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Risk profiles of scenarios for the low-carbon transition

C.J. Axon [a,*], R.C. Darton [b]

[a] Institute of Energy Futures, Brunel University London, Uxbridge, London, UB8 3PH, UK
[b] Department of Engineering Science, University of Oxford, Oxford, OX1 3PJ, UK

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ABSTRACT

Providing energy to an economy through fuel supply chains incurs risks which can be identified and quantified by systematic analysis. Scenario analysis and risk analysis are complementary tools for assessing possible changes to socio-technical systems. Applying a risk evaluation method to published future energy scenarios shows how risk in the energy system might vary with time. In a UK case study six scenarios to 2050 are analysed, focusing on installed electricity generating capacity. Of the seven categories of risk, political risk scored the highest over the whole period. Despite the installed capacity increasing by a factor of up to three by 2050 with reductions in GHG emissions, our analysis projects a reduction in risk and shows how significantly the pathways differ. To indicate the difficulty of such an expansion of the electricity system, we propose the use of a new metric – the Scale of Challenge (SoC) – equal to the total risk score times the installed capacity. The key to achieving a low-carbon transition may lie in moderating exposure to risk. Identifying the origin and type of risk can inform policy since net-zero is not zero risk.

1. Introduction

Finding and developing sources of primary energy and distributing it in a useable form to consumers is a huge global business. Global mean consumption of primary energy was 75.6 GJ per capita in 2021 [1]. The energy that heats, cools and lights our living and working spaces can no more be missed than the energy that keeps machinery working, transportation running or schools and hospitals functioning. Communication and IT systems need dependable energy, as do the supply chains of the goods that society needs - food, water, medicines, clothing and more.

Energy is such a useful commodity that the lack of it causes serious problems, whether in the life of a single family, a community, a business or a nation. Ensuring energy security, defined as the low-risk (dependable) meeting of needs for energy within the economy [2], is therefore a key policy goal for national governments. However this security must now be sought at a time of rapid change in the global energy system as a result of international agreement to significantly cut CO_2 emissions over the next few decades [3,4]. The transition to low-carbon sources of energy is changing risk in the energy system in many different ways [5,6]. The ability to determine how risk varies with configuration of the energy system is crucial in guiding us to energy choices and policies aimed at improving energy security.

The importance of energy security hardly needs emphasizing, yet the common appreciation of what causes energy *insecurity* – the risks to which the supply-demand balance is exposed – is rarely based on a comprehensive and evidence-based assessment [7]. Some risks attract much attention, particularly those associated with global politics or accidents and calamities, whereas the risks of skill shortages or lack of investment, say, are little recognised. Public perceptions of energy security depend more on personal experiences of vulnerability than on actual risks in the energy system [8]. The study of energy security generally lacks transparency and rigour [9,10]. In this it lags some way behind the norms for risk management in business and public life, where formal procedures are commonly used to identify and mitigate risk [11–13]. Perceptions of current and future risk affect the way resources are allocated, for example by investing in facilities, infrastructure and improvement of resilience [14].

The supply-demand balance must be maintained [15] but the majority of studies considering risk in energy systems do so in terms of the supply-side only. A comprehensive approach must also account for demand-side risks. For example, demand reduction, often an important feature of energy policy seeking to promote energy efficiency or change in behaviour, incurs a number of risks. These include the risk of changing policy and regulatory framework, lack of well-functioning markets, optimism bias, and other risks common to the supply-side [16].

A critical feature in energy and climate change discourse is the use of

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[*] Corresponding author.
E-mail addresses: colin.axon@brunel.ac.uk (C.J. Axon), Richard.Darton@eng.ox.ac.uk (R.C. Darton).

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scenarios [17]. Formulating and thinking about potential futures has become an element of strategic planning in the face of uncertainty, in various walks of life [18,19]. Scenarios are visions of the future, together with plausible pathway(s) to it from the present. The imagining and description of a scenario enables one to progress the unbounded envisioning of factors that might affect the future with all its uncertainty to a constrained picture that can be described in as much detail as required. A set of scenarios can be composed to illustrate various visions, each reflecting different sets of assumptions about the future [20,21]. Each scenario should present a self-consistent, plausible description of some future world. It is then possible to analyse these scenarios to see how features of interest might develop, an approach which is well-suited to the investigation of the security offered by future energy systems.

In the context of the low-carbon transition, futures to be considered are those in which the use of oil, gas and coal is greatly reduced as renewables are phased-in to replace them. Demand reduction and new fuels (currently uncompetitive) can be incorporated, together with relevant changes in society, environment and economy. This enables the scoping of options to guide decision and policy making. Scenario sets have been developed for many countries [3,22–30], but none explicitly consider risks associated with fuel sources, although risk is central to energy security which is generally a key objective of public policy.

In [31] Axon and Darton developed a novel Risk Assessment Method for analysing a national energy economy yielding a direct quantification of risk – an indicator of energy (in)security. The energy system is decomposed into staged supply chains for different fuels and each chain is screened to identify risks at each stage. The method enables the overall risk level of each fuel to be ranked, and also identifies the activities incurring the greatest risk [32]. The risk assessment can be carried out for any self-consistent portfolio of fuels within the energy economy, for example, to consider primary energy supply, final demand, or transport energy demand [32]. Such a projection of risk affords visibility of many possible effects of policy options.

The aim of this paper is to show how the Risk Assessment Method can be applied to future national energy systems as they are described in published energy scenarios, and to show how the risks might change over time. The focus is on electricity generation, a section of the energy economy which is expected to change significantly in the next few decades as fossil fuels are replaced by renewables. As in previous work [31, 32], the UK is taken as a case study.

2. Methodology

The Risk Assessment Method [31] considers that all risks in fuel supply chains originate either in the natural environment or from human activity. 34 distinct generic “causes of risk” were found to be necessary and sufficient to capture risks relevant to energy security. These varied from well-known economic risks such as *lack of a well-functioning market* or *lack of access to capital* and technical risks like *pollution event* and *operational failure*. Political risks included *lack of social stability*, *changing policy or regulatory framework*, *poor institutional governance* and *significant public concern*. The 34 causes of risk are grouped in seven generic categories (economic, environmental, innovation, manufacturing, political, skills, technical), and for each a description was made of the characteristics desirable for functioning of fuel supply chains, and the nature of the risk to them [31], to help identify specific risks.

At the heart of the method is the screening of each fuel supply chain in turn, to identify all risks that would hinder the dependable meeting of energy needs. These risks are quantified in terms of likelihood and severity in a systematic way, having regard to system resilience and making use of the well-known risk matrix [16]. Evidence for the risk quantification is deduced from meta-analysis specific to the country and the fuels studied, making use of published data, interpretation and comment, though risk is seldom directly articulated in publications. For each identified risk, its score is the product of its likelihood and its severity scores. Likelihood is judged in all cases using the same 3-point scale (rare (1), possible (2), likely (3)). The severity of risk impacts is judged using a consistent 4-point scale (insignificant (1), minor (2), moderate (3), major (4)). A major advantage of applying the same scoring scale to all risks from all causes is that the scores for a particular fuel supply chain can be summed to a total risk score for that fuel; the method does not require the assignment of weighting factors to various contributory characteristics, often arbitrarily chosen in other approaches. The total score for a supply chain indicates its overall risk [16]. Alternatively the risk scores for a particular cause of risk or category are totalled to discover which are most important.

Demand Reduction (DR), reducing energy demand whether by changing behaviour or using devices, requires a sequence of activities to be undertaken by various actors to bring it about. These activities are conveniently treated within the Risk Analysis Method as a DR supply chain in which every activity can incur risks which can be identified and quantified. DR therefore features in the list of fuels, as a “negafuel”, making a contribution to balancing supply and demand. DR does not usually feature explicitly in future energy scenarios, but can be interpreted from modelled improvements of energy efficiency or demand-side response, for example. Its inclusion is an important part of the method, that would otherwise focus overwhelmingly on supply-side issues.

2.1. *UK case study – individual fuel risks*

In a case study of the UK, of the 19 fuel categories found to be relevant (either because they are already in use in the UK, or are in commercial development), those with the highest overall risk were a group of fossil fuels and nuclear fission, and the least risky were renewables, including solar (electric and thermal), wind, and hydro sources [16]. Detailed error analysis [31] shows that even quite sizable changes in the total risk score are not likely to change the groupings of the fuels in the rank order of risk, suggesting that this approach is robust. For the UK, the three causes of risk with the greatest total score were ‘lack of access to capital’, ‘changing policy or regulatory framework’ and ‘significant public concern’, all of which were amongst the eight causes of risk noted as most significant at an expert verification workshop [31].

An advantage of the Risk Assessment Method is that quantification of risk is based on descriptive evidence, so it does not require detailed numerical modelling. Thus, the method can be applied to future scenarios, independently of how they were developed. For example, scenarios of energy futures can be based on system modelling using economic drivers [33], or stocks-and-flow models with bio-physical constraints [34] or alternative worlds envisioned for various portfolios of fuels [33]. The Risk Analysis Method only requires output describing the operation of the energy economy. It is the processes and the environment in which they are activated to reach the future world that give rise to risk. The ‘portfolio’ is a key concept in this approach: it means the set of fuels that, in any one year, comprise the energy system (or the section of it) under study. For example, the portfolio could be the set of fuels that comprise the total primary energy supply, or the set of fuels that could be described as ‘renewable’.

In this study of UK energy scenarios, the portfolio considered is the set of fuels contributing to electricity production. In the case of electricity generation each technology supplying electricity uses one, or occasionally multiple fuels. Thus, the proportion of each fuel

Table 1
The normalised risk scores for the fuels relevant to the portfolios in the CCC, NG, and 7see scenarios.

Fuel	Normalised Risk Score, NRS (a.u.)	Interconnector (renewables)	Interconnector (non-renewables)	Scenario set		
				7see	CCC	NG
Biogas	61	✓		✓		✓
Biomass	65	✓		✓	✓	✓
Coal	65		✓	✓	✓	
Demand Reduction	45		✓			✓
Gas	99		✓	✓	✓	✓
Gas (unconventional)	100		✓		✓	✓
Hydro	31	✓		✓	✓	✓
Nuclear (fission)	94		✓	✓	✓	✓
Ocean (tidal)	42	✓			✓	✓
Ocean (wave)	47	✓			✓	✓
Solar (electric	25	✓		✓	✓	✓
Solar (thermal, water)	20	✓			✓	✓
Thermal (geological)	80		✓		✓	
Thermal (low temperature)	37	✓			✓	✓
Waste	43		✓	✓	✓	
Wind (offshore)	34	✓		✓	✓	✓
Wind (onshore)	32	✓		✓	✓	✓

contributing can be derived and the risk score from Table 1 applied. In Table 1 the risk scores have been normalised by multiplying the total risk score for each fuel by the same factor, chosen to make the score for the most risky fuel, Gas (unconventional), exactly 100. No information is lost in this normalisation.

2.2. Generating risk profiles

Before a risk analysis can be performed on a portfolio of fuels in an energy scenario, or to allow comparison between scenario sets created by different organisations, there are several steps of preparation to be conducted. Scenario developers usually adopt different definitions for the fuels they include. These different definitions need to be mapped onto our categories of fuel so that the risk evaluation can be exploited. The general pre-processing method and the specific definitions adopted by scenario developers are described in the following sections.

(a) Dealing with groups of fuels

For all scenarios the temporal risk profiles are calculated for installed electricity generating capacity, based on knowledge of the risk scores for individual fuels gained from the Risk Analysis Method. In doing this it is essential to have a protocol for calculating the risks of *groups* of fuels since these arise in all scenarios, their composition depending on the scenario-developer's definitions. For example, groups arise if no distinction is drawn between the various biofuels, thus biogas and biomass form a group; or a number of fuels each making a small contribution may be grouped together; or a group may comprise fuels supplying energy received via interconnectors.

Defining a 'group' as a set comprising one or more fuels, the normalised total risk calculation can be generalised in the following way. At each timestep the portfolio P (of all fuels contributing to the electricity grid) comprises individual fuels or groups of fuels. Some scenario developers do not explicitly state the relative contributions to a group of (similar) fuels e.g. biofuels, so the average of the all the bio-routes assessed is taken. Let the average risk for a fuel group (G) be $\overline{R_G}$. If G is a group of n fuels (where n is one or more) each fuel with a normalised risk score (NRS_{fuel}) then

$$\overline{R_G} = \frac{1}{n}\sum_{fuel\in G} NRS_{fuel}$$

and the total installed (electricity) capacity C_{total} for the portfolio P at each timestep is

$$C_{total} = \sum_{G\in P} c_G$$

where c_G is the installed capacity provided by the group G. The fuel group G contributes to the portfolio a weighted amount of risk T_G in each year, proportional to the capacity represented by G. Thus

$$T_G = \frac{c_G}{C_{total}}\cdot\overline{R_G}$$

This calculation method for T_G is applied to the portfolio of fuels whenever grouping is encountered in a scenario. To generate the risk profile, the total risk for the portfolio of fuels T_P for any year is given by the summation

$$T_P = \sum_{G\in P} T_G$$

$$= \sum_{G\in P}\frac{c_G}{C_{total}}\cdot\overline{R_G}$$

$$= \sum_{G\in P}\left[\frac{c_G}{C_{total}}\cdot\frac{1}{n}\sum_{fuel\in G} NRS_{fuel}\right]$$

(b) Dealing with categories of risks

Additional insight can be obtained from considering how the risk profiles for individual categories of risk vary with time. This requires separate calculation. The total risk score T_G for a fuel or group of fuels is the sum of the values of the seven risk categories

$$T_G = \sum_{i=1}^{7} R_{cat,i}$$

Calculating the contributions of the normalised risk score for individual risk categories ($NRS_{Cat,i}$) must be based on the non-normalised risk scores for the risk category. The normalised score for each category (NRS_{cat}) is

$$NRS_{cat} = \frac{R_{cat}}{T_G} \cdot \frac{c_G}{C_{total}} \cdot \overline{R_G}$$

where R_{cat} is the risk score (non-normalised) for that category (across all stages) for a fuel (or group), and T_G is the total risk score (non-normalised) for the fuel (or group).

2.3. Interpreting the fuel grouping for UK energy scenarios

Experienced developers specify and generate scenarios to address clearly-defined questions. For this UK case study three well-considered scenario sets are selected, namely those produced by the Climate Change Committee (CCC) [35], National Grid (NG) [36], and the 7see whole-economy energy model [34,37]. The CCC advises the UK Government, and their scenarios inform the net-zero policy by generating carbon budgets [35,38]. National Grid is the UK electricity transmission system operator and the NG scenarios examine installed generating capacity of the electricity system, which makes these scenarios technology-driven, not fuel oriented. The 7see model is independent of any institution, being designed to examine economy-wide effects such as investment in energy systems [39].

The CCC scenario set describes a reference case, and five scenarios for achieving net-zero at or before 2050. Modelling is conducted using the Dynamic Dispatch Model [40] which examines investment decisions in the policy environment using fuel costs and carbon prices [41]. The CCC reference case, very similar to that of NG, is not considered further. NG created four scenarios [36] with the fastest credible decarbonisation scenario to meet net-zero being ‘Leading the Way’ (NG-LtW). Modelling is conducted using the technology-rich least-cost optimisation UK TIMES model [42]. The 7see modelling philosophy [43] is different from CCC and NG, using system dynamics and being bio-physically consistent [44].

The pre-processing operations and the definitions to form the mapped fuel groups are as follows:

(a) CCC scenarios

In the Balanced Net-Zero Pathway (CCC-BNZP) scenario the CCC use TWh of demand for the fuels given in Table 1. Conversion to installed capacity (GW) is achieved by proportionality referenced against fixed points of capacity at 2030 and/or 2050 (and interpolated monotonically) given for some fuel categories [45,46]. The load factor for all fuels is assumed to be equal and time-invariant.

1. The principal fuels considered are: Biomass, Gas, Nuclear (fission), Wind (offshore), and Wind (onshore).
2. The CCC definition of ‘Firm Power’ is wholly Nuclear (fission).
3. The CCC definition of ‘Unabated Generation’ is Gas.
4. The CCC definition of ‘Dispatchable Generation’ is Gas (with CCS), BECCS, and Hydrogen.
5. The two groups of ‘Interconnectors’ are assumed to be 50:50 renewable and non-renewable separately (Table 1). The interconnector capacity is taken from the National Grid estimates [36].
6. The group, ‘Other’ comprises: Biogas, Coal, Gas (unconventional), Hydro, Ocean (tidal), Ocean (wave), Solar (thermal, water), Thermal (geological), Thermal (low temperature), Waste [47].

‘Dispatchable Hydrogen’ is treated as Gas because CCC assume that it will all be produced by steam reforming of methane and combusted in a CCGT. Any hydrogen produced using electrolysis powered by curtailed wind is a storage system and not a fuel. The risk is accounted for by the installed capacity of wind (avoiding double counting). The storage requirements for this hydrogen are accounted for within the distribution system risk score. Hydrogen forms a small proportion of the portfolio for all years.

(b) NG scenarios

The National Grid Steady Progression (NG-SP) scenario is a reference case, whilst the Leading-the-Way (NG-LtW) scenario is the fastest to reach net-zero. NG mostly, but not exclusively, use TWh of demand for the fuels given in Table 1. Conversion to installed capacity (GW) is achieved by proportionality referenced against fixed points of capacity at 2030 and/or 2050 (and interpolated monotonically) given for some fuel categories [36]. The load factor for all fuels is assumed to be equal and time-invariant.

1. The NG definition of ‘Green Gas’ is Biogas.
2. The NG definition of ‘Shale’ is Gas (unconventional).
3. NG definition of ‘solar’ is Solar (electric).
4. NG definition of ‘Demand-side response’ is treated as Demand Reduction.
5. The Gas category comprises natural gas, hydrogen (steam reforming of methane), and natural gas with CCS.
6. All biomass use is associated with power generation, not residential use.
7. The two groups of ‘Interconnectors’ are assumed to be 50:50 renewable and non-renewable separately (Table 1).
8. The group ‘Other renewables’ comprises: Hydro, Ocean (tidal), Ocean (wave), Solar (thermal, water), and Thermal (low temperature).

The proportion of Hydrogen in the NG scenarios is greater than assumed by CCC. NG consider three routes for producing Hydrogen: steam reforming of methane, electrolysis (using excess wind and nuclear), and from bioresources. For the risk calculation Hydrogen is treated as Gas because most is combusted in a GGCT. For NG-LtW no Hydrogen is produced by steam reforming methane.

(c) 7see scenarios

For 7see the reference case is 7see-BAU, and the two low-carbon transition scenarios are fastest new nuclear build (7see-FNNB) and the fastest plausible deployment of offshore wind (7see-FOfW). The 7see model gives installed capacities in GW directly.

1. The 7see definition of ‘Thermal electrical capacity’ is Coal and co-fired Biomass.
2. The 7see definition of ‘CCT electrical capacity’ is Gas.
3. The group ‘Bioresources and Waste’ comprises: agricultural wastes, sewage, landfill gas, and municipal solid waste. It is treated as Biogas, Biomass, and Waste.

Currently, Hydrogen is not considered in any 7see scenario. Furthermore, 7see does not account for imported power, though this is small in all cases.

3. Assessing risk in energy scenarios

Using the total (normalised) risk score for a fuel, the overall risk for a portfolio of energy (fuel) sources can be estimated, showing how risk changes as the mix of fuel sources changes over time. Analysing the energy security of the UK’s installed electricity generating capacity in various scenarios provides a strong test of the flexibility of the method and illustrates the intricacies of defining multiple uses of sources of fuels. Furthermore, installed capacity is a concept directly coupled to physical infrastructure. The following scenarios were selected: two reference scenarios (NG-SP and 7see-BAU), two which represent

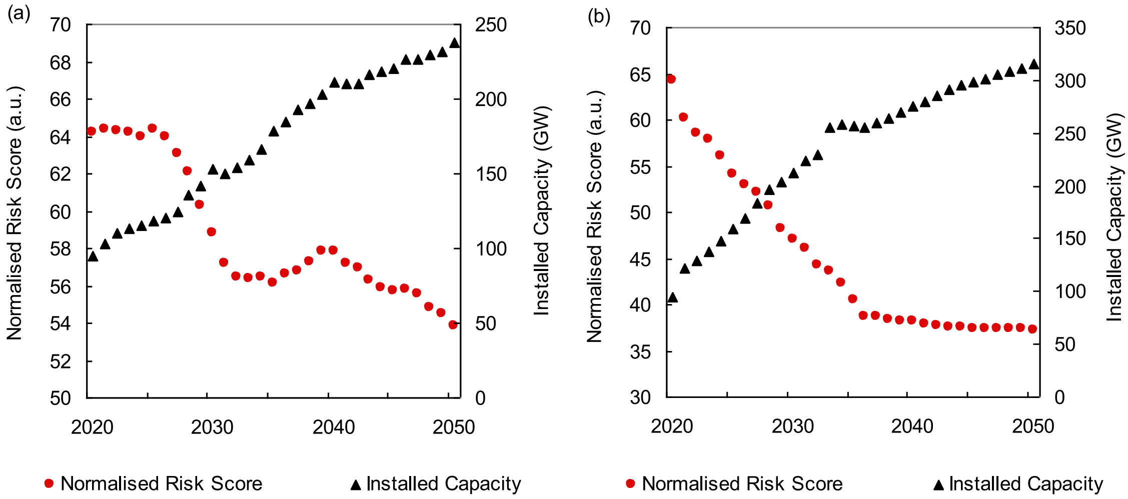

Fig. 1. The risk profile of installed electricity generating capacity for the National Grid scenarios (a) Steady Progression (NG-SP), (b) Leading the Way (NG-LtW). Profiles for other scenarios are given in Appendix A.1.

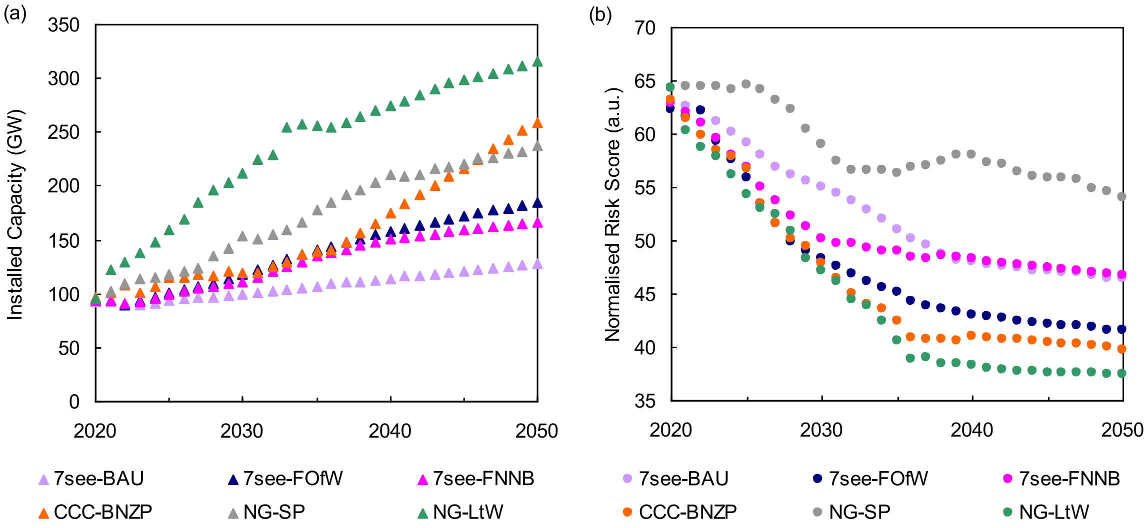

Fig. 2. Changes in (a) the installed electricity generating capacity and (b) the risk profiles, in the portfolios for the selected scenarios.

pathways for a low-carbon transition (7see 'Fastest Offshore Wind', 7see-FOfW), and 7see 'Fastest New Nuclear Build', 7see-FNNB), and two expressly net-zero carbon NG-LtW and the CCC Balanced Net-Zero Pathway (CCC-BNZP).

Fig. 1(a) shows that as the installed electricity generating capacity increases linearly in the NG reference scenario, the normalised risk score for the portfolio in each year follows a qualitatively different trajectory. The risk profile remains constant until the mid 2020s, falls quickly until the early 2030s, then gradually drifts lower to 2050. The sharp fall is due to two factors: natural gas reduces as a proportion of the total (though it slowly increases in absolute GW capacity terms) at a period when there is a rapid increase in offshore wind deployment. The small rise in risk centred on 2040 is due to new nuclear stations coming on-stream. Although the installed capacity increases by a factor 2.5 between 2020 and 2050 in this scenario, the risk *decreases* by approximately 15% (from 64 to 54 a.u.). By contrast, the fastest GHG reduction scenario (Fig. 1(b)) also shows a rising trend for installed capacity, but a very different risk profile with a steep decline followed by an inflection and plateauing of the risk score to 2050. Predicting the risk profile is not obvious simply from knowing the projected or planned growth in the installed capacity.

The installed capacity (Fig. 2(a)) is greatest for the NG-LtW scenario throughout the period to 2050, being 78 GW greater than the NG-SP (reference) scenario at 2050. The NG-SP scenario requires more installed capacity than the two low-carbon 7see scenarios and their reference 7see-BAU. None of the scenarios has levelled-off by 2050,

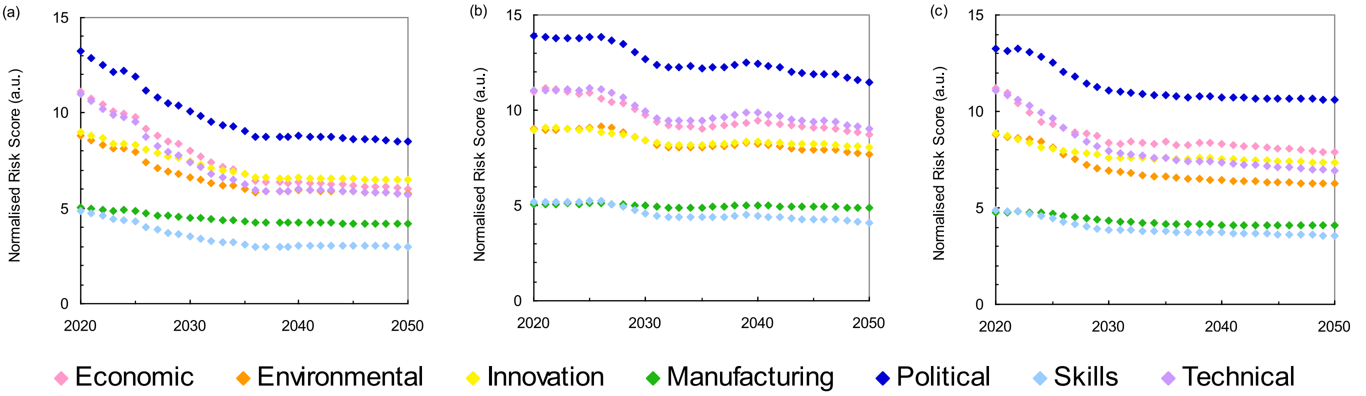

Fig. 3. The risk profiles for the individual categories of risk for the (a) CCC-BNZP, (b) NG-SP, (c) 7see-FNNB scenarios. Profiles for other scenarios are given in Appendix A.2.

though the growth rate of most is slowing. The CCC-BNZP shows a different pattern as capacity growth has to accelerate from the mid 2030s to meet the net-zero target by 2050. The capacity increase in both CCC and NG scenarios is driven by growth of offshore wind for electrolysis for hydrogen production and to accommodate growing demand from electric vehicles.

Plotting the risk profiles for all six scenarios (Fig. 2(b)) shows that the risk associated with the LC pathways is always less than in the reference scenarios. Risk in CCC-BNZP and NG-LtW declines steadily to 2035, then more slowly to 2050 reaching values about 40% lower than in 2020. The 7see-FOfW risk profile is similar to the two net-zero scenarios until 2030, risk then declining more slowly but reaching a very similar value by 2050. Notably, 7see-FOfW achieves this using 40% less installed capacity than NG-LtW with CCC-BNZP needing about 20% less (Fig. 2(a)). Risk declines during the 2020s in the 7see-FNNB scenario as investment is made in offshore wind whilst nuclear stations are constructed. The 7see-FNNB risk profile converges with the 7see-BAU in the late 2030s, because nuclear and gas have very similar risk scores.

Profiles of each of the seven categories of risk are shown in Fig. 3 and are derived from individual risk evaluations [31,32]. For the CCC-BNZP the political category is the largest source of risks. The total risk score for the economic, environmental, innovation, and technical categories converge by the mid 2030s. For the NG-SP scenario the greatest fluctuation is in the political category, but for most categories the variation is slight.

For all three scenario sets, the more optimistic scenarios have lower risk scores than the more pessimistic, holding true for both 2030 and 2050 (Table 2). Overall, the CCC-BNZP and NG-LtW scenarios, with their ambitious assumptions, score lower than any of the 7see cases. It is noteworthy that the largest fall in risk score (NG-LtW) is 41%, yet requires more than a trebling of installed capacity, an indication of the magnitude of the challenge implied by decarbonisation of electricity generation. The ratio of risk unit to capacity unit is a measure of 'risk efficacy' i.e. how much risk is incurred per GW of installed capacity. Despite increases of 2.5–3.3 times in the capacity, the two net-zero scenarios give the most favourable ratio.

UK policy aims to reach net-zero carbon emissions (all demand) by 2050 [35]. Although the net-zero target would be met in the CCC-BNZP and NG-LtW scenarios, they require doubling or trebling installed capacity and supporting infrastructure, which has a financial cost. The lack of access to capital is identified as a significant risk, but the analysis has not hitherto assessed risks beyond quantifying the level of impact. This may downplay the difficulty in achieving the net-zero aim, however. To better represent the 'scale of challenge' (SoC) in a scenario, a new metric is calculated in which the installed generating capacity is multiplied by the risk (Fig. 4). This metric is analogous to value-at-risk for investment portfolios which scales with both the size of an investment and its risk. The SoC metric is a measure of the challenge in developing, operating and maintaining the electricity generating and distribution system. This metric can favour schemes requiring a lower total installed capacity, which are more easily achievable, even if the risk of the portfolio is higher. For the SoC metric (Table 2), the two net-zero scenarios and the NG-SP have around twice the value by 2050 of the 7see-BAU. This suggests that the key to achieving a low-carbon transition might lie in moderating increases in installed capacity but still lowering risk.

In Fig. 5 the two pairs of expressly net-zero and reference scenarios are compared. Fig. 5(a)&(d) plot projected GHG emissions and installed electricity generating capacity. Emissions in the CCC-BNZP decline to 1 Mt yr^{-1} at 2050, whilst NG-LtW reaches zero in 2032, reaching −33 Mt yr^{-1} by 2050 through significant deployment of BECCS. To achieve this, NG-LtW requires 33% more installed capacity, which offsets assumptions about energy demand from other sectors such as transport and industry. The step changes arise from modelling assumptions. The CCC-BNZP relies less on using electricity generation to carry the burden of decarbonisation, and capacity initially grows slowly. In contrast, NG-LtW installed capacity grows faster earlier in the period, giving lower cumulative GHG emissions to 2050 [37] (Table 2). For the reference scenarios, installed capacity grows linearly with 7see-BAU needing only half that of NG-SP, but still reaching net-zero and 40% less cumulative emissions.

Fig. 5(b)&(e) shows the corresponding risk profile with emissions. It is notable that the GHG projections diverge significantly, yet the risk profiles are similar. For the net-zero scenarios the risk profiles are identical to the mid 2030s diverging only to a small extent by 2050. The reference scenario risk profiles diverge more than those for net-zero, yet the GHG projections diverge less. The fall in risk score by 2050 for 7see-BAU is nearly twice that of NG-SP (Table 2). Without analysing the electricity system separately and calculating the risk profile, this insight would not be apparent.

The plots of projected Scale of Challenge and GHG emissions in Fig. 5 (c)&(f) demonstrate significant differences between the two net-zero scenarios: NG-LtW presents a greater Scale of Challenge throughout the period but produces lower emissions more rapidly. The reference scenarios exhibit a greater difference, with 7see-BAU remaining flat throughout the period whilst delivering a net-zero system. The SoC in 2050 of NG-SP is twice that of 7see-BAU (Table 2).

Table 2
Summary of the normalised risk scores for the comparison of the CCC, NG, and 7see scenario sets for installed electricity generating capacity. The 2020 normalised risk score is 63 a.u. for all scenarios.

Scenario	Installed Capacity, 2050 (GW)	GHG Emissions, in 2050 ($MtCO_2e\ y^{-1}$)	GHG Emissions, cumulative to 2050 ($MtCO_2e$)	Normalised Risk Score (a.u.)		Change in Risk Score, 2020–2050 (%)	Installed Capacity 2050 relative to 2020	Risk unit/Installed Capacity unit (GW^{-1})	Scale of Challenge, 2050 ($GWx10^3$)
				2030	2050				
NG-SP	237	8	510	59	54	−16	2.5	0.23	13
NG-LtW	315	−33	−287	47	37	−41	3.3	0.12	12
CCC-BNZP	259	1	505	48	40	−37	2.7	0.15	10
7see-BAU	128	−3	317	55	46	−27	1.4	0.36	6
7see-FNNB	166	−3	169	50	47	−25	1.8	0.28	8
7see-FOfW	185	−3	144	48	42	−33	2.0	0.22	8

4. Conclusions

The reduction in emissions and improvement in energy security require a shift from fossil fuels towards renewables in a manner which balances exposure to different types and scales of risks. The CCC and NG project that the UK electricity generating system may need an installed capacity in 2050 some three times larger than in 2020. If the unprecedented level of investment to create such a system is to be forthcoming, then a deep understanding of the whole risk landscape is required. Analysis of the CCC-BNZP and NG-LtW scenarios, which meet the UK government target of net-zero GHG emissions by 2050, shows that they both reduce risk in the UK's electricity system by around 40%.

A new metric, the product of the risk and the installed capacity (GW), is suggested as a measure of the scale of challenge in developing, operating and maintaining the electricity generating system. This metric roughly doubles between 2020 and 2050 for the two net-zero scenarios investigated. Policies which accept more risk but require less expansion in generating capacity may be found preferable in implementation. It should be noted that risk arising in fuel supply chains was not considered when constructing any of the scenarios or models analysed here; the risk results are an emergent property of the projections.

Although various pathways with different characteristics can lead to lower GHG emissions, the difference between their risk profiles is less marked. This perhaps explains why the market finds 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 creates the barrier to change. The risk-profiling technique described here allows analysts to examine trade-offs between different categories of risk for fuels with seemingly similar profiles and apparently low-risk fuels which may have high-risk components.

Our comprehensive method for assessing risks, including both supply- and demand-side, was developed for an existing energy system using a description of that system as it is known to operate. When analysing scenarios the assumption was made that the aggregate view for a nation changes only slowly with time, the broad categorisation of likelihood and impact ensuring this robustly. Since the risk analysis looks both backwards and forwards, it accounts for historical knowledge and possible future outcomes. Well-established trends can also be projected forward in scenarios in defensible ways [34]. Moreover, extreme possibilities are 'priced-in' since the possible occurrence of abrupt serious forced changes (shutting down a site, operation, or activity) is taken into account in the evalution of risks.

The methodology described here highlights activities and risks needing policy attention but does not specify how barriers should be addressed. The level of detail required for policymaking necessitates additional and deeper analysis. Once the structure of the analysis is complete, more frequent updating of the risk database is much easier, for example if new risks are identified, or the quantification of particular risks changes. Private companies will make investment decisions incorporating a risk assessment; governments should do likewise. At present, policy decisions are mostly informed by the output from energy system models which omit explicit consideration of risk other than through a pricing mechanism.

In addition to installed electricity generating capacity, risk profiles for portfolios can be calculated for many common energy flow measures, such as total primary energy demand by fuel, final demand by fuel, or transport fuel demand. These demonstrate differences depending on which measure is used to examine the energy system.

Energy security, like sustainability, is multi-facetted and risk analysis shows the variability in projections. Incorporating risk adds a

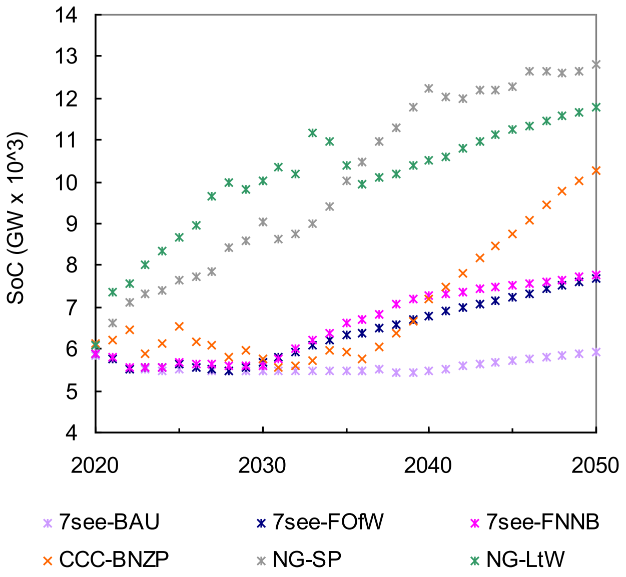

Fig. 4. The Scale of Challenge for the scenario set.

dimension to bridge the concepts of sustainability and security, but it is still not a predictive tool which can account for exogenous shocks. However scenario analysis and risk analysis are complementary and when used together offer a systematic way for assessing the value of proposed energy system configurations and the barriers or challenges that might be encountered when attempting to realise them.

Credit author statement

Colin Axon: conceptualization, methodology, investigation, writing, reviewing, editing. Richard Darton: conceptualization, methodology, writing, reviewing, editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

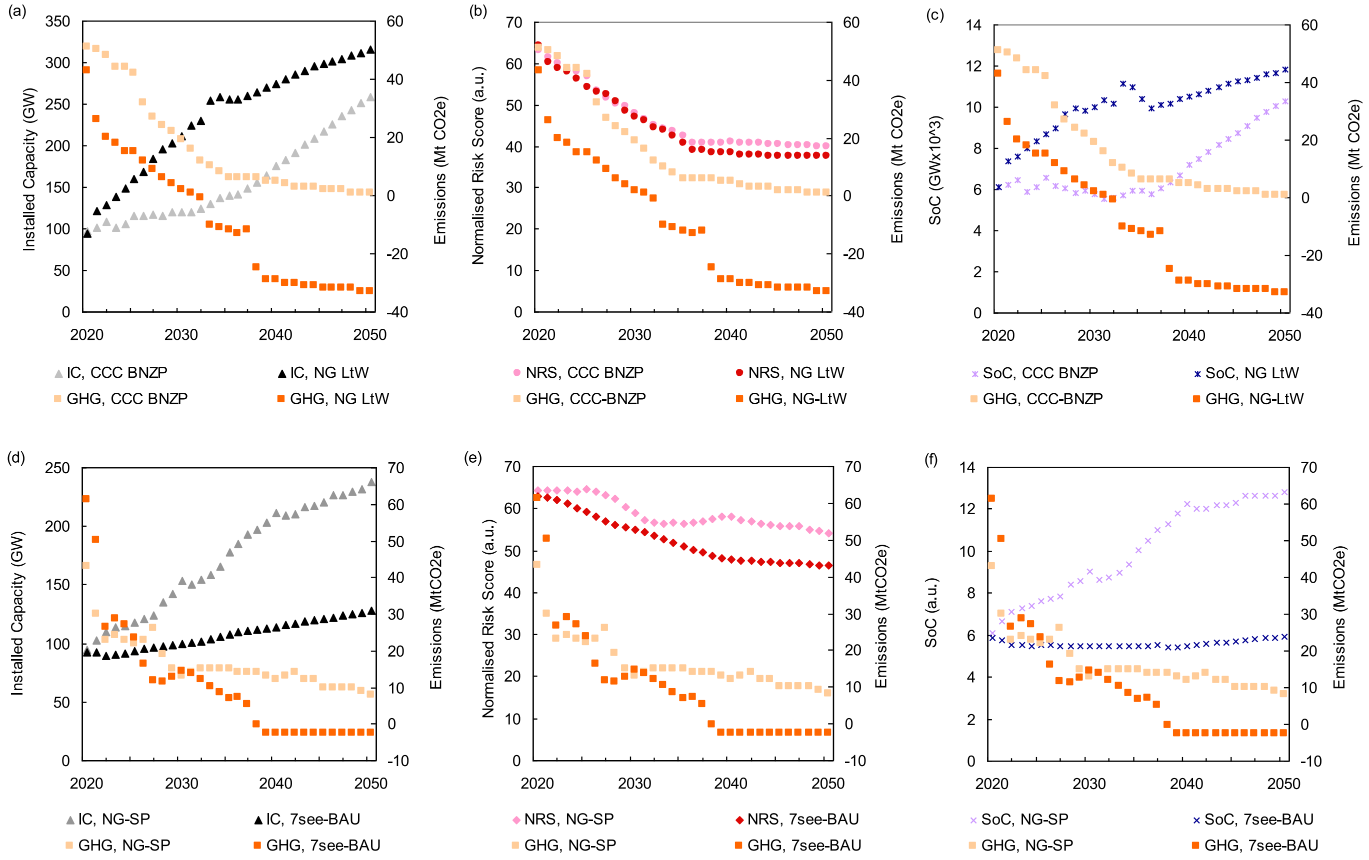

Fig. 5. Comparing the projected GHG emissions with (a) installed capacity, (b) risk profiles, (c) the Scale of Challenge, for the two net-zero scenarios CCC-BNZP and NG-LtW; with (d), (e), and (f) the corresponding plots for the two reference scenarios NG-SP and 7see-BAU. Plots for the 7see-FOfW and 7see-FNNB scenarios are given in Appendix A.3.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2023.127393.

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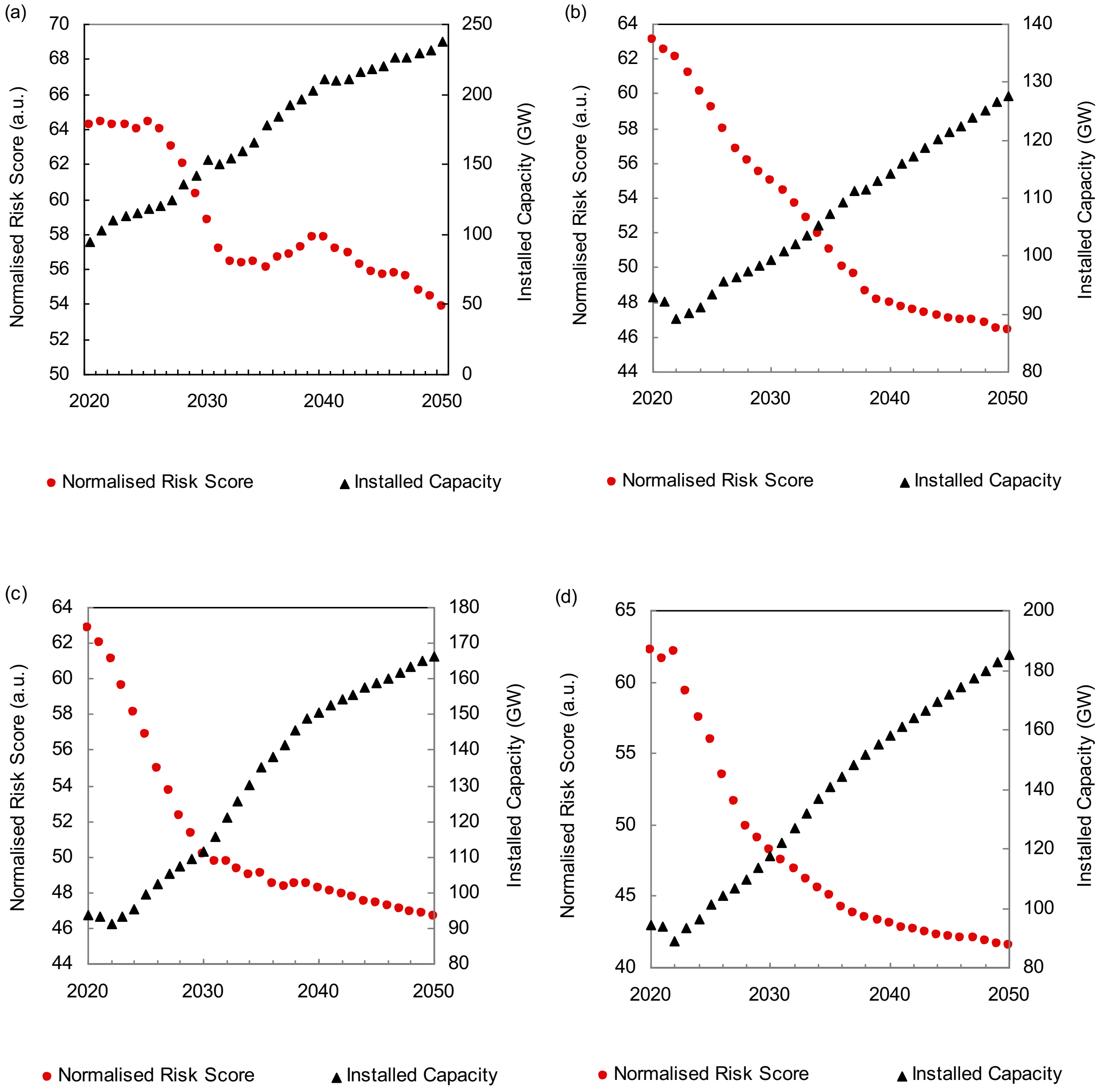
Appendix A

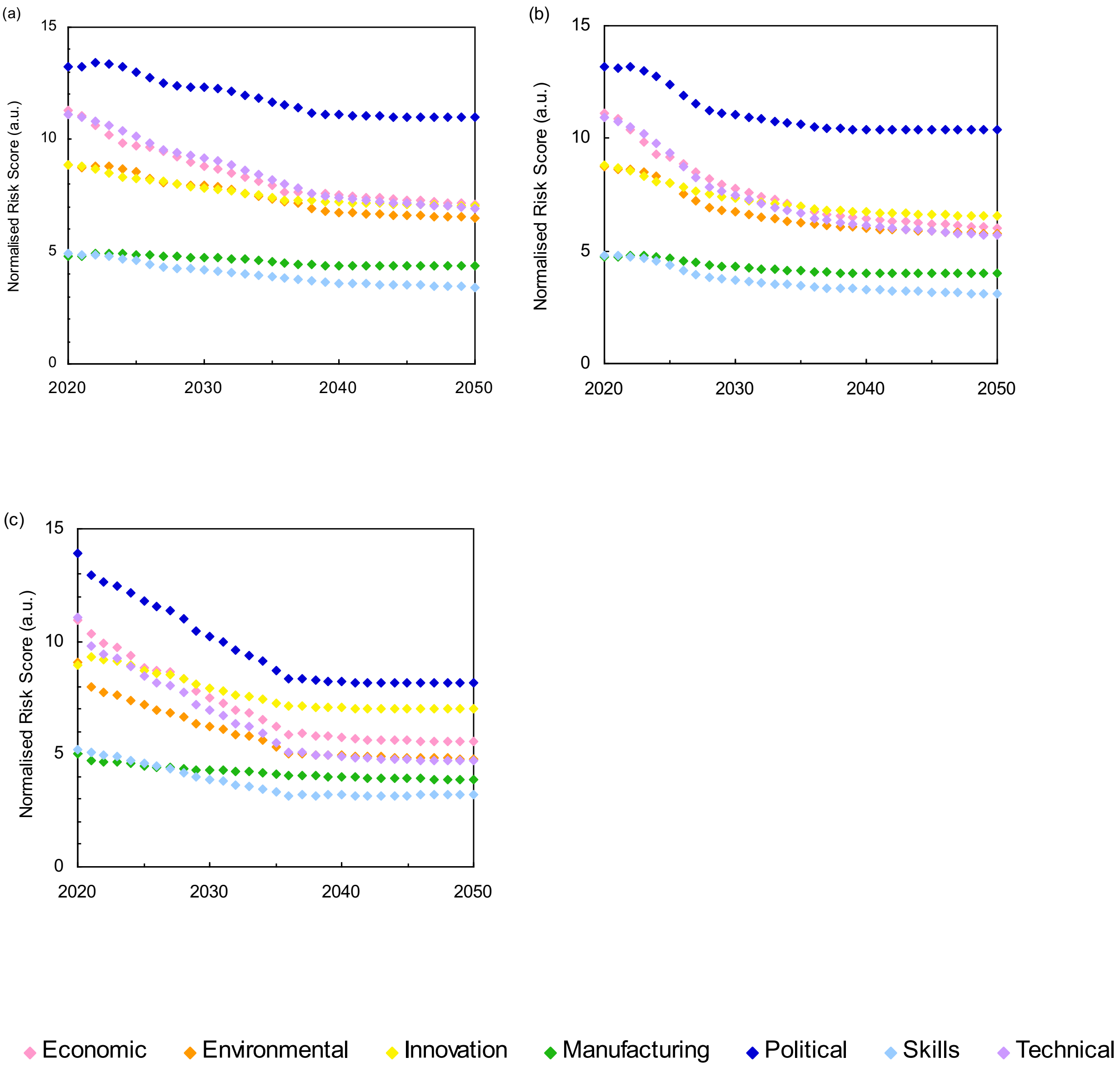
A.1. Supplementary information for Fig. 1.

The risk profiles of installed electricity generating capacity for the CCC scenario (a) Balanced Net-Zero Pathway (CCC-BNZP), and 7see scenarios (b) Reference (7see-BAU), (c) Fastest New Nuclear Build (7see-FNNB), (d) Fastest Offshore Wind (7see-FOfW).



A.2. Supplementary information for Fig. 3.

The risk profiles for the individual categories of risk for the (a) 7see-BAU, (b) 7see-FOfW, (c) NG-LtW scenarios.



A.3. Supplementary information for Fig. 5.

Comparing the projected GHG emissions with (a) installed capacity, (b) risk profiles, (c) the Scale of Challenge, for the 7see-FOfW and 7see-FNNB scenarios, and d) GHG profile for all scenarios.