Beck, S.B.M., Watson, M., Wild, A., 2011. Assessing the energy implications of replacing car trips with bicycle trips in Sheffield, UK. Energy Policy 39, 2075–2087. https://doi.org/10.1016/j.enpol.2011.01.051

Lovett, A., Sünnenberg, G., Dockerty, T., 2014. The availability of land for perennial energy crops in Great Britain. GCB Bioenergy 6, 99–107. https://doi.org/10.1111/gcbb.12147

Lowes, R., Woodman, B., Clark, M., 2018. A transformation to sustainable heating in the UK: risks and opportunities for UK heat sector businesses (Working Paper). UK Energy Research Centre, London, UK.

Lu, L., Thies, C.G., 2013. War, Rivalry, and State Building in the Middle East. Political Research Quarterly 66, 239–253.

LUC, Ecotec, 2001. Sustainability assessment of Renewable Energy Projects. Research report prepared for ETSU and The Countryside Agency by Land Use Consultants and Ecotec Research and Consulting (No. URN: 02/853). Department for Trade and Industry.

Lucia, U., Simonetti, M., Chiesa, G., Grisolia, G., 2017. Ground-source pump system for heating and cooling: Review and thermodynamic approach. Renewable and Sustainable Energy Reviews 70, 867–874. https://doi.org/10.1016/j.rser.2016.11.268
Lukawski, M.Z., Silverman, R.L., Tester, J.W., 2016. Uncertainty analysis of geothermal well drilling and completion costs. Geothermics 64, 382–391. https://doi.org/10.1016/j.geothermics.2016.06.017
Lunardi, M.M., Moore, S., Alvarez-Gaitan, J.P., Yan, C., Hao, X., Corkish, R., 2018. A comparative life cycle assessment of chalcogenide/Si tandem solar modules. Energy 145, 700–709. https://doi.org/10.1016/j.energy.2017.12.130
Lupa, C.J., Ricketts, L.J., Sweetman, A., Herbert, B.M.J., 2011. The use of commercial and industrial waste in energy recovery systems – A UK preliminary study. Waste Management 31, 1759–1764. https://doi.org/10.1016/j.wasman.2011.04.002
Lyons, G.J., 2000. Offshore technology—advances at the dawn of the new millennium reviewed from a UK perspective. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering 214, 1–21.
Ma, L., Spataru, C., 2015. The use of natural gas pipeline network with different energy carriers. Energy Strategy Reviews 8, 72–81. https://doi.org/10.1016/j.esr.2015.09.002
MacDougall, S.L., 2017. Confronting the financing impasse: Risk management through internationally staged investments in tidal energy development. International Journal of Marine Energy 18, 78–87. https://doi.org/10.1016/j.ijome.2017.03.002
MacGillivray, A., Jeffrey, H., Winskel, M., Bryden, I., 2014. Innovation and cost reduction for marine renewable energy: A learning investment sensitivity analysis. Technological Forecasting and Social Change 87, 108–124. https://doi.org/10.1016/j.techfore.2013.11.005
MacKenzie, C.A., 2014. Summarizing Risk Using Risk Measures and Risk Indices. Risk Analysis 34, 2143–2162. https://doi.org/10.1111/risa.12220
Mackinnon, K., Smith, H.C.M., Moore, F., van der Weijde, A.H., Lazakis, I., 2018. Environmental interactions of tidal lagoons: A comparison of industry perspectives. Renewable Energy 119, 309–319. https://doi.org/10.1016/j.renene.2017.11.066
Macknick, J., Newmark, R., Heath, G., Hallett, K.C., 2011. A review of operational water consumption and withdrawal factors for electricity generating technologies (Technical Report No. NREL/TP-6A20-50900). National Renewable Energy Lab, Golden, Colorado, USA.
MacLean, K., Sansom, R., Watson, T., Gross, R., 2016a. Managing Heat System Decarbonisation: Comparing the impacts and costs of transitions in heat infrastructure. Centre for Energy Policy and Technology, Imperial College London, London, UK.
MacLean, K., Sansom, R., Watson, T., Gross, R., 2016b. Managing Heat System Decarbonisation: Comparing the impacts and costs of transitions in heat infrastructure (annexes and literature review). Centre for Energy Policy and Technology, Imperial College London, London, UK.
Malinka, C.E., Gillespie, D.M., Macaulay, J.D.J., Joy, R., Sparling, C.E., 2018. First in situ passive acoustic monitoring for marine mammals during operation of a tidal turbine in Ramsey Sound, Wales. Marine Ecology Progress Series 590, 247–266. https://doi.org/10.3354/meps12467
Malkawi, S., Al-Nimr, M., Azizi, D., 2017. A multi-criteria optimization analysis for Jordan's energy mix. Energy 127, 680–696. https://doi.org/10.1016/j.energy.2017.04.015
Mallaburn, P.S., Eyre, N., 2014. Lessons from energy efficiency policy and programmesin the UK from 1973 to 2013. Energy Eff 7, 23–41. https://doi.org/10.1007/s12053-013-9197-7
Månsson, A., Johansson, B., Nilsson, L.J., 2014. Assessing energy security: An overview of commonly used methodologies. Energy 73, 1–14. https://doi.org/10.1016/j.energy.2014.06.073
Marchant, C.J., 1997. The uk - continent gas inerconnector. Proceedings of the Institution of Civil Engineers - Civil Engineering 120, 66–73. https://doi.org/10.1680/icien.1997.29329
Marchenko, N., Andreassen, N., Borch, O.J., Kuznetsova, S., Ingimundarson, V., Jakobsen, U., 2018. Arctic Shipping and Risks: Emergency Categories and Response Capacities. TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation 12, 107–114. https://doi.org/10.12716/1001.12.01.12
Mariaud, A., Acha, S., Ekins-Daukes, N., Shah, N., Markides, C.N., 2017. Integrated optimisation of photovoltaic and battery storage systems for UK commercial buildings. Applied Energy 199, 466–478. https://doi.org/10.1016/j.apenergy.2017.04.067

Markewitz, P., Kuckshinrichs, W., Leitner, W., Linssen, J., Zapp, P., Bongartz, R., Schreiber, A., Müller, T.E., 2012. Worldwide innovations in the development of carbon capture technologies and the utilization of CO2. Egy Env Sci 5, 7281–7305. https://doi.org/10.1039/C2EE03403D

Marshall, A., Fitton, R., Swan, W., Farmer, D., Johnston, D., Benjaber, M., Ji, Y., 2017. Domestic building fabric performance: Closing the gap between the in situ measured and modelled performance. Energy & Buildings 150, 307–317. https://doi.org/10.1016/j.enbuild.2017.06.028

Martin, N.P.D., Bishop, J.D.K., Boies, A.M., 2017. Emissions, performance, and design of UK passenger vehicles. International Journal of Sustainable Transportation 11, 230–236. https://doi.org/10.1080/15568318.2016.1243282

Martínez Ceseña, E.A., Good, N., Syrri, A.L.A., Mancarella, P., 2018. Techno-economic and business case assessment of multi-energy microgrids with co-optimization of energy, reserve and reliability services. App Egy 210, 896–913. https://doi.org/10.1016/j.apenergy.2017.08.131

Martin-Short, R., Hill, J., Kramer, S.C., Avdis, A., Allison, P.A., Piggott, M.D., 2015. Tidal resource extraction in the Pentland Firth, UK: Potential impacts on flow regime and sediment transport in the Inner Sound of Stroma. Renewable Energy 76, 596–607. https://doi.org/10.1016/j.renene.2014.11.079

Masden, E.A., Cook, A.S.C.P., 2016. Avian collision risk models for wind energy impact assessments. Env Impact Assessment Rev 56, 43–49. https://doi.org/10.1016/j.eiar.2015.09.001

Masden, E.A., Foster, S., Jackson, A.C., 2013. Diving behaviour of Black Guillemots *Cepphus grylle* in the Pentland Firth, UK: potential for interactions with tidal stream energy developments. Bird Study 60, 547–549. https://doi.org/10.1080/00063657.2013.842538

Mather, T.A., Harrison, R.G., Tsanev, V.I., Pyle, D.M., Karumudi, M.L., Bennett, A.J., Sawyer, G.M., Highwood, E.J., 2007. Observations of the Plume Generated by the December 2005 Oil Depot Explosions and Prolonged Fire at Buncefield (Hertfordshire, UK) and Associated Atmospheric Changes. Proc: Mathematical, Physical and Eng Sciences 463, 1153–1177.

Mazzucato, M., Semieniuk, G., 2018. Financing renewable energy: Who is financing what and why it matters. Technological Forecasting and Social Change 127, 8–22. https://doi.org/10.1016/j.techfore.2017.05.021

McAleenan, C., Weatherup, R., Bogle, G., McAleenan, P., 2015. Shale gas extraction – the case for a multi-disciplinary study. Proceedings of the Institution of Civil Engineers - Energy 168, 41–46. https://doi.org/10.1680/ener.14.00022

McGlade, C., Speirs, J., Sorrell, S., 2013a. Unconventional gas – A review of regional and global resource estimates. Energy 55, 571–584. https://doi.org/10.1016/j.energy.2013.01.048

McGlade, C., Speirs, J., Sorrell, S., 2013b. Methods of estimating shale gas resources – Comparison, evaluation and implications. Energy 59, 116–125. https://doi.org/10.1016/j.energy.2013.05.031

McIlveen-Wright, D.R., Huang, Y., Rezvani, S., Redpath, D., Anderson, M., Dave, A., Hewitt, N.J., 2013. A technical and economic analysis of three large scale biomass combustion plants in the UK. App En 112, 396–404. https://doi.org/10.1016/j.apenergy.2012.12.051

McLeod, C., Nerlich, B., Mohr, A., 2017. Working with bacteria and putting bacteria to work: The biopolitics of synthetic biology for energy in the United Kingdom. Energy Research & Social Science, Exploring the Anthropology of Energy: Ethnography, Energy and Ethics 30, 35–42. https://doi.org/10.1016/j.erss.2017.06.017

McMahon, R., Santos, H., Mourão, Z.S., 2018. Practical considerations in the deployment of ground source heat pumps in older properties—A case study. Energy and Buildings 159, 54–65. https://doi.org/10.1016/j.enbuild.2017.08.067

Membere, E., Sallis, P., 2018. Thermochemical characterization of brown seaweed, Laminaria digitata from UK shores. Journal of Analytical and Applied Pyrolysis 131, 42–51. https://doi.org/10.1016/j.jaap.2018.02.011

Mendes, P.A.S., Hall, J., Matos, S., Silvestre, B., 2014. Reforming Brazil′s offshore oil and gas safety regulatory framework: Lessons from Norway, the United Kingdom and the United States. Energy Policy 74, 443–453. https://doi.org/10.1016/j.enpol.2014.08.014

Meyer, A., Pac, G., 2017. Analyzing the characteristics of plants choosing to opt-out of the Large Combustion Plant Directive. Utilities Policy 45, 61–68. https://doi.org/10.1016/j.jup.2017.02.001

MHCLG, 2018. English Housing Survey: Stock condition, 2016. Ministry of Housing, Communities and Local Government, London, UK.
Middleton, R.S., Gupta, R., Hyman, J.D., Viswanathan, H.S., 2017. The shale gas revolution: Barriers, sustainability, and emerging opportunities. Applied Energy 199, 88–95. https://doi.org/10.1016/j.apenergy.2017.04.034
Mielke, E., Diaz Anadon, L., Narayanamurti, V., 2010. Water consumption of energy resource extraction, processing, and conversion: A review of the literature for estimates of water intensity of energy-resource extraction, processing to fuels, and conversion to electricity (Discussion Paper No. No. 2010-15), Energy Technology Innovation. Belfer Center for Science and Int Affairs, Harvard-Kennedy Sch, Harvard Univ, Cambridge, USA.
Milledge, J.J., Harvey, P.J., 2016. Potential process 'hurdles' in the use of macroalgae as feedstock for biofuel production in the British Isles: Potential process 'hurdles' in the use of macroalgae as feedstock. Journal of Chemical Technology & Biotechnology 91, 2221–2234. https://doi.org/10.1002/jctb.5003
Miller, D.D., Tooley, K., Sumaila, U.R., 2015. Large-scale oil spills and flag-use within the global tanker fleet. Environmental Conservation 42, 119–125.
Mills, N., Pearce, P., Farrow, J., Thorpe, R.B., Kirkby, N.F., 2014. Environmental & economic life cycle assessment of current & future sewage sludge to energy technologies. Waste Management 34, 185–195. https://doi.org/10.1016/j.wasman.2013.08.024
Mitchell, C., 2007. The Political Economy of Sustainable Energy. Palgrave Macmillan, Basingstoke, UK.
Mitchell, C., 1991. Coal-bed methane in the UK. Energy Policy 19, 849–854. https://doi.org/10.1016/0301-4215(91)90010-L
Mitchell, E.J.S., Coulson, G., Butt, E.W., Forster, P.M., Jones, J.M., Williams, A., 2017. Heating with Biomass in the United Kingdom: Lessons from New Zealand. Atmospheric Environment 152, 431–454. https://doi.org/10.1016/j.atmosenv.2016.12.042
Mitchell, J.V., Mitchell, B., 2014. Structural crisis in the oil and gas industry. Energy Policy 64, 36–42. https://doi.org/10.1016/j.enpol.2013.07.094
Mola-Yudego, B., Arevalo, J., Díaz-Yáñez, O., Dimitriou, I., Freshwater, E., Haapala, A., Khanam, T., Selkimäki, M., 2017. Reviewing wood biomass potentials for energy in Europe: the role of forests and fast growing plantations. Biofuels 8, 401–410. https://doi.org/10.1080/17597269.2016.1271627
Mola-Yudego, B., Díaz-Yáñez, O., Dimitriou, I., 2015. How Much Yield Should We Expect from Fast-Growing Plantations for Energy? Divergences Between Experiments and Commercial Willow Plantations. BioEnergy Res 8, 1769–1777. https://doi.org/10.1007/s12155-015-9630-1
Molyneaux, L., Brown, C., Wagner, L., Foster, J., 2016. Measuring resilience in energy systems: Insights from a range of disciplines. Renewable and Sustainable Energy Reviews 59, 1068–1079. https://doi.org/10.1016/j.rser.2016.01.063
Monahan, J., Powell, J.C., 2011. A comparison of the energy and carbon implications of new systems of energy provision in new build housing in the UK. Energy Policy 39, 290–298. https://doi.org/10.1016/j.enpol.2010.09.041
Montingelli, M.E., Tedesco, S., Olabi, A.G., 2015. Biogas production from algal biomass: A review. Renewable & Sustainable Energy Rev 43, 961–972. https://doi.org/10.1016/j.rser.2014.11.052
Morad, K., 2012. Selected topics in coalbed methane reservoirs. Journal of Natural Gas Science and Engineering, Unconventional Natural Gas 8, 99–105. https://doi.org/10.1016/j.jngse.2011.10.005
Moran, F., Natarajan, S., 2015. PV in historic dwellings: The potential to reduce domestic CO2 emissions. J. Building Engineering 3, 70–78. https://doi.org/10.1016/j.jobe.2015.06.004
Moro, A., Boelman, E., Joanny, G., Garcia, J.L., 2018. A bibliometric-based technique to identify emerging photovoltaic technologies in a comparative assessment with expert review. Renewable Energy 123, 407–416. https://doi.org/10.1016/j.renene.2018.02.016
Moroke, T., Schoeman, C., Schoeman, I., 2019. Developing a neighbourhood sustainability assessment model: An approach to sustainable urban development. Sustainable Cities and Society 48, 101433. https://doi.org/10.1016/j.scs.2019.101433

Mueller, M., Jeffrey, H., Wallace, R., von Jouanne, A., 2010. Centers for Marine Renewable Energy in Europe and North America. Oceanography 23, 42–52. https://doi.org/10.5670/oceanog.2010.42
Muhammad-Sukki, F., Ramirez-Iniguez, R., Munir, A.B., Mohd Yasin, S.H., Abu-Bakar, S.H., McMeekin, S.G., Stewart, B.G., 2013. Revised feed-in tariff for solar photovoltaic in the United Kingdom: A cloudy future ahead? Energy Policy, 52, 832–838. https://doi.org/10.1016/j.enpol.2012.09.062
Mukherjee, D., Rahman, M.A., 2016. To drill or not to drill? An econometric analysis of US public opinion. Energy Policy 91, 341–351. https://doi.org/10.1016/j.enpol.2015.11.023
Murrant, D., Quinn, A., Chapman, L., 2015. The water-energy nexus: future water resource availability and its implications on UK thermal power generation. Water Environ. J. 29, 307–319. https://doi.org/10.1111/wej.12126
Mustanen, D., Fianu, J., Pucknell, J., 2017. Account of hydraulically fractured onshore wells in the UK and seismicity associated with these wells. Journal of Petroleum Science and Engineering 158, 202–221. https://doi.org/10.1016/j.petrol.2017.07.053
Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., 2013. Anthropogenic and Natural Radiative Forcing, in: Stocker, T.F., Qin, D., Plattner, C.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ Press, Cambridge, UK, pp. 659–740.
Mylona, Z., Kolokotroni, M., Tassou, S.A., 2017. Frozen food retail: Measuring and modelling energy use and space environmental systems in an operational supermarket. Energy and Buildings 144, 129–143. https://doi.org/10.1016/j.enbuild.2017.03.049
Nakandala, D., Lau, H., Zhao, L., 2017. Development of a hybrid fresh food supply chain risk assessment model. International Journal of Production Research 55, 4180–4195. https://doi.org/10.1080/00207543.2016.1267413
NAO, 2013. Planning for economic infrastructure (No. HC 595). National Audit Off, London, UK.
NAO, 2016. Nuclear power in the UK (No. HC 511). National Audit Office, London, UK.
Narula, K., Reddy, B.S., 2015. Three blind men and an elephant: The case of energy indices to measure energy security and energy sustainability. Energy 80, 148–158. https://doi.org/10.1016/j.energy.2014.11.055
Nassar, N.T., Du, X., Graedel, T.E., 2015. Criticality of the Rare Earth Elements. Journal of Industrial Ecology 19, 1044–1054. https://doi.org/10.1111/jiec.12237
National Grid, 2017. Future Energy Scenarios (No. 4031152). National Grid, Warwick, UK.
Navarro-Espinosa, A., Mancarella, P., 2014. Probabilistic modeling and assessment of the impact of electric heat pumps on low voltage distribution networks. Applied Energy 127, 249–266. https://doi.org/10.1016/j.apenergy.2014.04.026
Nazroo, M., 1989. Operating experience with the experimental HDR system at the Camborne School of Mines (geothermal power), in: IEE Colloquium on Recent Progress in the Development of Geothermal Hot Dry Rock Technology. IEE Colloquium on Recent Progress in the Development of Geothermal Hot Dry Rock Technology.
NDA, 2015. Programmes and Major Projects Report: Sellafield. Nuclear Decommissioning Authority, Moor Row, UK.
NDA, 2016. Strategy: effective from April 2016. Nuclear Decommissioning Auth, Moor Row, UK.
NEA, IAEA, 2016. Uranium 2016: Resources, Production and Demand. A Joint Report by the Nuclear Energy Agency and the International Atomic Energy Agency (No. NEA No. 7301). OECD, Boulogne-Billancourt, France.
Neill, S.P., Lewis, M.J., Hashemi, M.R., Slater, E., Lawrence, J., Spall, S.A., 2014. Inter-annual and inter-seasonal variability of the Orkney wave power resource. Applied Energy 132, 339–348. https://doi.org/10.1016/j.apenergy.2014.07.023
Neill, S.P., Litt, E.J., Couch, S.J., Davies, A.G., 2009. The impact of tidal stream turbines on large-scale sediment dynamics. Renewable Energy 34, 2803–2812. https://doi.org/10.1016/j.renene.2009.06.015

Neumüller, C., Kellner, F., Gupta, J.N.D., Lasch, R., 2015. Integrating three-dimensional sustainability in distribution centre selection: the process analysis method-based analytic network process. International Journal of Production Research 53, 409–434. https://doi.org/10.1080/00207543.2014.939241
Neuparth, T., Moreira, S.M., Santos, M.M., Reis-Henriques, M.A., 2012. Review of oil and HNS accidental spills in Europe: Identifying major environmental monitoring gaps and drawing priorities. Marine Poll Bul 64, 1085–1095. https://doi.org/10.1016/j.marpolbul.2012.03.016
Neven, L., Walker, G., Brown, S., 2015. Sustainable thermal technologies and care homes: Productive alignment or risky investment? Energy Policy 84, 195–203. https://doi.org/10.1016/j.enpol.2014.11.027
Newbery, D., Grubb, M., 2015. Security of Supply, the Role of Interconnectors and Option Values : insights from the GB Capacity Auction. Economics of Energy & Environmental Policy 4. https://doi.org/10.5547/2160-5890.4.2.dnew
Ni, H., Chen, A., Chen, N., 2010. Some extensions on risk matrix approach. Safety Science 48, 1269–1278. https://doi.org/10.1016/j.ssci.2010.04.005
Nian, Y.-L., Cheng, W.-L., 2018. Insights into geothermal utilization of abandoned oil and gas wells. Renewable and Sustainable Energy Reviews 87, 44–60. https://doi.org/10.1016/j.rser.2018.02.004
NIC, 2016. Smart Power. National Infrastructure Commission, London, UK.
NIC, 2018. National Infrastructure Assessment. National Infrastructure Commission, London, UK.
Nickel, R., 2014. Uranium producer Cameco scraps production target, 7 February. Reuters. URL https://www.reuters.com/article/cameco-results/update-1-uranium-producer-cameco-scraps-production-target-idUSL2N0LD02K20140208 (accessed 17/4/14).
Nieto, A., Guelly, K., Kleit, A., 2013. Addressing criticality for rare earth elements in petroleum refining: The key supply factors approach. Resources Policy 38, 496–503. https://doi.org/10.1016/j.resourpol.2013.08.001
Nixon, J.D., Wright, D.G., Dey, P.K., Ghosh, S.K., Davies, P.A., 2013. A comparative assessment of waste incinerators in the UK. Waste Management 33, 2234–2244. https://doi.org/10.1016/j.wasman.2013.08.001
Noland, R.B., Polak, J.W., Bell, M.G.H., Thorpe, N., 2003. How much disruption to activities could fuel shortages cause? – The British fuel crisis of September 2000. Transportation 30, 459–481. https://doi.org/10.1023/A:1024790101698
NPSA, 2008. A risk matrix for risk managers (No. 0676). Natl Patient Safety Agy, London, UK.
NSSG, 2016. Nuclear Skills Strategic Plan. Nuclear Skills Strategy Group, Warrington, UK.
NSSG, 2017. Nuclear Workforce Assessment: Summary. Nuclear Skills Strategy Group, Warrington, UK.
Nuuttila, H.K., Bertelli, C.M., Mendzil, A., Dearle, N., 2018. Seasonal and diel patterns in cetacean use and foraging at a potential marine renewable energy site. Marine Pollution Bulletin 129, 633–644. https://doi.org/10.1016/j.marpolbul.2017.10.051
Ó Broin, E., Nässén, J., Johnsson, F., 2015. The influence of price and non-price effects on demand for heating in the EU residential sector. Energy 81, 146–158. https://doi.org/10.1016/j.energy.2014.12.003
O'Donnell, M.C., Gilfillan, S.M.V., Edlmann, K., McDermott, C.I., 2018. Wastewater from hydraulic fracturing in the UK: assessing the viability and cost of management. Environ. Sci.: Water Res. Technol. 4, 325–335. https://doi.org/10.1039/C7EW00474E
Ofgem, 2009a. Regulating Energy Networks for the Future: RPI-X@20 History of Energy Network Regulation (No. 13b/09).
Ofgem, 2009b. Innovation in energy networks: Is more needed and how can this be stimulated? (Working Paper No. 2), Regulating energy networks for the future: RPI-X@20. Office of Gas and Electricity Markets, London, UK.
Ofgem, 2010a. Regulating energy networks for the future: RPI-X@20 Recommendations:Implementing Sustainable Network Regulation (Supporting paper). Office of Gas and Electricity Markets, London, UK.
Ofgem, 2010b. RIIO: a new way to regulate energy networks (Final Decision No. 128/10). Office of Gas and Electricity Markets, London, UK.

Ofgem, 2014. Consultation on a proposal to make a market investigation reference in respect of the supply and acquisition of energy in Great Britain. Office of Gas and Electricity Markets, London, UK.
Ofgem, 2017. Our strategy for regulating the future energy system. Office of Gas and Electricity Markets, London, UK.
OGA, 2016a. Supply Chain Strategy. Oil and Gas Authority, Aberdeen, UK.
OGA, 2016b. Decommissioning Delivery Programme. Oil and Gas Authority, Aberdeen, UK.
OGA, 2016c. OGA Overview 2016. Oil and Gas Authority, Aberdeen, UK.
OGUK, 2016. Environmental Report 2016. Oil and Gas UK, London, UK.
O'Keeffe, J.M., Gilmour, D., Simpson, E., 2016. A network approach to overcoming barriers to market engagement for SMEs in energy efficiency initiatives such as the Green Deal. Energy Policy 97, 582–590. https://doi.org/10.1016/j.enpol.2016.08.006
Olaniyan, M.J., Evans, J., 2014. The importance of engaging residential energy customers' hearts and minds. Energy Policy 69, 273–284. https://doi.org/10.1016/j.enpol.2013.12.023
Olave, R.J., Forbes, E.G.A., Johnston, C.R., Relf, J., 2017. Particulate and gaseous emissions from different wood fuels during combustion in a small-scale biomass heating system. Atmospheric Environment 157, 49–58. https://doi.org/10.1016/j.atmosenv.2017.03.003
Oldmeadow, E., Marinova, D., Birks, D., Whittall, S., Brown, S., 2011. Low Temperature Geothermal Applications as Enablers of Sustainable Development: Practical Case Studies from Australia and UK. Water Resoure Mgt 25, 3053–3071. https://doi.org/10.1007/s11269-011-9785-2
O'Leary, F., Bazilian, M., Howley, M., Ó Gallachóir, B., 2007. Security of Supply in Ireland. Sustainable Energy Ireland, Dublin, Ireland.
Olumayegun, O., Wang, M., Kelsall, G., 2016. Closed-cycle gas turbine for power generation: A state-of-the-art review. Fuel 180, 694–717. https://doi.org/10.1016/j.fuel.2016.04.074
Olz, S., Sims, R., Kirchner, N., 2007. Contribution of renewables to Energy Security (Information Paper). International Energy Agency, Paris, France.
ONR, 2013. Chief Nuclear Inspector's Annual Report. Office for Nuclear Regulation.
Oreggioni, G., Gowreesunker, B., Tassou, S., Bianchi, G., Reilly, M., Kirby, M., Toop, T., Theodorou, M., 2017. Potential for Energy Production from Farm Wastes Using Anaerobic Digestion in the UK: An Economic Comparison of Different Size Plants. Energies 10, 1396. https://doi.org/10.3390/en10091396
Owen, A., Mitchell, G., Gouldson, A., 2014. Unseen influence—The role of low carbon retrofit advisers and installers in the adoption and use of domestic energy technology. Energy Policy 73, 169–179. https://doi.org/10.1016/j.enpol.2014.06.013
Oxera, 2011. Discount rates for low-carbon and renewable generation technologies: Prepared for the Committee on Climate Change. Oxford, UK.
Palmer, D., Koubli, E., Betts, T., Gottschalg, R., 2017. The UK Solar Farm Fleet: A Challenge for the National Grid? Energies 10, 1220. https://doi.org/10.3390/en10081220
Palmer, J., Cooper, I., 2014. United Kingdom housing energy fact file 2013 (No. URN: 13D/276). Department of Energy and Climate Change, London, UK.
Palmer, J., Terry, N., Pope, P., 2012. How much energy could be saved by making small changes to everyday household behaviours? (No. 12D/352). Dept Egy & Climate Change, London, UK.
Parra, D., Walker, G.S., Gillott, M., 2016. Are batteries the optimum PV-coupled energy storage for dwellings? Techno-economic comparison with hot water tanks in the UK. Energy and Buildings 116, 614–621. https://doi.org/10.1016/j.enbuild.2016.01.039
Partridge, T., Thomas, M., Harthorn, B.H., Pidgeon, N., Hasell, A., Stevenson, L., Enders, C., 2017. Seeing futures now: Emergent US and UK views on shale development, climate change and energy systems. Global Env Change 42, 1–12. https://doi.org/10.1016/j.gloenvcha.2016.11.002
Pasqualino, R., Monasterolo, I., Jones, A., 2019. An Integrated Global Food and Energy Security System Dynamics Model for Addressing Systemic Risk. Sustainability 11, 3995. https://doi.org/10.3390/su11143995
Patey, L., 2015. Oil in Uganda: hard bargaining and complex politics in East Africa (No. WPM 60), OIES Paper. Oxford Institute for Energy Studies, Oxford, UK.

Patterson, T., Esteves, S., Dinsdale, R., Guwy, A., 2011. An evaluation of the policy and techno-economic factors affecting the potential for biogas upgrading for transport fuel use in the UK. Energy Policy 39, 1806–1816. https://doi.org/10.1016/j.enpol.2011.01.017

Pavel, C.C., Thiel, C., Degreif, S., Blagoeva, D., Buchert, M., Schüler, D., Tzimas, E., 2017. Role of substitution in mitigating the supply pressure of rare earths in electric road transport applications. Sustainable Materials and Technologies 12, 62–72. https://doi.org/10.1016/j.susmat.2017.01.003

Peace, C., 2017. The risk matrix: uncertain results? Policy and Practice in Health and Safety 15, 131–144. https://doi.org/10.1080/14773996.2017.1348571

Peakman, A., Hodgson, Z., Merk, B., 2018. Advanced micro-reactor concepts. Progress in Nuclear Energy 107, 61–70. https://doi.org/10.1016/j.pnucene.2018.02.025

Pearce-Higgins, J.W., Stephen, L., Douse, A., Langston, R.H.W., 2012. Greater impacts of wind farms on bird populations during construction than subsequent operation: results of a multi-site and multi-species analysis. Journal of Applied Ecology 49, 386–394. https://doi.org/10.1111/j.1365-2664.2012.02110.x

Pearson, P.J.G., Arapostathis, S., 2017. Two centuries of innovation, transformation and transition in the UK gas industry: Where next? Proc. Inst. Mechanical Engineers, Part A: Journal of Power and Energy 231, 478–497. https://doi.org/10.1177/0957650917693482

Peck, H., 2006. Reconciling supply chain vulnerability, risk and supply chain management. International Journal of Logistics Research and Applications 9, 127–142. https://doi.org/10.1080/13675560600673578

Peischl, J., Ryerson, T.B., Aikin, K.C., de Gouw, J.A., Gilman, J.B., Holloway, J.S., Lerner, B.M., Nadkarni, R., Neuman, J.A., Nowak, J.B., Trainer, M., Warneke, C., Parrish, D.D., 2015. Quantifying atmospheric methane emissions from the Haynesville, Fayetteville, and northeastern Marcellus shale gas production regions: CH4 emissions from shale gas production. Journal of Geophysical Research: Atmospheres 120, 2119–2139. https://doi.org/10.1002/2014JD022697

Peoples, C., 2014. New nuclear, new security? Framing security in the policy case for new nuclear power in the United Kingdom. Security Dialogue 45, 156–173. https://doi.org/10.1177/0967010614521840

Perrow, M.R., Gilroy, J.J., Skeate, E.R., Tomlinson, M.L., 2011. Effects of the construction of Scroby Sands offshore wind farm on the prey base of Little tern Sternula albifrons at its most important UK colony. Marine Pollution Bulletin 62, 1661–1670. https://doi.org/10.1016/j.marpolbul.2011.06.010

Pethick, J.S., Morris, R.K.A., Evans, D.H., 2009. Nature conservation implications of a Severn tidal barrage – A preliminary assessment of geomorphological change. Journal for Nature Conservation 17, 183–198. https://doi.org/10.1016/j.jnc.2009.04.001

Petley, S., Aggidis, G., 2016. Swansea Bay tidal lagoon annual energy estimation. Ocean Engineering 111, 348–357. https://doi.org/10.1016/j.oceaneng.2015.11.022

Petrova, E., 2010. Critical Infrastructure in Russia: Geographical Analysis of Accidents Triggered by Natural Hazards, in: Environmental Engineering and Management Journal. 8th International Conference on Environmental Legislation, Safety Engineering and Disaster Management, Cluj Napoca, Romania, pp. 53–58.

Phillips, K.J.O., Longhurst, P.J., Wagland, S.T., 2014. Assessing the perception and reality of arguments against thermal waste treatment plants in terms of property prices. Waste Management 34, 219–225. https://doi.org/10.1016/j.wasman.2013.08.018

Piroozfar, P., Pomponi, F., Farr, E.R.P., 2016. Life cycle assessment of domestic hot water systems: a comparative analysis. International Journal of Construction Management 16, 109–125. https://doi.org/10.1080/15623599.2016.1146111

Pitt, V., 2014. Nuclear developer warns over UK skills shortage. Building.

Pitts, A., 2017. Passive House and Low Energy Buildings: Barriers and Opportunities for Future Development within UK Practice. Sustainability 9, 272. https://doi.org/10.3390/su9020272

Polzin, F., Migendt, M., Täube, F.A., von Flotow, P., 2015. Public policy influence on renewable energy investments—A panel data study across OECD countries. Energy Policy 80, 98–111. https://doi.org/10.1016/j.enpol.2015.01.026

Popp, J., Lakner, Z., Harangi-Rákos, M., Fári, M., 2014. The effect of bioenergy expansion: Food, energy, and environment. Renewable and Sustainable Energy Reviews 32, 559–578. https://doi.org/10.1016/j.rser.2014.01.056

Portugal-Pereira, J., Esteban, M., 2014. Implications of paradigm shift in Japan's electricity security of supply: A multi-dimensional indicator assessment. Applied Energy 123, 424–434. https://doi.org/10.1016/j.apenergy.2014.01.024

POST, 2017. Future Energy Efficiency Policy (No. 550), Postnote. Parliamentary Office of Science and Technology, London, UK.

Pozniak, H., 2017. The skills crisis in engineering, 6 June. The Telegraph. URL https://www.telegraph.co.uk/education/stem-awards/energy/the-great-uk-engineering-shortage/ (accessed 25/7/18).

Price, L., Bullard, M., Lyons, H., Anthony, S., Nixon, P., 2004. Identifying the yield potential of Miscanthus x giganteus: an assessment of the spatial and temporal variability of M. x giganteus biomass productivity across England and Wales. Biomass and Bioenergy 26, 3–13. https://doi.org/10.1016/S0961-9534(03)00062-X

Pritchard, R., Kelly, S., 2017. Realising Operational Energy Performance in Non-Domestic Buildings: Lessons Learnt from Initiatives Applied in Cambridge. Sustainability 9, 1345. https://doi.org/10.3390/su9081345

Prpich, G., Coulon, F., Anthony, E.J., 2016. Review of the scientific evidence to support environmental risk assessment of shale gas development in the UK. Science of The Total Environment 563–564, 731–740. https://doi.org/10.1016/j.scitotenv.2015.11.026

Pryshlakivsky, J., Searcy, C., 2013. Fifteen years of ISO 14040: a review. Journal of Cleaner Production 57, 115–123. https://doi.org/10.1016/j.jclepro.2013.05.038

Pullinger, M., Lovell, H., Webb, J., 2014. Influencing household energy practices: a critical review of UK smart metering standards and commercial feedback devices. Technology Analysis & Strategic Management 26, 1144–1162. https://doi.org/10.1080/09537325.2014.977245

Putte, A.V. de, Gates, D.F., Holder, A.K., 2012. Political risk insurance as an instrument to reduce oil and gas investment risk and manage investment returns. J World Energy Law Bus 5, 284–301. https://doi.org/10.1093/jwelb/jws025

Pyhäranta, M.-K., 2017. State ownership of petroleum resources: an obstacle to shale gas development in the UK? J World Energy Law Bus 10, 358–366. https://doi.org/10.1093/jwelb/jwx013

Pyrko, J., Darby, S., 2011. Conditions of energy efficient behaviour—a comparative study between Sweden and the UK. Energy Eff 4, 393–408. https://doi.org/10.1007/s12053-010-9099-x

Qadrdan, M., Chaudry, M., Jenkins, N., Baruah, P., Eyre, N., 2015. Impact of transition to a low carbon power system on the GB gas network. Applied Energy 151, 1–12. https://doi.org/10.1016/j.apenergy.2015.04.056

Qi, A., Holland, R.A., Taylor, G., Richter, G.M., 2018. Grassland futures in Great Britain – Productivity assessment and scenarios for land use change opportunities. Science of The Total Environment 634, 1108–1118. https://doi.org/10.1016/j.scitotenv.2018.03.395

Quoilin, S., Broek, M.V.D., Declaye, S., Dewallef, P., Lemort, V., 2013. Techno-economic survey of Organic Rankine Cycle (ORC) systems. Renewable and Sustainable Energy Reviews 22, 168–186. https://doi.org/10.1016/j.rser.2013.01.028

Rabie, M., Franck, C.M., 2018. Comparison of gases for electrical insulation: Fundamental concepts. IEEE Transactions on Dielectrics and Electrical Insulation 25, 649–656. https://doi.org/10.1109/TDEI.2018.006900

RAE, 2017. Sustainability of liquid biofuels. Royal Academy of Engineering, London, UK.

RAE, 2015. A critical time for UK energy policy: what must be done now to deliver the UK's future energy system. Royal Academy of Engineering, London, UK.

Raikova, S., Le, C.D., Beacham, T.A., Jenkins, R.W., Allen, M.J., Chuck, C.J., 2017. Towards a marine biorefinery through the hydrothermal liquefaction of macroalgae native to the United Kingdom. Biomass & Bioengy 107, 244–253. https://doi.org/10.1016/j.biombioe.2017.10.010

Raimi, K.T., Carrico, A.R., 2016. Understanding and beliefs about smart energy technology. Energy Research & Social Science 12, 68–74. https://doi.org/10.1016/j.erss.2015.12.018

Ramos, A., Chatzopoulou, M.A., Guarracino, I., Freeman, J., Markides, C.N., 2017. Hybrid photovoltaic-thermal solar systems for combined heating, cooling and power provision in the urban environment. Energy Conversion and Management 150, 838–850. https://doi.org/10.1016/j.enconman.2017.03.024
RAND Europe, 2012. What Works in Changing Energy-Using Behaviours in the Home? A Rapid Evidence Assessment (No. 12D/345). Dept of Energy and Climate Change, London, UK.
Reap, E., 2015. The risk of hydraulic fracturing on public health in the UK and the UK's fracking legislation. Env Sciences Europe 27, 27. https://doi.org/10.1186/s12302-015-0059-0
Reboredo, J.C., 2015. Is there dependence and systemic risk between oil and renewable energy stock prices? Energy Economics 48, 32–45. https://doi.org/10.1016/j.eneco.2014.12.009
Redmond, T.C., 1990. Piper Alpha-Cost of the Lessons, in: IChemE Symposium Series No. 122. Piper-Alpha Lessons for Life-Cycle Management, 26-27 Sept, Institution of Chemical Engineers, London, UK, pp. 113–119.
Rees, S., Curtis, R., 2014. National Deployment of Domestic Geothermal Heat Pump Technology: Observations on the UK Experience 1995–2013. Energies 7, 5460–5499. https://doi.org/10.3390/en7085460
Reid, L., McKee, K., Crawford, J., 2015. Exploring the stigmatization of energy efficiency in the UK: An emerging research agenda. Energy Research & Social Science 10, 141–149. https://doi.org/10.1016/j.erss.2015.07.010
Reniers, G.L.L., Sörensen, K., Dullaert, W., 2012. A multi-attribute Systemic Risk Index for comparing and prioritizing chemical industrial areas. Reliability Engineering & System Safety 98, 35–42. https://doi.org/10.1016/j.ress.2011.10.002
Renn, O., Lucas, K., Haas, A., Jaeger, C., 2019. Things are different today: the challenge of global systemic risks. J Risk Research 22, 401–415. https://doi.org/10.1080/13669877.2017.1409252
Renner, M., 2014. Carbon prices and CCS investment: A comparative study between the European Union and China. Energy Policy 75, 327–340. https://doi.org/10.1016/j.enpol.2014.09.026
Revesz, A., Chaer, I., Thompson, J., Mavroulidou, M., Gunn, M., Maidment, G., 2016. Ground source heat pumps and their interactions with underground railway tunnels in an urban environment: A review. Applied Thermal Engineering 93, 147–154. https://doi.org/10.1016/j.applthermaleng.2015.09.011
Revol, J.-P., 2015. Thorium: An energy source for the world of tomorrow, in: Cifarelli, L., Wagner, F. (Eds.), Lectures Notes - Joint Eps-Sif International School on Energy - Course 2 Energy: Basic Concepts and Forefront Ideas. EDP Sciences, Varenna, Italy.
Rice, T., Owen, P., 1999. Decommissioning the Brent Spar. Taylor & Francis, London, UK.
Rimmer, D.L., Vizard, C.G., Pless-Mulloli, T., Singleton, I., Air, V.S., Keatinge, Z.A.F., 2006. Metal contamination of urban soils in the vicinity of a municipal waste incinerator: One source among many. Science of The Total Environment 356, 207–216. https://doi.org/10.1016/j.scitotenv.2005.04.037
Ritchie, H., Hardy, M., Lloyd, M.G., McGreal, S., 2013. Big Pylons: Mixed signals for transmission. Spatial planning for energy distribution. Energy Policy 63, 311–320. https://doi.org/10.1016/j.enpol.2013.08.021
Robbins, M.P., Evans, G., Valentine, J., Donnison, I.S., Allison, G.G., 2012. New opportunities for the exploitation of energy crops by thermochemical conversion in Northern Europe and the UK. Progress in Energy and Combustion Science 38, 138–155. https://doi.org/10.1016/j.pecs.2011.08.001
Roberts, J.W., 2009. The Nuclear Engineering Doctorate and NTEC CPD and Masters Programmes: Education, Training and Research for the Decommissioning Skills base, in: Proceedings of the 12th Int Conference on Environmental Remediation and Radioactive Waste Management. Amer Soc Mechanical Engineers, Liverpool, UK, pp. 813–817.
Roberts, P., 2017. Using US project structures for UK unconventional gas projects. J Energy & Natural Resources Law 35, 87–91. https://doi.org/10.1080/02646811.2016.1228738
Roberts, S., 2008. Infrastructure challenges for the built environment. Energy Policy 36, 4563–4567. https://doi.org/10.1016/j.enpol.2008.09.010

Roberts, S.H., Axon, C.J., Foran, B.D., Goddard, N.H., Warr, B.S., 2015. A framework for characterising an economy by its energy and socio-economic activities. Sustainable Cities and Society 14, 99–113. https://doi.org/10.1016/j.scs.2014.08.004

Roberts, S.H., Axon, C.J., Goddard, N.H., Foran, B.D., Warr, B.S., 2016. A robust data-driven macro-socioeconomic-energy model. Sustainable Production and Consumption 7, 16–36. https://doi.org/10.1016/j.spc.2016.01.003

Roberts, S.H., Axon, C.J., Goddard, N.H., Foran, B.D., Warr, B.S., 2019. Modelling socio-economic and energy data to generate business-as-usual scenarios for carbon emissions. Journal of Cleaner Production 207, 980–997. https://doi.org/10.1016/j.jclepro.2018.10.029

Roberts, S.H., Foran, B.D., Axon, C.J., Warr, B.S., Goddard, N.H., 2018. Consequences of selecting technology pathways on cumulative carbon dioxide emissions for the United Kingdom. Applied Energy 228, 409–425. https://doi.org/10.1016/j.apenergy.2018.06.078

Roberts, T., Upham, P., 2012. Prospects for the use of macro-algae for fuel in Ireland and the UK: An overview of marine management issues. Marine Policy 36, 1047–1053. https://doi.org/10.1016/j.marpol.2012.03.001

Robinson, N., 2003. Fuel Protests: Governing the Ungovernable? Parliamentary Affairs 56, 423–440. https://doi.org/10.1093/pa/gsg098

Robison, R.A.V., Foulds, C., 2018. Constructing policy success for UK energy feedback. Building Research & Information 46, 316–331. https://doi.org/10.1080/09613218.2017.1358043

Röder, M., 2016. More than food or fuel. Stakeholder perceptions of anaerobic digestion and land use; a case study from the United Kingdom. Energy Policy 97, 73–81. https://doi.org/10.1016/j.enpol.2016.07.003

Röder, M., Thornley, P., 2018. Waste wood as bioenergy feedstock. Climate change impacts and related emission uncertainties from waste wood based energy systems in the UK. Waste Management 74, 241–252. https://doi.org/10.1016/j.wasman.2017.11.042

Rogner, H.-H., Aguilera, R.F., Archer, C., Bertani, A., Bhattacharya, S.C., Dusseault, M.B., Gargon, L., Haberl, H., Hoogwijk, M., Johnson, A., Rogner, M.L., Wagner, H., Yakushev, V., 2012. Chapter 7 - Energy Resources and Potentials, in: Global Energy Assessment - Toward a Sustainable Future. Cambridge University Press, Cambridge, UK & International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 423–512.

Rosenow, J., Eyre, N., 2013. The Green Deal and the Energy Company Obligation. Proc. Inst. Civil Engineers - Energy 166, 127–136. https://doi.org/10.1680/ener.13.00001

Rosenow, J., Guertler, P., Sorrell, S., Eyre, N., 2018. The remaining potential for energy savings in UK households. Energy Policy 121, 542–552. https://doi.org/10.1016/j.enpol.2018.06.033

Rosenow, J., Guertler, P., Sorrell, S., Eyre, N.J., 2017. Unlocking Britain's First Fuel: The potential for energy savings in UK housing (Briefing Note). UK Energy Research Centre, London, UK.

Rossebø, J.E., Wolthuis, R., Fransen, F., Björkman, G., Medeiros, N., 2017. An Enhanced Risk-Assessment Methodology for Smart Grids. Computer 50, 62–71.

Royal Society, Royal Academy of Engineering, 2012. Shale gas extraction in the UK: a review of hydraulic fracturing (No. DES2597). London, UK.

Rudd, A., 2015. Speech delivered at the Institution of Civil Engineers, London, on 18 November. URL https://www.gov.uk/government/speeches/amber-rudds-speech-on-a-new-direction-for-uk-energy-policy (accessed 21/7/16).

Russell, S., 1993. Writing energy history: explaining the neglect of CHP/DH in Britain. The British Journal for the History of Science 26, 33. https://doi.org/10.1017/S0007087400030120

Rusu, L., Onea, F., 2015. Assessment of the performances of various wave energy converters along the European continental coasts. Energy 82, 889–904. https://doi.org/10.1016/j.energy.2015.01.099

Rutherford, J.P., Scharpf, E.W., Carrington, C.G., 2007. Linking consumer energy efficiency with security of supply. En Policy 35, 3025–3035. https://doi.org/10.1016/j.enpol.2006.10.031

Salameh, M.G., 2000. Global oil outlook: return to the absence of surplus and its implications. Applied Energy 65, 239–250. https://doi.org/10.1016/S0306-2619(99)00122-1

Salter, E., Ford, J., 2001. Holistic Environmental Assessment and Offshore Oil Field Exploration and Production. Marine Poll Bull 42, 45–58. https://doi.org/10.1016/S0025-326X(00)00115-6

Sanchez, A., Magaña, G., Partida, M.I., Sanchez, S., 2016. Bi-dimensional sustainability analysis of a multi-feed biorefinery design for biofuels co-production from lignocellulosic residues and agro-industrial wastes. Chemical Engineering Research and Design, Biorefinery Value Chain Creation 107, 195–217. https://doi.org/10.1016/j.cherd.2015.10.041
Santangelo, A., Tondelli, S., 2017. Occupant behaviour and building renovation of the social housing stock: Current and future challenges. Energy and Buildings 145, 276–283. https://doi.org/10.1016/j.enbuild.2017.04.019
Sarhosis, V., Jaya, A.A., Thomas, H.R., 2016. Economic modelling for coal bed methane production and electricity generation from deep virgin coal seams. Energy 107, 580–594. https://doi.org/10.1016/j.energy.2016.04.056
Sartori, M., Schiavo, S., 2015. Connected we stand: A network perspective on trade and global food security. Food Policy 57, 114–127. https://doi.org/10.1016/j.foodpol.2015.10.004
Saulnier, J.-B., Maisondieu, C., Ashton, I., Smith, G.H., 2012. Refined sea state analysis from an array of four identical directional buoys deployed off the Northern Cornish coast (UK). Applied Ocean Research 37, 1–21. https://doi.org/10.1016/j.apor.2012.02.001
Saunders, P.J., McCoy, D., Goldstein, R., Saunders, A.T., Munroe, A., 2018. A review of the public health impacts of unconventional natural gas development. Environmental Geochemistry and Health 40, 1–57. https://doi.org/10.1007/s10653-016-9898-x
Scarpa, R., Willis, K., 2010. Willingness-to-pay for renewable energy: Primary and discretionary choice of British households' for micro-generation technologies. Energy Economics 32, 129–136. https://doi.org/10.1016/j.eneco.2009.06.004
Scheepers, M., Seebregts, A., de Jong, J., Maters, H., 2006. EU Standards for Energy Security of Supply (No. ECN-C-06-039/CIEP). Energy Research Centre of the Netherlands, The Hague, Netherlands.
Scheibe, K.P., Blackhurst, J., 2018. Supply chain disruption propagation: a systemic risk and normal accident theory perspective. International Journal of Production Research 56, 43–59. https://doi.org/10.1080/00207543.2017.1355123
Schleier, J.J., Peterson, R.K.D., 2010. Limitations of the Entomological Operational Risk Assessment Using Probabilistic and Deterministic Analyses. Military Medicine 175, 594–598. https://doi.org/10.7205/MILMED-D-09-00283
Schroeder, B., Jackson, J.A., 2007. Why Traditional Risk Management Fails in the Oil and Gas Sector: Empirical Front-Line Evidence and Effective Solutions, in: AACE Transactions. AACE International Annual Meeting, Nashville, Tennesse, USA, pp. RI11–RI16.
Scotchman, I.C., 2016. Shale gas and fracking: exploration for unconventional hydrocarbons. Proc. of the Geologists' Association 127, 535–551. https://doi.org/10.1016/j.pgeola.2016.09.001
Scott, C.W., Molyneux, J.D., 2001. Britain's concrete dams—the final 50 years? Proc. Inst. Civil Engineers - Civil Engineering 144, 170–180. https://doi.org/10.1680/cien.2001.144.4.170
Scott, J., Evans, G., 2007. Electricity Networks: The Innovation Supply Chain, in: Helm, D. (Ed.), The New Energy Paradigm. Oxford University Press, Oxford, UK, pp. 36–62.
Scrase, J.I., 2001. Curbing the growth in UK commercial energy consumption. Building Research & Information 29, 51–61. https://doi.org/10.1080/09613210010001150
Sellar, B., Harding, S., Richmond, M., 2015. High-resolution velocimetry in energetic tidal currents using a convergent-beam acoustic Doppler profiler. Measurement Science and Technology 26, 085801. https://doi.org/10.1088/0957-0233/26/8/085801
Selley, R.C., 2012. UK shale gas: The story so far. Marine and Petroleum Geology 31, 100–109. https://doi.org/10.1016/j.marpetgeo.2011.08.017
Shemfe, M.B., Whittaker, C., Gu, S., Fidalgo, B., 2016. Comparative evaluation of GHG emissions from the use of Miscanthus for bio-hydrocarbon production via fast pyrolysis and bio-oil upgrading. Applied Energy 176, 22–33. https://doi.org/10.1016/j.apenergy.2016.04.113
Sherry, A.H., Howarth, P.J.A., Kearns, P., Waterman, N., Jeapes, A., Fairhall, G., Clough, M., Barker, K., Rigby, J., Abram, T., 2010. A Review of the UK's Nuclear R&D Capability. Technology Strategy Board, Swindon, UK.
Shipworth, M., 2011. Thermostat settings in English houses: No evidence of change between 1984 and 2007. Building and Environment 46, 635–642. https://doi.org/10.1016/j.buildenv.2010.09.009

Shirley, R., Hawthorne, J., Black, L., 2015. Waste incinerator residue treatment: variability implications. Proceedings of the Institution of Civil Engineers - Waste and Resource Management 168, 131–143. https://doi.org/10.1680/warm.14.00002

Shortall, O.K., Raman, S., Millar, K., 2015. Are plants the new oil? Responsible innovation, biorefining and multipurpose agriculture. Energy Policy 86, 360–368. https://doi.org/10.1016/j.enpol.2015.07.011

Shove, E., 1998. Gaps, barriers and conceptual chasms: theories of technology transfer and energy in buildings. En Policy 26, 1105–1112. https://doi.org/10.1016/S0301-4215(98)00065-2

Shove, E., 2003. Converging Conventions of Comfort, Cleanliness and Convenience. Journal of Consumer Policy 26, 395–418. https://doi.org/10.1023/A:1026362829781

Shove, E., Southerton, D., 2000. Defrosting the Freezer: From Novelty to Convenience: A Narrative of Normalization. Journal of Material Culture 5, 301–319. https://doi.org/10.1177/135918350000500303

Side, J., 1997. The future of North Sea oil industry abandonment in the light of the Brent Spar decision. Marine Policy 21, 45–52. https://doi.org/10.1016/S0308-597X(96)00045-0

Simaan, M., Gupta, A., Kar, K., 2020. Filtering for risk assessment of interbank network. European Journal of Operational Research 280, 279–294. https://doi.org/10.1016/j.ejor.2019.06.049

Simonovska, V., Estorff, U. von, 2012. Putting into perspective the supply of and demand for nuclear experts by 2020 within the EU-27 nuclear energy sector. (No. JRC70083). Joint Research Centre, European Commission, Luxembourg.

Sims, S., Dent, P., Oskrochi, G.R., 2008. Modelling the impact of wind farms on house prices in the UK. International Journal of Strategic Property Management 12, 251–269. https://doi.org/10.3846/1648-715X.2008.12.251-269

Sinclair, P., Cohen, B., Hansen, Y., Basson, L., Clift, R., 2015. Stakeholder engagement within the sustainability assessment of bioenergy: Case studies in heat, power and perennial and annual crops from the UK. Biomass and Bioenergy 73, 11–22. https://doi.org/10.1016/j.biombioe.2014.11.017

Skea, J., 2015. The global energy context, in: Ekins, P., Bradshaw, M., Jim Watson (Eds.), Global Energy: Issues, Potentials, and Policy Implications. Oxford Univ Press, Oxford, UK, pp. 9–33.

Skea, J., Ekins, P., Winskel, M. (Eds.), 2011a. Energy 2050: Making the Transition to a Secure Low-Carbon Energy System. Earthscan, London, UK.

Slade, R., Bauen, A., Gross, R., 2010. The UK bio-energy resource base to 2050: estimates, assumptions, and uncertainties (Working Paper No. UKERC/WP/TPA/2010/002). UK Energy Research Centre, London, UK.

Slade, R., Saunders, R., Gross, R., Bauen, A., 2011. ￼Energy from biomass: the size of the global resource: An assessment of the evidence that biomass can make a major contribution to future global energy supply. UK Energy Research Centre, London, UK.

Smith, A., Kern, F., Raven, R., Verhees, B., 2014. Spaces for sustainable innovation: Solar photovoltaic electricity in the UK. Technological Forecasting and Social Change 81, 115–130. https://doi.org/10.1016/j.techfore.2013.02.001

Smith, E.D., Siefert, W.T., Drain, D., 2009. Risk matrix input data biases. Systems Engineering 12, 344–360. https://doi.org/10.1002/sys.20126

Smith, I.K., 1993. Existing installations, in: Crook, A.W. (Ed.), Profiting from Low Grade Heat: Thermodynamic Cycles for Low-Temperature Heat Sources (The Watt Committee on Energy Report No. 26), IEE Energy Series No. 7. Inst Eng & Technology, London, UK, pp. 90–98.

Smith, T.W., Axon, C.J., Darton, R.C., 2013a. A methodology for measuring the sustainability of car transport systems. Transp Policy 30, 308–317. https://doi.org/10.1016/j.tranpol.2013.09.019

Smith, T.W., Axon, C.J., Darton, R.C., 2013b. The impact on human health of car-related air pollution in the UK, 1995-2005. Atmospheric Environment 77, 260–266. https://doi.org/10.1016/j.atmosenv.2013.05.016

Snape, J., 2016. Spatial and Temporal Characteristics of PV Adoption in the UK and Their Implications for the Smart Grid. Energies 9, 210. https://doi.org/10.3390/en9030210

Song, C., Gardner, K.H., Klein, S.J.W., Souza, S.P., Mo, W., 2018. Cradle-to-grave greenhouse gas emissions from dams in the United States of America. Renewable and Sustainable Energy Reviews 90, 945–956. https://doi.org/10.1016/j.rser.2018.04.014

Sorahan, T., 2007. Mortality of UK oil refinery and petroleum distribution workers, 1951–2003. Occup Med (Lond) 57, 177–185. https://doi.org/10.1093/occmed/kql168

Sorrell, S., 2009. Jevons' Paradox revisited: The evidence for backfire from improved energy efficiency. Energy Policy 37, 1456–1469. https://doi.org/10.1016/j.enpol.2008.12.003

Sorrell, S., 2015. Reducing energy demand: A review of issues, challenges and approaches. Renewable and Sustainable Energy Rev 47, 74–82. https://doi.org/10.1016/j.rser.2015.03.002

Sorrell, S., Speirs, J., Bentley, R., Brandt, A., Miller, R., 2009. An assessment of the evidence for a near-term peak in global oil production. UKERC, London, UK.

Sovacool, B.K., Andersen, R., Sorensen, S., Sorensen, K., Tienda, V., Vainorius, A., Schirach, O.M., Bjorn-Thygesen, F., 2016. Balancing safety with sustainability: assessing the risk of accidents for modern low-carbon energy systems. J. Clean Prod. 112, 3952–3965. https://doi.org/10.1016/j.jclepro.2015.07.059

Sovacool, B.K., Kryman, M., Laine, E., 2015. Profiling technological failure and disaster in the energy sector: A comparative analysis of historical energy accidents. Energy 90, 2016–2027. https://doi.org/10.1016/j.energy.2015.07.043

Sovacool, B.K., Mukherjee, I., 2011. Conceptualizing and measuring energy security: A synthesized approach. Energy 36, 5343–5355. https://doi.org/10.1016/j.energy.2011.06.043

Spataru, C., Drummond, P., Zafeiratou, E., Barrett, M., 2015. Long-term scenarios for reaching climate targets and energy security in UK. Sustainable Cities and Society 17, 95–109. https://doi.org/10.1016/j.scs.2015.03.010

Speirs, J., Gross, B., Gross, R., Houari, Y., 2013a. Energy Materials Availability Handbook. UK Energy Research Centre, London, UK.

Speirs, J., Houari, Y., Contestabile, M., Gross, R., Gross, B., 2013b. Potential constraints to the future low- carbon economy Working Paper II: Batteries, Magnets and Materials (No. WP/TPA/2013/003). UK Energy Research Centre, London, UK.

Speirs, J., McGlade, C., Slade, R., 2015a. Uncertainty in the availability of natural resources: Fossil fuels, critical metals and biomass. Energy Policy 87, 654–664. https://doi.org/10.1016/j.enpol.2015.02.031

Speirs, J., McGlade, C., Slade, R., 2015b. Uncertainty in the availability of natural resources: Fossil fuels, critical metals and biomass. Energy Policy 87, 654–664. https://doi.org/10.1016/j.enpol.2015.02.031

Speirs, J., Roelich, K., 2015. Metals for the low-carbon energy system, in: Ekins, P., Bradshaw, M., Jim Watson (Eds.), Global Energy: Issues, Potentials, and Policy Implications. Oxford University Press, Oxford, UK, pp. 452–475.

Sprecher, B., Daigo, I., Spekkink, W., Vos, M., Kleijn, R., Murakami, S., Kramer, G.J., 2017. Novel Indicators for the Quantification of Resilience in Critical Material Supply Chains, with a 2010 Rare Earth Crisis Case Study. Environmental Science & Technology 51, 3860–3870. https://doi.org/10.1021/acs.est.6b05751

Squires, G.L., 2008. Practical Physics, 4th ed. Cambridge University Press, Cambridge, UK.

Staffell, I., Brett, D., Brandon, N., Hawkes, A., 2012. A review of domestic heat pumps. Energy Environ. Sci. 5, 9291–9306. https://doi.org/10.1039/C2EE22653G

Standards Australia (Ed.), 1999. Risk management, AS/NZS. Standards Association of Australia, Strathfield, Australia.

Stapleton, L., Sorrell, S., Schwanen, T., 2017. Peak car and increasing rebound: A closer look at car travel trends in Great Britain. Transportation Research Part D: Transport and Environment 53, 217–233. https://doi.org/10.1016/j.trd.2017.03.025

Stefansson, V., 2000. The renewability of geothermal energy. World Geothermal Congress, 28 May-10 June, International Geothermal Association, Kyushu-Tohoku, Japan, pp. 883–888.

Stern, J., 2002. Security of European natural gas supplies: The impact of import dependence and liberalization. Royal Institute of International Affairs, London, UK.

Stiehler, A., Gantori, S., 2016. Energy efficiency, Longer Term Investments. UBS Switzerland AG and UBS AG, New York, USA.

Stirling, A., 2009. What is security? Some key concepts. UK energy security: What do we know, and what should be done? London, 27 January, University of Sussex, London, UK.

Stoddard, E., 2012. A common vision of energy risk? Energy securitisation and company perceptions of risk in the EU. Journal of Contemporary European Research 8, 340–366.
Stokes, C., Beaumont, E., Russell, P., Greaves, D., 2014. Anticipated coastal impacts: What water-users think of marine renewables and why. Ocean & Coastal Management, Science in support of governance of wave and tidal energy developments 99, 63–71. https://doi.org/10.1016/j.ocecoaman.2014.04.003
Stokes, E., 2016. Regulatory Domain and Regulatory Dexterity: Critiquing the UK Governance of 'Fracking.' The Modern Law Review 79, 961–986. https://doi.org/10.1111/1468-2230.12226
Striolo, A., Cole, D.R., 2017. Understanding Shale Gas: Recent Progress and Remaining Challenges. Egy Fuels 31, 10300–10310. https://doi.org/10.1021/acs.energyfuels.7b01023
Stroebel, J., van Benthem, A., 2012. Resource Extraction Contracts Under Threat of Expropriation: Theory and Evidence. Review of Economics and Statistics 95, 1622–1639. https://doi.org/10.1162/REST_a_00333
Stulberg, A.N., 2012. Strategic bargaining and pipeline politics: Confronting the credible commitment problem in Eurasian energy transit. Review of International Political Economy 19, 808–836. https://doi.org/10.1080/09692290.2011.603662
Styles, D., Dominguez, E.M., Chadwick, D., 2016. Environmental balance of the UK biogas sector: An evaluation by consequential life cycle assessment. Science of The Total Environment 560–561, 241–253. https://doi.org/10.1016/j.scitotenv.2016.03.236
Styles, D., Gibbons, J., Williams, A.P., Dauber, J., Stichnothe, H., Urban, B., Chadwick, D.R., Jones, D.L., 2015. Consequential life cycle assessment of biogas, biofuel and biomass energy options within an arable crop rotation. GCB Bioenergy 7, 1305–1320. https://doi.org/10.1111/gcbb.12246
Summerbell, D.L., Khripko, D., Barlow, C., Hesselbach, J., 2017. Cost and carbon reductions from industrial demand-side management: Study of potential savings at a cement plant. Applied Energy 197, 100–113. https://doi.org/10.1016/j.apenergy.2017.03.083
Sun, X., Brown, M.A., Cox, M., Jackson, R., 2016. Mandating better buildings: a global review of building codes and prospects for improvement in the United States: A global review of building codes and prospects for improvement in the U.S. Wiley Interdisciplinary Reviews: Energy and Environment 5, 188–215. https://doi.org/10.1002/wene.168
Sun, X., Liu, C., Chen, X., Li, J., 2017. Modeling systemic risk of crude oil imports: Case of China's global oil supply chain. Energy 121, 449–465. https://doi.org/10.1016/j.energy.2017.01.018
Sunikka-Blank, M., Galvin, R., 2016. Irrational homeowners? How aesthetics and heritage values influence thermal retrofit decisions in the United Kingdom. Energy Research & Social Science 11, 97–108. https://doi.org/10.1016/j.erss.2015.09.004
Swinbank, A., Tranter, R., Jones, P., 2011. Mandates, buyouts and fuel-tax rebates: Some economic aspects of biofuel policies using the UK as an example. Energy Policy 39, 1249–1253. https://doi.org/10.1016/j.enpol.2010.11.052
Tagliaferri, C., Clift, R., Lettieri, P., Chapman, C., 2017. Liquefied natural gas for the UK: a life cycle assessment. International Journal of Life Cycle Assessment 22, 1944–1956. https://doi.org/10.1007/s11367-017-1285-z
Tagliaferri, C., Evangelisti, S., Clift, R., Lettieri, P., 2018. Life cycle assessment of a biomass CHP plant in UK: The Heathrow energy centre case. Chemical Engineering Research and Design 133, 210–221. https://doi.org/10.1016/j.cherd.2018.03.022
Tang, C.S., 2006. Perspectives in supply chain risk management. International Journal of Production Economics 103, 451–488. https://doi.org/10.1016/j.ijpe.2005.12.006
Tassou, S.A., Kolokotroni, M., Gowreesunker, B., Stojceska, V., Azapagic, A., Fryer, P., Bakalis, S., 2014. Energy demand and reduction opportunities in the UK food chain. Proc. Inst. Civil Engineers - Energy 167, 162–170. https://doi.org/10.1680/ener.14.00014
Tate, G., Mbzibain, A., Ali, S., 2012. A comparison of the drivers influencing farmers' adoption of enterprises associated with renewable energy. Energy Policy, Special Section: Fuel Poverty Comes of Age: Commemorating 21 Years of Research and Policy 49, 400–409. https://doi.org/10.1016/j.enpol.2012.06.043

Taylor, G., 2008a. Biofuels and the biorefinery concept. Energy Policy, Foresight Sustainable Energy Management and the Built Environment Project 36, 4406–4409. https://doi.org/10.1016/j.enpol.2008.09.069
Taylor, G., 2008b. Bioenergy for heat and electricity in the UK: A research atlas and roadmap. Energy Policy, Foresight Sustainable Energy Management and the Built Environment Project 36, 4383–4389. https://doi.org/10.1016/j.enpol.2008.09.034
Taylor, G.A., Wallom, D.C.H., Grenard, S., Huete, A.Y., Axon, C.J., 2011. Recent developments towards novel high performance computing and communications solutions for smart distribution network operation, in: 2011 2nd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies (ISGT Europe). 2nd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies (ISGT Europe), pp. 1–8. https://doi.org/10.1109/ISGTEurope.2011.6162812
Taylor, S., 2016. The Fall and Rise of Nuclear Power in Britain: A History. UIT, Cambridge, UK.
Tempest, P., 1993. Can a third oil shock be avoided? Energy Policy 21, 1079–1083. https://doi.org/10.1016/0301-4215(93)90258-H
Teräväinen, T., Lehtonen, M., Martiskainen, M., 2011. Climate change, energy security, and risk—debating nuclear new build in Finland, France and the UK. Energy Policy 39, 3434–3442. https://doi.org/10.1016/j.enpol.2011.03.041
The Crown Estate, 2012. UK Wave and Tidal Key Resource Areas Project: Summary Report. The Crown Estate, London, UK.
The Engineer, 2017. Engineering skills shortage: overcoming the fear and uncertainty. The Engineer. URL www.theengineer.co.uk/engineering-skills-shortage-overcoming-the-fear-and-uncertainty/ (accessed 7.25.18).
The Hon. Lord Cullen, 1990. The report of the public inquiry into the Piper Alpha disaster. Department of Energy, London, UK.
Thomas, M., Partridge, T., Harthorn, B.H., Pidgeon, N., 2017. Deliberating the perceived risks, benefits, and societal implications of shale gas and oil extraction by hydraulic fracturing in the US and UK. Nature Energy 2, 17054. https://doi.org/10.1038/nenergy.2017.54
Thomas, P., Bratvold, R.B., Bickel, E., 2014. The Risk of Using Risk Matrices. SPE Economics and Management 6, 56–66. https://doi.org/10.2118/166269-MS
Thomas, S., 2005. The economics of nuclear power: analysis of recent studies. Public Services International Research Unit, University of Greenwich, London, UK.
Thomas, S., 2010. Competitive energy markets and nuclear power: Can we have both, do we want either? Energy Policy 38, 4903–4908. https://doi.org/10.1016/j.enpol.2010.04.051
Thomas, S., 2015. Construction delays at Generation III+ Nuclear Power Plants. Public Services International Research Unit, University of Greenwich, London, UK.
Thomas, S., Dawe, R.A., 2003. Review of ways to transport natural gas energy from countries which do not need the gas for domestic use. Energy 28, 1461–1477. https://doi.org/10.1016/S0360-5442(03)00124-5
Thornley, P., Upham, P., Tomei, J., 2009. Sustainability constraints on UK bioenergy development. Energy Policy 37, 5623–5635. https://doi.org/10.1016/j.enpol.2009.08.028
Tkaczyk, A.H., Bartl, A., Amato, A., Lapkovskis, V., Petranikova, M., 2018. Sustainability evaluation of essential critical raw materials: cobalt, niobium, tungsten and rare earth elements. Journal of Physics D: Applied Physics 51, 203001. https://doi.org/10.1088/1361-6463/aaba99
Tranter, R.B., Swinbank, A., Jones, P.J., Banks, C.J., Salter, A.M., 2011. Assessing the potential for the uptake of on-farm anaerobic digestion for energy production in England. Energy Policy 39, 2424–2430. https://doi.org/10.1016/j.enpol.2011.01.065
Trkman, P., McCormack, K., 2009. Supply chain risk in turbulent environments—A conceptual model for managing supply chain network risk. International Journal of Production Economics 119, 247–258. https://doi.org/10.1016/j.ijpe.2009.03.002
Trutnevyte, E., McDowall, W., Tomei, J., Keppo, I., 2016. Energy scenario choices: Insights from a retrospective review of UK energy futures. Renewable and Sustainable Energy Reviews 55, 326–337. https://doi.org/10.1016/j.rser.2015.10.067

Turkenburg, W.C., Arent, D.J., Bertani, R., Faaij, A., Hand, M., Krewitt, W., Larson, E.D., Lund, J., Mehos, M., Merrigan, T., Mitchell, C., Moreira, J.R., Sinke, W., Sonntag-O'Brien, V., Thresher, B., van Sark, W., Usher, Eric, Usher, E., 2012. Chapter 11 - Renewable Energy, in: Global Energy Assessment - Toward a Sustainable Future. Cambridge University Press, Cambridge, UK & International Institute for App Systems Analysis, Laxenburg, Austria, pp. 761–900.

Uddin, K., Gough, R., Radcliffe, J., Marco, J., Jennings, P., 2017. Techno-economic analysis of the viability of residential photovoltaic systems using lithium-ion batteries for energy storage in the United Kingdom. App Energy 206, 12–21. https://doi.org/10.1016/j.apenergy.2017.08.170

UKPIA, 2011. Fuelling the UK's future - the role of our refining and downstream oil industry. UK Petroleum Industry Association, London, UK.

UKPIA, 2016. UKPIA Statistical Review 2016. UK Petroleum Industry Association, London, UK.

UNEP, 2006. Challenges to international waters: regional assessments in a global perspective (No. UNEP/GCSS.IX/INF/9). United Nations Environment Programme, Nairobi, Kenya.

UNFCCC, 2016. Report of the Conference of the Parties on its twenty-first session (No. FCCC/CP/2015/10/Add.1). UN Framework Convention on Climate Change, Bonn, Germany.

United Nations, 1987. Report of the World Commission on Environment and Development: Our Common Future. Oslo, Norway.

Upham, P., Kivimaa, P., Virkamäki, V., 2013. Path dependence and technological expectations in transport policy: the case of Finland and the UK. Journal of Transport Geography 32, 12–22. https://doi.org/10.1016/j.jtrangeo.2013.08.004

U.S. Geological Survey, 2018. Gas Hydrates Project. URL https://woodshole.er.usgs.gov/project-pages/hydrates/database.html (accessed 25/4/18).

USDoE, 2014. The Water-Energy Nexus: Challenges and Opportunities (Technical Report No. DOE/EPSA-0002). US Department of Energy, Washington, D.C. USA.

Valdés, J., 2018. Arbitrariness in Multidimensional Energy Security Indicators. Ecological Economics 145, 263–273. https://doi.org/10.1016/j.ecolecon.2017.09.002

Valentić, V., Žiković, S., Višković, A., 2016. Can CCS save coal fired power plants – The European perspective. International Journal of Greenhouse Gas Control 47, 266–278. https://doi.org/10.1016/j.ijggc.2016.01.037

van Dijk, J., der Vlist, M. van, van Tatenhove, J., 2011. Water Assessment as controlled informality. Environmental Impact Assessment Rev 31, 112–119. https://doi.org/10.1016/j.eiar.2010.04.009

van Duren, I., Voinov, A., Arodudu, O., Firrisa, M.T., 2015. Where to produce rapeseed biodiesel and why? Mapping European rapeseed energy efficiency. Renewable Energy 74, 49–59. https://doi.org/10.1016/j.renene.2014.07.016

Vantoch-Wood, A., Connor, P.M., 2013. Using network analysis to understand public policy for wave energy. Energy Policy 62, 676–685. https://doi.org/10.1016/j.enpol.2013.07.066

Vatanpour, S., Hrudey, S.E., Dinu, I., 2015. Can Public Health Risk Assessment Using Risk Matrices Be Misleading? International Journal of Environmental Research and Public Health 12, 9575–9588. https://doi.org/10.3390/ijerph120809575

Vazquez, A., Iglesias, G., 2015. Device interactions in reducing the cost of tidal stream energy. Energy Conversion and Mgt 97, 428–438. https://doi.org/10.1016/j.enconman.2015.03.044

Vazquez, A., Iglesias, G., 2016. Capital costs in tidal stream energy projects – A spatial approach. Energy 107, 215–226. https://doi.org/10.1016/j.energy.2016.03.123

Vengosh, A., Jackson, R.B., Warner, N., Darrah, T.H., Kondash, A., 2014. A Critical Review of the Risks to Water Resources from Unconventional Shale Gas Development and Hydraulic Fracturing in the United States. Environmental Science & Technology 48, 8334–8348. https://doi.org/10.1021/es405118y

Venkatasubramanian, V., Zhang, Z., 2016. TeCSMART: A hierarchical framework for modeling and analyzing systemic risk in sociotechnical systems. AIChE Journal 62, 3065–3084. https://doi.org/10.1002/aic.15302

Venugopal, V., Nemalidinne, R., 2015. Wave resource assessment for Scottish waters using a large scale North Atlantic spectral wave model. Renewable Energy 76, 503–525. https://doi.org/10.1016/j.renene.2014.11.056

Verbruggen, A., Laes, E., Lemmens, S., 2014. Assessment of the actual sustainability of nuclear fission power. Renewable and Sustainable Energy Reviews 32, 16–28. https://doi.org/10.1016/j.rser.2014.01.008
Verbruggen, A., Van de Graaf, T., 2013. Peak oil supply or oil not for sale? Futures 53, 74–85. https://doi.org/10.1016/j.futures.2013.08.005
Vianello, J.M., Costa, L., Teixeira, J.P., 2014. Dynamic modeling of uncertainty in the planned values of investments in petrochemical and refining projects. Energy Economics 45, 10–18. https://doi.org/10.1016/j.eneco.2014.06.002
Vijay, A., Hawkes, A., 2017. The Techno-Economics of Small-Scale Residential Heating in Low Carbon Futures. Energies 10, 1915. https://doi.org/10.3390/en10111915
Vlek, C., 2013. How Solid Is the Dutch (and the British) National Risk Assessment? Overview and Decision-Theoretic Evaluation. Risk Analysis 33, 948–971. https://doi.org/10.1111/risa.12052
Volland, B., 2017. The role of risk and trust attitudes in explaining residential energy demand: Evidence from the United Kingdom. Ecological Economics 132, 14–30. https://doi.org/10.1016/j.ecolecon.2016.10.002
von Hippel, D., Suzuki, T., Williams, J., Hayes, P., 2011. Evaluating the energy security impacts of energy policies, in: Sovacool, B.K. (Ed.), The Routledge Handbook of Energy Security. Routledge, Abingdon, UK, pp. 74–95.
von Hippel, F., Bunn, M., Diakov, A., Ding, M., Goldston, R., Katsuta, T., Ramana, M.V., Suzuki, T., Suyuan, Y., 2012. Chapter 14 - Nuclear Energy, in: Global Energy Assessment - Toward a Sustainable Future. Cambridge University Press, Cambridge, UK and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 1069–1130.
Voormolen, J.A., Junginger, H.M., van Sark, W.G.J.H.M., 2016. Unravelling historical cost developments of offshore wind energy in Europe. Energy Policy 88, 435–444. https://doi.org/10.1016/j.enpol.2015.10.047
Voyles, T.B., 2015. Wastelanding: Legacies of Uranium Mining in Navajo Country. Univ Of Minnesota Press, Minneapolis, USA.
Wade, F., Hitchings, R., Shipworth, M., 2016. Understanding the missing middlemen of domestic heating: Installers as a community of professional practice in the United Kingdom. Energy Research & Social Science 19, 39–47. https://doi.org/10.1016/j.erss.2016.05.007
Waggitt, J.J., Dunn, H.K., Evans, P.G.H., Hiddink, J.G., Holmes, L.J., Keen, E., Murcott, B.D., Piano, M., Robins, P.E., Scott, B.E., Whitmore, J., Veneruso, G., 2018. Regional-scale patterns in harbour porpoise occupancy of tidal stream environments. ICES J Mar Sci 75, 701–710. https://doi.org/10.1093/icesjms/fsx164
Waggitt, J.J., Robbins, A.M.C., Wade, H.M., Masden, E.A., Furness, R.W., Jackson, A.C., Scott, B.E., 2017. Comparative studies reveal variability in the use of tidal stream environments by seabirds. Marine Policy 81, 143–152. https://doi.org/10.1016/j.marpol.2017.03.023
Waggitt, J.J., Scott, B.E., 2014. Using a spatial overlap approach to estimate the risk of collisions between deep diving seabirds and tidal stream turbines: A review of potential methods and approaches. Marine Policy 44, 90–97. https://doi.org/10.1016/j.marpol.2013.07.007
Walker, B., Holling, C.S., Carpenter, S.R., Kinzig, A.P., 2004. Resilience, Adaptability and Transformability in Social-ecological Systems. Ecology and Society 9. https://doi.org/10.5751/ES-00650-090205
Wall, M., 2014. Skills shortages holding back the UK's economic recovery, 1 December. BBC News. URL www.bbc.co.uk/news/business-30224320 (accessed 25/7/18).
Walsh, C., Mander, S., Larkin, A., 2017. Charting a low carbon future for shipping: A UK perspective. Marine Policy 82, 32–40. https://doi.org/10.1016/j.marpol.2017.04.019
Wang, L., Littlewood, J., Murphy, R.J., 2013. Environmental sustainability of bioethanol production from wheat straw in the UK. Renewable and Sustainable Energy Reviews 28, 715–725. https://doi.org/10.1016/j.rser.2013.08.031
Wang, L., Weller, C.L., Jones, D.D., Hanna, M.A., 2008. Contemporary issues in thermal gasification of biomass and its application to electricity and fuel production. Biomass and Bioenergy 32, 573–581. https://doi.org/10.1016/j.biombioe.2007.12.007
Wang, Q., Li, R., 2017. Research status of shale gas: A review. Renewable and Sustainable Energy Reviews 74, 715–720. https://doi.org/10.1016/j.rser.2017.03.007

Wang, Shifeng, Wang, Sicong, Hastings, A., Pogson, M., Smith, P., 2012. Economic and greenhouse gas costs of Miscanthus supply chains in the United Kingdom. GCB Bioenergy 4, 358–363. https://doi.org/10.1111/j.1757-1707.2011.01125.x

Want, A., Crawford, R., Kakkonen, J., Kiddie, G., Miller, S., Harris, R.E., Porter, J.S., 2017. Biodiversity characterisation and hydrodynamic consequences of marine fouling communities on marine renewable energy infrastructure in the Orkney Islands Archipelago, Scotland, UK. Biofouling 33, 567–579. https://doi.org/10.1080/08927014.2017.1336229

Warren, C.R., Burton, R., Buchanan, O., Birnie, R.V., 2016. Limited adoption of short rotation coppice: The role of farmers' socio-cultural identity in influencing practice. Journal of Rural Studies 45, 175–183. https://doi.org/10.1016/j.jrurstud.2016.03.017

Warwick-Evans, V., Atkinson, P.W., Walkington, I., Green, J.A., 2018. Predicting the impacts of wind farms on seabirds: An individual-based model. Journal of Applied Ecology 55, 503–515. https://doi.org/10.1111/1365-2664.12996

Waters, S., Aggidis, G., 2016. A World First: Swansea Bay Tidal lagoon in review. Renewable and Sustainable Energy Reviews 56, 916–921. https://doi.org/10.1016/j.rser.2015.12.011

Watkins, P., McKendry, P., 2015a. Assessment of waste derived gases as a renewable energy source – Part 1. Sustainable Energy Technologies and Assessments 10, 102–113. https://doi.org/10.1016/j.seta.2015.03.001

Watkins, P., McKendry, P., 2015b. Assessment of waste derived gases as a renewable energy source – Part 2. Sustainable Energy Technologies and Assessments 10, 114–124. https://doi.org/10.1016/j.seta.2015.03.004

Watson, J., 1997. The technology that drove the "dash for gas." Power Engineering Journal 11, 11–19. https://doi.org/10.1049/pe:19970103

Watson, J., Gross, R., Ketsopoulou, I., Winskel, M., 2014. UK energy strategies under uncertainty: synthesis report. UKERC, London, UK.

Watson, K.J., 2015. Understanding the role of building management in the low-energy performance of passive sustainable design: Practices of natural ventilation in a UK office building. Indoor and Built Environment 24, 999–1009. https://doi.org/10.1177/1420326X15601478

Weaver, T., 2012. Financial appraisal of operational offshore wind energy projects. Renewable and Sustainable Energy Reviews 16, 5110–5120. https://doi.org/10.1016/j.rser.2012.05.003

Webb, J., 2015. Improvising innovation in UK urban district heating: The convergence of social and environmental agendas in Aberdeen. Energy Policy 78, 265–272. https://doi.org/10.1016/j.enpol.2014.12.003

WEC, 2013. Peat, in: World Energy Resources 2013 Survey. World Energy Council, London, UK.

WEC, 2018. 2018 Energy Trilemma Index. World Energy Council, London, UK.

WEF, 2017. The Global Risks Report 2017: 12th Edition (No. 050117). World Economic Forum, Geneva, Switzerland.

Wegenast, T., 2016. Oil, Natural Gas, and Intrastate Conflict: Does Ownership Matter? International Interactions 42, 31–55. https://doi.org/10.1080/03050629.2015.1046599

Welfle, A., Gilbert, P., Thornley, P., 2014. Increasing biomass resource availability through supply chain analysis. Biomass and Bioenergy 70, 249–266. https://doi.org/10.1016/j.biombioe.2014.08.001

West, C., Kenway, S., Hassall, M., Yuan, Z., 2016. Why do residential recycled water schemes fail? A comprehensive review of risk factors and impact on objectives. Water Research 102, 271–281. https://doi.org/10.1016/j.watres.2016.06.044

Westaway, R., 2016a. The importance of characterizing uncertainty in controversial geoscience applications: induced seismicity associated with hydraulic fracturing for shale gas in northwest England. Proc Geologists' Association 127, 1–17. https://doi.org/10.1016/j.pgeola.2015.11.011

Westaway, R., 2016b. Repurposing of disused shale gas wells for subsurface heat storage: preliminary analysis concerning UK issues. Quarterly Journal of Engineering Geology and Hydrogeology 49, 213–227. https://doi.org/10.1144/qjegh2016-016

Westaway, R., Younger, P.L., 2014. Quantification of potential macroseismic effects of the induced seismicity that might result from hydraulic fracturing for shale gas exploitation in the UK. Quarterly J Eng Geology and Hydrogeol 47, 333–350. https://doi.org/10.1144/qjegh2014-011

Whipple, T., Pitblado, R., 2010. Applied risk-based process safety: A consolidated risk register and focus on risk communication. Process Safety Progress 29, 39–46. https://doi.org/10.1002/prs.10320

Whitaker, J., Field, J.L., Bernacchi, C.J., Cerri, C.E.P., Ceulemans, R., Davies, C.A., DeLucia, E.H., Donnison, I.S., McCalmont, J.P., Paustian, K., Rowe, R.L., Smith, P., Thornley, P., McNamara, N.P., 2018. Consensus, uncertainties and challenges for perennial bioenergy crops and land use. GCB Bioenergy 10, 150–164. https://doi.org/10.1111/gcbb.12488

Whitmarsh, L., Nash, N., Upham, P., Lloyd, A., Verdon, J.P., Kendall, J.-M., 2015. UK public perceptions of shale gas hydraulic fracturing: The role of audience, message and contextual factors on risk perceptions and policy support. Applied Energy 160, 419–430. https://doi.org/10.1016/j.apenergy.2015.09.004

Whittington, H.W., 2002. Electricity generation: options for reduction in carbon emissions. Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences 360, 1653–1668. https://doi.org/10.1098/rsta.2002.1025

Whitton, J., Brasier, K., Charnley-Parry, I., Cotton, M., 2017. Shale gas governance in the United Kingdom and the United States: Opportunities for public participation and the implications for social justice. Energy Res & Social Sci 26, 11–22. https://doi.org/10.1016/j.erss.2017.01.015

Willams, T.M., 1994. Using a risk register to integrate risk management in project definition. International J Project Mgt 12, 17–22. https://doi.org/10.1016/0263-7863(94)90005-1

Williams, E., Hittinger, E., Carvalho, R., Williams, R., 2017. Wind power costs expected to decrease due to technological progress. Energy Policy 106, 427–435. https://doi.org/10.1016/j.enpol.2017.03.032

Williams, L., Macnaghten, P., Davies, R., Curtis, S., 2017. Framing ‘fracking’: Exploring public perceptions of hydraulic fracturing in the United Kingdom. Public Understanding of Science 26, 89–104. https://doi.org/10.1177/0963662515595159

Wilson, C., 2013. Input, Output, and OutcomeMetrics for Assessing Energy Technology Innovation, in: Grubler, A., Wilson, C. (Eds.), Energy Technology Innovation: Learning from Historical Successes and Failures. Cambridge University Press, New York.

Wilson, G.A., Dyke, S.L., 2016. Pre- and post-installation community perceptions of wind farm projects: the case of Roskrow Barton (Cornwall, UK). Land Use Policy 52, 287–296. https://doi.org/10.1016/j.landusepol.2015.12.008

Wilson, M.P., Davies, R.J., Foulger, G.R., Julian, B.R., Styles, P., Gluyas, J.G., Almond, S., 2015. Anthropogenic earthquakes in the UK: A national baseline prior to shale exploitation. Marine and Petroleum Geology 68, 1–17. https://doi.org/10.1016/j.marpetgeo.2015.08.023

Wilson, R., May-Gillings, M., Pirie, J., Beaven, R., 2016a. Working Futures 2014-2024: Technical report on sources and methods. UK Commission for Employment and Skills, Rotherham.

Wilson, R., Sofroniou, N., Beaven, R., May-Gillings, M., Perkins, S., Lee, M., Glover, P., Limmer, H., Leach, A., 2016b. Working Futures 2014-2024: Evidence report 100. UK Commission for Employment and Skills, Rotherham.

Winzer, C., 2012. Conceptualizing energy security. Energy Policy 46, 36–48. https://doi.org/10.1016/j.enpol.2012.02.067

Wiser, R., Jenni, K., Seel, J., Baker, E., Hand, M., Lantz, E., Smith, A., 2016. Expert elicitation survey on future wind energy costs. Nature Energy 1, 16135. https://doi.org/10.1038/nenergy.2016.135

Witt, M.J., Sheehan, E.V., Bearhop, S., Broderick, A.C., Conley, D.C., Cotterell, S.P., Crow, E., Grecian, W.J., Halsband, C., Hodgson, D.J., Hosegood, P., Inger, R., Miller, P.I., Sims, D.W., Thompson, R.C., Vanstaen, K., Votier, S.C., Attrill, M.J., Godley, B.J., 2012. Assessing wave energy effects on biodiversity: the Wave Hub experience. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 370, 502–529. https://doi.org/10.1098/rsta.2011.0265

Wolsink, M., 2007. Planning of renewables schemes: Deliberative and fair decision-making on landscape issues instead of reproachful accusations of non-cooperation. Energy Policy 35, 2692–2704. https://doi.org/10.1016/j.enpol.2006.12.002

Won, W., Lee, S.K., Choi, K., Kwon, Y., 2014. Current trends for the floating liquefied natural gas (FLNG) technologies. Korean Journal of Chemical Engineering 31, 732–743. https://doi.org/10.1007/s11814-014-0047-x

Wood, D., Capuzzo, E., Kirby, D., Mooney-McAuley, K., Kerrison, P., 2017. UK macroalgae aquaculture: What are the key environmental and licensing considerations? Marine Policy 83, 29–39. https://doi.org/10.1016/j.marpol.2017.05.021

World Bank, 2018. Worldwide Governance Indicators. URL https://info.worldbank.org/governance/wgi/index.aspx#home (accessed 20/4/19).

WRI, UNEP, UNDP, World Bank, 2005. World Resources 2005: The Wealth of the Poor—Managing Ecosystems to Fight Poverty. World Resources Inst, Washington, D.C. USA.

Wright, D.G., Dey, P.K., Brammer, J., 2014. A barrier and techno-economic analysis of small-scale bCHP (biomass combined heat and power) schemes in the UK. Energy 71, 332–345. https://doi.org/10.1016/j.energy.2014.04.079

Wright, G., 2016. Regulating wave and tidal energy: An industry perspective on the Scottish marine governance framework. Marine Pol 65, 115–126. https://doi.org/10.1016/j.marpol.2015.12.014

Wrigley, E.A., 2010. Energy and the English Industrial Revolution. Cambridge University Press, Cambridge, UK.

Wu, D., Chen, Z., 2016. Quantitative risk assessment of fire accidents of large-scale oil tanks triggered by lightning. Engineering Failure Analysis 63, 172–181. https://doi.org/10.1016/j.engfailanal.2015.11.029

Wu, H., Darton, R., Borthwick, A., 2015. Defining and measuring river basin sustainability: a case study of the Yellow River. WIT Transactions on The Built Environment 168, 383–394. https://doi.org/10.2495/SD150331

Wu, J., Pu, G., Ma, Q., Qi, H., Wang, R., 2017. Quantitative environmental risk assessment for the iron and steel industrial symbiosis network. Journal of Cleaner Production 157, 106–117. https://doi.org/10.1016/j.jclepro.2017.04.094

Wüstenhagen, R., Wolsink, M., Bürer, M.J., 2007. Social acceptance of renewable energy innovation: An introduction to the concept. Energy Policy 35, 2683–2691. https://doi.org/10.1016/j.enpol.2006.12.001

Wyatt, P., 2013. A dwelling-level investigation into the physical and socio-economic drivers of domestic energy consumption in England. Energy Policy 60, 540–549. https://doi.org/10.1016/j.enpol.2013.05.037

Xenias, D., Axon, C., Balta-Ozkan, N., Cipcigan, L.M., Connor, P., Davidson, R., Spence, A., Taylor, G., Whitmarsh, L.E., 2014. Scenarios for the development of smart grids in the UK: literature review (No. UKERC/WP/ES/2014/001). UKERC, London.

Xenias, D., Axon, C.J., Whitmarsh, L., Connor, P.M., Balta-Ozkan, N., Spence, A., 2015. UK smart grid development: An expert assessment of the benefits, pitfalls and functions. Renew. Energy 81, 89–102. https://doi.org/10.1016/j.renene.2015.03.016

Yafimava, K., 2011. The Transit Dimension of EU Energy Security: Russian Gas Transit Across Ukraine, Belarus, and Moldova. Oxford University Press, Oxford, UK.

Yassin, L., Lettieri, P., Simons, S.J.R., Germanà, A., 2009. Techno-economic performance of energy-from-waste fluidized bed combustion and gasification processes in the UK context. Chemical Engineering Journal 146, 315–327. https://doi.org/10.1016/j.cej.2008.06.014

Yates, N., Walkington, I., Burrows, R., Wolf, J., 2013. Appraising the extractable tidal energy resource of the UK's western coastal waters. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 371, 20120181–20120181. https://doi.org/10.1098/rsta.2012.0181

Yeeles, A., Akporiaye, A., 2016. Risk and resilience in the Nigerian oil sector: The economic effects of pipeline sabotage and theft. Energy Policy 88, 187–196. https://doi.org/10.1016/j.enpol.2015.10.018

Yenikeyeff, S.M., 2008. The Georgia-Russia standoff and the future of Caspian and Central Asian energy supplies, Oxford Energy Comment. Oxford Inst for Energy Studies, Oxford, UK.

Younger, P.L., 2015. Geothermal Energy: Delivering on the Global Potential. Energies 8, 11737–11754. https://doi.org/10.3390/en81011737

Younger, P.L., 2014. Hydrogeological challenges in a low-carbon economy. Quarterly Journal of Engineering Geology and Hydrogeology 47, 7–27. https://doi.org/10.1144/qjegh2013-063
Younger, P.L., Boyce, A.J., Waring, A.J., 2015. Chloride waters of Great Britain revisited: from subsea formation waters to onshore geothermal fluids. Proceedings of the Geologists' Association 126, 453–465. https://doi.org/10.1016/j.pgeola.2015.04.001
Younger, P.L., Gluyas, J.G., Stephens, W.E., 2012. Development of deep geothermal energy resources in the UK. Proceedings of the Institution of Civil Engineers - Energy 165, 19–32. https://doi.org/10.1680/ener.11.00009
Younger, P.L., Gonalez, G., Amezaga, J.M., 2010. Water management issues in the underground gasification of coal and the subsequent use of the voids for long-term carbon dioxide storage, in: Wolkersdorfer, C., Freund, A. (Eds.), Mine Water and Innovative Thinking. Int. Mine Water Association Symp, 5-9 Sept, Sydney, Nova Scotia, Canada, pp. 67–70.
Younger, P.L., Manning, D.A.C., 2010. Hyper-permeable granite: lessons from test-pumping in the Eastgate Geothermal Borehole, Weardale, UK. Quarterly Journal of Engineering Geology and Hydrogeology 43, 5–10. https://doi.org/10.1144/1470-9236/08-085
Younger, P.L., Manning, D.A.C., Millward, D., Busby, J.P., Jones, C.R.C., Gluyas, J.G., 2016. Geothermal exploration in the Fell Sandstone Formation (Mississippian) beneath the city centre of Newcastle upon Tyne, UK: the Newcastle Science Central Deep Geothermal Borehole. Quarterly Journal of Engineering Geology and Hydrogeology 49, 350–363. https://doi.org/10.1144/qjegh2016-053
Yuan, J., Luo, D., Feng, L., 2015. A review of the technical and economic evaluation techniques for shale gas development. App Egy 148, 49–65. https://doi.org/10.1016/j.apenergy.2015.03.040
Zare-Garizy, T., Fridgen, G., Wederhake, L., 2018. A Privacy Preserving Approach to Collaborative Systemic Risk Identification: The Use-Case of Supply Chain Networks. Security and Communication Networks 2018, 1–18. https://doi.org/10.1155/2018/3858592
Zeyringer, M., Fais, B., Keppo, I., Price, J., 2018. The potential of marine energy technologies in the UK – Evaluation from a systems perspective. Renewable Energy 115, 1281–1293. https://doi.org/10.1016/j.renene.2017.07.092
Zglobisz, N., Castillo-Castillo, A., Grimes, S., Jones, P., 2010. Influence of UK energy policy on the deployment of anaerobic digestion. Energy Policy, The socio-economic transition towards a hydrogen economy - findings from European research, with regular papers 38, 5988–5999. https://doi.org/10.1016/j.enpol.2010.05.054
Zhang, X., Shen, J., Lu, Y., He, W., Xu, P., Zhao, X., Qiu, Z., Zhu, Z., Zhou, J., Dong, X., 2015. Active Solar Thermal Facades (ASTFs): From concept, application to research questions. Renewable and Sustainable Energy Reviews 50, 32–63. https://doi.org/10.1016/j.rser.2015.04.108
Ziolkowska, J.R., Ziolkowski, B., 2015. Energy efficiency in the transport sector in the EU-27: A dynamic dematerialization analysis. Energy Economics 51, 21–30. https://doi.org/10.1016/j.eneco.2015.06.012
Ziyad, F., Stevenson, F., 2018. Domestic photovoltaic systems: the governance of occupant use. Building Res & Information 46, 23–41. https://doi.org/10.1080/09613218.2017.1313661

A. The Risk Matrix

The following tables, one for each stage (all fuels), are the complete risk matrix. The arguments and information supporting the choice of values are given in chapters 4-7. The analysis (chapter 9) was conducted using these tables in Microsoft Excel.

Abbreviations:

L Likelihood

I Impact

R Risk score (determines the consequence level)

Colour key:

	Low consequence level
	Moderate consequence level
	High consequence level
	Risk not relevant for this fuel at this stage
	Indicates that stage is co-located

Stage 1: Explore

Fuel Category		Biogas				Bioliquids				Biomass (solids)				Coal				Demand reduction				Gas				Gas (unconventional)			
Principal Means or Technology		Find agri. waste				Find energy & waste crops				Find woody crops				Geology, dig				Measure potential				Geology, drill				Geology, drill			
Principal Risk Location		UK				UK				UK				Global				UK				Global				UK			
Cause of Risk	**Risk Category**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**
Lack of a well-functioning market	Economic	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Macro	1	1	1	Meso	2	1	2	Macro	2	1	2	Macro	2	1	2
Lack of access to capital	Economic	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Macro	1	1	1	Meso	3	1	3	Macro	2	2	4	Macro	2	2	4
Unable to agree a price for licence or permits	Economic				0				0				0	Meso	1	1	1				0	Meso	1	2	2	Meso	1	2	2
Uncertain decommissioning costs	Economic				0				0				0				0				0	Micro	1	2	2	Micro	1	2	2
Price volatility	Economic				0				0				0	Macro	1	1	1	Meso	1	1	1	Macro	2	2	4	Macro	2	2	4
Difficult physical access	Environmental	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	2	1	2				0	Micro	3	2	6	Micro	1	2	2
Natural hazards	Environmental				0				0				0				0				0	Micro	1	2	2	Micro	1	1	1
Quality of fuel source	Environmental	Micro	3	1	3	Micro	3	1	3	Micro	3	1	3	Micro	3	2	6	Micro	3	3	9	Micro	3	4	12	Micro	3	4	12
Lack of water availability	Environmental				0				0				0				0				0				0				0
Lack of critical materials availability	Environmental				0				0				0				0				0				0				0
Weak technology transfer environment	Innovation				0				0				0				0				0	Macro	1	2	2	Macro	1	2	2
Lack of public subsidy	Innovation				0				0				0				0	Meso	2	3	6				0				0
Only marginal improvements likely	Innovation				0				0				0				0	Meso	1	1	1	Macro	2	2	4	Macro	1	2	2
Lack of material substitutability	Innovation				0				0				0				0				0				0				0
R&D capacity or capability does not match the challenge	Innovation				0				0				0				0	Meso	1	1	1	Macro	1	1	1	Macro	1	1	1
Optimism bias	Innovation	Meso	3	1	3	Meso	3	1	3	Meso	3	1	3	Macro	1	1	1	Meso	3	1	3	Macro	1	3	3	Macro	1	3	3
Insufficient capacity to manufacture system components or conversion devices	Manufacturing				0				0				0				0				0	Macro	1	2	2	Macro	1	2	2
Insufficient capacity to construct sites	Manufacturing				0				0				0				0				0	Macro	2	1	2	Micro	1	1	1
Insufficient rate of infrastructure construction	Manufacturing				0				0				0				0				0				0				0
Denial of permission to access sites	Political	Micro	2	1	2	Micro	2	1	2	Micro	2	1	2	Micro	2	1	2	Micro	2	1	2	Meso	2	1	2	Micro	2	3	6
Lack of social stability	Political	Meso	1	2	2	Meso	1	2	2	Meso	1	2	2	Meso	1	2	2	Meso	1	2	2	Meso	2	3	6	Meso	1	2	2
Changing policy or regulatory framework	Political	Meso	2	1	2	Meso	2	1	2	Meso	2	1	2				0	Meso	2	2	4	Meso	1	2	2	Meso	2	3	6
Poor institutional governance	Political	Meso	1	2	2	Meso	1	2	2	Meso	1	2	2	Meso	1	2	2	Meso	1	2	2	Meso	2	3	6	Meso	1	2	2
Disputed landrights or resource ownership	Political	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	2	1	2				0	Micro	2	3	6	Micro	1	1	1
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Political				0				0				0				0				0				0				0
Significant public concern	Political	Meso	2	1	2	Meso	2	1	2	Meso	2	1	2	Micro	2	1	2	Meso	2	1	2	Micro	2	2	4	Micro	3	3	9
Lack of basic education levels in the local workforce	Skills				0				0				0				0				0				0				0
Lack of vocational training of the local workforce	Skills	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	2	2
Lack of specialists in the local workforce	Skills	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	2	2	4
Pollution event	Technical	Micro	1	1	1				0				0	Micro	1	1	1				0	Micro	2	2	4	Micro	2	4	8
Unable to neutralise waste at decommissioning	Technical	Micro	1	1	1				0				0	Micro	1	1	1				0	Micro	1	2	2	Micro	1	2	2
Specialist equipment unavailable	Technical	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Macro	2	2	4	Macro	2	2	4
Operational failure	Technical	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	2	2	4	Micro	2	2	4
Infrastructure failure	Technical				0				0				0				0				0				0				0

Fuel Category		Hydro				Nuclear (fission)				Ocean (tidal)				Ocean (wave)				Oil				Solar (electric)				Solar (thermal, water)			
Principal Means or Technology		Geology				Geology, dig				Measure potential				Measure potential				Geology, drill				Measure potential				Measure potential			
Principal Risk Location		UK				Global				UK				UK				Global				UK				UK			
Cause of Risk	**Risk Category**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**
Lack of a well-functioning market	Economic	Macro	2	1	2	Macro	1	1	1	Meso	1	1	1	Meso	3	2	6	Macro	2	1	2	Meso	1	1	1	Meso	1	1	1
Lack of access to capital	Economic	Macro	1	1	1	Macro	1	1	1	Meso	2	2	4	Meso	2	2	4	Macro	2	2	4	Meso	1	1	1	Meso	1	1	1
Unable to agree a price for licence or permits	Economic				0	Meso	1	1	1				0				0	Meso	1	2	2				0				0
Uncertain decommissioning costs	Economic				0				0				0				0	Micro	1	2	2				0				0
Price volatility	Economic	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1	Macro	2	2	4	Macro	1	1	1	Macro	1	1	1
Difficult physical access	Environmental	Micro	1	2	2	Micro	2	1	2	Micro	3	1	3	Micro	3	1	3	Micro	3	2	6	Micro	1	1	1	Micro	1	1	1
Natural hazards	Environmental	Micro	2	1	2				0	Micro	2	1	2	Micro	2	1	2	Micro	1	2	2	Micro	1	1	1	Micro	1	1	1
Quality of fuel source	Environmental	Micro	1	1	1	Micro	2	3	6	Micro	1	1	1	Micro	1	1	1	Micro	3	4	12	Micro	1	1	1	Micro	1	1	1
Lack of water availability	Environmental				0				0				0				0				0				0				0
Lack of critical materials availability	Environmental				0				0				0				0				0				0				0
Weak technology transfer environment	Innovation				0				0				0				0	Macro	1	2	2				0				0
Lack of public subsidy	Innovation				0				0				0				0				0				0				0
Only marginal improvements likely	Innovation				0				0				0				0	Macro	2	2	4				0				0
Lack of material substitutability	Innovation				0				0				0				0				0				0				0
R&D capacity or capability does not match the challenge	Innovation				0				0				0				0	Macro	1	1	1				0				0
Optimism bias	Innovation	Macro	1	1	1	Macro	1	1	1	Meso	3	1	3	Meso	3	1	3	Macro	1	3	3	Meso	2	1	2	Meso	3	1	3
Insufficient capacity to manufacture system components or conversion devices	Manufacturing	Macro	1	1	1				0	Macro	1	1	1	Macro	1	1	1	Macro	1	2	2				0				0
Insufficient capacity to construct sites	Manufacturing				0				0				0				0	Macro	2	1	2				0				0
Insufficient rate of infrastructure construction	Manufacturing				0				0				0				0				0				0				0
Denial of permission to access sites	Political	Micro	1	3	3	Micro	2	1	2	Micro	1	3	3	Micro	1	3	3	Meso	2	1	2	Micro	2	1	2	Micro	2	1	2
Lack of social stability	Political	Meso	1	2	2	Meso	3	1	3	Meso	1	2	2	Meso	1	2	2	Meso	2	3	6	Meso	1	2	2	Meso	1	2	2
Changing policy or regulatory framework	Political				0				0				0				0	Meso	1	2	2				0				0
Poor institutional governance	Political	Meso	1	2	2	Meso	3	1	3	Meso	1	2	2	Meso	1	2	2	Meso	2	3	6	Meso	1	2	2	Meso	1	2	2
Disputed landrights or resource ownership	Political	Micro	1	1	1	Micro	2	1	2	Micro	1	1	1	Micro	1	1	1	Micro	2	3	6	Micro	1	1	1	Micro	1	1	1
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Political				0				0				0				0				0				0				0
Significant public concern	Political	Micro	3	4	12	Micro	2	1	2	Micro	1	1	1	Micro	1	1	1	Micro	2	2	4				0				0
Lack of basic education levels in the local workforce	Skills				0				0				0				0				0				0				0
Lack of vocational training of the local workforce	Skills	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Lack of specialists in the local workforce	Skills	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Pollution event	Technical				0	Micro	1	1	1				0				0	Micro	2	3	6				0				0
Unable to neutralise waste at decommissioning	Technical				0	Micro	1	1	1				0				0	Micro	1	2	2				0				0
Specialist equipment unavailable	Technical	Meso	1	2	2	Meso	1	1	1	Meso	2	2	4	Meso	2	2	4	Macro	2	2	4	Meso	1	1	1	Meso	1	1	1
Operational failure	Technical	Micro	1	1	1	Micro	1	1	1	Micro	2	2	4	Micro	2	2	4	Micro	2	2	4				0				0
Infrastructure failure	Technical				0				0				0				0				0				0				0

Fuel Category		Thermal (geological)				Thermal (low temperature)				Waste				Wind (offshore)				Wind (onshore)			
Principal Means or Technology		Geology, drill				Measure potential				Find waste				Measure potential				Measure potential			
Principal Risk Location		UK				UK				UK				UK				UK			
Cause of Risk	**Risk Category**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**
Lack of a well-functioning market	Economic	Macro	2	1	2	Meso	1	1	1	Meso	1	1	1	Macro	1	1	1	Macro	1	1	1
Lack of access to capital	Economic	Macro	3	4	12	Micro	1	1	1	Micro	1	1	1	Macro	2	2	4	Meso	1	1	1
Unable to agree a price for licence or permits	Economic				0				0				0				0				0
Uncertain decommissioning costs	Economic	Micro	1	2	2				0				0				0				0
Price volatility	Economic	Macro	2	2	4	Macro	1	1	1				0	Macro	1	1	1	Macro	1	1	1
Difficult physical access	Environmental	Micro	1	2	2	Micro	1	1	1	Micro	1	1	1	Micro	3	1	3	Micro	1	1	1
Natural hazards	Environmental	Micro	1	1	1	Micro	1	1	1				0	Micro	2	1	2	Micro	1	1	1
Quality of fuel source	Environmental	Micro	3	4	12	Micro	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Lack of water availability	Environmental				0				0				0				0				0
Lack of critical materials availability	Environmental				0				0				0				0				0
Weak technology transfer environment	Innovation	Macro	1	2	2				0				0				0				0
Lack of public subsidy	Innovation				0				0				0				0				0
Only marginal improvements likely	Innovation	Macro	1	2	2				0				0				0				0
Lack of material substitutability	Innovation				0				0				0				0				0
R&D capacity or capability does not match the challenge	Innovation	Macro	2	1	2				0				0				0				0
Optimism bias	Innovation	Meso	2	2	4	Meso	3	1	3	Meso	1	1	1	Meso	2	1	2	Meso	2	2	4
Insufficient capacity to manufacture system components or conversion devices	Manufacturing	Macro	1	2	2				0				0				0				0
Insufficient capacity to construct sites	Manufacturing	Meso	1	1	1				0				0				0				0
Insufficient rate of infrastructure construction	Manufacturing				0				0				0				0				0
Denial of permission to access sites	Political	Micro	1	1	1	Micro	2	1	2	Micro	1	1	1	Micro	1	3	3	Micro	2	3	6
Lack of social stability	Political	Meso	1	2	2	Meso	1	2	2	Meso	1	2	2	Meso	1	2	2	Meso	1	2	2
Changing policy or regulatory framework	Political	Meso	1	2	2				0	Meso	2	1	2				0				0
Poor institutional governance	Political	Meso	1	2	2	Meso	1	2	2	Meso	1	2	2	Meso	1	2	2	Meso	1	2	2
Disputed landrights or resource ownership	Political	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1				0				0
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Political				0				0				0				0				0
Significant public concern	Political	Micro	1	1	1				0	Micro	1	1	1	Meso	1	1	1	Micro	2	1	2
Lack of basic education levels in the local workforce	Skills				0				0				0				0				0
Lack of vocational training of the local workforce	Skills	Meso	1	2	2	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Lack of specialists in the local workforce	Skills	Meso	2	2	4	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Pollution event	Technical	Micro	2	1	2				0	Micro	1	1	1				0				0
Unable to neutralise waste at decommissioning	Technical	Micro	1	2	2				0	Micro	1	1	1				0				0
Specialist equipment unavailable	Technical	Macro	2	2	4	Meso	1	1	1	Meso	1	1	1	Macro	2	2	4	Meso	1	2	2
Operational failure	Technical	Micro	2	2	4				0	Micro	1	1	1	Micro	2	2	4	Micro	1	1	1
Infrastructure failure	Technical				0				0				0				0				0

Table A.1 The risk matrix, Stage 1.

Stage 2: Exploit

Fuel Category		Biogas				Bioliquids				Biomass (solids)				Coal			
Principal Means or Technology		Gather agri. waste				Gather energy & waste crops				Gather woody crops				Mine			
Principal Risk Location		UK				UK				UK				Global			
Cause of Risk	**Risk Category**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**
Lack of a well-functioning market	Economic	Meso	2	1	2	Meso	2	1	2	Meso	2	1	2	Macro	2	1	2
Lack of access to capital	Economic	Micro	1	2	2	Meso	2	2	4	Meso	2	2	4	Macro	2	4	8
Unable to agree a price for licence or permits	Economic				0				0				0	Meso	1	2	2
Uncertain decommissioning costs	Economic	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	1	2	2
Price volatility	Economic	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1	Macro	3	2	6
Difficult physical access	Environmental	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	2	2	4
Natural hazards	Environmental	Micro	1	2	2	Micro	1	2	2	Micro	1	2	2	Micro	1	2	2
Quality of fuel source	Environmental	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	1	2	2
Lack of water availability	Environmental	Micro	2	2	4	Micro	2	2	4	Micro	2	2	4	Micro	2	3	6
Lack of critical materials availability	Environmental				0				0				0				0
Weak technology transfer environment	Innovation	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Macro	1	1	1
Lack of public subsidy	Innovation	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Only marginal improvements likely	Innovation	Macro	3	1	3	Macro	2	1	2	Macro	2	1	2	Macro	3	1	3
Lack of material substitutability	Innovation				0				0				0				0
R&D capacity or capability does not match the challenge	Innovation	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1
Optimism bias	Innovation	Meso	3	1	3	Meso	3	1	3	Meso	3	1	3	Macro	1	1	1
Insufficient capacity to manufacture system components or conversion devices	Manufacturing	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1
Insufficient capacity to construct sites	Manufacturing				0				0				0	Micro	1	1	1
Insufficient rate of infrastructure construction	Manufacturing	Micro	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	2	2
Denial of permission to access sites	Political	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1	Micro	1	2	2
Lack of social stability	Political				0				0				0				0
Changing policy or regulatory framework	Political	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	2	3	6
Poor institutional governance	Political				0				0				0				0
Disputed landrights or resource ownership	Political	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	1	3	3
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Political	Meso	1	1	1	Meso	2	1	2	Meso	1	1	1	Meso	2	1	2
Significant public concern	Political	Meso	2	1	2	Meso	2	1	2	Meso	2	1	2	Micro	2	1	2
Lack of basic education levels in the local workforce	Skills	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Lack of vocational training of the local workforce	Skills	Meso	2	1	2	Meso	2	1	2	Meso	2	1	2	Meso	2	1	2
Lack of specialists in the local workforce	Skills	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	2	1	2
Pollution event	Technical	Micro	3	1	3	Micro	3	1	3	Micro	3	1	3	Micro	2	3	6
Unable to neutralise waste at decommissioning	Technical	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	1	3	3
Specialist equipment unavailable	Technical	Micro	1	2	2	Micro	1	2	2	Micro	1	2	2	Meso	1	2	2
Operational failure	Technical	Micro	1	2	2	Micro	3	1	3	Micro	1	2	2	Micro	1	2	2
Infrastructure failure	Technical	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1

Fuel Category		Demand reduction				Gas				Gas (unconventional)				Hydro			
Principal Means or Technology		Create dev, serv & comm camps				Drill				Drill				Operate turbine			
Principal Risk Location		UK				Global				UK				UK			
Cause of Risk	**Risk Category**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**
Lack of a well-functioning market	Economic	Meso	2	3	6	Macro	1	2	2	Macro	1	2	2	Macro	1	2	2
Lack of access to capital	Economic	Meso	2	2	4	Macro	2	3	6	Macro	2	4	8	Macro	2	4	8
Unable to agree a price for licence or permits	Economic				0	Meso	2	2	4	Meso	2	2	4				0
Uncertain decommissioning costs	Economic	Micro	1	1	1	Micro	2	3	6	Micro	2	3	6	Micro	2	1	2
Price volatility	Economic	Meso	1	1	1	Macro	2	1	2	Macro	2	1	2	Macro	2	1	2
Difficult physical access	Environmental				0	Micro	3	3	9	Micro	1	2	2	Micro	1	1	1
Natural hazards	Environmental				0	Micro	3	4	12	Micro	2	2	4	Micro	2	2	4
Quality of fuel source	Environmental				0	Micro	2	1	2	Micro	3	2	6	Micro	1	3	3
Lack of water availability	Environmental				0	Micro	1	2	2	Micro	2	2	4				0
Lack of critical materials availability	Environmental	Macro	2	1	2	Macro	1	1	1	Macro	1	1	1	Macro	2	2	4
Weak technology transfer environment	Innovation	Meso	2	2	4	Macro	1	2	2	Macro	1	2	2	Macro	1	1	1
Lack of public subsidy	Innovation	Meso	2	3	6	Meso	2	1	2	Meso	2	3	6	Meso	2	1	2
Only marginal improvements likely	Innovation	Meso	1	2	2	Macro	2	2	4	Macro	2	1	2	Macro	3	1	3
Lack of material substitutability	Innovation	Macro	2	1	2	Macro	1	1	1	Macro	1	1	1	Macro	2	3	6
R&D capacity or capability does not match the challenge	Innovation	Meso	1	1	1	Macro	1	1	1	Macro	1	1	1	Macro	2	1	2
Optimism bias	Innovation	Meso	3	1	3	Macro	2	1	2	Meso	3	3	9	Meso	1	1	1
Insufficient capacity to manufacture system components or conversion devices	Manufacturing	Macro	1	1	1	Macro	2	1	2	Macro	2	1	2	Macro	2	2	4
Insufficient capacity to construct sites	Manufacturing	Micro	3	3	9	Macro	2	1	2	Micro	2	2	4	Meso	2	2	4
Insufficient rate of infrastructure construction	Manufacturing				0	Meso	2	2	4	Meso	2	3	6	Meso	2	2	4
Denial of permission to access sites	Political				0	Meso	2	1	2	Meso	2	3	6	Micro	2	1	2
Lack of social stability	Political				0	Meso	2	4	8				0				0
Changing policy or regulatory framework	Political	Meso	2	2	4	Meso	1	2	2	Meso	2	3	6	Meso	2	2	4
Poor institutional governance	Political				0	Meso	2	4	8				0				0
Disputed landrights or resource ownership	Political				0	Micro	2	2	4	Micro	1	2	2	Micro	1	1	1
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Political	Meso	1	1	1	Meso	2	1	2	Meso	1	3	3	Meso	1	1	1
Significant public concern	Political	Meso	2	3	6	Micro	2	2	4	Micro	3	3	9	Micro	3	3	9
Lack of basic education levels in the local workforce	Skills	Meso	1	1	1	Meso	2	1	2	Meso	1	1	1	Meso	2	1	2
Lack of vocational training of the local workforce	Skills	Meso	2	2	4	Meso	3	1	3	Meso	2	2	4	Meso	2	2	4
Lack of specialists in the local workforce	Skills	Meso	2	2	4	Meso	3	2	6	Meso	2	1	2	Meso	2	2	4
Pollution event	Technical				0	Micro	3	2	6	Micro	3	4	12	Micro	1	1	1
Unable to neutralise waste at decommissioning	Technical	Micro	2	1	2	Micro	3	3	9	Micro	3	3	9	Micro	1	1	1
Specialist equipment unavailable	Technical				0	Macro	1	2	2	Macro	1	2	2	Meso	2	1	2
Operational failure	Technical	Micro	2	1	2	Micro	2	4	8	Micro	2	3	6	Micro	1	4	4
Infrastructure failure	Technical	Micro	1	1	1	Micro	1	3	3	Micro	1	2	2	Micro	1	2	2

Fuel Category		Nuclear (fission)				Ocean (tidal)				Ocean (wave)				Oil			
Principal Means or Technology		Mine				Operate device				Operate device				Drill			
Principal Risk Location		Global				UK				UK				Global			
Cause of Risk	**Risk Category**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**
Lack of a well-functioning market	Economic	Macro	2	1	2	Macro	3	2	6	Macro	3	2	6	Macro	1	2	2
Lack of access to capital	Economic	Macro	3	4	12	Macro	3	3	9	Macro	3	3	9	Macro	2	3	6
Unable to agree a price for licence or permits	Economic	Meso	1	2	2	Meso	1	1	1	Meso	1	1	1	Meso	2	2	4
Uncertain decommissioning costs	Economic	Micro	3	2	6	Micro	3	1	3	Micro	1	1	1	Micro	2	3	6
Price volatility	Economic	Macro	2	2	4	Macro	2	1	2	Macro	2	1	2	Macro	2	1	2
Difficult physical access	Environmental	Micro	2	2	4	Micro	3	2	6	Micro	3	2	6	Micro	3	3	9
Natural hazards	Environmental	Micro	1	2	2	Micro	2	3	6	Micro	3	4	12	Micro	3	4	12
Quality of fuel source	Environmental	Micro	2	2	4	Micro	2	1	2	Micro	3	2	6	Micro	2	1	2
Lack of water availability	Environmental	Micro	3	2	6				0				0	Micro	2	2	4
Lack of critical materials availability	Environmental				0	Macro	2	2	4	Macro	1	2	2	Macro	1	1	1
Weak technology transfer environment	Innovation	Macro	1	1	1	Meso	2	3	6	Meso	2	3	6	Macro	1	2	2
Lack of public subsidy	Innovation	Meso	1	1	1	Meso	3	3	9	Meso	3	3	9	Meso	2	1	2
Only marginal improvements likely	Innovation	Macro	3	1	3	Meso	2	1	2	Meso	2	1	2	Macro	2	2	4
Lack of material substitutability	Innovation				0	Macro	2	3	6	Macro	2	3	6	Macro	1	1	1
R&D capacity or capability does not match the challenge	Innovation	Macro	1	1	1	Meso	3	2	6	Meso	3	2	6	Macro	1	1	1
Optimism bias	Innovation	Macro	1	1	1	Meso	3	1	3	Meso	3	2	6	Macro	2	1	2
Insufficient capacity to manufacture system components or conversion devices	Manufacturing	Macro	1	1	1	Meso	2	3	6	Macro	2	3	6	Macro	2	1	2
Insufficient capacity to construct sites	Manufacturing	Micro	1	1	1	Micro	2	3	6	Micro	1	2	2	Macro	2	1	2
Insufficient rate of infrastructure construction	Manufacturing	Meso	2	2	4	Meso	3	4	12	Meso	3	4	12	Meso	2	2	4
Denial of permission to access sites	Political	Micro	2	2	4	Meso	1	4	4	Meso	1	4	4	Meso	2	1	2
Lack of social stability	Political	Meso	2	2	4				0				0	Meso	2	4	8
Changing policy or regulatory framework	Political	Meso	1	2	2	Meso	3	3	9	Meso	3	3	9	Meso	1	2	2
Poor institutional governance	Political	Meso	2	3	6				0				0	Meso	2	4	8
Disputed landrights or resource ownership	Political	Micro	2	3	6	Meso	1	1	1	Meso	1	1	1	Micro	2	2	4
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Political	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	2	1	2
Significant public concern	Political	Micro	2	1	2	Micro	1	2	2	Micro	3	3	9	Micro	2	2	4
Lack of basic education levels in the local workforce	Skills	Meso	2	1	2				0				0	Meso	2	1	2
Lack of vocational training of the local workforce	Skills	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4	Meso	3	1	3
Lack of specialists in the local workforce	Skills	Meso	2	1	2	Meso	3	2	6	Meso	3	2	6	Meso	3	2	6
Pollution event	Technical	Micro	3	3	9	Micro	3	1	3	Micro	1	2	2	Micro	3	3	9
Unable to neutralise waste at decommissioning	Technical	Micro	3	3	9	Micro	1	2	2	Micro	1	2	2	Micro	3	3	9
Specialist equipment unavailable	Technical	Meso	2	1	2	Meso	2	1	2	Meso	2	1	2	Macro	1	2	2
Operational failure	Technical	Micro	2	1	2	Micro	2	3	6	Micro	3	4	12	Micro	2	4	8
Infrastructure failure	Technical	Micro	2	1	2	Micro	1	3	3	Micro	1	3	3	Micro	1	3	3

Fuel Category		Solar (electric)				Solar (thermal, water)				Thermal (geological)				Thermal (low temperature)			
Principal Means or Technology		Operate PV array				Operate panel				Drill				Operate HP			
Principal Risk Location		UK				UK				UK				UK			
Cause of Risk	**Risk Category**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**
Lack of a well-functioning market	Economic	Macro	2	1	2	Meso	3	1	3	Macro	1	2	2	Macro	3	2	6
Lack of access to capital	Economic	Meso	2	2	4	Meso	3	2	6	Macro	3	4	12	Meso	3	3	9
Unable to agree a price for licence or permits	Economic				0				0				0				0
Uncertain decommissioning costs	Economic	Micro	1	1	1	Micro	1	1	1	Micro	2	2	4	Micro	2	1	2
Price volatility	Economic	Macro	2	1	2	Meso	2	1	2	Macro	2	1	2	Macro	2	1	2
Difficult physical access	Environmental				0				0	Micro	1	2	2	Micro	2	1	2
Natural hazards	Environmental	Micro	2	1	2	Micro	2	1	2	Micro	2	1	2				0
Quality of fuel source	Environmental	Micro	3	2	6	Micro	3	1	3	Micro	2	4	8	Micro	1	1	1
Lack of water availability	Environmental				0				0	Micro	2	1	2				0
Lack of critical materials availability	Environmental	Macro	2	2	4	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1
Weak technology transfer environment	Innovation	Macro	2	2	4	Meso	2	2	4	Macro	1	2	2	Macro	2	2	4
Lack of public subsidy	Innovation	Meso	2	2	4	Meso	1	2	2	Meso	2	3	6	Meso	3	2	6
Only marginal improvements likely	Innovation	Macro	2	1	2	Macro	1	1	1	Macro	2	2	4	Macro	1	2	2
Lack of material substitutability	Innovation	Macro	2	1	2	Macro	1	1	1	Macro	2	1	2	Macro	1	1	1
R&D capacity or capability does not match the challenge	Innovation	Macro	2	1	2	Meso	3	1	3	Macro	1	1	1	Macro	3	1	3
Optimism bias	Innovation	Macro	2	2	4	Meso	2	1	2	Macro	3	3	9	Macro	2	2	4
Insufficient capacity to manufacture system components or conversion devices	Manufacturing	Macro	1	2	2	Meso	1	2	2	Macro	2	1	2	Macro	1	2	2
Insufficient capacity to construct sites	Manufacturing	Micro	1	2	2	Micro	1	1	1	Meso	2	2	4	Micro	2	2	4
Insufficient rate of infrastructure construction	Manufacturing	Meso	2	2	4				0	Meso	2	2	4	Meso	2	4	8
Denial of permission to access sites	Political	Micro	1	2	2				0	Micro	1	1	1				0
Lack of social stability	Political				0				0				0				0
Changing policy or regulatory framework	Political	Meso	3	3	9	Meso	3	3	9	Meso	3	3	9	Meso	3	3	9
Poor institutional governance	Political				0				0				0				0
Disputed landrights or resource ownership	Political	Micro	1	1	1				0	Micro	1	2	2				0
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Political	Meso	1	1	1	Meso	1	1	1	Meso	1	3	3	Meso	2	1	2
Significant public concern	Political	Micro	2	2	4	Meso	2	2	4	Micro	1	2	2	Meso	2	2	4
Lack of basic education levels in the local workforce	Skills	Meso	2	1	2	Meso	2	1	2	Meso	1	1	1	Meso	2	1	2
Lack of vocational training of the local workforce	Skills	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4
Lack of specialists in the local workforce	Skills	Meso	2	2	4	Meso	1	1	1	Meso	2	1	2	Meso	2	2	4
Pollution event	Technical	Micro	1	1	1				0	Micro	3	1	3	Micro	1	2	2
Unable to neutralise waste at decommissioning	Technical	Micro	3	1	3	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1
Specialist equipment unavailable	Technical	Micro	1	1	1				0	Macro	1	2	2	Micro	1	1	1
Operational failure	Technical	Micro	1	2	2	Micro	1	2	2	Micro	1	2	2	Micro	2	1	2
Infrastructure failure	Technical	Micro	1	2	2	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1

Fuel Category		Waste				Wind (offshore)				Wind (onshore)			
Principal Means or Technology		Gather waste				Operate turbine				Operate turbine			
Principal Risk Location		UK				UK				UK			
Cause of Risk	**Risk Category**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**	**Scale**	**L**	**I**	**R**
Lack of a well-functioning market	Economic	Meso	2	1	2	Macro	2	1	2	Macro	2	1	2
Lack of access to capital	Economic	Meso	1	2	2	Macro	1	2	2	Macro	3	2	6
Unable to agree a price for licence or permits	Economic				0	Meso	1	4	4				0
Uncertain decommissioning costs	Economic	Micro	1	1	1	Micro	3	1	3	Micro	1	1	1
Price volatility	Economic	Macro	1	1	1	Macro	2	1	2	Macro	2	1	2
Difficult physical access	Environmental	Micro	1	1	1	Micro	3	2	6	Micro	1	1	1
Natural hazards	Environmental	Micro	1	2	2	Micro	2	2	4	Micro	2	3	6
Quality of fuel source	Environmental	Micro	1	1	1	Micro	2	2	4	Micro	3	1	3
Lack of water availability	Environmental	Micro	1	1	1				0				0
Lack of critical materials availability	Environmental				0	Macro	2	2	4	Macro	2	2	4
Weak technology transfer environment	Innovation	Meso	1	1	1	Macro	1	1	1	Macro	1	1	1
Lack of public subsidy	Innovation	Meso	1	1	1	Meso	2	2	4	Meso	1	2	2
Only marginal improvements likely	Innovation	Macro	2	1	2	Macro	3	1	3	Macro	3	1	3
Lack of material substitutability	Innovation				0	Macro	2	3	6	Macro	2	3	6
R&D capacity or capability does not match the challenge	Innovation	Macro	1	1	1	Macro	2	2	4	Macro	2	1	2
Optimism bias	Innovation	Meso	1	1	1	Meso	1	2	2	Meso	1	2	2
Insufficient capacity to manufacture system components or conversion devices	Manufacturing	Macro	1	1	1	Macro	2	2	4	Macro	2	2	4
Insufficient capacity to construct sites	Manufacturing				0	Meso	2	3	6	Meso	2	2	4
Insufficient rate of infrastructure construction	Manufacturing	Meso	1	1	1	Meso	3	4	12	Meso	2	4	8
Denial of permission to access sites	Political	Micro	1	1	1	Meso	2	3	6	Micro	3	4	12
Lack of social stability	Political				0				0				0
Changing policy or regulatory framework	Political	Meso	1	1	1	Meso	2	4	8	Meso	3	2	6
Poor institutional governance	Political				0				0				0
Disputed landrights or resource ownership	Political	Micro	1	1	1	Meso	1	1	1	Meso	1	2	2
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Political	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Significant public concern	Political	Meso	1	1	1	Meso	1	1	1	Micro	3	4	12
Lack of basic education levels in the local workforce	Skills	Meso	1	1	1				0				0
Lack of vocational training of the local workforce	Skills	Meso	1	1	1	Meso	2	1	2	Meso	2	1	2
Lack of specialists in the local workforce	Skills	Meso	1	1	1	Meso	2	1	2	Meso	2	1	2
Pollution event	Technical	Micro	2	1	2	Micro	2	1	2	Micro	2	1	2
Unable to neutralise waste at decommissioning	Technical	Micro	1	1	1	Micro	2	2	4	Micro	1	1	1
Specialist equipment unavailable	Technical	Micro	1	2	2	Macro	2	1	2	Meso	1	1	1
Operational failure	Technical	Micro	1	2	2	Micro	1	2	2	Micro	1	2	2
Infrastructure failure	Technical	Micro	1	1	1	Micro	1	3	3	Micro	1	2	2

Table A.2 The risk matrix, Stage 2.

Stage 3: Condition

Fuel Category		Biogas				Bioliquids				Biomass (solids)				Coal			
Principal Means or Technology		Anaerobic digestion				Chemical processing				Mechanical processing				Mechanical processing			
Principal Risk Location		UK				UK				UK				UK			
Cause of Risk	Risk Category	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R
Lack of a well-functioning market	Economic	Macro	1	1	1	Macro	1	3	3	Macro	1	1	1	Macro	1	1	1
Lack of access to capital	Economic	Meso	2	2	4	Macro	3	3	9	Meso	2	1	2	Meso	2	1	2
Unable to agree a price for licence or permits	Economic				0	Meso	1	2	2				0				0
Uncertain decommissioning costs	Economic	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1	Micro	1	1	1
Price volatility	Economic	Macro	1	2	2	Macro	2	1	2	Macro	1	1	1	Macro	1	1	1
Difficult physical access	Environmental	Micro	1	1	1				0				0				0
Natural hazards	Environmental	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1	Micro	1	1	1
Quality of fuel source	Environmental	Micro	3	2	6	Micro	3	2	6	Micro	2	1	2	Micro	2	1	2
Lack of water availability	Environmental	Micro	1	1	1	Micro	1	1	1				0				0
Lack of critical materials availability	Environmental	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1
Weak technology transfer environment	Innovation	Macro	1	2	2	Macro	2	2	4	Macro	1	1	1	Macro	1	1	1
Lack of public subsidy	Innovation	Meso	2	2	4	Meso	2	2	4	Meso	1	1	1	Meso	1	1	1
Only marginal improvements likely	Innovation	Macro	2	1	2	Macro	1	3	3	Macro	3	1	3	Macro	3	1	3
Lack of material substitutability	Innovation	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1
R&D capacity or capability does not match the challenge	Innovation	Macro	1	2	2	Macro	2	2	4	Macro	1	1	1	Macro	1	1	1
Optimism bias	Innovation	Macro	2	2	4	Macro	3	2	6	Macro	1	1	1	Macro	1	1	1
Insufficient capacity to manufacture system components or conversion devices	Manufacturing	Macro	1	1	1	Macro	1	2	2	Macro	2	1	2	Macro	2	1	2
Insufficient capacity to construct sites	Manufacturing	Micro	1	1	1	Micro	1	2	2	Micro	2	1	2	Micro	2	1	2
Insufficient rate of infrastructure construction	Manufacturing	Meso	2	2	4	Meso	1	1	1	Micro	2	1	2	Micro	2	1	2
Denial of permission to access sites	Political	Micro	1	4	4	Micro	1	2	2				0				0
Lack of social stability	Political				0				0				0				0
Changing policy or regulatory framework	Political	Meso	3	2	6	Meso	3	2	6	Meso	1	1	1	Meso	1	2	2
Poor institutional governance	Political				0				0				0				0
Disputed landrights or resource ownership	Political	Micro	1	1	1				0				0				0
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Political	Meso	1	1	1	Meso	1	2	2	Meso	1	1	1	Meso	1	1	1
Significant public concern	Political	Micro	2	2	4	Micro	2	1	2	Micro	1	1	1	Micro	1	1	1
Lack of basic education levels in the local workforce	Skills	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Lack of vocational training of the local workforce	Skills	Meso	2	1	2	Meso	2	2	4	Meso	2	1	2	Meso	2	1	2
Lack of specialists in the local workforce	Skills	Meso	2	1	2	Meso	2	3	6	Meso	2	1	2	Meso	2	1	2
Pollution event	Technical	Micro	3	1	3	Micro	3	2	6	Micro	1	1	1	Micro	1	3	3
Unable to neutralise waste at decommissioning	Technical	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1	Micro	2	2	4
Specialist equipment unavailable	Technical	Micro	1	1	1	Macro	1	2	2	Micro	1	1	1	Micro	1	1	1
Operational failure	Technical	Micro	2	2	4	Micro	1	4	4	Micro	1	1	1	Micro	3	1	3
Infrastructure failure	Technical	Meso	1	2	2	Meso	1	2	2	Meso	1	2	2	Meso	1	2	2

Fuel Category	Demand reduction				Gas				Gas (unconventional)				Hydro				Nuclear (fission)			
Principal Means or Technology					Chemical processing				Chemical processing								Chemical processing			
Principal Risk Location					UK				UK								Global			
Cause of Risk	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R
Lack of a well-functioning market				0	Macro	1	3	3	Macro	1	3	3				0	Macro	2	2	4
Lack of access to capital				0	Macro	3	3	9	Macro	2	4	8				0	Macro	3	4	12
Unable to agree a price for licence or permits				0	Meso	1	2	2	Meso	1	2	2				0	Meso	1	4	4
Uncertain decommissioning costs				0	Micro	1	2	2	Micro	1	2	2				0	Micro	3	3	9
Price volatility				0	Macro	2	1	2	Macro	2	1	2				0	Macro	2	2	4
Difficult physical access				0				0				0				0				0
Natural hazards				0	Micro	1	2	2	Micro	1	2	2				0	Micro	1	1	1
Quality of fuel source				0	Macro	1	1	1	Macro	2	2	4				0	Macro	3	1	3
Lack of water availability				0	Micro	1	1	1	Micro	1	1	1				0	Micro	1	2	2
Lack of critical materials availability				0	Macro	1	1	1	Macro	1	1	1				0	Macro	1	1	1
Weak technology transfer environment				0	Macro	1	1	1	Macro	1	1	1				0	Macro	1	1	1
Lack of public subsidy				0	Meso	1	1	1	Meso	1	1	1				0	Meso	2	1	2
Only marginal improvements likely				0	Macro	3	1	3	Macro	3	1	3				0	Macro	3	1	3
Lack of material substitutability				0	Macro	1	1	1	Macro	1	1	1				0	Macro	3	1	3
R&D capacity or capability does not match the challenge				0	Macro	1	1	1	Macro	1	1	1				0	Macro	1	2	2
Optimism bias				0	Macro	1	2	2	Macro	1	2	2				0	Macro	1	1	1
Insufficient capacity to manufacture system components or conversion devices				0	Macro	1	2	2	Macro	1	2	2				0	Macro	1	2	2
Insufficient capacity to construct sites				0	Macro	1	2	2	Micro	1	2	2				0	Meso	2	1	2
Insufficient rate of infrastructure construction				0	Meso	2	2	4	Meso	2	3	6				0	Meso	2	1	2
Denial of permission to access sites				0	Micro	1	2	2	Micro	2	3	6				0	Meso	1	2	2
Lack of social stability				0	Meso	1	2	2				0				0	Meso	2	2	4
Changing policy or regulatory framework				0	Meso	2	2	4	Meso	2	2	4				0	Meso	1	2	2
Poor institutional governance				0	Meso	1	1	1				0				0	Meso	1	2	2
Disputed landrights or resource ownership				0				0				0				0				0
Insufficient rate of improvement in, or lack of enforcement of, standards and codes				0	Meso	1	2	2	Meso	1	2	2				0	Meso	1	1	1
Significant public concern				0	Micro	3	3	9	Micro	3	3	9				0	Micro	3	1	3
Lack of basic education levels in the local workforce				0	Meso	1	1	1	Meso	1	1	1				0	Meso	1	1	1
Lack of vocational training of the local workforce				0	Meso	3	1	3	Meso	2	2	4				0	Meso	1	2	2
Lack of specialists in the local workforce				0	Meso	2	2	4	Meso	2	1	2				0	Meso	1	2	2
Pollution event				0	Micro	2	3	6	Micro	2	3	6				0	Micro	2	4	8
Unable to neutralise waste at decommissioning				0	Micro	1	2	2	Micro	1	2	2				0	Micro	3	3	9
Specialist equipment unavailable				0	Macro	1	2	2	Macro	1	2	2				0	Macro	1	1	1
Operational failure				0	Micro	1	4	4	Micro	1	4	4				0	Micro	1	2	2
Infrastructure failure				0	Meso	2	1	2	Meso	2	1	2				0	Meso	1	1	1

Fuel Category	Ocean (tidal)				Ocean (wave)				Oil				Solar (electric)				Solar (thermal, water)			
Principal Means or Technology									Refine											
Principal Risk Location									UK											
Cause of Risk	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R
Lack of a well-functioning market				0				0	Macro	1	3	3				0				0
Lack of access to capital				0				0	Macro	3	3	9				0				0
Unable to agree a price for licence or permits				0				0	Meso	1	2	2				0				0
Uncertain decommissioning costs				0				0	Micro	1	2	2				0				0
Price volatility				0				0	Macro	2	1	2				0				0
Difficult physical access				0				0				0				0				0
Natural hazards				0				0	Micro	1	2	2				0				0
Quality of fuel source				0				0	Macro	1	2	2				0				0
Lack of water availability				0				0	Micro	1	1	1				0				0
Lack of critical materials availability				0				0	Macro	1	3	3				0				0
Weak technology transfer environment				0				0	Macro	1	1	1				0				0
Lack of public subsidy				0				0	Meso	1	1	1				0				0
Only marginal improvements likely				0				0	Macro	3	1	3				0				0
Lack of material substitutability				0				0	Macro	3	1	3				0				0
R&D capacity or capability does not match the challenge				0				0	Macro	1	1	1				0				0
Optimism bias				0				0	Macro	1	2	2				0				0
Insufficient capacity to manufacture system components or conversion devices				0				0	Macro	1	2	2				0				0
Insufficient capacity to construct sites				0				0	Macro	1	2	2				0				0
Insufficient rate of infrastructure construction				0				0	Meso	2	2	4				0				0
Denial of permission to access sites				0				0	Micro	1	2	2				0				0
Lack of social stability				0				0	Meso	1	2	2				0				0
Changing policy or regulatory framework				0				0	Meso	2	2	4				0				0
Poor institutional governance				0				0	Meso	1	1	1				0				0
Disputed landrights or resource ownership				0				0				0				0				0
Insufficient rate of improvement in, or lack of enforcement of, standards and codes				0				0	Meso	1	2	2				0				0
Significant public concern				0				0	Micro	2	4	8				0				0
Lack of basic education levels in the local workforce				0				0	Meso	1	1	1				0				0
Lack of vocational training of the local workforce				0				0	Meso	3	1	3				0				0
Lack of specialists in the local workforce				0				0	Meso	2	2	4				0				0
Pollution event				0				0	Micro	3	2	6				0				0
Unable to neutralise waste at decommissioning				0				0	Micro	1	2	2				0				0
Specialist equipment unavailable				0				0	Macro	1	2	2				0				0
Operational failure				0				0	Micro	1	4	4				0				0
Infrastructure failure				0				0	Meso	2	2	4				0				0

Fuel Category	Thermal (geological)				Thermal (low temperature)				Waste				Wind (offshore)				Wind (onshore)			
Principal Means or Technology									Mechanical processing											
Principal Risk Location									UK											
Cause of Risk	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R
Lack of a well-functioning market				0				0	Macro	1	2	2				0				0
Lack of access to capital				0				0	Meso	2	2	4				0				0
Unable to agree a price for licence or permits				0				0	Meso	1	1	1				0				0
Uncertain decommissioning costs				0				0	Micro	1	1	1				0				0
Price volatility				0				0	Macro	1	1	1				0				0
Difficult physical access				0				0				0				0				0
Natural hazards				0				0	Micro	1	1	1				0				0
Quality of fuel source				0				0	Micro	3	1	3				0				0
Lack of water availability				0				0				0				0				0
Lack of critical materials availability				0				0	Macro	1	1	1				0				0
Weak technology transfer environment				0				0	Macro	1	1	1				0				0
Lack of public subsidy				0				0	Meso	1	1	1				0				0
Only marginal improvements likely				0				0	Macro	2	1	2				0				0
Lack of material substitutability				0				0	Macro	1	1	1				0				0
R&D capacity or capability does not match the challenge				0				0	Macro	1	1	1				0				0
Optimism bias				0				0	Macro	1	1	1				0				0
Insufficient capacity to manufacture system components or conversion devices				0				0	Macro	2	1	2				0				0
Insufficient capacity to construct sites				0				0	Micro	2	1	2				0				0
Insufficient rate of infrastructure construction				0				0	Micro	2	1	2				0				0
Denial of permission to access sites				0				0				0				0				0
Lack of social stability				0				0				0				0				0
Changing policy or regulatory framework				0				0	Meso	1	2	2				0				0
Poor institutional governance				0				0				0				0				0
Disputed landrights or resource ownership				0				0				0				0				0
Insufficient rate of improvement in, or lack of enforcement of, standards and codes				0				0	Meso	1	1	1				0				0
Significant public concern				0				0	Micro	1	1	1				0				0
Lack of basic education levels in the local workforce				0				0	Meso	1	1	1				0				0
Lack of vocational training of the local workforce				0				0	Meso	2	1	2				0				0
Lack of specialists in the local workforce				0				0	Meso	2	1	2				0				0
Pollution event				0				0	Micro	2	1	2				0				0
Unable to neutralise waste at decommissioning				0				0	Micro	1	2	2				0				0
Specialist equipment unavailable				0				0	Micro	1	1	1				0				0
Operational failure				0				0	Micro	1	2	2				0				0
Infrastructure failure				0				0	Meso	1	2	2				0				0

Table A.3 The risk matrix, Stage 3.

Stage 4: Convert

Fuel Category		Biogas		Bioliquids	Biomass (solids)		Coal	Demand reduction	Gas		Gas (unconventional)	
Principal Means or Technology		Combustion (CCGT)			Combustion (CHP)		Combustion	Operate device or social practice	Combustion (CCGT)		Combustion (CCGT)	
Principal Risk Location		UK			UK		UK	UK	UK		UK	
Cause of Risk	**Risk Category**	**Scale L I R**	**Scale L I R**	**Scale L I R**	**Scale L I R**	**Scale L I R**	**Scale L I R**	**Scale L I R**	**Scale L I R**	**Scale L I R**	**Scale L I R**	**Scale L I R**
Lack of a well-functioning market	Economic	Macro 2 2 4	0	0	Macro 1 2 2	0	Macro 2 2 4	Meso 3 2 6	Macro 2 2 4	0	Macro 2 2 4	0
Lack of access to capital	Economic	Macro 2 2 4	0	0	Meso 2 4 8	0	Macro 3 4 12	Micro 2 3 6	Macro 2 2 4	0	Macro 2 2 4	0
Unable to agree a price for licence or permits	Economic	Meso 1 3 3	0	0	Meso 1 1 1	0	Meso 3 4 12	0	Meso 1 3 3	0	Meso 1 3 3	0
Uncertain decommissioning costs	Economic	Micro 1 2 2	0	0	Micro 1 2 2	0	Micro 2 2 4	Micro 1 2 2	Micro 1 2 2	0	Micro 1 2 2	0
Price volatility	Economic	Macro 1 2 2	0	0	Macro 1 2 2	0	Macro 1 2 2	Meso 2 1 2	Macro 1 2 2	0	Macro 1 2 2	0
Difficult physical access	Environmental	Micro 1 1 1	0	0	0	0	Micro 1 1 1	0	Micro 1 1 1	0	Micro 1 1 1	0
Natural hazards	Environmental	Micro 1 2 2	0	0	Micro 1 2 2	0	Micro 1 2 2	0	Micro 1 2 2	0	Micro 1 2 2	0
Quality of fuel source	Environmental	Meso 1 1 1	0	0	Meso 3 2 6	0	Meso 2 1 2	0	Meso 1 1 1	0	Meso 1 1 1	0
Lack of water availability	Environmental	Micro 2 3 6	0	0	Micro 2 2 4	0	Micro 2 3 6	0	Micro 2 3 6	0	Micro 2 3 6	0
Lack of critical materials availability	Environmental	Macro 1 1 1	0	0	Macro 1 1 1	0	Macro 1 1 1	Macro 2 1 2	Macro 1 1 1	0	Macro 1 1 1	0
Weak technology transfer environment	Innovation	Macro 1 2 2	0	0	Macro 1 2 2	0	Macro 3 2 6	Meso 2 2 4	Macro 1 2 2	0	Macro 1 2 2	0
Lack of public subsidy	Innovation	Meso 1 1 1	0	0	Meso 2 2 4	0	Meso 1 1 1	Meso 2 3 6	Meso 1 1 1	0	Meso 1 1 1	0
Only marginal improvements likely	Innovation	Macro 2 2 4	0	0	Macro 2 2 4	0	Macro 2 3 6	Meso 2 1 2	Macro 3 1 3	0	Macro 2 2 4	0
Lack of material substitutability	Innovation	Macro 1 1 1	0	0	Macro 1 1 1	0	Macro 1 1 1	Macro 2 1 2	Macro 1 1 1	0	Macro 1 1 1	0
R&D capacity or capability does not match the challenge	Innovation	Macro 1 3 3	0	0	Macro 2 2 4	0	Macro 2 3 6	0	Macro 1 3 3	0	Macro 1 3 3	0
Optimism bias	Innovation	Macro 2 1 2	0	0	Macro 2 1 2	0	Macro 2 1 2	Meso 3 3 9	Macro 2 1 2	0	Macro 2 1 2	0
Insufficient capacity to manufacture system components or conversion devices	Manufacturing	Macro 1 1 1	0	0	Macro 1 1 1	0	Macro 1 1 1	Meso 1 2 2	Macro 1 1 1	0	Macro 1 1 1	0
Insufficient capacity to construct sites	Manufacturing	Micro 2 1 2	0	0	Micro 2 1 2	0	Micro 2 1 2	0	Micro 2 1 2	0	Micro 2 1 2	0
Insufficient rate of infrastructure construction	Manufacturing	Meso 1 1 1	0	0	Meso 2 1 2	0	Meso 1 1 1	Meso 1 1 1	Meso 1 1 1	0	Meso 1 1 1	0
Denial of permission to access sites	Political	Micro 1 2 2	0	0	Micro 1 2 2	0	Micro 1 2 2	0	Micro 1 2 2	0	Micro 1 2 2	0
Lack of social stability	Political	0	0	0	0	0	0	0	0	0	0	0
Changing policy or regulatory framework	Political	Meso 1 3 3	0	0	Meso 3 3 9	0	Meso 1 3 3	Meso 3 3 9	Meso 1 3 3	0	Meso 1 3 3	0
Poor institutional governance	Political	0	0	0	0	0	0	0	0	0	0	0
Disputed landrights or resource ownership	Political	Micro 1 1 1	0	0	Micro 1 1 1	0	Micro 1 1 1	0	Micro 1 1 1	0	Micro 1 1 1	0
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Political	Meso 2 1 2	0	0	Meso 2 1 2	0	Meso 2 1 2	Meso 3 2 6	Meso 2 1 2	0	Meso 2 1 2	0
Significant public concern	Political	Micro 1 2 2	0	0	Micro 2 2 4	0	Meso 3 3 9	Meso 2 2 4	Micro 1 2 2	0	Micro 1 2 2	0
Lack of basic education levels in the local workforce	Skills	Meso 1 1 1	0	0	Meso 1 1 1	0	Meso 1 1 1	Meso 1 1 1	Meso 1 1 1	0	Meso 1 1 1	0
Lack of vocational training of the local workforce	Skills	Meso 2 2 4	0	0	Meso 2 3 6	0	Meso 2 1 2	Meso 3 2 6	Meso 2 2 4	0	Meso 2 2 4	0
Lack of specialists in the local workforce	Skills	Meso 2 2 4	0	0	Meso 2 2 4	0	Meso 2 2 4	Meso 2 2 4	Meso 2 2 4	0	Meso 2 2 4	0
Pollution event	Technical	Macro 3 4 12	0	0	Macro 3 1 3	0	Macro 3 4 12	Micro 1 1 1	Micro 3 4 12	0	Micro 3 4 12	0
Unable to neutralise waste at decommissioning	Technical	Micro 1 2 2	0	0	Micro 1 2 2	0	Micro 2 2 4	Micro 2 1 2	Micro 1 2 2	0	Micro 1 2 2	0
Specialist equipment unavailable	Technical	Meso 1 2 2	0	0	Meso 1 2 2	0	Meso 1 2 2	0	Meso 1 2 2	0	Meso 1 2 2	0
Operational failure	Technical	Micro 2 2 4	0	0	Micro 2 2 4	0	Micro 2 2 4	Micro 2 4 8	Micro 2 2 4	0	Micro 2 2 4	0
Infrastructure failure	Technical	Meso 1 2 2	0	0	Meso 1 2 2	0	Meso 1 2 2	Meso 1 1 1	Meso 1 2 2	0	Meso 1 2 2	0

Fuel Category	Hydro	Nuclear (fission)	Ocean (tidal)	Ocean (wave)	Oil	Solar (electric)	Solar (thermal, water)	Thermal (geological)		Thermal (low temperature)	Waste	Wind (offshore)	Wind (onshore)
Principal Means or Technology		Reactor						ORC turbine			Combustion		
Principal Risk Location		UK						UK			UK		
Cause of Risk	**Scale L I R**	**Scale L I R**	**Scale L I R**	**Scale L I R**	**Scale L I R**	**Scale L I R**	**Scale L I R**	**Scale L I R**	**Scale L I R**	**Scale L I R**	**Scale L I R**	**Scale L I R**	**Scale L I R**
Lack of a well-functioning market	0	Macro 3 3 9	0	0	0	0	0	Macro 3 2 6	0	0	Macro 1 2 2	0	0
Lack of access to capital	0	Macro 3 4 12	0	0	0	0	0	Meso 2 2 4	0	0	Meso 2 2 4	0	0
Unable to agree a price for licence or permits	0	Meso 2 3 6	0	0	0	0	0	0	0	0	Meso 1 2 2	0	0
Uncertain decommissioning costs	0	Meso 3 3 9	0	0	0	0	0	Micro 1 2 2	0	0	Micro 1 2 2	0	0
Price volatility	0	Macro 3 4 12	0	0	0	0	0	Macro 2 2 4	0	0	Macro 1 2 2	0	0
Difficult physical access	0	0	0	0	0	0	0	0	0	0	0	0	0
Natural hazards	0	Micro 1 1 1	0	0	0	0	0	Micro 1 2 2	0	0	Micro 1 2 2	0	0
Quality of fuel source	0	0	0	0	0	0	0	Micro 2 1 2	0	0	Micro 3 1 3	0	0
Lack of water availability	0	Micro 1 3 3	0	0	0	0	0	0	0	0	Micro 1 2 2	0	0
Lack of critical materials availability	0	Macro 2 1 2	0	0	0	0	0	Macro 1 1 1	0	0	Macro 1 1 1	0	0
Weak technology transfer environment	0	Meso 2 2 4	0	0	0	0	0	Macro 1 3 3	0	0	Macro 1 2 2	0	0
Lack of public subsidy	0	Meso 3 4 12	0	0	0	0	0	Meso 2 3 6	0	0	Meso 1 2 2	0	0
Only marginal improvements likely	0	Macro 2 2 4	0	0	0	0	0	Macro 1 3 3	0	0	Macro 2 1 2	0	0
Lack of material substitutability	0	Macro 3 2 6	0	0	0	0	0	Macro 1 1 1	0	0	Macro 1 1 1	0	0
R&D capacity or capability does not match the challenge	0	Meso 2 4 8	0	0	0	0	0	Macro 2 3 6	0	0	Macro 2 1 2	0	0
Optimism bias	0	Macro 3 3 9	0	0	0	0	0	Macro 3 2 6	0	0	Macro 2 1 2	0	0
Insufficient capacity to manufacture system components or conversion devices	0	Macro 2 2 4	0	0	0	0	0	Macro 1 1 1	0	0	Macro 1 1 1	0	0
Insufficient capacity to construct sites	0	Meso 2 3 6	0	0	0	0	0	Micro 2 1 2	0	0	Micro 1 2 2	0	0
Insufficient rate of infrastructure construction	0	Meso 1 1 1	0	0	0	0	0	Meso 2 4 8	0	0	Meso 1 2 2	0	0
Denial of permission to access sites	0	Meso 1 2 2	0	0	0	0	0	0	0	0	Micro 1 2 2	0	0
Lack of social stability	0	Meso 1 2 2	0	0	0	0	0	0	0	0	0	0	0
Changing policy or regulatory framework	0	Meso 2 4 8	0	0	0	0	0	Meso 2 2 4	0	0	Meso 2 2 4	0	0
Poor institutional governance	0	Meso 1 2 2	0	0	0	0	0	0	0	0	0	0	0
Disputed landrights or resource ownership	0	0	0	0	0	0	0	0	0	0	Micro 1 1 1	0	0
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	0	Meso 1 2 2	0	0	0	0	0	Meso 2 1 2	0	0	Meso 2 1 2	0	0
Significant public concern	0	Meso 3 1 3	0	0	0	0	0	Micro 1 2 2	0	0	Meso 3 3 9	0	0
Lack of basic education levels in the local workforce	0	Meso 1 1 1	0	0	0	0	0	Meso 1 1 1	0	0	Meso 1 1 1	0	0
Lack of vocational training of the local workforce	0	Meso 2 2 4	0	0	0	0	0	Meso 2 2 4	0	0	Meso 2 1 2	0	0
Lack of specialists in the local workforce	0	Meso 3 2 6	0	0	0	0	0	Meso 2 2 4	0	0	Meso 1 1 1	0	0
Pollution event	0	Micro 1 3 3	0	0	0	0	0	Micro 1 2 2	0	0	Macro 3 3 9	0	0
Unable to neutralise waste at decommissioning	0	Meso 3 3 9	0	0	0	0	0	Micro 1 2 2	0	0	Micro 2 2 4	0	0
Specialist equipment unavailable	0	Meso 1 2 2	0	0	0	0	0	Meso 1 2 2	0	0	Meso 1 2 2	0	0
Operational failure	0	Micro 2 2 4	0	0	0	0	0	Micro 2 2 4	0	0	Micro 2 2 4	0	0
Infrastructure failure	0	Meso 1 2 2	0	0	0	0	0	Meso 1 2 2	0	0	Meso 1 2 2	0	0

Table A.4 The risk matrix, Stage 4.

Stage 5: Distribute

	Fuel Category	Biogas								Bioliquids				Biomass (solids)							
	Principal Means or Technology	Electricity networks				Pipelines (gas)				Tankers				Electricity networks							
	Principal Risk Location	UK				UK				UK				UK							
Cause of Risk	Risk Category	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R
Lack of a well-functioning market	Economic	Macro	1	1	1	Macro	2	2	4	Macro	1	1	1	Macro	1	1	1				0
Lack of access to capital	Economic	Macro	2	2	4	Macro	2	2	4	Meso	1	2	2	Macro	2	2	4				0
Unable to agree a price for licence or permits	Economic				0	Meso	1	1	1				0				0				0
Uncertain decommissioning costs	Economic	Micro	1	1	1	Micro	2	1	2	Micro	1	1	1	Micro	1	1	1				0
Price volatility	Economic	Macro	2	1	2	Macro	2	1	2	Macro	1	2	2	Macro	2	1	2				0
Difficult physical access	Environmental	Micro	1	2	2	Micro	2	2	4				0	Micro	1	2	2				0
Natural hazards	Environmental	Micro	2	2	4	Micro	1	2	2	Micro	1	2	2	Micro	2	2	4				0
Quality of fuel source	Environmental				0				0				0				0				0
Lack of water availability	Environmental				0				0				0				0				0
Lack of critical materials availability	Environmental	Macro	2	2	4				0				0	Macro	2	2	4				0
Weak technology transfer environment	Innovation	Meso	1	1	1	Meso	1	1	1	Macro	1	1	1	Meso	1	1	1				0
Lack of public subsidy	Innovation	Meso	2	3	6	Meso	1	1	1				0	Meso	2	3	6				0
Only marginal improvements likely	Innovation	Macro	2	1	2	Macro	3	1	3	Macro	3	1	3	Macro	2	1	2				0
Lack of material substitutability	Innovation	Macro	1	1	1	Macro	1	1	1				0	Macro	1	1	1				0
R&D capacity or capability does not match the challenge	Innovation	Meso	2	1	2	Meso	1	1	1	Macro	1	1	1	Meso	2	1	2				0
Optimism bias	Innovation	Meso	2	1	2				0				0	Meso	2	1	2				0
Insufficient capacity to manufacture system components or conversion devices	Manufacturing	Macro	1	2	2	Macro	1	1	1	Macro	1	1	1	Macro	1	2	2				0
Insufficient capacity to construct sites	Manufacturing	Micro	1	2	2	Micro	2	1	2				0	Micro	1	2	2				0
Insufficient rate of infrastructure construction	Manufacturing				0				0	Meso	1	1	1				0				0
Denial of permission to access sites	Political	Micro	1	1	1	Micro	1	1	1				0	Micro	1	1	1				0
Lack of social stability	Political				0				0				0				0				0
Changing policy or regulatory framework	Political	Meso	3	2	6	Meso	2	1	2	Meso	1	2	2	Meso	3	2	6				0
Poor institutional governance	Political				0				0				0				0				0
Disputed landrights or resource ownership	Political	Micro	1	2	2	Micro	1	1	1				0	Micro	1	2	2				0
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Political	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1				0
Significant public concern	Political	Micro	1	2	2	Micro	1	1	1	Meso	1	1	1	Micro	1	2	2				0
Lack of basic education levels in the local workforce	Skills	Meso	1	1	1	Meso	1	1	1	Meso	1	2	2	Meso	1	1	1				0
Lack of vocational training of the local workforce	Skills	Meso	2	2	4	Meso	2	2	4	Meso	1	2	2	Meso	2	2	4				0
Lack of specialists in the local workforce	Skills	Meso	3	2	6	Meso	2	1	2				0	Meso	3	2	6				0
Pollution event	Technical	Micro	1	1	1	Micro	1	3	3	Micro	3	2	6	Micro	1	1	1				0
Unable to neutralise waste at decommissioning	Technical	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1	Micro	1	1	1				0
Specialist equipment unavailable	Technical	Meso	1	2	2	Micro	1	1	1				0	Meso	1	2	2				0
Operational failure	Technical	Meso	1	1	1	Micro	1	2	2	Micro	1	2	2	Meso	1	1	1				0
Infrastructure failure	Technical				0	Meso	1	1	1	Meso	1	1	1				0				0

Fuel Category	Coal				Demand reduction				Gas								Gas (unconventional)			
Principal Means or Technology	Electricity networks								Electricity networks				Pipelines (gas)				Electricity networks			
Principal Risk Location	UK								UK				UK				UK			
Cause of Risk	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R
Lack of a well-functioning market	Macro	1	1	1				0	Macro	1	1	1	Macro	2	2	4	Macro	1	1	1
Lack of access to capital	Macro	2	2	4				0	Macro	2	2	4	Macro	2	2	4	Macro	2	2	4
Unable to agree a price for licence or permits				0				0				0	Meso	1	1	1				0
Uncertain decommissioning costs	Micro	1	1	1				0	Micro	1	1	1	Micro	2	1	2	Micro	1	1	1
Price volatility	Macro	2	1	2				0	Macro	2	1	2	Macro	2	1	2	Macro	2	1	2
Difficult physical access	Micro	1	2	2				0	Micro	1	2	2	Micro	2	2	4	Micro	1	2	2
Natural hazards	Micro	2	2	4				0	Micro	2	2	4	Micro	1	2	2	Micro	2	2	4
Quality of fuel source				0				0				0				0				0
Lack of water availability				0				0				0				0				0
Lack of critical materials availability	Macro	2	2	4				0	Macro	2	2	4				0	Macro	2	2	4
Weak technology transfer environment	Meso	1	1	1				0	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Lack of public subsidy	Meso	2	3	6				0	Meso	2	3	6	Meso	1	1	1	Meso	2	3	6
Only marginal improvements likely	Macro	2	1	2				0	Macro	2	1	2	Macro	3	1	3	Macro	2	1	2
Lack of material substitutability	Macro	1	1	1				0	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1
R&D capacity or capability does not match the challenge	Meso	2	1	2				0	Meso	2	1	2	Meso	1	1	1	Meso	2	1	2
Optimism bias	Meso	2	1	2				0	Meso	2	1	2				0	Meso	2	1	2
Insufficient capacity to manufacture system components or conversion devices	Macro	1	2	2				0	Macro	1	2	2	Macro	1	1	1	Macro	1	2	2
Insufficient capacity to construct sites	Micro	1	2	2				0	Micro	1	2	2	Micro	2	1	2	Micro	1	2	2
Insufficient rate of infrastructure construction				0				0				0				0				0
Denial of permission to access sites	Micro	1	1	1				0	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1
Lack of social stability				0				0				0				0				0
Changing policy or regulatory framework	Meso	3	2	6				0	Meso	3	2	6	Meso	2	1	2	Meso	3	2	6
Poor institutional governance				0				0				0				0				0
Disputed landrights or resource ownership	Micro	1	2	2				0	Micro	1	2	2	Micro	1	1	1	Micro	1	2	2
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Meso	1	1	1				0	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Significant public concern	Micro	1	2	2				0	Micro	1	2	2	Micro	1	1	1	Micro	1	2	2
Lack of basic education levels in the local workforce	Meso	1	1	1				0	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Lack of vocational training of the local workforce	Meso	2	2	4				0	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4
Lack of specialists in the local workforce	Meso	3	2	6				0	Meso	3	2	6	Meso	2	1	2	Meso	3	2	6
Pollution event	Micro	1	1	1				0	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1
Unable to neutralise waste at decommissioning	Micro	1	1	1				0	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1
Specialist equipment unavailable	Meso	1	2	2				0	Meso	1	2	2	Micro	1	1	1	Meso	1	2	2
Operational failure	Meso	1	1	1				0	Meso	1	1	1	Micro	1	2	2	Meso	1	1	1
Infrastructure failure				0				0				0	Meso	1	1	1				0

Fuel Category	Gas (unconventional)				Hydro				Nuclear (fission)				Ocean (tidal)				Ocean (wave)			
Principal Means or Technology	Pipelines (gas)				Electricity networks				Electricity networks				Electricity networks				Electricity networks			
Principal Risk Location	UK				UK				UK				UK				UK			
Cause of Risk	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R
Lack of a well-functioning market	Macro	2	2	4	Macro	1	1	1	Macro	1	1	1	Macro	2	2	4	Macro	2	2	4
Lack of access to capital	Macro	2	2	4	Macro	2	2	4	Macro	2	2	4	Macro	3	3	9	Macro	3	3	9
Unable to agree a price for licence or permits	Meso	1	1	1	Micro	1	1	1				0	Micro	1	3	3	Micro	1	3	3
Uncertain decommissioning costs	Micro	2	1	2	Micro	1	1	1	Micro	1	1	1	Micro	2	1	2	Micro	2	1	2
Price volatility	Macro	2	1	2	Macro	2	1	2	Macro	2	1	2	Macro	2	2	4	Macro	2	2	4
Difficult physical access	Micro	2	2	4	Micro	1	2	2	Micro	1	2	2	Micro	3	2	6	Micro	3	2	6
Natural hazards	Micro	1	2	2	Micro	2	2	4	Micro	2	2	4	Micro	2	3	6	Micro	2	3	6
Quality of fuel source				0				0				0				0				0
Lack of water availability				0				0				0				0				0
Lack of critical materials availability				0	Macro	2	2	4	Macro	2	2	4	Macro	2	2	4	Macro	2	2	4
Weak technology transfer environment	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	2	2	4	Meso	2	2	4
Lack of public subsidy	Meso	1	1	1	Meso	2	3	6	Meso	2	3	6	Meso	2	3	6	Meso	2	3	6
Only marginal improvements likely	Macro	3	1	3	Macro	2	1	2	Macro	2	1	2	Macro	2	1	2	Macro	2	1	2
Lack of material substitutability	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1
R&D capacity or capability does not match the challenge	Meso	1	1	1	Meso	2	1	2	Meso	2	1	2	Meso	2	2	4	Meso	2	2	4
Optimism bias				0	Meso	2	1	2	Meso	2	1	2	Meso	2	1	2	Meso	2	1	2
Insufficient capacity to manufacture system components or conversion devices	Macro	1	1	1	Macro	1	2	2	Macro	1	2	2	Macro	3	2	6	Macro	3	2	6
Insufficient capacity to construct sites	Micro	2	1	2	Micro	1	2	2	Micro	1	2	2	Micro	2	3	6	Micro	2	3	6
Insufficient rate of infrastructure construction				0				0				0				0				0
Denial of permission to access sites	Micro	1	1	1	Micro	2	3	6	Micro	1	1	1	Micro	1	2	2	Micro	1	2	2
Lack of social stability				0				0				0				0				0
Changing policy or regulatory framework	Meso	2	1	2	Meso	3	2	6	Meso	3	2	6	Meso	2	2	4	Meso	2	2	4
Poor institutional governance				0				0				0				0				0
Disputed landrights or resource ownership	Micro	1	1	1	Micro	1	2	2	Micro	1	2	2	Meso	1	1	1	Meso	1	1	1
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	2	2	Meso	1	2	2
Significant public concern	Micro	1	1	1	Micro	3	3	9	Micro	1	2	2	Micro	1	2	2	Micro	1	2	2
Lack of basic education levels in the local workforce	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Lack of vocational training of the local workforce	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4	Meso	3	2	6	Meso	3	2	6
Lack of specialists in the local workforce	Meso	2	1	2	Meso	3	2	6	Meso	3	2	6	Meso	3	2	6	Meso	3	2	6
Pollution event	Micro	1	3	3	Micro	1	1	1	Micro	1	1	1	Micro	1	2	2	Micro	1	2	2
Unable to neutralise waste at decommissioning	Micro	1	2	2	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1
Specialist equipment unavailable	Micro	1	1	1	Meso	1	2	2	Meso	1	2	2	Macro	2	2	4	Macro	2	2	4
Operational failure	Micro	1	2	2	Meso	1	1	1	Meso	1	1	1	Micro	1	3	3	Micro	1	3	3
Infrastructure failure	Meso	1	1	1				0				0				0				0

Fuel Category	Oil								Solar (electric)				Solar (thermal, water)				Thermal (geological)			
Principal Means or Technology	Tankers				Pipelines (oil)				Electricity networks								Electricity networks			
Principal Risk Location	UK				UK				UK								UK			
Cause of Risk	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R
Lack of a well-functioning market	Macro	1	1	1	Macro	2	2	4	Macro	1	1	1				0	Macro	1	1	1
Lack of access to capital	Meso	1	2	2	Macro	2	3	6	Meso	2	2	4				0	Macro	2	2	4
Unable to agree a price for licence or permits				0	Meso	1	1	1	Micro	1	2	2				0	Micro	1	2	2
Uncertain decommissioning costs	Micro	1	1	1	Micro	2	1	2	Micro	1	1	1				0	Micro	1	1	1
Price volatility	Macro	1	2	2	Macro	2	2	4	Macro	2	1	2				0	Macro	2	1	2
Difficult physical access				0	Micro	2	2	4	Micro	1	2	2				0	Micro	1	2	2
Natural hazards	Micro	1	2	2	Micro	1	2	2	Micro	1	2	2				0	Micro	1	2	2
Quality of fuel source				0				0				0				0				0
Lack of water availability				0				0				0				0				0
Lack of critical materials availability				0				0	Macro	2	2	4				0	Macro	2	2	4
Weak technology transfer environment	Macro	1	1	1	Meso	1	1	1	Meso	1	1	1				0	Meso	1	1	1
Lack of public subsidy				0	Meso	1	1	1	Meso	2	3	6				0	Meso	3	1	3
Only marginal improvements likely	Macro	3	1	3	Macro	3	1	3	Macro	2	1	2				0	Macro	3	1	3
Lack of material substitutability				0	Macro	1	1	1	Macro	1	1	1				0	Macro	1	1	1
R&D capacity or capability does not match the challenge	Macro	1	1	1	Meso	1	1	1	Meso	2	1	2				0	Meso	2	1	2
Optimism bias				0				0	Meso	2	1	2				0	Meso	2	1	2
Insufficient capacity to manufacture system components or conversion devices	Macro	1	1	1	Macro	1	1	1	Macro	2	1	2				0	Macro	3	1	3
Insufficient capacity to construct sites				0	Micro	2	1	2	Micro	1	2	2				0	Micro	1	2	2
Insufficient rate of infrastructure construction	Meso	1	1	1				0				0				0				0
Denial of permission to access sites				0	Micro	2	3	6	Micro	2	3	6				0	Micro	2	3	6
Lack of social stability				0				0				0				0				0
Changing policy or regulatory framework	Meso	1	2	2	Meso	2	1	2	Meso	3	2	6				0	Meso	2	2	4
Poor institutional governance				0				0				0				0				0
Disputed landrights or resource ownership				0	Micro	1	1	1	Micro	1	2	2				0	Micro	1	2	2
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1				0	Meso	1	1	1
Significant public concern	Meso	1	1	1	Micro	2	2	4	Micro	3	3	9				0	Micro	3	3	9
Lack of basic education levels in the local workforce	Meso	1	2	2	Meso	1	1	1	Meso	1	1	1				0	Meso	1	1	1
Lack of vocational training of the local workforce	Meso	1	2	2	Meso	2	2	4	Meso	2	2	4				0	Meso	2	2	4
Lack of specialists in the local workforce				0	Meso	2	1	2	Meso	3	2	6				0	Meso	3	2	6
Pollution event	Micro	3	2	6	Micro	1	3	3	Micro	1	1	1				0	Micro	1	1	1
Unable to neutralise waste at decommissioning	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1				0	Micro	1	1	1
Specialist equipment unavailable				0	Micro	1	1	1	Meso	1	2	2				0	Meso	1	2	2
Operational failure	Micro	1	2	2	Micro	1	2	2	Micro	1	1	1				0	Meso	1	1	1
Infrastructure failure	Meso	1	1	1	Meso	1	1	1				0				0				0

Fuel Category	Thermal (geological)				Thermal (low temperature)				Waste				Wind (offshore)				Wind (onshore)			
Principal Means or Technology	Pipelines (heat)								Electricity networks				Electricity networks				Electricity networks			
Principal Risk Location	UK								UK				UK				UK			
Cause of Risk	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R
Lack of a well-functioning market	Macro	1	1	1				0	Macro	1	1	1	Macro	2	2	4	Macro	1	1	1
Lack of access to capital	Meso	3	3	9				0	Macro	2	2	4	Macro	3	3	9	Macro	2	2	4
Unable to agree a price for licence or permits				0				0				0	Micro	1	3	3	Micro	1	2	2
Uncertain decommissioning costs	Micro	1	1	1				0	Micro	1	1	1	Micro	2	1	2	Micro	1	1	1
Price volatility	Macro	1	1	1				0	Macro	2	1	2	Macro	2	2	4	Macro	2	1	2
Difficult physical access				0				0	Micro	1	2	2	Micro	3	2	6	Micro	1	2	2
Natural hazards	Micro	1	2	2				0	Micro	2	2	4	Micro	2	3	6	Micro	2	2	4
Quality of fuel source	Micro	1	1	1				0				0				0				0
Lack of water availability				0				0				0				0				0
Lack of critical materials availability				0				0	Macro	2	2	4	Macro	2	2	4	Macro	2	2	4
Weak technology transfer environment	Meso	1	1	1				0	Meso	1	1	1	Meso	2	2	4	Meso	1	1	1
Lack of public subsidy				0				0	Meso	2	3	6	Meso	2	3	6	Meso	2	3	6
Only marginal improvements likely	Meso	3	1	3				0	Macro	2	1	2	Macro	2	1	2	Macro	2	1	2
Lack of material substitutability	Macro	1	1	1				0	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1
R&D capacity or capability does not match the challenge	Meso	1	1	1				0	Meso	2	1	2	Meso	2	2	4	Meso	2	1	2
Optimism bias	Meso	1	1	1				0	Meso	2	1	2	Meso	2	1	2	Meso	2	1	2
Insufficient capacity to manufacture system components or conversion devices	Meso	1	1	1				0	Macro	1	2	2	Macro	3	2	6	Macro	1	2	2
Insufficient capacity to construct sites	Micro	3	1	3				0	Micro	1	2	2	Micro	2	3	6	Micro	1	2	2
Insufficient rate of infrastructure construction	Meso	3	3	9				0				0				0				0
Denial of permission to access sites	Micro	1	2	2				0	Micro	1	1	1	Micro	1	2	2	Micro	2	3	6
Lack of social stability				0				0				0				0				0
Changing policy or regulatory framework	Meso	2	3	6				0	Meso	3	2	6	Meso	2	2	4	Meso	3	2	6
Poor institutional governance				0				0				0				0				0
Disputed landrights or resource ownership				0				0	Micro	1	2	2	Meso	1	1	1	Micro	1	2	2
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Meso	2	3	6				0	Meso	1	1	1	Meso	1	2	2	Meso	1	1	1
Significant public concern	Micro	3	2	6				0	Micro	1	2	2	Micro	1	2	2	Micro	3	3	9
Lack of basic education levels in the local workforce	Meso	1	1	1				0	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Lack of vocational training of the local workforce	Meso	2	2	4				0	Meso	2	2	4	Meso	3	2	6	Meso	2	2	4
Lack of specialists in the local workforce	Meso	2	2	4				0	Meso	3	2	6	Meso	3	2	6	Meso	3	2	6
Pollution event	Micro	3	1	3				0	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1
Unable to neutralise waste at decommissioning	Micro	1	1	1				0	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1
Specialist equipment unavailable				0				0	Meso	1	2	2	Macro	2	2	4	Meso	1	2	2
Operational failure	Micro	2	2	4				0	Meso	1	1	1	Micro	1	3	3	Meso	1	1	1
Infrastructure failure	Micro	2	2	4				0				0				0				0

Table A.5 The risk matrix, Stage 5.

Stage 6: Use

	Fuel Category	Biogas								Bioliquids				Biomass (solids)								Coal			
	Principal Means or Technology	Electrical devices				Heat (onsite)				Vehicles				Electrical devices				Heat (network)				Electrical devices			
	Principal Risk Location	UK				UK				UK				UK				UK				UK			
Cause of Risk	Risk Category	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R
Lack of a well-functioning market	Economic	Macro	1	1	1	Meso	1	1	1	Macro	2	1	2	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1
Lack of access to capital	Economic				0	Micro	2	1	2	Micro	1	2	2				0	Meso	3	3	9				0
Unable to agree a price for licence or permits	Economic				0				0				0				0				0				0
Uncertain decommissioning costs	Economic				0				0	Micro	1	1	1				0	Micro	1	1	1				0
Price volatility	Economic	Micro	1	1	1	Meso	1	1	1	Meso	1	1	1	Micro	1	1	1	Meso	1	1	1	Micro	1	1	1
Difficult physical access	Environmental				0				0				0				0				0				0
Natural hazards	Environmental	Micro	1	2	2	Micro	1	1	1	Micro	1	2	2	Micro	1	2	2	Micro	1	2	2	Micro	1	2	2
Quality of fuel source	Environmental	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Lack of water availability	Environmental				0				0				0				0				0				0
Lack of critical materials availability	Environmental	Macro	2	2	4	Macro	1	1	1	Macro	2	1	2	Macro	2	2	4	Macro	1	1	1	Macro	2	2	4
Weak technology transfer environment	Innovation	Macro	2	2	4	Meso	1	1	1	Macro	1	1	1	Macro	2	2	4	Meso	1	1	1	Macro	2	2	4
Lack of public subsidy	Innovation				0				0				0				0				0				0
Only marginal improvements likely	Innovation	Macro	1	2	2	Meso	3	1	3	Macro	3	2	6	Macro	1	2	2	Meso	3	1	3	Macro	1	2	2
Lack of material substitutability	Innovation	Macro	2	3	6	Macro	1	1	1	Macro	1	2	2	Macro	2	3	6	Macro	1	1	1	Macro	2	3	6
R&D capacity or capability does not match the challenge	Innovation	Meso	2	2	4	Meso	2	3	6	Macro	1	1	1	Meso	2	2	4	Macro	1	1	1	Meso	2	2	4
Optimism bias	Innovation	Meso	2	3	6	Meso	1	1	1	Macro	3	1	3	Meso	2	3	6	Meso	1	1	1	Meso	2	3	6
Insufficient capacity to manufacture system components or conversion devices	Manufacturing	Macro	2	2	4	Meso	2	3	6	Macro	1	1	1	Macro	2	2	4	Macro	1	1	1	Macro	2	2	4
Insufficient capacity to construct sites	Manufacturing	Meso	3	3	9	Meso	3	1	3				0	Meso	3	3	9	Meso	3	1	3	Meso	3	3	9
Insufficient rate of infrastructure construction	Manufacturing				0				0	Meso	1	1	1				0	Meso	3	3	9				0
Denial of permission to access sites	Political				0				0				0				0	Micro	1	2	2				0
Lack of social stability	Political				0				0				0				0				0				0
Changing policy or regulatory framework	Political	Meso	2	2	4	Meso	2	3	6	Macro	2	2	4	Meso	2	2	4	Meso	2	3	6	Meso	2	2	4
Poor institutional governance	Political				0				0				0				0				0				0
Disputed landrights or resource ownership	Political				0				0				0				0				0				0
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Political	Meso	2	2	4	Meso	2	3	6	Meso	2	1	2	Meso	2	2	4	Meso	2	3	6	Meso	2	2	4
Significant public concern	Political	Meso	3	1	3	Meso	3	1	3	Meso	3	2	6	Meso	3	1	3	Meso	3	2	6	Meso	3	1	3
Lack of basic education levels in the local workforce	Skills	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Lack of vocational training of the local workforce	Skills	Meso	2	2	4	Meso	2	2	4	Meso	3	1	3	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4
Lack of specialists in the local workforce	Skills	Meso	2	1	2	Meso	2	1	2	Meso	3	1	3	Meso	2	1	2	Meso	2	2	4	Meso	2	1	2
Pollution event	Technical	Micro	1	1	1	Micro	3	1	3	Micro	3	1	3	Micro	1	1	1	Micro	3	1	3	Micro	1	1	1
Unable to neutralise waste at decommissioning	Technical	Micro	2	2	4	Meso	2	1	2	Micro	2	1	2	Micro	2	2	4	Micro	1	1	1	Micro	2	2	4
Specialist equipment unavailable	Technical				0				0				0				0				0				0
Operational failure	Technical	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1	Micro	1	1	1	Micro	2	2	4	Micro	1	1	1
Infrastructure failure	Technical	Micro	1	2	2	Micro	1	2	2	Micro	1	1	1	Micro	1	2	2	Micro	2	2	4	Micro	1	2	2

Fuel Category	Demand reduction				Gas								Gas (unconventional)								Hydro			
Principal Means or Technology					Electrical devices				Heat (onsite)				Electrical devices				Heat (onsite)				Electrical devices			
Principal Risk Location					UK				UK				UK				UK				UK			
Cause of Risk	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R
Lack of a well-functioning market				0	Macro	1	1	1	Meso	1	1	1	Macro	1	1	1	Meso	1	1	1	Macro	1	1	1
Lack of access to capital				0				0	Micro	2	1	2				0	Micro	2	1	2				0
Unable to agree a price for licence or permits				0				0				0				0				0				0
Uncertain decommissioning costs				0				0				0				0				0				0
Price volatility				0	Micro	1	1	1	Meso	1	1	1	Micro	1	1	1	Meso	1	1	1	Micro	1	1	1
Difficult physical access				0				0				0				0				0				0
Natural hazards				0	Micro	1	2	2	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1	Micro	1	2	2
Quality of fuel source				0	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Lack of water availability				0				0				0				0				0				0
Lack of critical materials availability				0	Macro	2	2	4	Macro	1	1	1	Macro	2	2	4	Macro	1	1	1	Macro	2	2	4
Weak technology transfer environment				0	Macro	2	2	4	Meso	1	1	1	Macro	2	2	4	Meso	1	1	1	Macro	2	2	4
Lack of public subsidy				0				0				0				0				0				0
Only marginal improvements likely				0	Macro	1	2	2	Meso	3	1	3	Macro	1	2	2	Meso	3	1	3	Macro	1	2	2
Lack of material substitutability				0	Macro	2	3	6	Macro	1	1	1	Macro	2	3	6	Macro	1	1	1	Macro	2	3	6
R&D capacity or capability does not match the challenge				0	Meso	2	2	4	Meso	2	3	6	Meso	2	2	4	Meso	2	3	6	Meso	2	2	4
Optimism bias				0	Meso	2	3	6	Meso	1	1	1	Meso	2	3	6	Meso	1	1	1	Meso	2	3	6
Insufficient capacity to manufacture system components or conversion devices				0	Macro	2	2	4	Meso	2	3	6	Macro	2	2	4	Meso	2	3	6	Macro	2	2	4
Insufficient capacity to construct sites				0	Meso	3	3	9	Meso	3	1	3	Meso	3	3	9	Meso	3	1	3	Meso	3	3	9
Insufficient rate of infrastructure construction				0				0				0				0				0				0
Denial of permission to access sites				0				0				0				0				0				0
Lack of social stability				0				0				0				0				0				0
Changing policy or regulatory framework				0	Meso	2	2	4	Meso	2	3	6	Meso	2	2	4	Meso	2	3	6	Meso	2	2	4
Poor institutional governance				0				0				0				0				0				0
Disputed landrights or resource ownership				0				0				0				0				0				0
Insufficient rate of improvement in, or lack of enforcement of, standards and codes				0	Meso	2	2	4	Meso	2	3	6	Meso	2	2	4	Meso	2	3	6	Meso	2	2	4
Significant public concern				0	Meso	3	1	3	Meso	3	1	3	Meso	3	1	3	Meso	3	1	3	Meso	3	1	3
Lack of basic education levels in the local workforce				0	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Lack of vocational training of the local workforce				0	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4
Lack of specialists in the local workforce				0	Meso	2	1	2	Meso	2	1	2	Meso	2	1	2	Meso	2	1	2	Meso	2	1	2
Pollution event				0	Micro	1	1	1	Micro	3	1	3	Micro	1	1	1	Micro	3	1	3	Micro	1	1	1
Unable to neutralise waste at decommissioning				0	Micro	2	2	4	Meso	2	1	2	Micro	2	2	4	Meso	2	1	2	Micro	2	2	4
Specialist equipment unavailable				0				0				0				0				0				0
Operational failure				0	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1	Micro	1	2	2	Micro	1	1	1
Infrastructure failure				0	Micro	1	2	2	Micro	1	2	2	Micro	1	2	2	Micro	1	2	2	Micro	1	2	2

Fuel Category	Nuclear (fission)				Ocean (tidal)				Ocean (wave)				Oil				Solar (electric)				Solar (thermal, water)			
Principal Means or Technology	Electrical devices				Electrical devices				Electrical devices				Vehicles				Electrical devices				Heat (onsite)			
Principal Risk Location	UK				UK				UK				UK				UK				UK			
Cause of Risk	Scale	L	I	L*I	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R
Lack of a well-functioning market	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1	Meso	1	1	1
Lack of access to capital				0				0				0	Micro	1	2	2				0	Micro	1	1	1
Unable to agree a price for licence or permits				0				0				0				0				0				0
Uncertain decommissioning costs				0				0				0	Micro	1	1	1				0	Micro	1	1	1
Price volatility	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Meso	1	1	1	Micro	1	1	1	Meso	1	1	1
Difficult physical access				0				0				0				0				0				0
Natural hazards	Micro	1	2	2	Micro	1	2	2	Micro	1	2	2	Micro	1	2	2	Micro	1	2	2				0
Quality of fuel source	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Micro	2	2	4
Lack of water availability				0				0				0				0				0				0
Lack of critical materials availability	Macro	2	2	4	Macro	2	2	4	Macro	2	2	4	Macro	2	1	2	Macro	2	2	4				0
Weak technology transfer environment	Macro	2	2	4	Macro	2	2	4	Macro	2	2	4	Macro	1	1	1	Macro	2	2	4	Meso	1	1	1
Lack of public subsidy				0				0				0				0				0				0
Only marginal improvements likely	Macro	1	2	2	Macro	1	2	2	Macro	1	2	2	Macro	3	2	6	Macro	1	2	2	Meso	2	1	2
Lack of material substitutability	Macro	2	3	6	Macro	2	3	6	Macro	2	3	6	Macro	1	2	2	Macro	2	3	6	Macro	1	1	1
R&D capacity or capability does not match the challenge	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4	Macro	1	1	1	Meso	2	2	4	Meso	1	1	1
Optimism bias	Meso	2	3	6	Meso	2	3	6	Meso	2	3	6	Macro	3	1	3	Meso	2	3	6	Meso	2	1	2
Insufficient capacity to manufacture system components or conversion devices	Macro	2	2	4	Macro	2	2	4	Macro	2	2	4	Macro	1	1	1	Macro	2	2	4	Meso	2	3	6
Insufficient capacity to construct sites	Meso	3	3	9	Meso	3	3	9	Meso	3	3	9				0	Meso	3	3	9	Meso	3	1	3
Insufficient rate of infrastructure construction				0				0				0	Meso	1	1	1				0				0
Denial of permission to access sites				0				0				0				0				0				0
Lack of social stability				0				0				0				0				0				0
Changing policy or regulatory framework	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4	Macro	2	2	4	Meso	2	2	4	Meso	2	3	6
Poor institutional governance				0				0				0				0				0				0
Disputed landrights or resource ownership				0				0				0				0				0				0
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4	Meso	2	1	2	Meso	2	2	4	Meso	2	3	6
Significant public concern	Meso	3	1	3	Meso	3	1	3	Meso	3	1	3	Meso	3	2	6	Meso	3	1	3				0
Lack of basic education levels in the local workforce	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Lack of vocational training of the local workforce	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4	Meso	3	1	3	Meso	2	2	4	Meso	2	2	4
Lack of specialists in the local workforce	Meso	2	1	2	Meso	2	1	2	Meso	2	1	2	Meso	3	1	3	Meso	2	1	2	Meso	2	1	2
Pollution event	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	3	1	3	Micro	1	1	1	Micro	1	1	1
Unable to neutralise waste at decommissioning	Micro	2	2	4	Micro	2	2	4	Micro	2	2	4	Meso	1	1	1	Micro	2	2	4	Meso	1	1	1
Specialist equipment unavailable				0				0				0				0				0				0
Operational failure	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1	Micro	1	2	2
Infrastructure failure	Micro	1	2	2	Micro	1	2	2	Micro	1	2	2	Micro	1	1	1	Micro	1	2	2	Micro	1	2	2

Fuel Category	Thermal (geological)								Thermal (low temperature)				Waste				Wind (offshore)				Wind (onshore)			
Principal Means or Technology	Electrical devices								Heat (onsite)				Electrical devices				Electrical devices				Electrical devices			
Principal Risk Location	UK								UK				UK				UK				UK			
Cause of Risk	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R	Scale	L	I	R
Lack of a well-functioning market	Macro	1	1	1				0	Meso	2	1	2	Macro	1	1	1	Macro	1	1	1	Macro	1	1	1
Lack of access to capital				0				0				0				0				0				0
Unable to agree a price for licence or permits				0				0				0				0				0				0
Uncertain decommissioning costs				0				0	Micro	1	1	1				0				0				0
Price volatility	Micro	1	1	1				0	Meso	2	1	2	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1
Difficult physical access				0				0				0				0				0				0
Natural hazards	Micro	1	2	2				0				0	Micro	1	2	2	Micro	1	2	2	Micro	1	2	2
Quality of fuel source	Meso	1	1	1				0	Micro	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Lack of water availability				0				0				0				0				0				0
Lack of critical materials availability	Macro	2	2	4				0				0	Macro	2	2	4	Macro	2	2	4	Macro	2	2	4
Weak technology transfer environment	Macro	2	2	4				0	Meso	2	1	2	Macro	2	2	4	Macro	2	2	4	Macro	2	2	4
Lack of public subsidy				0				0				0				0				0				0
Only marginal improvements likely	Macro	1	2	2				0	Meso	2	1	2	Macro	1	2	2	Macro	1	2	2	Macro	1	2	2
Lack of material substitutability	Macro	2	3	6				0	Macro	1	1	1	Macro	2	3	6	Macro	2	3	6	Macro	2	3	6
R&D capacity or capability does not match the challenge	Meso	2	2	4				0	Meso	2	1	2	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4
Optimism bias	Meso	2	3	6				0	Meso	2	1	2	Meso	2	3	6	Meso	2	3	6	Meso	2	3	6
Insufficient capacity to manufacture system components or conversion devices	Macro	2	2	4				0	Macro	1	1	1	Macro	2	2	4	Macro	2	2	4	Macro	2	2	4
Insufficient capacity to construct sites	Meso	3	3	9				0	Meso	3	4	12	Meso	3	3	9	Meso	3	3	9	Meso	3	3	9
Insufficient rate of infrastructure construction				0				0				0				0				0				0
Denial of permission to access sites				0				0				0				0				0				0
Lack of social stability				0				0				0				0				0				0
Changing policy or regulatory framework	Meso	2	2	4				0	Meso	2	3	6	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4
Poor institutional governance				0				0				0				0				0				0
Disputed landrights or resource ownership				0				0				0				0				0				0
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Meso	2	2	4				0	Meso	2	3	6	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4
Significant public concern	Meso	3	1	3				0				0	Meso	3	1	3	Meso	3	1	3	Meso	3	1	3
Lack of basic education levels in the local workforce	Meso	1	1	1				0	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1	Meso	1	1	1
Lack of vocational training of the local workforce	Meso	2	2	4				0	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4	Meso	2	2	4
Lack of specialists in the local workforce	Meso	2	1	2				0	Meso	2	1	2	Meso	2	1	2	Meso	2	1	2	Meso	2	1	2
Pollution event	Micro	1	1	1				0	Micro	1	2	2	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1
Unable to neutralise waste at decommissioning	Micro	2	2	4				0	Meso	1	1	1	Micro	2	2	4	Micro	2	2	4	Micro	2	2	4
Specialist equipment unavailable				0				0				0				0				0				0
Operational failure	Micro	1	1	1				0	Micro	1	2	2	Micro	1	1	1	Micro	1	1	1	Micro	1	1	1
Infrastructure failure	Micro	1	2	2				0	Micro	1	2	2	Micro	1	2	2	Micro	1	2	2	Micro	1	2	2

Table A.6 The risk matrix, Stage 6.

B. Additional Data Tables

Table B.1 The causes of risk listed account for 50% or more of the total (absolute) risk score for each stage. The figure for the proportion is that of the mains causes of risk compared with the risk score of the stage.

Stage	Rank	Cause of Risk	Category	Score
1: Explore	1	Quality of fuel source	Environmental	87
	2	Lack of access to capital	Economic	50
	3	Optimism bias	Innovation	49
	4	Denial of permission to access sites	Political	48
	5	Significant public concern	Political	48
	6	Lack of social stability	Political	47
	7	Poor institutional governance	Political	47
	8	Specialist equipment unavailable	Technical	42
			Proportion	**54%**
2: Exploit	1	Lack of access to capital	Economic	121
	2	Changing policy or regulatory framework	Political	98
	3	Insufficient rate of infrastructure construction	Manufacturing	88
	4	Significant public concern	Political	81
	5	Natural hazards	Environmental	78
	6	Operational failure	Technical	71
	7	Pollution event	Technical	69
	8	Lack of public subsidy	Innovation	66
	9	Unable to neutralise waste at decommissioning	Technical	62
	10	Optimism bias	Innovation	61
	11	Lack of vocational training of the local workforce	Skills	59
	12	Lack of specialists in the local workforce	Skills	57
			Proportion	**52%**

3: Condition	1	Lack of access to capital	Economic	59
	2	Pollution event	Technical	41
	3	Significant public concern	Political	38
	4	Changing policy or regulatory framework	Political	31
	5	Quality of fuel source	Environmental	29
	6	Operational failure	Technical	28
	7	Insufficient rate of infrastructure construction	Manufacturing	27
	8	Lack of specialists in the local workforce	Skills	26
	9	Only marginal improvements likely	Innovation	25
	10	Unable to neutralise waste at decommissioning	Technical	25
			Proportion	**50%**
4: Convert	1	Pollution event	Technical	66
	2	Lack of access to capital	Economic	58
	3	Changing policy or regulatory framework	Political	46
	4	Lack of a well-functioning market	Economic	41
	5	Operational failure	Technical	40
	6	Significant public concern	Political	37
	7	Optimism bias	Innovation	36
	8	Lack of vocational training of the local workforce	Skills	36
	9	R&D capacity or capability does not match the challenge	Innovation	35
	10	Lack of specialists in the local workforce	Skills	35
	11	Lack of public subsidy	Innovation	34
			Proportion	**53%**

5: Distribute	1	Lack of access to capital	Economic	102
	2	Lack of specialists in the local workforce	Skills	96
	3	Changing policy or regulatory framework	Political	94
	4	Lack of vocational training of the local workforce	Skills	86
	5	Lack of public subsidy	Innovation	85
	6	Natural hazards	Environmental	72
	7	Significant public concern	Political	71
	8	Difficult physical access	Environmental	56
	9	Lack of critical materials availability	Environmental	56
			Proportion	**51%**
6: Use	1	Insufficient capacity to construct sites	Manufacturing	153
	2	Changing policy or regulatory framework	Political	100
	3	Optimism bias	Innovation	98
	4	Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Political	96
	5	Lack of material substitutability	Innovation	94
	6	Lack of vocational training of the local workforce	Skills	86
	7	Insufficient capacity to manufacture system components or conversion devices	Manufacturing	84
	8	R&D capacity or capability does not match the challenge	Innovation	80
			Proportion	**55%**