What price near-zero emissions?

Energy and economic modelling for the UK using real-world data to 2050 and beyond

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Report

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Key messages:

1. With the UK Government's existing measures, greenhouse gas emissions attributed to the economy in 2050 will reduce by only 57% compared with the 1990 level; a long way from net zero.

2. The pursuit of net zero as a target encourages a reliance on unproved technological fixes. Rather than putting off too-difficult-to-transition activities within 'net-zero' emission targets, we show that a 'near zero by 2050' target for 2050 is plausible for the UK. It is better to travel slowly in the right direction, than quickly in the wrong one.

3. This near-zero scenario is only possible with extensive use of hydrogen across the economy where electrification is not feasible and as a precursor to renewable ammonia in the long term for transport. Decarbonised hydrogen (from natural gas with CCS) will be needed as a transition fuel in 2050. Aviation – the hard to decarbonise sector – can be fuelled by ammonia, which is a near-term technology, alongside ammonia for maritime.

4. Overall zero emissions for the UK would be underpinned by aggressive growth of offshore wind, of both fixed and floating technologies, complemented by hydrogen production and use.

5. Costs for the additional investment to reach and maintain this scenario would likely rise to 3.0% of GDP annually with a slow decline to 2.5%.

6. Jobs would increase in construction balanced by a reduction in the services industries. There would be no overall change in the number of manufacturing jobs but their type would shift to supporting more investment in the economy.

7. Modelling to 2080 shows that reduced dependence on blue hydrogen would only be possible if all ammonia is imported.

8. We use whole-economy modelling calibrated by historical data since 1990.

Policy implications

Current measures cannot deliver net zero at any point in the foreseeable future. All policy underpinning 'net zero by 2050' should be revisited, and new policy should look beyond 2050. Risks arise pursuing net zero from unintended consequences such as the likelihood of stranded assets or becoming locked into technological pathways with short-term uses but long-term disadvantages. The analysis presented in this report has implications for current and future UK Government policy:

1. Consider mechanisms to incentivise investment in and support of floating offshore wind technology development and deployment.
2. Explore trade policy and agreements for importing renewable ammonia from countries which have good potential for renewable generation.
3. Sponsor research and development, feasibility studies, and trials of ammonia for aviation and hydrogen combustion engines for HGVs.
4. For heating homes, acknowledge the low rate of heat pump installations and develop better understanding of householder requirements and market dynamics.
5. The UK Government should be more forthcoming with the public concerning the diversion of GDP (the costs) of low-emission measures since 3% of GDP is a significant level that needs wide commitment and buy-in to succeed.

A caveat about scenarios

Scenarios are not predictions – they are ways of thinking about possible futures, whether it be a desirable or undesirable picture (which are relative positions that need defining as part of the analysis). Once the key characteristics of a scenario are identified, the modelling is useful to give hints about how the (un)desirable features can be avoided or incorporated, and how the pathway to that possible future might come about and what the milestones might be. We are academics – not activists – so we are not advocating for any of the scenarios we present. We are simply investigating 'what if' questions from a technical and economy-wide (national accounting) viewpoint underpinned by defensible engineering estimates operating within the bounds set by the physics of thermodynamics. It is for a nation's elected representatives to decide, with buy-in from civic society, whether the policy and regulation that may be required makes such scenarios feasible or not.

Contents

Abbreviations

CCS	carbon capture and sequestration
GDP	gross domestic product
GHG	greenhouse gases
GVA	gross value added
H-B	Haber-Bosch (process for making ammonia)
HGV	heavy goods vehicle
HP	heat pumps
ICE	internal combustion engine
LCV	light commercial vehicle
LULUCF	land use, land use change and forestry
NIS	National Inventory Submissions
PV	photovoltaics (solar electricity)
SAF	sustainable aviation fuel
VAT	value-added tax
WAM	with additional measures
WEM	with existing measures

1. A plausible transition to 'Near zero by 2050'?

"Net zero by 2050" has become a mantra for the majority of UK Parliamentarians, policy makers, and academics. The term 'net' arose to address those sectors with emissions deemed too difficult to become emission-free, by 2050, otherwise the overall emissions reduction target and endeavour might be undermined. Sequential carbon budgets[1] defined in the UK Climate Change Act of 2008 are milestones on a path towards a long-term objective of decarbonising residential, commercial, and industrial activities. The original target of an overall cut in greenhouse gas emissions of at least 80 per cent by 2050, relative to 1990, was replaced with a target of achieving *net-zero* emissions by 2050. The Sixth Carbon Budget[2] in December 2020 reflected this updated target.[3] The UK Government's 'Net Zero Strategy: Build Back Greener' notes "greenhouse gas removals (GGRs) will also play a critical role in balancing residual emissions from the hardest to decarbonise sectors such as aviation, agriculture, and heavy industry."[4]

Climate scientists James Dyke, Bob Watson, and Wolfgang Knorr argue that the concept of net zero has been harmful to the cause of emissions reductions stating that they *"[arrived] at the painful realisation that the idea of net zero has licensed a recklessly cavalier 'burn now, pay later' approach which has seen carbon emissions continue to soar"*[5]. In other words, the pursuit of net zero as a target encourages a reliance on unproved technological fixes[6]. For *net* zero, the difficult elements might divert investment, resources, and intellectual effort into necessarily temporary solutions with few long-term prospects. Therefore, these temporary solutions are unattractive to investors as the risk of stranded assets increases.

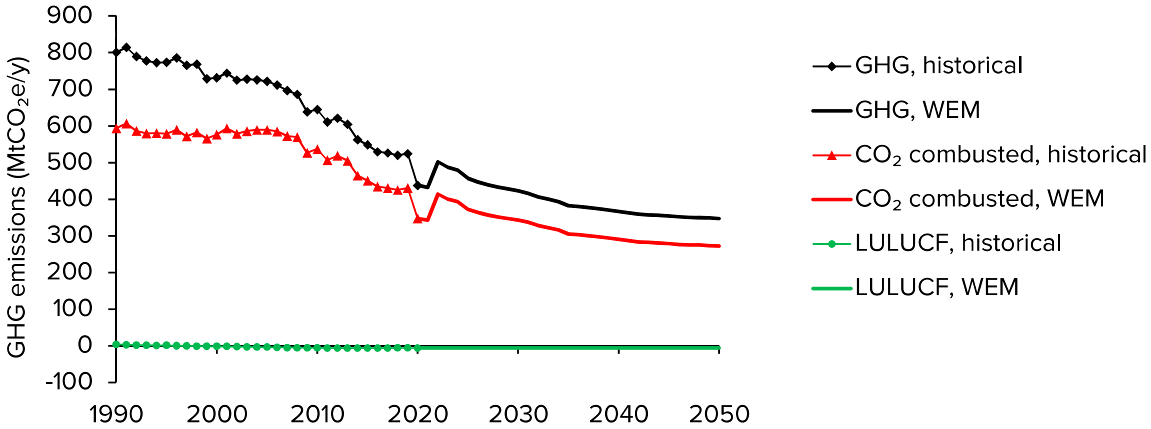
We explore how to reach 'near zero by 2050' with known technologies and physically defensible assumptions. In addition to addressing the concerns of Dyke, Watson, and Knorr, another reason to model near zero by 2050 is to explore how soon beyond 2050 sustainability can be achieved, such as ending dependence on fossil fuels and carbon capture and storage (CCS).

2. Where are the UK emissions heading?

The policy context in which UK emissions are currently managed we term 'with existing measures' (WEM). These are existing rates of installation of renewables and new electric and hybrid vehicles. We assume that the annual installation of domestic heat pumps grows year on year at the same rate of increase since 2020, and that the supply of bio-sourced fuels for aviation grows as planned under the Sixth Carbon Budget. To model UK GHG emissions to 2050 with these measures, we use a whole-economy model based on the 7see framework[7–11] which is calibrated by historical data since 1990. This contrasts with scenarios developed by others which, for example, use least-cost optimisation and price estimates, and lack whole-economy effects. National Grid's Future Energy Scenarios[12] suggested that the earliest date by which the electricity grid could be decarbonised is 2036, however, the current UK Government's target year is 2030[13]. New work by the National Energy System Operator (formerly National Grid) claims that the target may be possible at an annual cost of at least £40 billion[14], furthermore the report notes that this would be a "*huge challenge*" requiring a "*dramatic acceleration in progress compared to anything achieved historically*".

Figure 1 shows by how much the 2050 net-zero target is likely to be missed. We expect that by 2050 GHG emissions will be reduced by approximately 57% compared with the 1990 level. As time proceeds, the easy savings are made first, so the rate of reduction slows, with only a further third of GHG emissions likely to be reduced from the 2019 level. We note that many of the early reductions were achieved by offshoring manufacturing. We are not judging whether the UK's existing measures for emissions reduction are good or bad, desirable, or undesirable, noting only that they are the current trajectory.

Figure 1. Emissions sources (GHG), including international bunkers for aviation and maritime, and sinks (LULUCF) as historical[15] and projected (modelled) for WEM (with existing measures). Also shown is the sub-section of GHG of CO_2 from combustion (NIS category 1A, energy, fuel combustion).



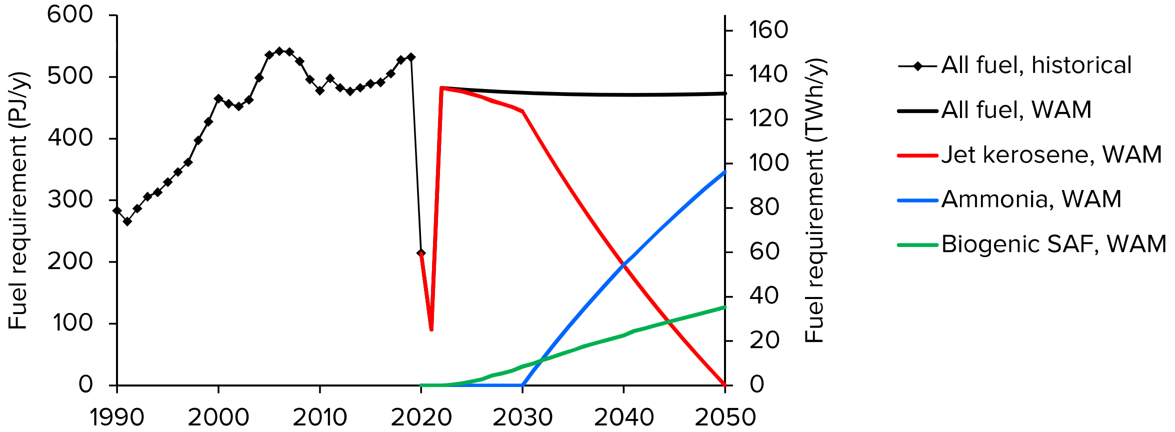
3. Difficult demand-side transitions

Much commentary and analysis emphasizes the supply side by discussing future capacity requirement. On the demand side, some sectors have been identified as being difficult to decarbonise, notably transport and residential heating. We model the demand side 'with additional measures' (WAM), using technology options demonstrating continuous improvement in efficiency. We avoid mandated changes in levels of demand by consumers as we consider this unlikely to be a successful strategy.

For aviation, the simplest solution is the so-called 'drop-in fuels' (synthetic jet kerosene) since this entails minimal changes to jet engine technology or airport fuel supply infrastructure. The UK Government's strategy[16] is to maximise the use of bio-sourced fuels (sustainable aviation fuel, SAF) but these are limited by the availability of agricultural land and could likely only meet about 20% of the demand[17]. Ammonia is another alternative fuel receiving considerable attention[18–20]. Studies[21] suggest that ammonia-burning engine designs are possible, potentially efficient with minimal NOx emissions. Switching to ammonia would involve major changes to engines and fuel storage in planes along with new infrastructure at airports for fuel supply and management[22]. However ammonia sourced renewably appears to be the only fuel not requiring carbon that can be stored sufficiently on planes to enable long-haul flights. We select ammonia for our scenario as the investment will be beneficial for the long term (Figure 2).

For heavy goods vehicles (HGV) one view is to await reduction in the cost of fuel cells, which convert hydrogen directly to electricity on-board. However, despite many years of research and extensive investment, mass produced fuel cells for widespread use have not been successful in the market. In contrast, simply burning the same hydrogen fuel in a slightly modified ICE is a known technology, with improvements being developed for HGVs[24–26]. We model these in Figure 3.

Figure 2. Historical[23] and projected (assumed) energy demand by aviation (UK aviation bunkers) is met in 2050 by biogenic sustainable aviation fuel (SAF) and ammonia.



For heating dwellings, heat pumps are the UK Government's preferred retrofit option for existing homes[28] with the current net zero target requiring 600,000 installations per year by 2028[29,30], however, the installation rate is only 35,000 per year in 2023[31]. We model a much reduced but still very ambitious retrofit rate of 300,000 per year, though this will be insufficient to retrofit all existing dwellings by 2050 (Figure 4). We propose replacing natural gas by hydrogen in the distribution system as a transition[32] whilst acknowledging the difficulties involved[33]. We assume that all new homes are fitted with a heat pump.

Figure 3. Historic[27] and projected (assumed) size of the HGV fleet and how it changes over from conventional diesel ICE to new hydrogen ICE reaching 100% by 2042.

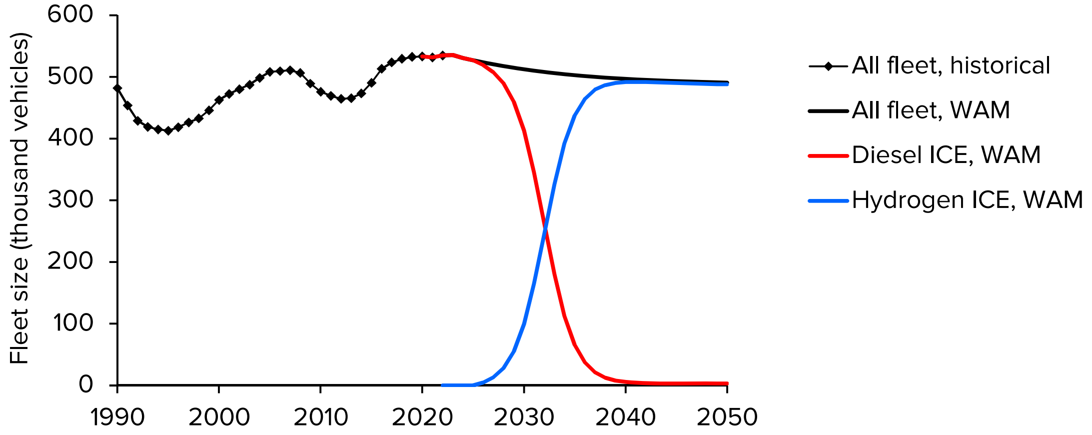
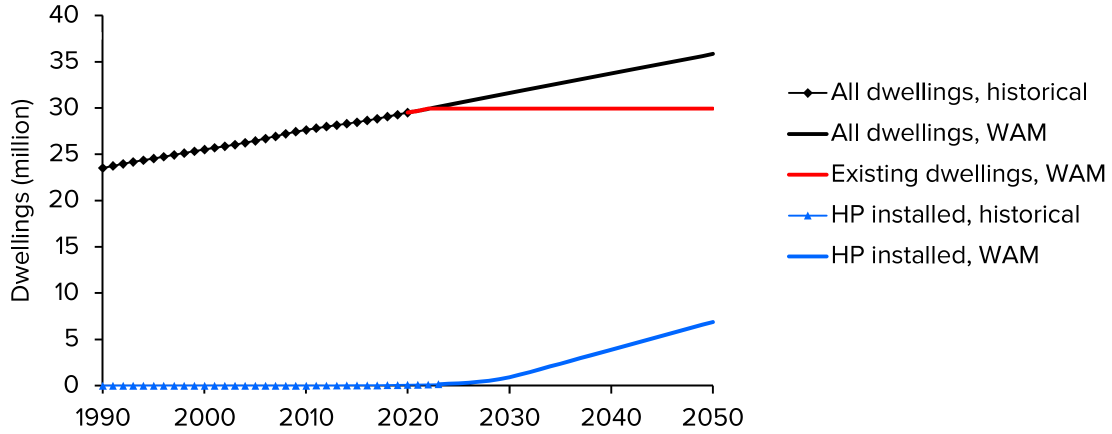


Figure 4. Historical housing stock of dwellings[34–37] which we term 'existing dwellings' in the future, for assumed retrofit with heat pumps (HP) following on from historical installations[38].

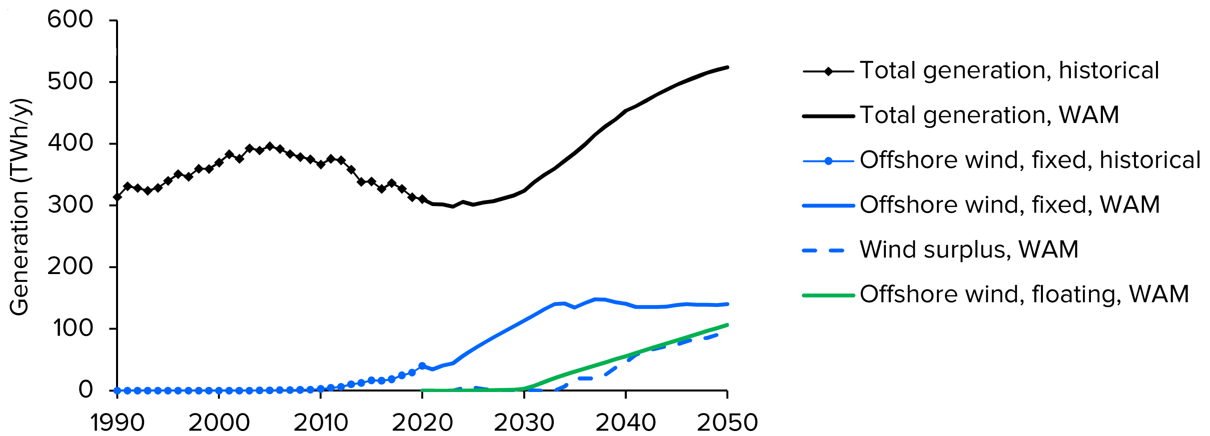


4. Supply – increasing electricity generating capacity

From the additional demands – the electrification of heat and transport – most analysts are predicting a significant expansion in electricity generation by 2050[39]: CCC's Sixth Carbon Budget[40] requires 780 TWh/y; modelling by DNV[41] indicates 700 TWh/y; and National Grid[12] requires 730-790 TWh/y. Indeed, National Grid are projecting a tripling of installed capacity by 2050, plus growth in the addition infrastructure to serve the new generators.

We meet the increasing demand in our scenario by increasing the number of offshore wind installations at the fastest plausible (engineerable) rate (Figures 5 and 6)[42]. However, the picture is not so simple. All engineered objects require maintenance and have a design lifetime, including wind turbines and PV arrays. It is not reasonable to assume that the manufacturing, installation, and maintenance capacity for wind turbines expands unconstrained, therefore some upper limit will be reached for the number of turbines in the fleet, as some capacity will be diverted to replacing turbines at their end of their design life.

Figure 5. Historical[23] and projected (modelled) electricity demand (excluding renewable hydrogen). Contributions to supply are shown from assumed installation of fixed and floating offshore wind. Also shown is surplus supply, otherwise curtailed, that will produce renewable hydrogen.



The real-world build-rate is limited by port capacity and accounts for both new and replacement turbines. The design life is taken to be 25 years, so after this period the build-rate is replacing old units and not adding additional generating capacity, capping the total installed capacity ('running to stand still'). Looking at the installed capacity for offshore wind (Figure 7), fixed offshore wind plateaus at 2050 and floating offshore at 2060.

Figure 6. Historical[43,44] and projected generating capacity, modelled for total capacity and assumed for offshore wind.

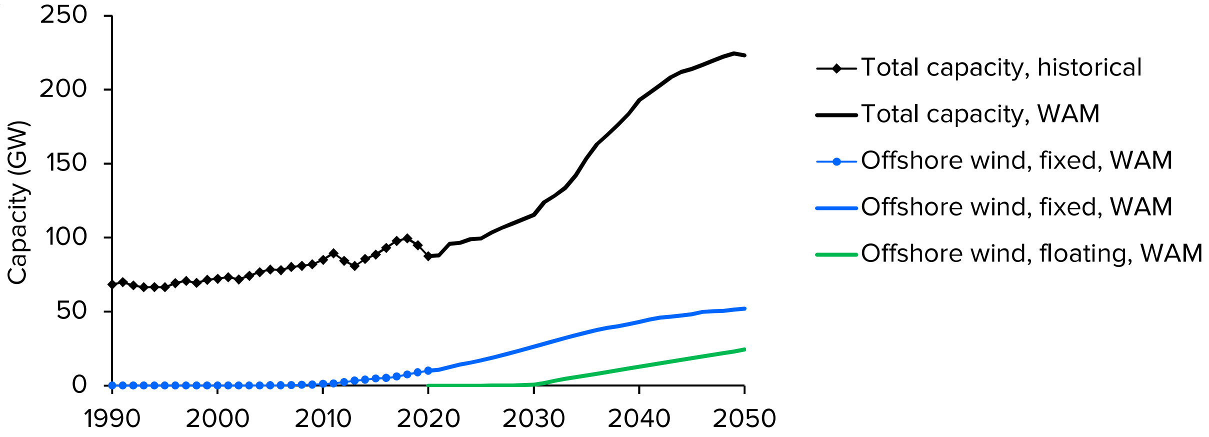
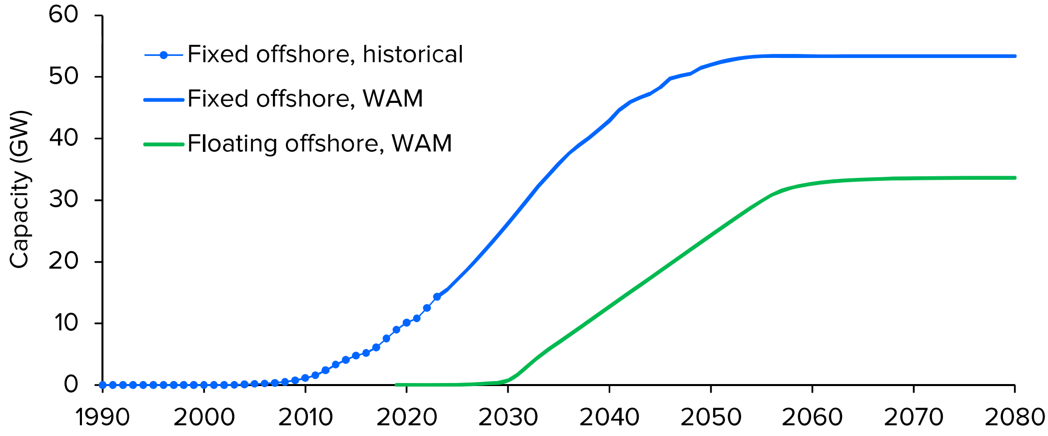


Figure 7. Historical[43] and projected (assumed) installed generating capacity for fixed offshore wind and projected (assumed) only for floating offshore wind. The levelling-off of generating capacity is due constrained installation capacity needing progressively to divert to replacing turbines at the end of their design life.



5. Supply - hydrogen complements electricity

Once electricity generation from renewables exceeds demand (allowing for load factor), rather than curtailing supply, we model all surplus generation diverted to the electrolysis of water to produce renewable hydrogen. Demand for hydrogen is dominated by: heating existing dwellings, ammonia production (using the Haber-Bosch process), HGVs, manufacturing (substituting for gas) and thermal generation (Figure 8). Some hydrogen is routed to storage caverns where it can be drawn upon – over hours or days – for thermal generation to make up for the intermittency of renewables (PV and wind)[45]. Gas for decarbonised hydrogen was expected only to be a transition energy source, but projecting beyond 2050 to 2080 (Figure 9) shows that demand is still high in 2080.

Figure 8. Projected (modelled) total demand for hydrogen and the larger components of its demand.

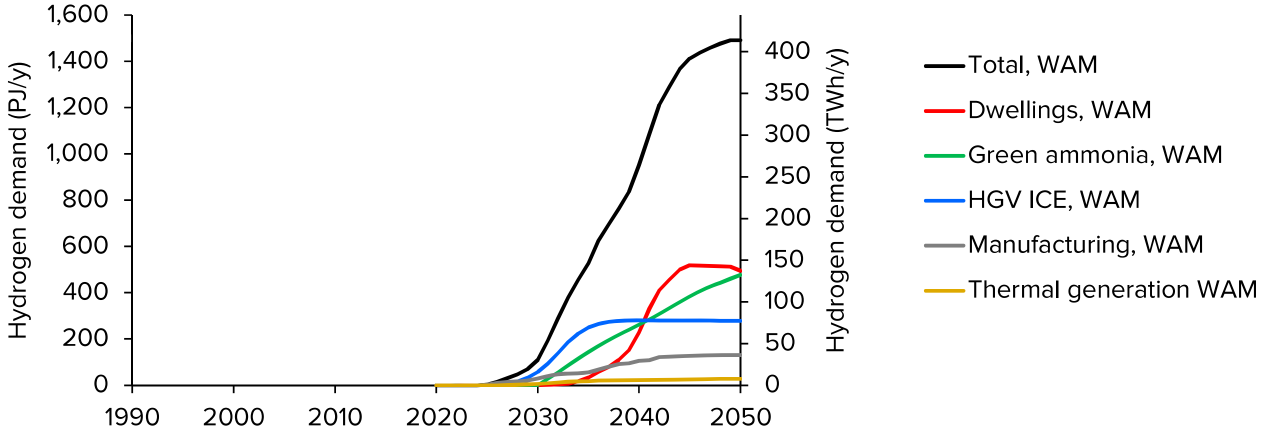
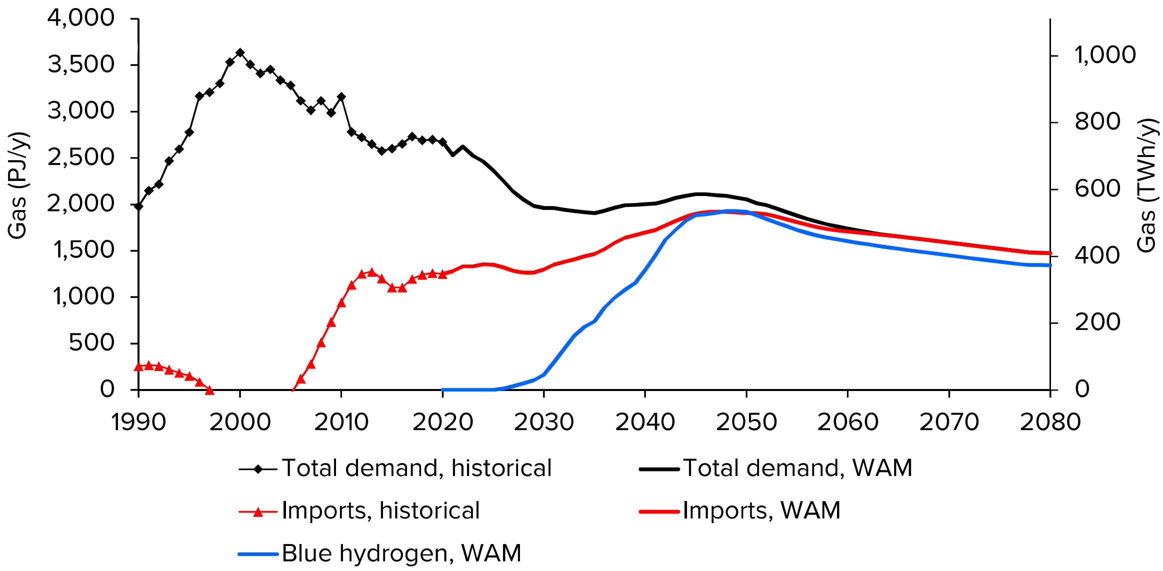


Figure 9. Historical[23] and projected[46] (modelled) total demand for, and imports of, gas. Also shown is gas demand for production (modelled) of decarbonised hydrogen.



6. The whole economy in a diagram

A compact way to represent one year's economic activity and an overview of all of the data we use is by using a Sankey diagram (Figure 10). This single diagram visually captures all the important flows and relationships: employment, energy, economic and transport. In simple terms it shows how most people are employed, generators of electricity, the role hydrogen plays and where it is needed, the components of GDP, the balance of trade, and all forms of transport requiring energy. To produce this diagram and to examine scenarios we use the 7see framework and model[7–11]. For further details of how the Sankey and the 7see framework operate see Appendix A.

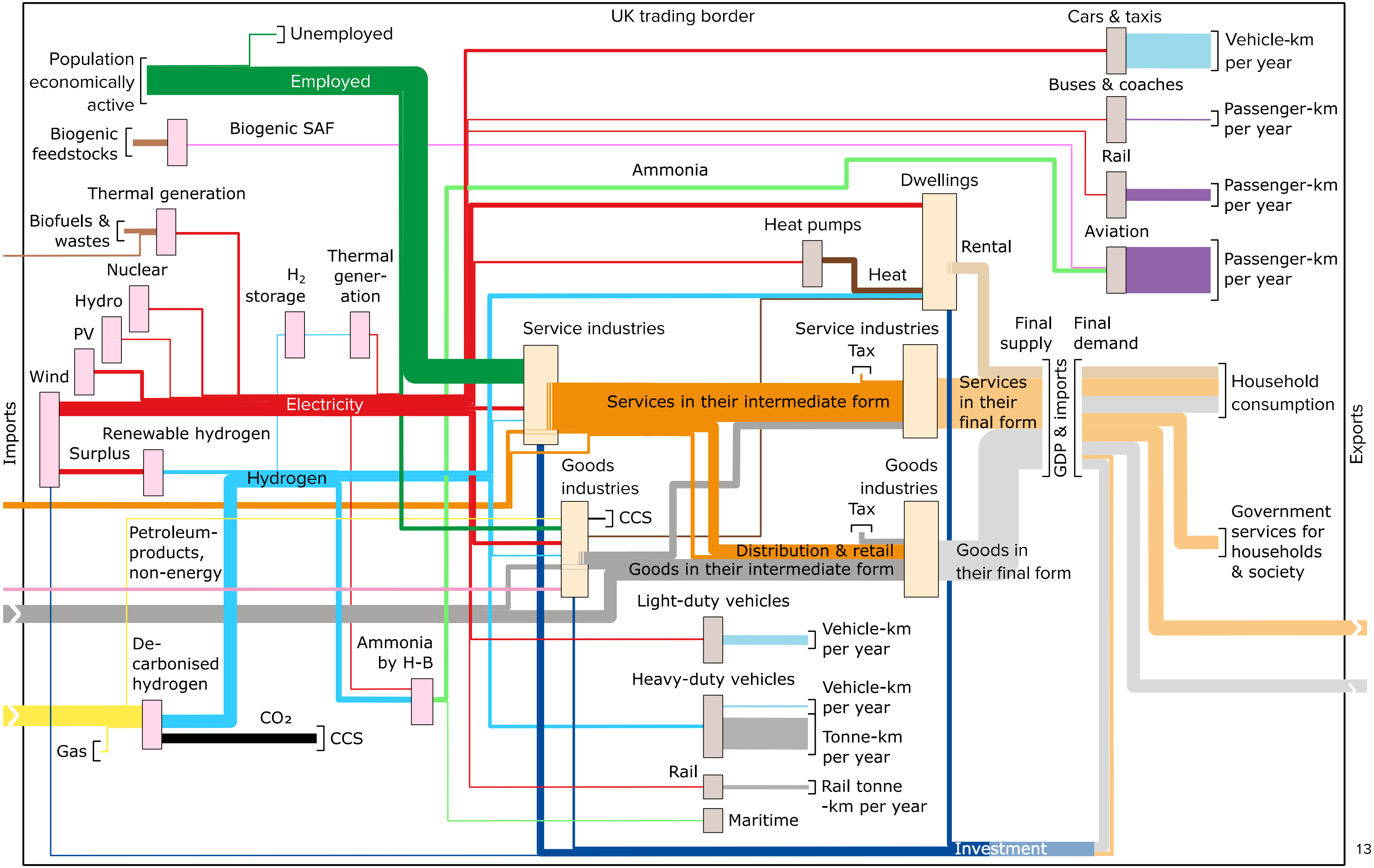
Looking at the UK Sankey diagram, we can pick out the difficult-to-decarbonise passenger aviation which shows a substantial demand (top right). Part of its energy supply is sustainable aviation fuel (SAF) but the bulk of energy supply for aviation is in the form of ammonia, and much more than needed for maritime (bottom). For freight transport (bottom right), HGVs use hydrogen while LCVs are all electric.

For heating dwellings, heat pumps provide most of the input. The thinner red line for electricity to heat pumps than heat out emphasises the efficiency of the technology. However, hydrogen is needed whilst heat pump retrofits progress through the existing housing stock.

The capacity of 'Wind' for electricity generation (left), comprising onshore, offshore fixed and offshore floating, continues to grow in 2050, as shown by the blue investment line. Excess generation, that would otherwise be curtailed, is used for electrolysis to produce 'Renewable hydrogen'. However, the supply of renewable hydrogen will be insufficient to meet the demand for hydrogen, so this must be supplemented by 'Decarbonised hydrogen' with its associated CO_2 emissions requiring carbon capture and sequestration (CCS). This decarbonised hydrogen will be produced using natural gas, some of which will be from domestic extraction in 2050, but most will be imported. A small amount of gas will be required for those parts of manufacturing (under 'Goods industries') that will remain dependent on gas (plus CCS).

Figure 10 (next page). Sankey diagram of the 7see model with flows data for 2050. The WAM (with additional measures) scenario is for the combination of renewable and decarbonised hydrogen meeting all demand for hydrogen, including production of ammonia, as needed for aviation and maritime. The thickness of flow lines is proportionate to the size of flow. The Sankey diagram reads and flows rightwards from raw materials and other inputs on the left, each in their own colours, progressing through to final products and uses on the right. There is one exception to this – investment – which flows right to left.

Flows of energy, people and products in the UK economy in 2050 for the with-additional-measures scenario



7. The cost and impact on jobs of near-zero emissions

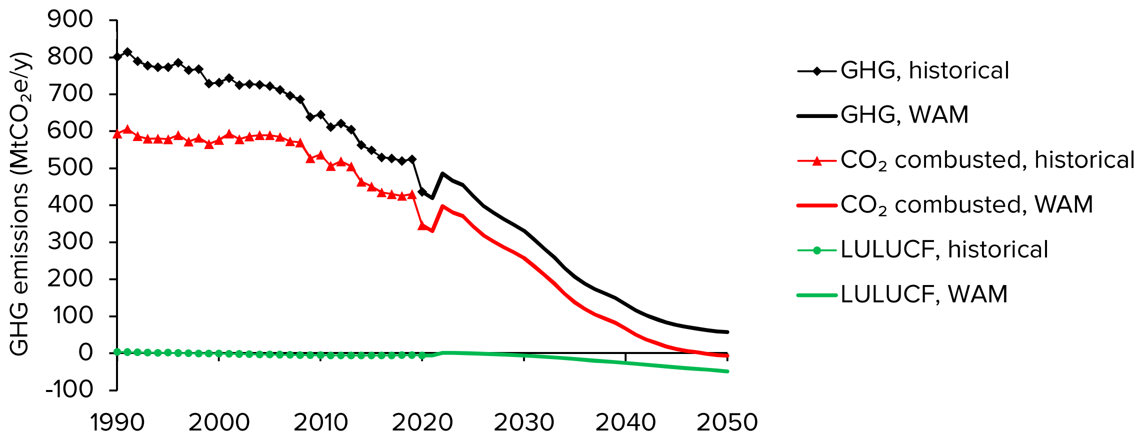
The measures outlined for WAM (with additional measures) suggest that it might be possible by 2050 to reduce to zero the CO_2 emissions from the combustion of fossil fuels and for the remaining GHG to be comparable in size to emission sinks of LULUCF (Figure 11).

The indicative cost to the economy of the additional investment with respect to WEM (with existing measures) for low emission measures is shown in Figure 12(a) in comparison to GDP. As a proportion of GDP (Figure 12(b)), the additional investment rises to 3.0% of GDP by 2034 then settles around 2.5%. Total investment (gross fixed capital formation, GFCF) for the whole economy was 16-17% during the 2010s, rising to 17-19% from 2020 onwards.

As a comparison, the UK defence and health budgets are approximately 2% and 7% of GDP, respectively. However, it should be noted that the energy system is a private concern (excepting state subsidies), not solely state funded. When investment is expressed in this form, as a part of national accounts alongside GDP, it is irrespective of whether provided by the public or private sectors and is unaffected by subsidies, carbon pricing and taxation (including the creation of GB Energy). This first step of analysis simply shows what impact the quantity of investment would have on the economy as a whole.

The second step is the detail of implementation, especially the need to alleviate impacts on low-income households. Whatever the mechanism used to provide the investment, the consumer will eventually foot the bill. Government could regulate industry to invest in the additional measures. Although costs would be transferred to consumers via prices, industry would be motivated to invest efficiently in a competitive market for their products and services. Using taxation or specific means such as carbon pricing, Government could fund additional measures by direct investment or subsidies to others. Finally, consumers might use their own funds directly, such as solar energy on their own home or the premium for electric vehicles over conventional engines.

Figure 11. Historical and projected (modelled) GHG emissions, including international bunkers for aviation and maritime, where CO_2 from combustion reaches zero by 2050 and the emission sinks of LULUCF almost balance the residual GHG sources.



To examine the impact of near-zero emissions on jobs, we start with the ONS projections (to 2050) for the total and working age populations. We apply a proportion for economically active of 77% (as typical since 1990) and model for an unemployment rate of 6% (Figure 13(a)). From the 7see model for the two scenarios, WEM and WAM, we find that for construction there are 240,000 more jobs for WAM by 2050, an increase of 8% of the construction workforce, while for manufacturing there is no change (Figure 13(b)). Jobs in the service industry (Figure 13(c)) rise with the growing work force, but less quickly for WAM with 245,000 less by 2050, though this is only 0.7% down compared to WEM.

GDP is essentially the same between WEM and WAM. The increased investment under WAM is achieved through a shift in final demand from 'Household consumption' (Figure 10). The number of manufacturing jobs remains unchanged because reduced household consumption is compensated by increased investment, though the profile of jobs will change to more construction materials.

Figure 12. The cost of the WAM scenario compared to WEM in terms of UK GDP. (a) Historical[47,48] and projected (modelled) total GDP, and the proportion diverted to investment (gross fixed capital formation, GFCF). (b) Investment as a proportion of GDP.

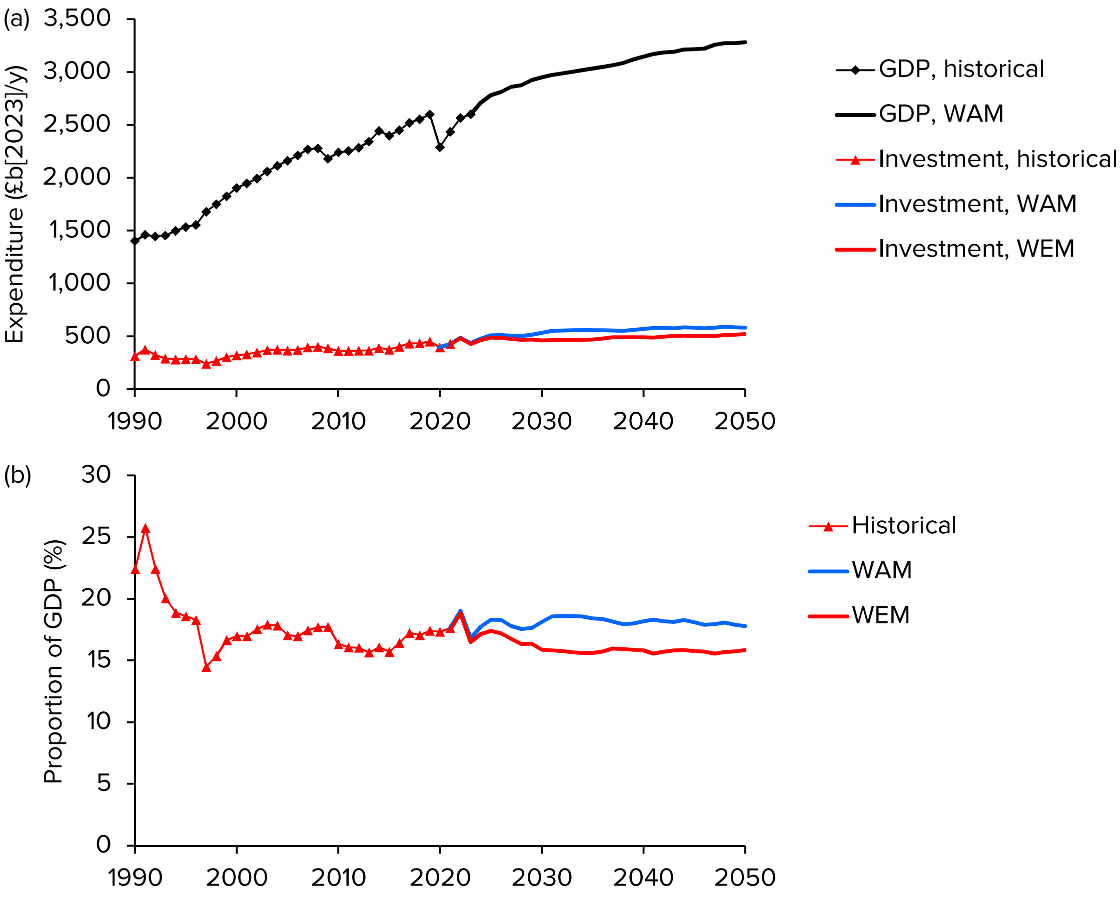
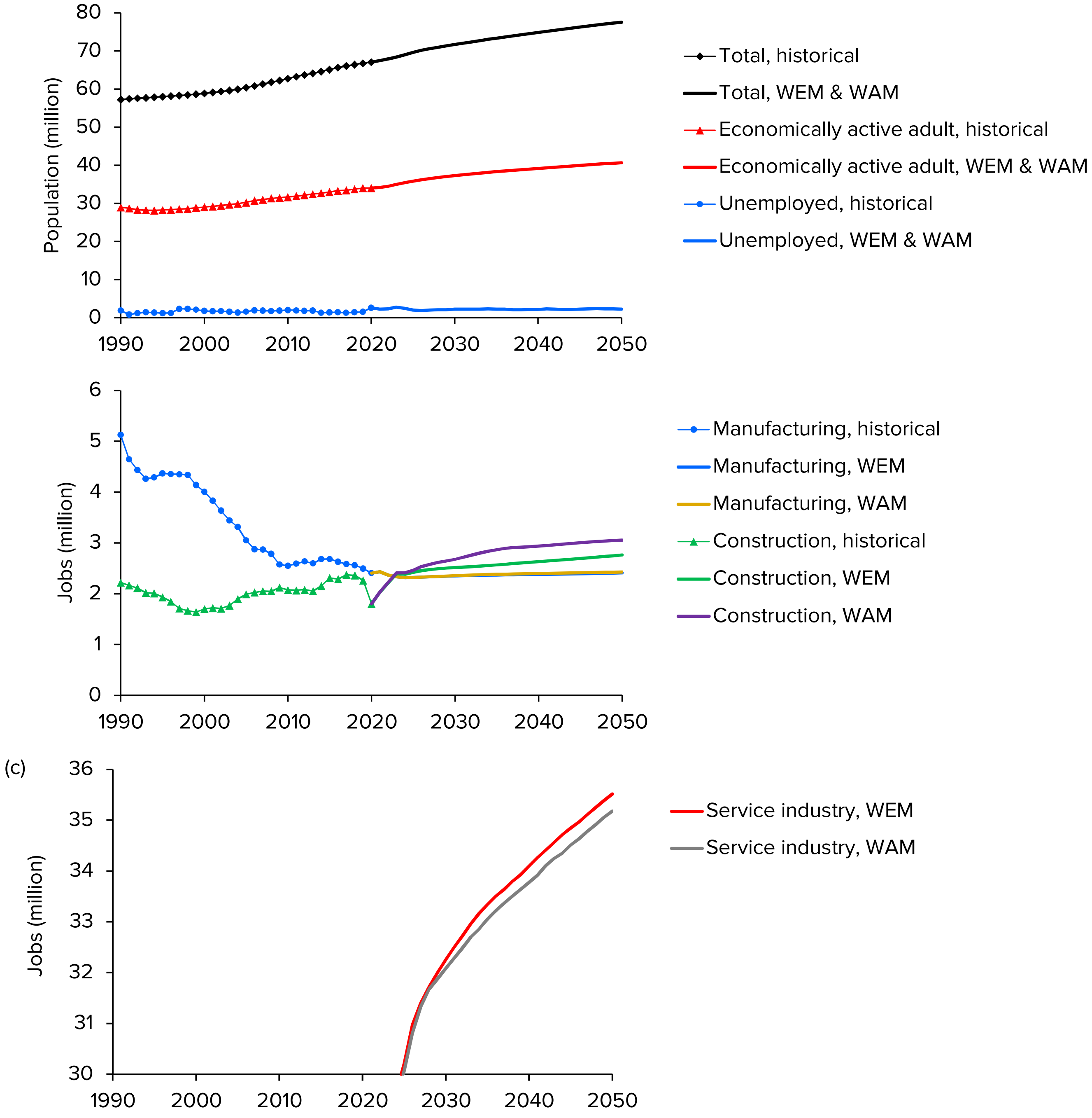


Figure 13. UK population and jobs. (a) Historical[47] and projected[48] (assumed) populations. (b) Historical[49] and modelled jobs in manufacturing and construction. (c) Historical[49] and modelled jobs in the service industries.

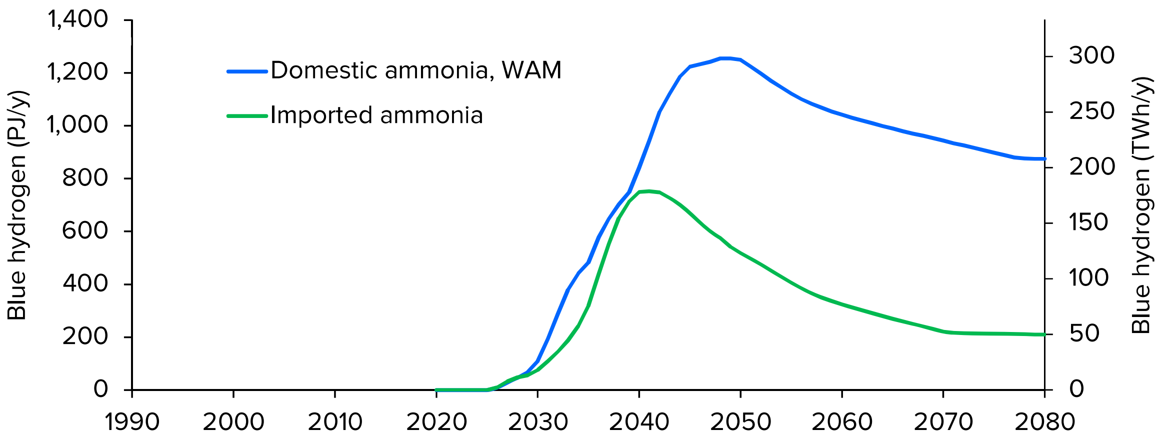


8. Is near zero a sustainable and secure future?

If we define sustainable domestic energy generation in the long-term as without using fossil fuels and their consequent dependence on CCS, we have shown this cannot be achieved by 2050, even with aggressive growth of offshore wind capacity replacing generation using natural gas. Domestic renewable generation is inadequate to meet the demand for hydrogen; the supply of renewable hydrogen must be supplemented by decarbonised hydrogen. Although the pathway to near zero potentially achieves near-term political goals, it is not sustainable.

To address this deficiency, importing ammonia may be possible as it is already transported by ship globally[52,53]. There is a case for countries with a high level of sunshine (for PV) and a plentiful supply of water (even sea water) to specialise in producing renewable ammonia for export[54]. Such countries might be the north of Africa bordering the Mediterranean Sea for whom such exports would be an economic benefit[55]. In modelling the effect of importing renewable ammonia, we find that the need for decarbonised hydrogen is much reduced (Figure 14) though reaching a floor by 2070. Further reductions in domestic decarbonised hydrogen will require increased and faster investment in offshore wind.

Figure 14. Comparison of the modelled demand for decarbonised hydrogen with domestically produced ammonia under WAM (with additional measures) to imported ammonia.



9. Conclusions

With UK Government's existing measures (WEM), we find that GHG emissions attributed to the UK economy by 2050 will reduce by approximately 57% compared with the 1990 level, with only a further third of GHG emissions likely to be reduced from the 2019 level; a long way from net or near zero. By examining additional measures (WAM) we have found a near-zero emissions pathway to 2050 that is physically possible. In this pathway, CO_2 emissions from combustion reduce to zero while residual GHG emissions are almost cancelled by LULUCF sinks. The most significant measure in the switch from net zero to near zero is the transition of aviation fuelling to ammonia derived from hydrogen.

We find that retrofitting heat pumps to existing dwellings will be incomplete, requiring hydrogen for heating as a transition. The increasing demand for renewable hydrogen, together with progressive electrification of home heating and transportation, requires an aggressive growth of offshore wind, of both fixed and floating technologies. For heavy duty road haulage, we have modelled use of hydrogen in ICE powered HGVs.

The additional investment required for these additional measures would likely peak at 3.0% of GDP in 2034 falling to 2.5%. By 2050, jobs in construction would rise and in the service industry decline a little with respect to the existing measures scenario.

While the number of jobs in manufacturing will likely remain the same, their nature will shift to more construction materials and related products.

Electricity generation will be insufficient to meet all the demand for renewable hydrogen, so decarbonised hydrogen will be needed along with its requirement for CCS and dependence on gas imports. Extending our projection to 2080 we find a continuing use of natural gas and CCS, suggesting that the existing measures are not sustainable. Moving all domestically produced decarbonised ammonia to imports of renewable ammonia, still requires natural gas and CCS in 2080. The UK's ability to deploy offshore wind is constrained by onshore technical capability, so increasing the capacity of ports is an option. Further research is needed on what is plausible or possible from economic and engineering standpoints.

The scenarios discussed account for the engineering, economic, and physical limitations of the current UK energy system configuration and the historical state of the economy. The technology pathways suggested are likely to be the only ones which have any possibility of meeting the stated aims. It is for those in the political sphere – the elected representatives – to decide whether the scenarios and pathways are feasible, and not just technically plausible.

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About

Dr. Simon Roberts is Honorary Professor in the Institute of Energy Futures at Brunel University of London. He is a physicist interested in a country's capacity to transition to a net-carbon future and our options for realistic, evidenced-based policies to that end. This has led him to investigating whole country modelling and developing a model calibrated from extensive historical data and with the fewest assumptions for projecting into the future. The model is called 7see®, as started while he worked in the Foresight Group at Arup, his last employer. Types of data underpinning 7see include economic stocks and flows, energy capacity and use, employment, transport, and housing.

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The Institute of Energy Futures at Brunel University of London carries out technical and socio-technical research relevant to the net-zero targets. The areas of expertise are energy efficiency and sustainability for cost-effective zero-emission buildings, urban climate and micro climate impacts on energy efficiency of buildings and districts, sustainable infrastructure construction and maintenance, and technology development for heating and cooling, hydrogen generation, and photovoltaics.

7see® is a whole economy analytical framework which harmonises multiple national accounting procedures. In a modular fashion, the framework curates and maintains disparate accounts (economic stocks and flows, energy use, employment, transport) in parallel, but retains each of their unique measurement unit and accounting requirements. Crucially it is calibrated by historical data, most going back to 1990. Furthermore, each year of the future scenario includes fully reconciled and balanced national accounts. The 7see framework can be used to examine the systemic effects of future innovation and technologies, such as up-stream in the net change in demand for energy, employment and imports given the impact on other parts of the economy.

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Appendix A: How to read the Sankey 7see diagram

While Sankey diagrams are common place in engineering for showing the flow of energy or materials, or in other contexts the flow of variables with the same units, our inclusion of economic volume flows for goods and services and other units in Figure 10 is unique. To introduce this diagram, the version in Figure A.1 shows only parts of the final diagram relevant to an individual's direct experience: their abode, car travel, employment and shopping. Boxes represent the constant physical aspects consisting of numbers of cars, dwellings and heat pumps and the buildings for the service and goods industries. Dwellings depend on electricity and heat from heat pumps, also powered by electricity, hydrogen and district heating from goods industries. The 'output' or benefit of cars can be represented by vehicle-km and in 2050 will all run or depend on an 'input' of electricity. The service industries and in goods industries depend on employment, as met by the economically active population. The whole economy, greyed out, has an output of goods in their final form which go for household consumption and export.

Returning to the full diagram, its significance here is showing the proportion of total economic output going to investment into capital items, such as for new renewable energy generation and energy efficiency measures. The diagram is read left to right except for the dark blue lines that represent investment in fixed capital and are a combination of goods and services. The transition to a single colour, dark blue, is simply for clarity in the diagram.

1 The outline of the diagram represents the geographic trading boundary of the UK. Crossing the boundary on the left are imports of biofuels, services, goods, petroleum products for non-energy use (chemicals, etc.) and gas. Crossing the boundary on the right are exports of services and goods.

2 Boxes represent fixed physical capital such as buildings, plant and machinery, electricity generators, or vehicles (box-size has no significance). Lines represent the flow of inputs, products and uses, and their width is proportionate to the volume of the flow with different line colours for different quantities of flow. The types of units for the flows are number of people, energy, mass of CO2, economic volume (in monetary terms), vehicle-km, passenger-km and freight tonne-km. Each coloured flow has a maximum width at one point, dividing up to the left according to sources and to the right according to destinations.

3 The fixed capital in each box transforms the input into a usable product or service. For example: the 'Thermal generation' fixed capital (power stations) takes in fuel and outputs (generates) electricity, the 'Cars & taxis' fixed capital provides vehicle-km of travel, 'Service industries' produce services, and 'Goods industries' manufactured goods. Goods industries have been combined for this diagram from agriculture, extraction, manufacturing, and construction.

4 The fixed capital of the boxes require investment of goods and services for their maintenance and growth. Investment in fixed capital is one of the components of 'Final demand' and investment lines from final demand flow back into the bottom of the boxes. Although all boxes require investment at some time, the diagram shows just the larger investments.

5 The services and goods industries boxes are in pairs, representing a simplified form of the input/output nature of industrial activity where products pass through many stages and businesses ('b2b' activity). An example of this intermediate form of goods is companies A and B manufacture components (intermediate goods) for company C to assemble into a final (complete) product that a consumer can purchase. The distribution of goods is provided by the 'Service industries'. Goods imports bypassing the 'Goods industries' left box are already in their final form.

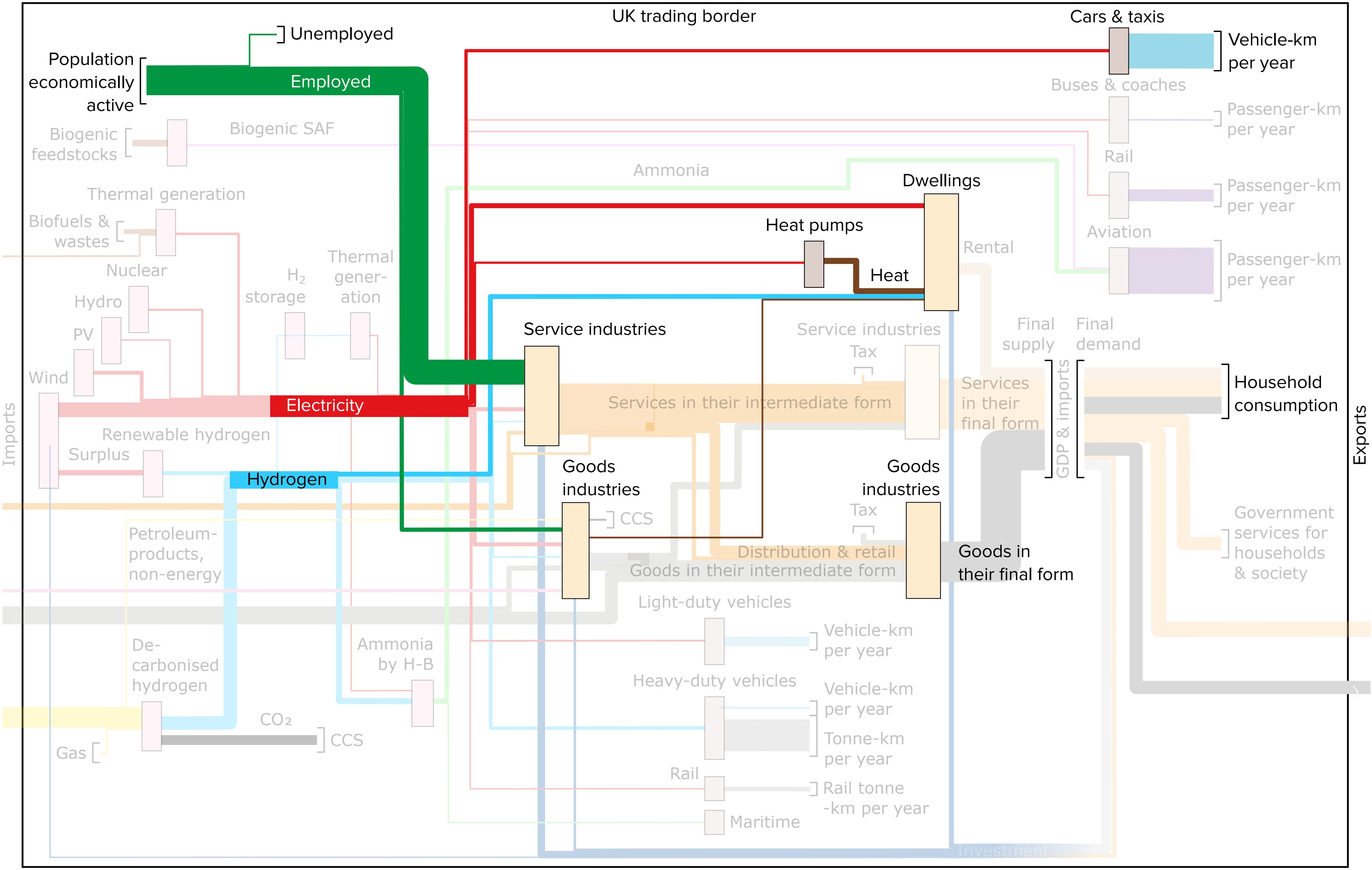
6 The output from the left-hand Goods box is 'Goods in their intermediate form', representing gross value added (GVA) for the goods industries. The sum of GVA from the left-hand boxes of 'Goods industries' and 'Service industries' and rental from dwellings corresponds to GDP (at basic prices).

7 Goods and services in their final form, as would be purchased by households, appear on the right-hand side. They are purchased at market prices because they include tax on products (VAT). Though taxes in the diagram are not technically inputs, they are included to show how the Sankey lines become wider according to the unit of measure for products in their final form, and the line colours are shaded lighter with these additions.

8 Each form of transport has its own box, representing the carrier that converts energy to travel, but the economic cost of providing transport is counted as part of the service industry. Thus the investment line to the 'Service industries' box includes transport.

Figure A.1 (next page). A version of the Sankey diagram (Figure 10) as an introduction to the format. To highlight only those parts relevant to an individual's direct experience, most of the full diagram is greyed out leaving: their abode, car travel, employment, and shopping.

Flows of energy, people and products in the UK economy in 2050 for the with-additional-measures scenario



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