Energy Innovation Needs Assessment

Overview report

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Acronyms and abbreviations

Table 1. **Key acronyms and abbreviations**

Acronym/abbreviation	Definition
AI	Artificial Intelligence
AMR	Advanced Modular Reactor
BEIS	Department for Business, Energy & Industrial Strategy
CAPEX	Capital Expenditure
CCUS	Carbon Capture, Utilisation, and Storage
DSR	Demand-side Response
EINA	Energy Innovation Needs Assessment
ESC	Energy Systems Catapult
ESME	Energy System Modelling Environment
GDP	Gross Domestic Product
GVA	Gross Value Added
IEA	International Energy Agency
Li-ion	Lithium-ion
OPEX	Operating Expenditure
ORE Catapult	Offshore Renewable Energy Catapult
PEM	Polymer Electrolyte Membrane
RCA	Revealed Comparative Advantage
RD&D	Research, Development, and Demonstration
SMR	Small Modular Reactor
TINA	Technology Innovation Needs Assessment
TRL	Technology Readiness Level

Glossary

Table 2. **Key terms used throughout this report**

Term	Definition
Learning by doing	Improvements such as reduced cost and/or improved performance. These are driven by knowledge gained from actual manufacturing, scale of production, and use. Other factors, such as the impact of standards which tend to increase in direct proportion to capacity increases.
Learning by research, development and demonstration	Improvements such as proof of concept or viability, reduced costs, or improved performance driven by research, development, and demonstration (RD&D); increases with spend in RD&D and tends to precede growth in capacity.
Sub-theme	Groups of technology families which perform similar services which allow users to, at least partially, substitute between the technologies. For example, a variety of technology families (heat pumps, district heating, hydrogen heating) have overlapping abilities to provide low-carbon thermal regulation services and can provide flexibility to the power system.
System value and Innovation value	Estimates of change in total system cost (measured in cumulative £GBP to 2050, discounted at 3.5%) as a result of cost reduction and performance improvements in selected technologies. This is the key output of the EINAs and the parameter by which improvements in different technologies are compared. System benefits result from increasing deployment of a technology which helps the energy system deliver energy services more efficiently while meeting greenhouse gas targets. Energy system modelling is a vital tool in order to balance the variety of interactions determining the total system costs. Innovation value is the component of system value that results from research and development (rather than from 'learning by doing').
Technology family	The level at which technologies have sufficiently similar innovation characteristics. For example, heat pumps are a technology family, as air-source, ground-source, and water-source heat pumps all involve similar technological components (compressors and refrigerants). Electric vehicles are also a technology family, given that the battery is a common component across plug-in hybrids and battery electric vehicles.
Gross value added	Gross Value Added (GVA) measures the generated value of an activity in an industry. It is equal to the difference between the value of the outputs and the cost of intermediate inputs.

Executive summary

This project provides evidence to identify the key innovation needs across the UK's energy system, to inform the prioritisation of public sector investment in low-carbon innovation including any future phases of the Department for Business, Energy & Industrial Strategy (BEIS) Energy Innovation[1] Programme. The BEIS Energy Innovation Programme aims to accelerate the commercialisation of innovative clean energy technologies and processes into the 2020s and 2030s. The current Programme, with a budget of £505 million from 2015-2021, consists of six themes and invests in smart systems, industry & CCS (Carbon, Capture and Storage), the built environment, nuclear, renewables, and support for energy entrepreneurs and green financing.

Vivid Economics was contracted to lead a consortium with technical expertise in each of the Energy Innovation Needs Assessment (EINA) priority areas. The programme relied on evidence from a programme of workshops with over 180 participants, energy system modelling, and detailed technical advice. Partners include the Carbon Trust, E4tech, Imperial College London, and Fraser-Nash. The Energy Systems Catapult (ESC) provided analytical evidence using their Energy System Modelling Environment (ESME) to support an early pre-screening of technologies.

Innovations have been prioritised where there is a strong case for UK Government investment. The prioritisation in this report is based on evidence of the potential benefits to the UK, via a lower cost energy system and larger export markets. We also consider whether there is a need for UK Government intervention, in addition to private and international efforts.

A distinctive feature of this project is its focus on innovation that benefits the whole energy system. Internationally, there are other efforts attempting to answer the question of where to target resources to maximise benefits from innovation[2]. In selecting priorities, we identify innovations that can unlock value across electricity, heat, transport sectors and the rest of the economy.

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[1] While 'innovation' encompasses learning that occurs across the technology life cycle, the Energy Innovation Programme is focussed on technological research, development, and demonstration (RD&D) and support for entrepreneurs to develop and trial business models to enable the technologies to find a way to market. The design of policies and markets are the focus of other programmes within Government.

[2] IRENA (2018) Innovation Priorities to Transform the Energy System: an overview for policy makers. https://irena.org/publications/2018/May/Innovation-priorities-to-transform-the-energy-system; https://arpa-e.energy.gov/; Energy Futures Initiative (2019) Advancing the Landscape of Clean Energy Innovation. https://energyfuturesinitiative.org/news/2019/2/6/clean-energy-innovation-report

Innovations were first prioritised within technology groups and then across the entire system. The within-group (or ‘sub-theme’) prioritisation is described in the sub-theme reports. The entire system assessment results are the focus of this overview report. This report focusses on the top innovations from a much longer list of innovations that are detailed in the sub-theme reports. The results of the innovation screening process are shown in Table 3, alongside the sub-theme they sit within (the ‘primary sub-theme’). Other sub-themes to which the innovation is also linked (‘secondary sub-themes’) are noted. The process by which these innovations were prioritised is shown in Figure 2. In Figure 2, Steps 1 and 2 were part of the EINAs, but the final ranking (Step 3) is not. This represents the next and final policy design step that would need to be undertaken to design the Energy Innovation Programme.

Further, we highlight where innovation in the delivery of supporting infrastructure (e.g. transporting and storing carbon dioxide (CO_2)) is needed for the low-carbon transition. The UK Government has a unique coordinating role in delivering infrastructure, which is required to enable innovation across the system. While these opportunities do not emerge from our quantitative modelling as high value, they are necessary to support the transition. In delivering this infrastructure there are opportunities for cost reduction and performance improvements. We report these priorities separately, as they are less likely to be within the scope of the Energy Innovation Programme.

This overview report includes the method and results for the innovation prioritisation. Earlier innovation screening exercises, undertaken in 12 technology areas are reported in an associated set of detailed reports and Excel databases. Further methodology guidance and analytical calculators have been provided as part of a comprehensive evidence base.

Table 3. **Priority innovation areas**

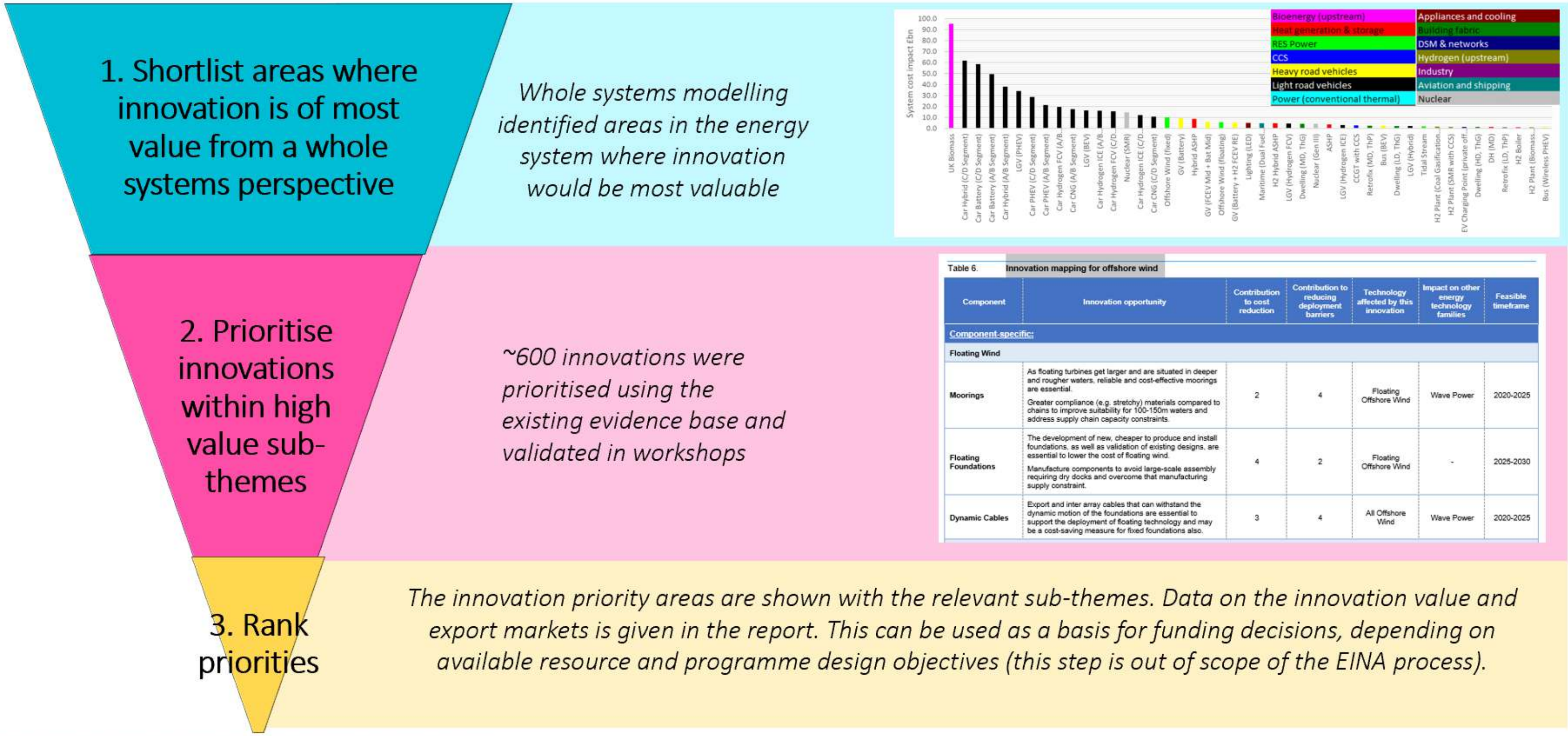
Priority innovation areas	Primary sub-theme	Secondary sub-themes
Digital optimisation, design and artificial intelligence to optimise the electricity system, in the design of nuclear and offshore wind and in industry	Smart systems	Offshore wind, Nuclear
Demonstration of early commercial gasification-based routes for bioenergy to produce liquid or gaseous biofuels, including in combination with CCUS	Bioenergy	CCUS
Piloting the pre-treatment and hydrolysis steps and developing processes that are tailored to feedstocks.	Bioenergy	
Development of miscanthus breeds and its use in energy processes	Bioenergy	
Innovation in storage, including bulk storage, advanced lithium-ion battery production chain and materials, and post-lithium-ion options for the post-2030 market	Smart systems	Buildings, transport
Demonstration of reformers in combination with CCUS and hydrogen	Hydrogen	CCUS
Automation and robotics, with specific applications in nuclear, industry and offshore wind	Smart systems	Nuclear, Offshore wind
Nuclear modularisation (SMRs) and simplification (Gen III and AMR), and use of heat	Nuclear	Heating and cooling
Advanced materials and manufacture of low cost electrolysers for hydrogen production	Hydrogen	
Advanced materials and manufacture of low cost fuel cells for use of hydrogen	Hydrogen	
Innovations for offshore wind such as new blade technologies and turbine components	Offshore wind	
Develop floating or long-reach foundations for offshore wind to access deeper waters	Offshore wind	
A set of innovations for heat pumps including sorption, new compressors and expanders	Heating and cooling	
Post-combustion CCUS, new solvents and absorption processes	CCUS	

Supporting Infrastructure Innovations
1. **CCUS storage:** Re-characterising old wells, monitoring, pressure management, techniques. 2. **Industrial CCUS demonstrations and clusters:** Full-scale end-to-end demonstration of CCUS, including transport and storage and the institutions and business models to deliver it. 3. **Heat networks:** Low-temperature heat networks and advances in heat network optimisation 4. **Gas grids:** Proving the feasibility of repurposing the gas grid to hydrogen 5. **Buildings energy efficiency:** improve monitoring and performance of housing stock energy efficiency measures

Source: *Vivid Economics, Carbon Trust, E4tech*

Notes: *Prioritisation is based on the process is described in Figure 1.*

Figure 1. **Innovation screening process**



Source: Vivid Economics E4tech, Carbon Trust, Energy Systems Catapult

Introduction

Successful innovation is critical to successful decarbonisation. The UK needs to decarbonise in a way that ensures energy reliability and affordability and supports economic growth and employment. While the market will innovate new technologies to some extent, there is a rationale for the UK to intervene to overcome barriers, such the high risk associated with speculative technologies, long payback periods, and lack of a clear market signal for low-carbon goods and services.

The UK already has an ambitious programme of energy innovation. This programme is key to meeting carbon budgets and long-term emissions targets. Alongside its legal commitment to cutting domestic greenhouse gas (GHG) emissions to net zero by 2050[3], the UK Government has embarked upon an ambitious programme of energy innovation, culminating in a commitment made in the 2015 Autumn Statement to double energy innovation spending – a commitment of more than £400 million per year by 2021 across the public sector.

The Industrial Strategy and the Clean Growth Strategy (CGS) both emphasise the need for focussed investment on innovation in low-carbon energy. RD&D in low-carbon technologies is key to the future affordability, security, and sustainability of energy supply and use, and will help UK businesses maximise opportunities from the low-carbon economy. The Energy Innovation Programme will form part of the increase in R&D spend to meet a target of 2.4% of GDP by 2027 and 3.0% in the long term. The programme also facilitates progress toward with the Clean Growth Grand Challenge, as well as other Grand Challenges including AI and the Future of Mobility.

There is a need to prioritise innovation areas, in order that this funding is allocated effectively. The purpose of this project is to prioritise innovation areas across the energy system in terms of contribution to UK value, either through reducing the cost of energy or increasing the potential export market. Lower cost energy technologies can underpin a more competitive industry overall, which can enhance exports.

However, there is a high degree of uncertainty in projecting future innovation needs. It is therefore important to gather insights from multiple lines of evidence and

[3] This report was commissioned prior to advice being received from the CCC on meeting a net zero target, and reflects priorities to meet the previous 80% target in 2050. The newly legislated net zero target is not expected to change the set of innovation priorities, rather it will make them all more valuable on the whole. Further work is required to assess detailed implications

to consider a wide range of potential futures. In constructing innovation priorities, the authors of this report took account of the following sources of evidence:

- **Energy systems modelling:** Given the high degree of uncertainty in technology costs and performance, energy systems modelling is useful to find "stable regions" or "dominant deployment strategies[4]" rather than a precise view of the expected future. To do this, a central scenario was assumed, and a range of sensitivities tested, along with a qualitative assessment of how different scenarios would impact the results (Appendix 3). Experts that used other modelling frameworks were consulted to ensure that insights from multiple models were considered.
- **Structured stakeholder consultation:** Stakeholder workshops were held for each EINA (12 in total), involving over 180 participants from the public and private sectors, academia, and other expert organisations (e.g. industry associations). A wide range of follow-up meetings and workshops were held to confirm assumptions and approaches.
- **Technical advice:** Given the technical understanding required across the whole energy system, it was important to involve technical experts in each EINA area. The project team included a technical expert in each EINA (for example, E4tech on bioenergy and road transport, Fraser Nash on nuclear) which provided a robust and independent check on the results from workshops and modelling.
- **Further evidence collection and analysis:** The research team conducted further research and analysis, including technical literature reviews, analysis of business opportunities and assessments of international innovation efforts.

The scope of the EINA project is the whole energy system, including power, heat, and transport. Technologies are limited to those that provide clean energy supply or reduce demand for energy and cross-cutting technologies that facilitate the delivery of clean energy; a hierarchy of technologies is discussed in Appendix 1. The work does not investigate technologies that would achieve scale beyond 2050. It does, however, consider technologies that could be disruptive[5] on a 2050 timescale.

The process for collecting and analysing this evidence is described below:

1. Energy system modelling and selection of EINAs

Quantified estimates of the energy system benefits of innovation at the sub-theme level were developed using the Energy Systems Modelling Environment (ESME). These results informed the selection of the sub-theme EINAs in the first instance, but

[4] Stable regions / dominant deployment strategies relate to technologies that are deployed irrespective of the uncertainties on costs and performance, because they are fundamentally valuable. A dominant deployment strategy is electrification, which is a low-cost lever for decarbonising the energy system.
[5] In the EINAs we define 'disruptive' as innovations or other shocks which move the UK energy system substantially (more than 10% of primary energy demand) away from our central scenario.

not the final prioritisation. For example, the results led to a report being completed on offshore wind but not wave energy.

The sub-theme list was validated with other UK-based energy modellers and UK energy system experts, and BEIS. Some of the ESME results were supplemented with supporting evidence from other modelling studies (in particular, in CCUS and smart systems).

At the top of each sub-theme report we note the innovation value of that sub-theme[6]. These benefits are quantified using energy system modelling, and the system value is reported in each of the sub-theme reports. A component of this value can be attributed to innovation ('learning by research', as opposed to 'learning by deployment'). In applying these figures to UK Government decisions, it may be necessary to isolate a sub-component can be attributed to UK Government innovation activities (as opposed to market-driven innovation, or international innovation activity). Appendix 2 sets out a potential method for attributing value to the UK Government.

2. Development of evidence

The innovation needs assessments resulted in a set of sub-theme reports, which include a detailed description of the:

a) **Innovation needs assessment** including detailed assessment of innovation opportunities within each EINA, workshops with industry, government, and academic experts for each EINA, and targeted follow-up interviews.

b) **Business opportunities assessment** including analysis of the potential for innovation to increase UK competitiveness, GVA, and jobs. An increase in export opportunities merit greater emphasis because they are more likely to be linked to UK innovation. In contrast, domestic business opportunities relate to services which are not strongly trade exposed (such as building retrofits), and therefore there is less of an opportunity for UK innovation to displace imports and create value. Nonetheless, domestic market size is an important contextual consideration in understanding the importance of innovations within the economy.

c) **Market barriers assessment** including identification of market barriers that need to be addressed in order to unlock innovation potential.

These reports are provided alongside this overview report and should be consulted for further detail on the analysis and innovations.

3. Prioritisation

[6] The innovation value of all systems can also be found in Figure 10 of this report.

This final step collates the key innovations from each of the sub-theme EINAs. These results are presented in the tables and charts of this overview report, alongside the potential to create value for the UK (through lower cost low-carbon energy or export markets). In order to design the Energy Innovation Programme, a further ranking of innovations may be needed, and the evidence on energy system value and export potential can be used to inform these discussions.

The purpose of this overview report is to present the final prioritisations and methodology for the final prioritisation phase. Outputs of this project also include:

- **Sub-theme EINA reports:** The supporting EINA reports include a full description of steps 1 and 2 and their results.
- **An Innovation database**, which includes over 600 innovations and the innovation assessment results, full business opportunities assessment, and energy system modelling results.
- **Business opportunity calculators**, which set out the disaggregated calculations for the additional value and jobs that could result from innovation.
- **Supporting EINA methodology,** a full EINA methodology document setting out the process and steps in detail.

Necessarily, the time and resources available to this project were limited[7], giving rise to further areas for development to continue to improve the evidence base. A full list is included in section 4, including:

- The use of scenarios to show how priorities change in the case of a different structure of the energy system.
- Further detailed modelling of specific innovations, to get a more accurate understanding of their value. Further modelling is particularly important in the industry sub-theme.
- A full assessment of the role of UK innovation in the international landscape.

[7] The full EINAs methodology is designed to be run over a much longer 20-month period, and for which a full methodology is available. During EINAs Phase 1, it was announced that the next Government Spending Review would be brought forward to take place in 2019. Therefore, a ‘compressed’ EINAs process of 7 months was designed, with a greater reliance on evidence from workshops.

Figure 2. **The Energy Innovation Needs Assessments process**

1. EINA Selection

Energy system modelling and selection of EINAs

- Estimate of energy system benefits of innovation per technology, using the Energy Systems Modelling Environment (ESME)
- These results informed the selection of the EINAs
- The EINA list was validated with other UK based energy modellers and UK energy system experts

2. Development of Evidence

a. Innovation needs assessment

- Detailed assessment of innovation opportunities within each EINA
- Workshops with industry, government and academia experts for each EINA
- Targeted follow up interviews

b. Business opportunities assessment

- Analysis of the potential for innovation to increase UK competitiveness, GVA and jobs
- Reports focus on export markets and domestic markets

c. Market barriers assessment

- Identification of market barriers that need to be addressed in order to unlock innovation potential
- Does not develop policy recommendations

3. Prioritisation

Innovation prioritisation

- Assemble the key innovations areas from each of the sub-themes
- Group similar innovations (e.g. AI applications in multiple sub-themes)
- For policy design, a final ranking step may be needed, although this is not completed here.

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Selected EINAs	
1. Nuclear fission	7. Hydrogen and fuel cells
2. Offshore wind	8. Building fabric
3. Tidal stream	9. Industry
4. Heating and cooling	10. Smart systems and flexibility
5. CCUS	11. Transport
6. Biomass and bioenergy	12. Disruptive technologies

Partners: CARBON TRUST, E4tech, Imperial College London, FRAZER-NASH CONSULTANCY

Modelling support by: CATAPULT Energy Systems

Final outputs

1. **Overview report**, summarising the innovation priorities and method
2. **Innovation database**, including over 600 innovations, business opportunity data and energy system results
3. **12 EINA reports** on evidence base and detailed innovations
4. **Business opportunity calculators** for each EINA
5. **Supporting EINA methodology** paper

Source: Vivid Economics

1. Description of innovation priorities

Implementing the method outlined above, the priority innovations are described in this section. Sub-theme EINA reports include technical details on each of these innovations.

Digital optimisation, design and artificial intelligence to optimise the electricity system, in the design of nuclear and offshore wind and in industry

Artificial intelligence and machine learning are general purpose technologies that can be deployed to improve the optimisation, design, operations and decommissioning stages of the energy sector. Priority applications of this technology were identified in the electricity system, offshore wind, nuclear and industry.

Smart electricity systems:

- Optimisation and control strategies for demand-side response (DSR) across the system, including improved interaction between different levels of aggregation in the system (e.g. the System Operator and the Distribution System Operator).
- Develop and test large-scale platforms to manage coordination of decentralised resources and align with distributed aggregation needs
- Use of digital technologies in the transmission and distribution networks to allow local energy grids.

Nuclear fission:

- Improved diagnostics which enhance the understanding of operations and safety.
- Optimised design which can reduce cost and risks.

Offshore wind:

- Control systems to increase availability and performance.
- Improved design that reduces risk in far-from-shore plant.

In industrial applications the use of advanced sensors and algorithms to

- Optimise processes and detect faults early.
- Analyse the impact of other innovations, which can help to understand behaviour and optimise the way new innovations are introduced.

Demonstration of early commercial gasification-based routes for bioenergy to produce liquid or gaseous biofuels, including in combination with CCUS

Gasification is a route to generating useful bioenergy, using a range of technologies such as Bio-SNG, Biohydrogen or the Fischer-Tropsch process. Gasification is particularly useful in the energy system fuel to the flexibility of the technology in terms of the feedstocks it can use and the products it can make.

For gasification-based routes, innovation priorities are building demonstration and early commercial plants, based on today's technology. The innovation need is demonstration at-scale of high octane fuels for heating and transport, due to the complex and high-capital cost characteristics of this technology. Demonstration is required to provide this technology at scale, for delivery across bioenergy and to develop CCUS technologies.

This opportunity differs from the technologies supported in gasification under the Contracts-for-Difference scheme, which do not produce clean syngas that could be used to produce liquid fuels, bioSNG, or hydrogen.

Bioenergy: Piloting the pre-treatment and hydrolysis steps and developing processes that are tailored to particular feedstocks

Bioenergy has substantial potential to increase use across the energy system in a wide range of pathways. Biological processes (hydrolysis and fermentation) are one path to useful bioenergy production alongside gasification and anaerobic digestion. It is particularly valuable as a means to utilise organic waste feedstocks. Given the value of biomass as a result of its scarcity, increasing the productivity of production is very valuable.

Pre-treatment and hydrolysis of lignocellulosic feedstocks are critical enablers for this path. Innovation needs are piloting and developing processes tailored to specific feedstocks, such as municipal solid waste and crop residues (rather than being designed to be feedstock-flexible, since plants will likely be cost-optimal if designed for feedstocks).

Bioenergy: development of miscanthus breeds and its use in energy processes

Miscanthus is uniquely suited to UK conditions, and is a fast-growing energy crop suitable for use across several sectors. Innovation support should target its use in innovative energy processes and breeding programmes. As with the biological routes, is it the ability to increase the availability and productivity of a scarce low-carbon fuel that is so valuable to the energy system.

Innovation areas include seed-based planting for Miscanthus, including aspects such as seed coating, identifying and breeding for desirable traits linked to end uses (e.g anaerobic digestion and fermentation), breeding for resilience and drought, investing in improved weed and pest control techniques to increase yields.

Innovation in storage, including bulk storage, advanced lithium-ion battery production chain and materials, and post-lithium-ion options for the post-2030 market

The decreasing cost of electricity storage technologies is unlocking new potential to integrate renewables and for smart systems. Storage technologies provide value to the system by reducing the capacity of low-carbon generation needed, enabling balancing at lower cost and increasing the utilisation of conventional generation. Key technologies include distributed storage (Li-ion, sodium sulphur, redox, liquid air, flywheels, and super-capacitors).

The greatest innovation potential is expected in lithium-ion (Li-ion) technologies, given they are expected to dominate the storage market in the near and medium term, further innovations would bring the greatest system benefit. There are various innovation opportunities focussed on stationary batteries which are unlikely to be driven by the EV industry, where there may be a role for government. In some developments the UK is well placed to capitalise, despite substantial global innovation. Innovations that lead to improvements in the Li-ion production chain, low-cost materials, and efficient manufacturing techniques with material recovery from old batteries.

There are also opportunities relating to increasing the Technology Readiness Level (TRL) of novel components for the electrode architecture to increase the specific energy, cycle-life, and calendar life cost. For the post-2030 market, innovation in advanced chemistries such as Lithium-sulphur and lithium-air batteries.

Demonstration of reformers for hydrogen production in combination with pre-combustion CCUS

CCUS unlocks hydrogen production from reformers. Reformers are already used successfully in methanol production and new innovations in combination with pre-combustion CCUS can help manufacture hydrogen efficiently. Innovations in reformers add value by bolting on hydrogen production to CCUS and therefore enabling further opportunities for low-carbon energy use across the system.

Priority innovation needs are to integrate CCS and reformers at scale (to ensure thermal and mechanical optimisation) and there are also opportunities to develop more innovative reformer types, both in auto-thermal reformers and using the water-gas shift reaction. Cost reduction is also possible using cheaper and more energy-efficient materials and processes.

Automation and robotics, with specific applications in nuclear, offshore wind and industry

Robotics for greater automation of mechanical processes is a general purpose technology with specific applications in optimising the operation and maintenance of key technologies and in improving the efficiency of industrial processes.

- Nuclear: innovations in robotics and processes can support efficient decommissioning operations and innovations in thermal technologies can speed up waste decomposition
- Offshore wind: innovations that improve the remote operations of offshore wind farms will lead to large cost reductions. These technologies include drones and robotics for control and command strategies.
- Industry: higher efficiencies in energy intensive industries can be achieved via enabling technologies such as digital twinning (the creation of a real-time digital image of the physical objects and processes of manufacturing). This allows for whole-system energy models and simulations. For example, a digital twin could illustrate precisely how electrification of processes would impact costs, emissions, and energy use, as well as provide solutions for how to optimise these.

Nuclear modularisation (SMRs) and simplification (Gen III and AMRs), and use of heat produced

Nuclear fission's role in the energy system is predominantly as a firm source of low-carbon power that can be provided at a large scale. An additional role for nuclear could be as a provider of heat, by capturing the waste heat from the nuclear power generation process and using it in, for example, district heating schemes. This is particularly relevant to SMRs where there is potentially greater locational flexibility than larger-scale reactors. In addition, some AMR technologies could provide high-temperature industrial process heat.

There are substantial savings from a programme of low-cost, well-designed and modular nuclear:

- Modularisation can reduce cost through more effective construction that benefits from efficient resource use, such as shared infrastructure and materials, labour specialisation, and time planning. It permits a more rapid transition from "first of a kind" to "nth of a kind".
- Design simplification innovations allow for the incorporation of considerations such as design replicability and project approval, capital needs, scalability and

construction, modularity, time management, operation and maintenance needs, waste management, and decommissioning.

- SMRs is one of the largest value technologies as it can enable substantial system value if the ‘waste’ heat is utilised. This innovation value relies on the development of district heating infrastructure to distribute the heat to consumers.

Electrolysers: advanced materials and low-cost manufacturing

Electrolysis is a method of hydrogen production using electricity, alongside gasification and reforming. Hydrogen is an energy vector that could be used in many applications across the economy and in providing system flexibility through creating a storable fuel (potentially for longer periods than battery storage).

A set of innovations to reduce the cost of electrolysers include high-volume production methods and better materials. Advancements in electrolyser cell component materials can improve performance and reduce cost. A significant capital cost reduction for all types of electrolysers can be delivered by shifting to high-volume and highly automated production methods. This would be enabled by scaling up production rates. Examples of advanced manufacturing methods include tape casting, expanded metal cutting, hydroforming, and additive manufacturing processes. Considering that advanced manufacturing techniques are widely implemented in other industries this innovation could be reasonably achieved before 2025.

Fuel cells: advanced materials and low-cost manufacturing

Fuel cells have widespread applications across the energy system and in our scenarios are primarily deployed for use in heavy good vehicles. The opportunities for fuel cells are similar to electrolysers, including high-volume production methods, which would enable significant capital cost reduction. There are UK opportunities in Solid Oxide Fuel Cells and polymer electrolyte membrane (PEM), with both stationary and mobile applications.

Innovations for offshore wind such as new blade technologies and turbine components

Offshore wind is expected to form a core part of the energy system in future, as it has high scope for deployment and its cost is falling. The expected scale of deployment will, however, require the energy system to become significantly more flexible if it is to cope with the increased variability.

Experience in composites, electrical systems and drivetrains can be utilised for future turbine designs. Innovations including new blade technology and materials, turbine components, higher voltage electrical subsystems and composites manufactures, as well as innovations in turbine control and yield optimisation can both reduce cost and increase revenue, having a significant impact on cost. This opportunity could maintain and improve the UK's current strength as a global leader in offshore wind, alongside Denmark and Germany.

Develop floating or long-reach foundations for offshore wind to access deeper waters

Floating or long-reach foundation technology is used to deploy offshore wind in sea areas that have high wind speeds but are too deep to be cost effective for fixed foundation installation. The value of innovation in this area is significant and will support the commercialisation and future deployment to enable the UK to tap into new high wind speed resources. There is a significant expected growth in the floating offshore wind market, in the UK, wider Europe, and internationally. Innovations in this sector will include dynamic high voltage cable systems, moorings for challenging seabed conditions as well as for very deep and shallow water, foundations and new installation, maintenance and fabrication innovations.

A set of innovations in heat pumps including sorption, new compressors and expanders

Heat pumps use electricity and/or gas combined with energy from the air, water or ground to create an efficient heat source for homes and businesses. Improving heat pumps designs, in particular to allow for higher output temperatures have the benefit of being able to integrate with existing radiator system and well as in homes with a high heat loss rate. This avoids the need for disruptive and costly refurbishments to the building.

While these technologies exist, they are currently expensive. Innovations that could reduce cost include Gas sorption heat pumps with significant efficiency improvements over gas boilers and avoid switching to using more expensive electricity. The innovation need is around design, for manufacturers to reduce the installed system cost per unit and further enhance reliability. Further innovations include new compressors and expanders currently in R&D phase to increase efficiency (e.g. building on current research, which is already at TRLs 3-7 on new compressor designs). Although the UK is not currently a leader in this area, substantial domestic demand and novel use-cases (in hybrids with gas network; inefficient UK housing stock) create niche export potential.

Post-combustion CCUS, new solvents and absorption processes

CCUS has significant value across the economy as it enables continued use of fossil fuels in a low-carbon way for electricity, industrial decarbonisation, negative emissions technologies and the production of hydrogen to be used flexibly in a wide range of end uses.

Absorbers are currently the main component of the capture unit and there is particularly high value for innovation relating to reducing the cost and increasing the performance of absorbers and new solvents. Specific opportunities involve lower-cost and improved performance capture can be achieved, whilst also having the potential to reduce regeneration costs, corrosion effects, environmental impact, and product degradation.

A further list of innovations important to developing low-**cost infrastructure to underpin a low-carbon energy system** is:

Table 4. **Priority innovations**

Description
CCUS storage Innovation need: Re-characterising old wells, monitoring, pressure management, techniques. Domestic need: Storage infrastructure is needed to unlock CCUS, and existing domestic infrastructure and assets can be repurposed to create these stores at lower cost.
Industrial CCUS demonstrations and clusters Innovation needs: Full-scale end-to-end demonstration of CCUS, including transport and storage and the institutions and business models to deliver it. Domestic need: Industrial CCUS can be delivered at lower cost if done in clusters. The demonstration is very specific to regional industrial clusters, such as the Teesside Collective.
Low-temperature heat networks and advances in heat network optimisation Innovation need: In providing district heating infrastructure there are several innovation opportunities regarding temperature and optimisation. Domestic need: Government has a unique co-ordinating role in network infrastructure, which is unlikely to be provided at the optimal level by the private sector.
Proving the feasibility of repurposing the gas grid to hydrogen Innovation need: Proving safety and operability of repurposing the existing gas network for use with hydrogen could also reduce deployment barriers to hydrogen use in industry and transport. Domestic need: The UK gas grid is an unique infrastructure, and the challenges of repurposing it must be addressed in the UK.
Buildings energy efficiency Innovation need: Improving the monitoring and performance of buildings stock energy efficiency measures. Domestic need: The UK housing stock is inefficient relative to other countries, and therefore requires innovations that are well suited to these conditions.

Source: Vivid Economics

2. Business opportunity benefits

This section sets out high level results of the business opportunities assessment. Long term business opportunity projections are highly uncertain (Box 2). Nonetheless, the results provide a guide to the potential value creation from innovation, and results driven by a common methodology across sub-themes, making them directly comparable. The assessment of the UK's future competitive position is informed by its existing market share of goods and services, the market share of competitors, industry trends, and workshop feedback. The methodology and a worked example are set out in Appendix 5. Individual subtheme reports include further sub-theme specific methodological notes.

The EINA considers opportunities to create value to the UK from both exports and the UK's domestic market. However, only export opportunities are directly used to prioritise innovation needs. An increase in export opportunities merit greater emphasis because they are more likely to be linked to UK innovation. In contrast, domestic business opportunities relate to services which are not strongly trade exposed (such as building retrofits), and therefore there is less of an opportunity for UK innovation to displace imports and create value.

The size of the UK business opportunities across sub-themes are the result the following key drivers:

- *The expected market size:* For example, road transport presents a very large business opportunity, primarily because of the size of the global automotive market. On the other hand, tidal stream is a relatively small energy technology with niche deployment opportunities globally, compared to e.g. wind. Even though the UK could be a competitive exporter of tidal stream equipment and services, the market size limits the business opportunity.
- *Level of trade:* Certain goods and services are more highly traded than others. For example, heat pumps are highly traded internationally. However, the installation of heat pumps is likely provided by local companies. The distribution of value between these different types of goods and services has a large impact on the split between export and domestic opportunities. Particularly for sub-themes with large service components which are typically not traded (e.g. building retrofits), domestic opportunities are relatively large compared to export opportunities.
- *UK competitiveness:* UK competitiveness will determine the share of the traded market UK firms could capture, both internationally and domestically. Predicting UK competitiveness out to 2050 is highly uncertain, however current competitiveness provides some indication. For example, existing UK expertise in the oil and gas industry, and ongoing involvement of UK firms in international CCS projects suggests the UK is well placed to capture a

significant market share in global CCS trade, particularly services.[8] On the other hand, limited current competitiveness in heat pump manufacture, combined with the expected economies of scale in the production of heat pumps by competitors, suggests the UK is likely to capture a modest share of the global (non-EU) market.[9]

Table 5 summarises the quantitative business opportunity results, with a full description provided within individual sub-theme reports. Note, the quantitative assessment should not be considered a forecast, and is primarily intended as a tool to inform the *relative* size of opportunities across sub-themes, rather than the absolute size of the opportunity within a sub-theme. Box 2 provides further detail on the interpretation of the business opportunity results and a qualitative assessment of the uncertainty associated with the estimates is provided in Appendix 6.

The estimates are intended to illustrate a plausible but optimistic scenario. To size the opportunity, a UK market share is assumed which reflects strong UK competitiveness, reflecting strong UK innovation. The size of the export market reflects a global 2-degree climate scenario, and the domestic market reflects high innovation (in the technology considered) and an 80% decarbonisation target (this study was commissioned before the new net zero advice from the CCC).

Table 5. **Drivers of business opportunity per sub-theme**

EINAs sub-theme	Estimated export opportunities (£m GVA)	Estimated domestic opportunities (£m GVA)	Key drivers behind opportunity
Road transport	2050: 11,000 2030: 2,500	2050: 3,300 2030: 390	• The size of the automotive market, particularly EVs both domestically and in Europe • The UK's existing automotive industry suggests the UK is well placed to capture a meaningful market share.
Offshore wind	2050: 2,300 2030: 1,000	2050: 2,600 2030: 1,400	• North Sea deployment both for domestic and export market. • O&M is the primary over half of both the export and domestic opportunity.
CCUS	2050: 4,300 2030: 3,600	2050: 600 2030: 310	• Global CCS deployment provides a potentially large market. • EPCm services, given relevant O&G strength, are ~1/2 of the opportunity.
Smart systems	2050: >2,000 2030: 200	2050: 1,320 2030: 80	• Smart opportunities are diffuse and straddle several markets. • UK strength in digital services, and the value associated with aggregation suggests aggregation services are the key opportunity, up

[8] As described in the CCUS subtheme report, the analysis assumes a 12% market share of the global market engineering, procurement, construction and management (EPCm) services for CCS. Similar to the UK's current market share for these services in the oil and gas sector.
[9] The analysis assumed as 2.9% market share of the global market (non-EU) is plausible given market shares of other EU countries. Current UK market share of the global market (non-EU) is <1%.

			to 50% of the overall smart opportunity assessed.
Biomass and bioenergy	2050: 1,500 2030: 760	2050: 1,400 2030: 930	• EPCm service exports are ~50% of the export opportunity and gasification-based routes are expected to be the largest market. • Domestic opportunities are of a similar scale as exports, driven primarily by O&M (over 40% of domestic opportunity).
Industry	2050: 1,400 2030: 420	2050: 520 2030:270	• The UK has limited competitive advantage in industrial machinery and is unlikely to capture a major market share of equipment and service exports. • Domestically, specialised equipment and installation is likely to be imported.
Heating and cooling	2050: 900 2030: 280	2050: 3,900 2030: 460	• Export opportunities are likely modest, primarily because of strong international competition in heating and cooling equipment manufacturing at scale. • Domestic opportunities are sizeable, driven by installation and O&M. However, a large proportion of this opportunity is likely to displace installation and O&M of traditional gas boilers etc.
Nuclear fission	2050: 700 2030: 1,300	2050: 9,600 2030: 4,700	• A large proportion of the total market is unlikely to be traded with nuclear sectors often closely tied to national governments. Furthermore, the UK industry faces strong competition from e.g. China, where a large-scale domestic roll out has created strong economies of scale. • Domestic opportunities dominate in Nuclear, primarily in O&M, decommissioning and waste management.
Tidal stream	2050: 540 2030: 35	NA	• Despite strong UK expertise, the international market for tidal stream is small, limiting export opportunities.
Building fabric	2050: 390 2030: 720	2050: 2,600 2030: 6,000	• Export opportunities are modest as most services and a large proportion of goods are not highly traded. • UK export market share is expected to be relatively low, given relative weakness in e.g. pre-fab products compared to others. • Domestic opportunities dominate as the limited level of international trade implies UK business is likely to capture the majority of the domestic market.
Hydrogen and fuel cells	2050: 500 2030: 24	2050: 1,500 2030: 200	• Hydrogen generation and fuel cell equipment is expected to be a relatively small market globally, limiting export opportunities. • Domestic opportunities are driven by O&M and construction/installation of generation and distribution infrastructure, which is typically not traded. • Note, as discussed in the hydrogen sub-theme report, hydrogen opportunities are cross-cutting. This estimate only focusses on hydrogen production equipment and fuel cells. All hydrogen related opportunities combined sum to approximately £5 bn GVA by 2050.

Note: GVA estimates are annual, undiscounted estimates in 2019 pounds. Opportunities associated with disruptive technologies were not sized. Please see the sub-theme reports for a more granular analysis at the technology level.

Source: Vivid Economics

Box 2. **Interpretation of the business opportunities estimates**

Sizing opportunities associated with immature technologies is inherently uncertain and care is required when interpreting results. The following provides several notes to the readers on both the interpretation of the results and the uncertainty associated with quantitative estimates.

Notes on interpretation of jobs and GVA supported

- *Quantitative estimates are not forecasts*. The analysis provides a point estimate of the size of GVA and jobs that could be supported by the production of goods, and delivery of services, associated with innovative energy technologies. This is not intended as a forecast of economic growth in these sectors, but as an illustration of the relative size of the business opportunities to inform the prioritisation of innovation support.
- *The estimates are intended to illustrate a plausible but optimistic scenario*. To size the opportunity, a UK market share is assumed which reflects strong UK competitiveness, reflecting strong UK innovation. The size of the export market reflects a global 2-degree climate scenario, and the domestic market reflects high innovation (in the technology considered) and an 80% decarbonisation target (this study was commissioned before the new net zero advice from the CCC).[10]
- *The GVA and jobs estimates cannot be fully attributed to government.* The analysis assumes high levels of innovation but remains agnostic about whether this is private or public. Government support alone is unlikely to unlock the full opportunity.
- *The jobs and GVA supported* estimates *are not necessarily additional.* A full judgement of additionality would require a regional breakdown of GVA and jobs, combined with an understanding of local skills and structural labour characteristics. The business opportunity assessment for the EINAs does not go to this level of detail.

Notes on uncertainty

The presented opportunities are based on the best available current information. Nonetheless, they are highly uncertain[11]. Plausible UK market shares in immature supply chains are difficult to estimate. Even in established industries, market structures can change significantly over 30 years. For example, China could plausibly become a major player in the European vehicle market, reducing UK market share. When considering the results, the level of uncertainty should be kept in mind. Appendix 6 provides qualitative assessment of the relative level of uncertainty across sub-themes.

The largest export opportunities exist in road transport, CCUS, offshore wind. As shown in Figure 4, there are broadly three groups of sub-themes in terms of overall size of the export opportunity. In addition to the drivers summarised in Table 4, there are three notable cross-cutting drivers to the business opportunities:

- *Current UK strength in related goods.* A wide set of qualitative and qualitative drivers were considered in the analysis. However, as shown in Figure 6, current revealed comparative advantage (RCA) in related goods strongly correlates with our assessment of future opportunities.[12] Although RCA only corresponds to goods, Figure 6 provides an indication of the key *growth* opportunities compared to today, where future GVA opportunities are significantly higher than current RCA suggest. These areas are offshore wind, smart systems and CCUS.[13]
- *UK strength in engineering services* suggests there is a large opportunity across sub-themes which require engineering, procurement, construction and management (EPCm) expertise. Given the UK's oil and gas expertise, the UK is likely to have a particular strength in CCUS, however similar opportunities exist in bioenergy projects. Hydrogen could also provide these opportunities, however global uptake of hydrogen technology is expected to be significantly lower than CCUS and bioenergy, limiting the market opportunity.[14]
- *Limited trade in key goods and services associated with some sub-themes¸* such as building retrofits in building fabric, limits export opportunities. On the other hand, this often implies significant domestic opportunities, as discussed below.

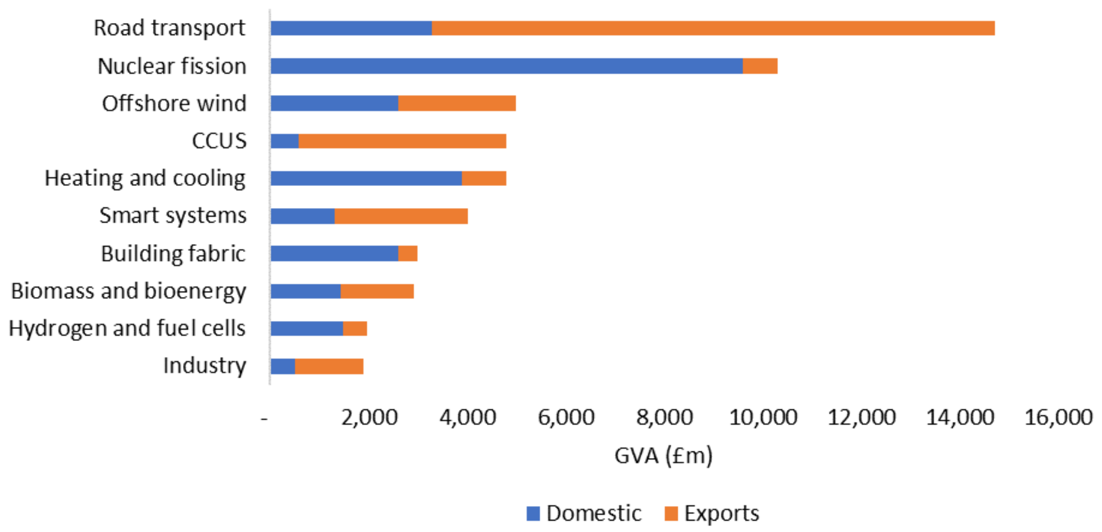
The distribution of domestic and export opportunities varies significantly by sub-theme. Overall, the analysis has identified £27 billion of domestic business opportunities, and £26 billion of export opportunities. However, the distribution of domestic and export opportunities is not even. As shown in Figure 4, domestic opportunities are around 50% or more of the opportunities in the nuclear, heating and cooling, building fabric, offshore wind, bioenergy hydrogen subthemes. The

[10] High innovation refers to a world where priority innovations identified in the EINAs analysis enable widespread deployment of the technology considered. Full details of deployment under this scenario can be seen in Appendix 3.
[11] Point estimates are presented based on the methodology in Appendix 5, as sensitivity analysis would require additional understanding and assumptions surrounding a number of variable factors such as market share and deployment. The calculators used to calculate these figures are published alongside this report, with the ability to change assumptions and conduct sensitivity analysis if desired.
[12] RCA is calculated as the relative share of a good in a countries export basket compared to share of that good in total world trade. If RCA>1, then a country is said to have a revealed comparative advantage. A World Bank definition is available here: https://wits.worldbank.org/wits/wits/witshelp/Content/Utilities/e1.trade_indicators.htm
[13] Note, road transport is not shown on the graph because the market size skews the analysis
[14] Based on IEA and Shell Sky scenarios

large domestic opportunities in these sub-themes are driven by services which are typically not traded, as set out in Table 4.

Taking domestic opportunities into account impacts the potential prioritisation of support across sub-themes. As discussed above, the EINA prioritisation focusses on exports given the importance of innovation in competitiveness. This suggest road transport, CCUS, offshore wind and smart systems are priority sub-themes while hydrogen, nuclear, building fabric, and heating and cooling look relatively low priority. If domestic business opportunities are considered, hydrogen, building fabric and heating and cooling are of a similar order as the other sub-themes. Nuclear business opportunities increase notably, driven primarily by domestic services such as construction, decommissioning and waste management.

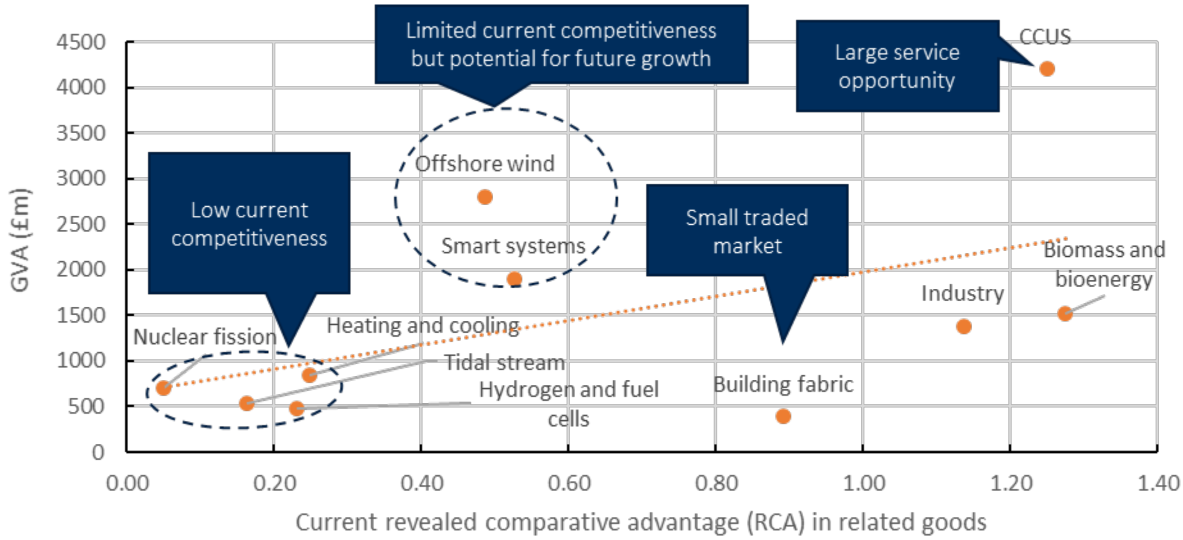
Figure 3. **Overview of business opportunities in 2050**



Note: *GVA estimates are annual, undiscounted estimates in 2019 pounds. Domestic business opportunities were not sized for the tidal sub-theme*

Source: *Vivid Economics*

Figure 4. **Future opportunities and current competitiveness**



Note: *A low current RCA in a sub-theme does preclude pockets of competitiveness. Stakeholder evidence suggests relative competitive strength in tidal stream and hydrogen and fuel cell technology, however trade data likely lacks the granularity to identify this.*

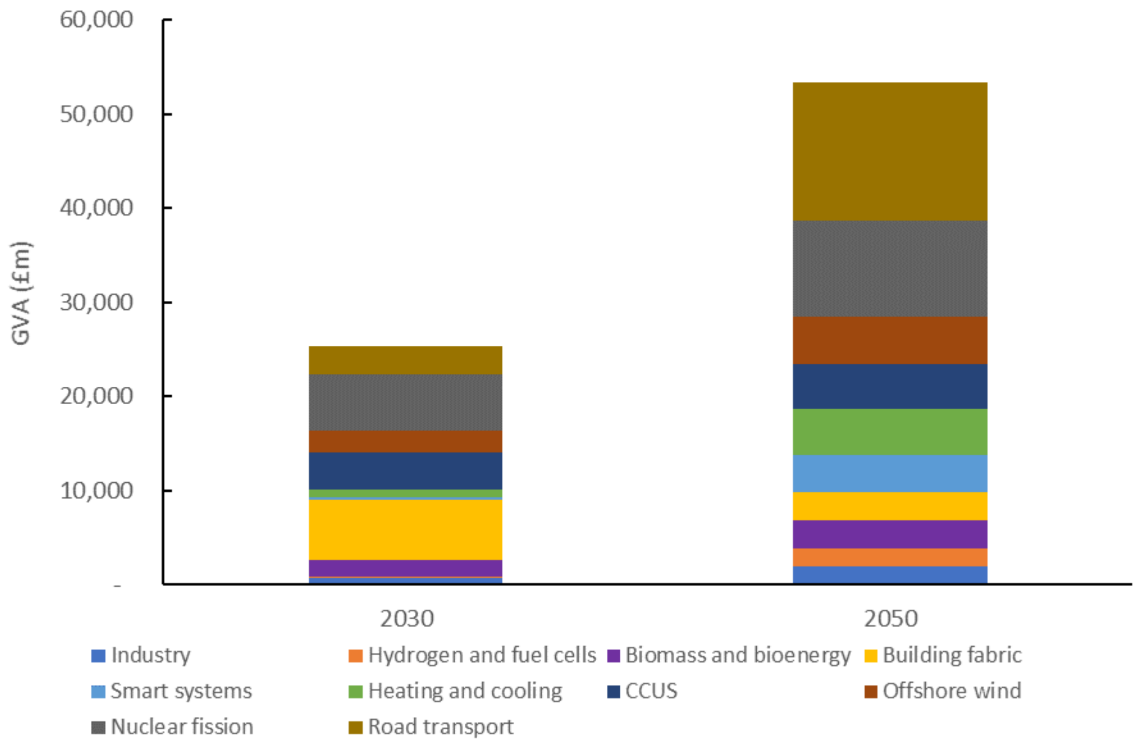
Source: *Vivid Economics*

Overall, business opportunities are expected to increase over time. As shown in Figure 6, 2050 business opportunities are expected to be significantly larger than 2030 business opportunities. This is primarily driven by expected deployment of the technologies considered. For example, a significant proportion of vehicles sales in 2030 will still have internal combustion engines. By 2050 however, most vehicles (in key UK export markets) are likely to be electric or fuel cell vehicles, which are opportunities considered in the EINA.

There are some business opportunities which will likely peak before 2050. The largest example is building fabric. A key opportunity within building fabric are building retrofits within the UK. The rate of retrofits are expected to peak during the 2030s, and largely complete by the 2050.[15] Other examples include the construction and installation of offshore wind turbines and nuclear plants, where activity is expected to peak before 2050. However, in these sub-themes other growth in other opportunities (such as operation and maintenance) means overall GVA associated with the sub-theme is expected to continue to grow.

[15] This is based on ESME modelling results, and would likely require a significant increase in policy action.

Figure 5. **Business opportunities in 2030 and 2050**

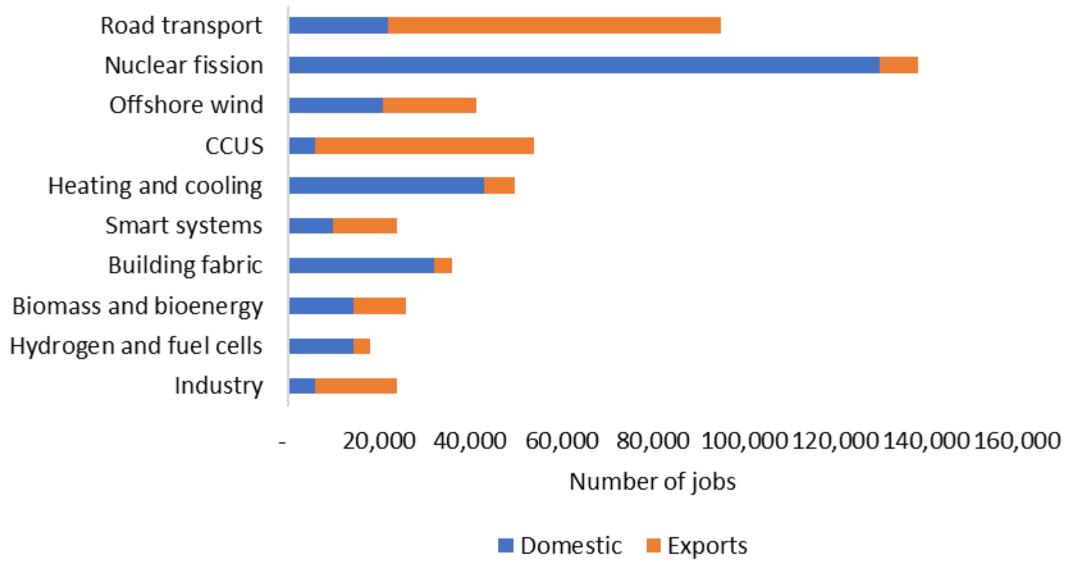


Source: *Vivid Economics*

The business opportunities analysed in the EINA could support approximately 500,000 jobs in the UK by 2050. The domestic market is expected to support more jobs (299,000) than the export market (208,000), despite the GVA from both markets being nearly equal. This is primarily because the O&M jobs, which are a large share of the domestic jobs, are expected to be somewhat less productive.[16] Figure 7 highlights how the numbers of jobs supported does not directly correlate with GVA across sub-themes. In particular nuclear fission, heating and cooling and building fabric support a relatively high number of jobs, primarily driven by O&M. As highlighted in Box 2, not all jobs supported by the identified business opportunities will be additional. In particular, jobs associated with, for example, installation of heat pumps are likely to displace existing jobs associated with gas boiler installation. On the other hand, jobs associated with export opportunities are more plausibly additional. The individual sub-theme reports provide further context on whether jobs associated with sub-themes are likely to displace existing jobs. Appendix 7 provides a brief note on the potential quality of jobs.

[16] Job/GVA ratios for all opportunities analysed are based on ONS Annual Business Survey data for similar industries today. Full details are available in the sub-theme reports and supplementary calculators.

Figure 6. **Overview of jobs supported in 2050**



Note: *Domestic business opportunities were not sized for the tidal sub-theme*

Source: Vivid Economics

3. Opportunities for further work

In order to further improve the evidence base for innovation prioritisation further information gathering and analysis would be required. Key areas for further work include:

- **Industry sector modelling.** ESME modelling for the industry sector only includes fuel switching and not a wider range of opportunities. More detailed modelling of this sector is therefore required to fully include it in the quantitative assessment.
- **Assumption benchmarking.** To build trust in the modelling assumptions, detailed benchmarking of cost and performance input assumptions against the latest evidence is required.
- **Scenario modelling.** To understand how results would change in the case of different energy system structures (e.g. higher hydrogen penetration) it is important to develop model scenarios and sensitivities. Although cost sensitivities were included in this study, further scenarios could include the Clean Growth Scenarios and tighter emissions constraint.
- **Innovation modelling.** Modelling was conducted at the level of technology sub-themes. More detailed modelling, that starts with the priority innovations and attempts to model them more precisely, would improve the accuracy of the results in this study.
- **International role.** A full assessment of the role of UK innovation in the international landscape. This could include an analysis of patent data and innovation spend in each country, combined with interviews, to develop a positioning and set of strategic international partnerships that could be pursued. Appendix 4 sets out a brief summary of international innovation efforts in each of the priority areas.

Appendix 1: Technology tree

Figure 7. **Mapping of EINAs (marked with *) to energy system sectors**

Theme	Sub-theme	Family	Technology (e.g.)
Energy system			
Power	Renewables	Wind	Onshore; offshore*
		Solar PV	Utility scale and distributed solar
		Tidal	Lagoon; stream*
		Biomass	Combustion
		Other	Wave; hydro, geothermal; CSP
	Nuclear Fission*	Full scale	Advanced reactor; Pressurised
		Small modular	SMR
Buildings	Building fabric*	Construction	Advanced retrofit
		Materials	Insulation, double glazing
		Operation	Building controls
	Heating and cooling*	Heat pump	ASHP, ASHP + storage, hybrid
		Hydrogen	Hydrogen boiler
		Biomass	Heat pumps, heat networks, heat storage, and cooling and hydrogen boilers
		Networks	District heating
Transport*	LDVs	Electric	Hybrid; full electric
		Biofuels	1st and 2nd generation
	HGVs	Electric	Light truck; heavy truck; rail
		Hydrogen	Light and heavy trucks
		Biofuels	
Smart systems*		Storage	Utility and distributed scale
		DSM	Home hubs, smart meters
		Vector coupling	Power to liquids,
		Digital	Smart logistics; CAV; blockchain
Industry*		Efficiency + digital	Motors; insulating blast furnace
		Electrification	Electric arc furnaces
		Materials	Light-weighting; glass recycling
		Heating	Biomass; hydrogen
Hydrogen and fuel cells (stationary)*		Production	Electrolysis; SMR; biomass
		Infrastructure	Blending, gas grid conversion
		Fuel Cell	Fuel cell
CCUS*		Power	Oxy; Post-comb.; pre-comb.; BECCS
		Industry	CCS by sector
Bioenergy*		Conversion	AD; SNG; Pyrolysis; gasification, fermentation
		New feedstocks	Algae; woody/grassy crops

Notes: ** These are the groupings that were shortlisted in the EINA process. Offshore wind and Tidal stream are not at the sub-theme level; however, for simplicity the reports are referred to as the "sub-theme reports". Appliance efficiency for buildings is assumed, rather than innovated.* ***Themes:*** *Sectors of the energy system;* ***Sub-theme:*** *Groups of technology families which perform similar services in the energy system, and which allow users to, at least partially, substitute between the technologies.* ***Technology family:*** *The level at which technologies have sufficiently similar innovation characteristics.* ***Technology****: Individual technologies.*

Appendix 2: Attribution value methodology

In utilising the results of this study for Government decisions on spending, it may be important to isolating the component of value that can be attributed to UK Government actions. This appendix sets out a methodology that was developed by BEIS and applied by Vivid Economics to do this. The full analysis provided in the associated innovation database spreadsheet.

An important factor in innovation prioritisation is the relative value of different innovations to the energy system. Innovation can reduce the cost of delivering low-carbon energy. These benefits are quantified using energy system modelling, and then a component of this can be attributed to UK Government innovation activities. The energy system modelling is described in Appendix 3 and in the associated Energy Systems Catapult modelling report. This section therefore focusses on how these values are then attributed to UK Government R&D activity.

The methodology below seeks to identify what portion of the "innovation value" is theoretically attributable to UK Government R&D support. The modelling carried out for the EINAs has provided estimates of the overall value that reductions in technology costs could provide to the energy system between now and 2050. At the core of estimating the attribution of benefits is isolating benefits that result from UK Government actions from those of the market, private actors, or that could occur through international actions. The key steps in the calculation are set out below.

Step 1: Estimate total innovation value
This step involves identifying the total value to the energy system of cost reduction and performance improvements technology areas. An estimate of this value can be gained from energy systems modelling. In the ESME modelling, this involves taking the cumulative benefits between a baseline run and a 'high innovation' run to 2050. Details of the central modelling scenario are included in Appendix 3.

Step 2: Estimate impact of international innovation
In this step we isolate the system value that could accrue from UK actions (in ESME, the difference between the low-innovation case and the high-innovation one). With more resources, an improved methodology would specify the low scenario as an estimate of potential innovation developments that could occur without UK government involvement based on historical learning rates. In this instance, a factor of 30% was assumed to be applied as an illustrative fraction of value that could be attributed to international actions.

Step 3: Isolate deployment-driven innovation
As noted in the EINA reports, innovation and learning occur from both:

- the process of deployment (e.g. standardisation of componentry) and
- research and development (e.g. invention of new technologies, and improvements in efficiency that occur during the demonstration and early deployment phase).

It is challenging to draw a distinct line between these two processes, but an estimate can be gained from empirical estimates in the literature.

In this step we follow the approach previously adopted by BEIS which attributed a higher possible value to UK Government where a technology was less mature. This is because a greater share of the value can be attributed to R&D programmes in this case. A more detailed explanation is included in Box 4 of the EINA reports.

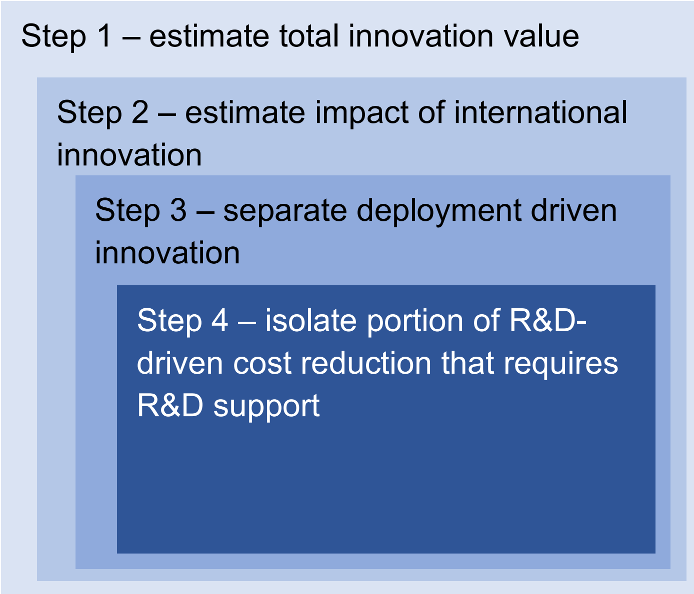
Step 4: Separate R&D-driven value into a component that will result from existing market signals, and that which requires additional policy and R&D efforts

In step 4 the value subdivides into two components: value that is unlocked from existing market signals and value that requires further R&D support. To do this, we use the market barriers assessment that is conducted in workshops and presented in each of the EINA reports. The severity rating in these assessments is an indicator of how far innovation is constrained as a result of imperfect markets. If addressed, the severity is a measure of how much further innovation flourishes with perfect markets.

Specifically, a ‘critical’ barrier constrains innovation completely, a ‘severe’ barrier by 75%, a ‘moderate’ barrier by 50%, and a ‘low’ barrier by 25%.

For example, assume a market barrier, such as policy risk, constrains innovation activity to 25% of its full level given a perfect markets design. If its full innovation value is £10 billion, then only £2.5 billion of the value can be unlocked from existing market signals. If markets barriers are addressed, a further £7.5 billion of value can be unlocked.

Figure 8. **Estimating the share of EINAs innovation value attributable to UK Government R&D programmes**



Source: *Vivid Economics*

Using this methodology, the attributable benefits to UK Government of innovation, in the context of perfect markets and fully funded innovation programmes across all technology areas, is in the table below.

Table 6. **Key results at the sub-theme level: attributable UK innovation value (£billion)**

Sub-theme	Energy system value (step 1)			UK attributed value (Step 2)			UK innovation value (step 3)			UK Government innovation value (step 4)		
	Low	Central	High	Low	Central	High	Low	Central	High	Low	Central	High
Nuclear fission	12.3	15.4	23.7	8.6	10.8	16.6	5.7	7.2	11.0	5.7	7.1	11.0
Offshore wind	5.4	11.8	16.3	3.8	8.2	11.4	2.5	5.5	7.6	2.4	5.3	7.4
Tidal stream	1.0	1.5	1.5	0.7	1.0	1.1	0.5	0.7	0.7	0.5	0.7	0.7
Heating and cooling	5.9	10.6	15.4	4.1	7.4	10.8	1.2	2.2	3.2	1.2	2.1	3.1
CCUS	1.5	3.3	6.0	1.0	2.3	4.2	0.7	1.5	2.8	0.7	1.5	2.8
Biomass and bioenergy	47.5	78.7	78.5	33.3	55.1	55.0	22.2	36.7	36.6	22.2	36.7	36.6
Hydrogen and fuel cells	0.9	2.1	4.3	0.6	1.5	3.0	0.4	1.0	2.0	0.4	1.0	2.0
Building fabric	4.5	8.9	16.3	3.1	6.2	11.4	1.0	2.1	3.8	1.0	2.1	3.8
Industry	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Smart systems	17.0	28.5	40.0	11.9	20.0	28.0	7.9	13.3	18.7	7.9	13.3	18.7
Transport	73.9	155.3	176.2	18.5	38.8	44.0	12.3	25.9	29.4	12.2	25.6	29.0
Disruptive technologies	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Notes: *1 – CCS results - Energy Technologies Institute (2016)*

2 – Industry modelling was not included in final outputs

3 – Smart systems modelling is from Strbac et al. (2016)

4 – No modelling conducted for the disruptive technologies sub-theme EINA

Source: *Vivid Economics*

Appendix 3: Energy system modelling and scenarios

Figure 9. **Central scenario energy system overview**

Sector	Central scenario characteristics in 2050 (80% emission reduction)
Electricity	• Annual electricity demand increases nearly 50% to 440-terawatt hour (TWh) • Offshore wind provides 40% of generation, nuclear 30%, and onshore wind 10% • Solar photovoltaics and gas CCS generate 10% and other renewables (biomass, energy from waste, hydro, and tidal) generate the remaining 10% • 140GW of total capacity • 8GW of storage • 13GW of hydrogen turbine capacity for daily demand peaks • 16GW of unabated gas capacity for back up • One third of peak demand is flexible
Transport	• There are 30m light duty electric vehicles (EVs) on the road and 35m hybrid internal combustion engine (ICEs) • Almost no uptake of fuel cell electric vehicles (FCEVs) • Electricity is 20% of all road transport energy consumption by 2050[17] • Medium-duty vehicles (MDVs) and heavy-duty vehicles (HDVs) diversify fuel consumption across electricity, natural gas, and conventional liquid fuels • Hard-to-treat transport, such as aviation and shipping, remain conventionally powered
Buildings	• Household thermal efficiency improves in new builds and from retrofits, enabling widespread heat pump deployment. Total energy use for heating is 380 TWh • Heat pumps produce 55% of building space heat • Remaining space heating demand is met from near equal parts hydrogen (15%) boilers, gas boilers (15%), and district heating (15%)

[17] Low HDV decarbonisation, widespread hybrid usage, and higher efficiency of EVs compared to ICEs are likely to drive this relatively low electrification of road transport by 2050 in the central scenario.

Sector	Central scenario characteristics in 2050
Industry	• Industry emissions decline 55% from today to 33 Mt of CO_2 annually by 2050 • Industrial energy consumption declines 12% from today to around 300 TWh in 2050 through energy efficiency improvement • CCS is deployed to capture 7 Mt of CO_2 per annum • Natural gas supplies 34% of industrial energy, electricity 30%, hydrogen 15%, liquid hydrocarbon fuels 14%, biomass 4%, and coal 3%
Hydrogen	160 TWh of annual production from mostly coal and biomass gasification There is limited uptake of hydrogen production from electrolysis Hydrogen is prioritised for use in space heating 2,000 GWh of hydrogen storage is required to ensure security of supply during peak space heating demand in winter months

Source: Vivid Economics and the Energy Systems Catapult

A range of cost sensitivities are used around this scenario to explore the impact of uncertainties in cost and performance of technologies. These results are below and described in the attached ESME modelling report by the Energy Systems Catapult.

Figure 10. **ESME modelling results for sensitivities (£bn, cumulative in 2050, discounted at 3.5%)**

Subtheme	Low	High	Very high
Nuclear	14.9	18.8	29.4
Offshore wind	6.6	14.4	20.3
Tidal	1.2	1.8	1.9
Heating and cooling	7.2	12.9	19.1
CCUS	1.8	4.0	7.4
Biomass and bioenergy	57.6	96.5	97.5
Hydrogen and fuel cells	1.1	2.6	5.3
Building fabric	5.4	10.9	20.3
Industry	0.1	0.1	0.4

Subtheme	Low	High	Very high
Transport	89.6	190.4	218.8
Total	185.5	352.4	420.4

Note: *As explained above, smart systems and disruptive EINAs are not included in the ESME modelling results.*
Source: *Vivid Economics*

Key insights that emerge from this modelling:

- Opportunities that occur in the bioenergy and transport EINAs, and possibly also smart systems, are likely to be the most valuable. The innovation value of these EINAs is above £50 billion
- Opportunities in offshore wind, nuclear, building fabric, and heating and cooling are the next most valuable group of innovations. The innovation value of these EINAs is around £10 billion.
- Opportunities in the hydrogen and CCUS EINAs are still significant, in the low £billions of innovation value.
- Tidal and industry (non-CCS) have a low innovation value and therefore these opportunities are not included (except where they form part of a larger group – digitisation and robotics).

As well as cost sensitivities, different 'scenarios' can also modify the outcomes from energy system modelling but were not modelled in this project. Most likely outcomes could be a blend of scenarios. Scenarios, in this project, refer to structural changes to the model, beyond simply cost variation, that can change the uptake of different technologies. There are three 2050 pathways discussed in the UK Governments' CGS, and the central scenario is most like Pathway 1:

- Pathway 1 (Electricity) – represents a future where there is a significant increase in electrification to almost double that of today. In this pathway all cars and vans are battery electric, and there is a 76% share of electricity use in the heating sector by 2050. It is also assumed in this pathway that the increased electrification is delivered without CCUS (which is assumed not to be available). Hydrogen does not appear in this pathway.
- Pathway 2 (Hydrogen) – represents a future where hydrogen plays a huge role in decarbonising cars and buildings, and where the rollout of hydrogen production technologies is accelerated. In this pathway all cars and vans are fuelled by hydrogen, and there is there is a 62% share of hydrogen use in the heating sector by 2050 via a hydrogen grid. Hydrogen production is primarily via steam methane / auto-thermal reforming (SMR or ATR) and CCUS, with over 170 Mt of CO_2 being captured and stored in 2050. However, negative emissions (via bioenergy with CCS) is not available.

- Pathway 3 (Emissions removal) – represents a future where a negative emissions technology (in this case bioenergy with CCS) makes a major contribution to decarbonisation. In this pathway negative emissions of around 20 Mt of CO_2 create a "headroom" for other sectors, such as transport, buildings, and agriculture, to decarbonise more slowly. Around 80% of cars and vans and around 60% of home heating is electric.

The key difference is the lack of CCUS in Pathway 1. Therefore, if Pathway 1 were modelled, it is likely that the priority list would be largely like that we have presented, with the following adjustments:

- No hydrogen innovations, as hydrogen doesn't feature in this pathway.
- No CCUS innovations, as CCUS doesn't feature in this pathway.

If Pathway 2 were to be modelled, it would have a much more profound impact on the prioritisation list:

- Electric technologies would not be as highly prioritised (electric vehicles, heat pumps) and some of these innovations may not appear in the prioritised list.
- CCUS technologies are likely to increase in value, given that this technology is required for the dominant production route for hydrogen.

If Pathway 3 were to be modelled it is likely to have a small impact on the modelling results. The main difference is that less innovation is needed overall (because emissions are offset by biomass in combination with CCUS, or another negative emissions technology). The prioritisation within that system, however, would remain similar.

Appendix 4: Role for the UK in the international innovation landscape

This section sets out a high-level discussion of the international initiatives in each of the key innovation areas stated above. In a prioritisation of innovation spend, it is important to consider whether the UK has a meaningful role to play in the international innovation landscape. In each of the priority areas it does appear that innovation programmes internationally are not fully advanced, and that there is a meaningful role for the UK to play. Further work is required to assess this in detail.

Digital optimisation, design and artificial intelligence to optimise the electricity system and in the design of nuclear and offshore wind

The UK can gain a first-mover advantage in the digitisation of offshore wind. For example, the UK's world-leading foundation design can enable the domestic supply chain to be at the forefront of advanced digital simulation at the engineering stage in offshore wind projects[18].

As in the case of offshore wind, the UK can be an early mover in the digitalisation of nuclear. There have been limited innovations to automate nuclear power processes globally; however, the UK has been active here, particularly in digitising control and instrumentation technology[19]. In conjunction with the possible development of a UK reactor design, there is significant scope to combine this with digitisation of design and construction.

Given widespread international innovation efforts, including in China and the United States, to deliver the digitalisation of industry, the UK is unlikely to be a first mover. However, deep domestic data analytics and artificial- intelligence strength can enable the UK to be part of a global effort to enable industry digitalisation.

There are only a handful of electricity grids worldwide with the regulatory and technical requirements in place to enable and encourage the use of smart technologies on the grid. Examples include ERCOT in Texas, the Nordic electricity market, and the cross-state PJM market. The UK's relatively liberalised framework is at pace with these markets and often cited as a world leading liberalised electricity

[18] UK Government (2017). Made Smarter Review 2017 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/655570/20171027_MadeSmarter_FINAL_DIGITAL.pdf
[19] Energiforsk website https://www.energiforsk.se/program/omvarldsbevakning-karnkraft/nyheter/ny-karnkraftsteknik/digitalization-brings-new-opportunities-for-nuclear-power/

grid[20]. The UK's relatively liberalised system, ecosystem of start-ups, and publicly supported pilots, combined with the UK's established strength in machine learning, AI, and broader IT suggests the UK can be one of the leading countries in smart systems.

Demonstration of early commercial gasification-based routes for bioenergy to produce liquid or gaseous biofuels, including in combination with CCUS

Innovation is underway throughout gasification-based routes in the US, China, and Europe. The UK is among a small group of countries piloting projects in gasification-based routes to biofuels, such as bioSNG production[21]. However, strength in gasifiers themselves is limited, with the UK lagging behind other countries in this area, notably the US.

Nevertheless, by leveraging strong industry and research expertise in the later stages of gasification-based routes, including catalysis, the UK can gain a first-mover advantage in a section of the gasification-based routes value chain[22].

Piloting the pre-treatment and hydrolysis steps and developing processes that are tailored to feedstocks

Despite limited UK industry activity in hydrolysis and fermentation, there is research strength at universities. For example, the UK is a major research hub for syngas fermentation. Innovation could enable the UK supply chain to become competitive in hydrolysis and fermentation routes and unlock export opportunities

Development of miscanthus breeds and its use in energy processes

Many innovation efforts at universities in the US, Germany, and the UK are ongoing for the development of Miscanthus. Using selective breeding of new variants, for further innovation to increase crop yields substantially[23],[24].

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[20] ENA (2018). Electricity Network Innovation Strategy. http://www.energynetworks.org/assets/files/electricity/futures/network_innovation/electricity_network_innovation_strategy/Energy%20Networks%20Association%20-%20Electricity%20Network%20Innovation%20Strategy-March%202018.pdf

[21] E4tech (2018). Innovations Needs Assessment for Biomass Heat https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/699669/BE2_Innovation_Needs_Final_report_Jan18.pdf

[22] E4tech (2010). The potential for bioSNG production in the UK http://www.e4tech.com/wp-content/uploads/2016/01/BioSNG-final-report-E4tech-14-06-10.pdf

[23] SEIL website http://www.recrops.com/miscanthus

[24] E4tech (2018). Innovation needs assessment for low-carbon heat https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/699669/BE2_Innovation_Needs_Final_report_Jan18.pdf

Biomass and bioenergy workshop evidence indicates that the UK has world-leading Miscanthus research across several institutions, and along with other countries, has led Miscanthus research in recent years[25]. Additionally, the Research Council has awarded funding for Miscanthus research. This support, coupled with entrenched and leading expertise, can enable the UK to gain a first-mover advantage in Miscanthus research.

Innovation in storage, including bulk storage, advanced lithium-ion battery production chain and materials, and post-lithium-ion options for the post-2030 market

There is widespread innovation in Li-ion batteries globally, with China, South Korea, Japan, and the United States highly active in this area. Commercialisation of Li-ion batteries has been achieved, but scale-up and component innovation will continue to drive substantial cost reductions[26].

The UK is likely to lag behind other countries in Li-ion manufacturing and export, using current established chemistries, because of the scale many countries, such as China, can achieve. However, early stage lithium-ion solid-state battery projects, coupled with strong government support and existing strength in advanced chemistries, could enable the UK to gain a first-mover advantage in lithium-ion battery engineering for the post-2030 market[27],[28].

Demonstration of hydrogen production through reforming[29] in combination with CCS

The UK is a global leader in CCS technology, partly driven by the significant North Sea CO_2 storage potential, existing oil and gas (O&G) expertise, several existing CCS projects, and a growing supply chain of key technologies[30].

The development of novel reformers is in the early stages, with only four international demonstration projects. The development of reformers equipped with

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[25] Ibid.
[26] BloombergNEF (2019). A behind the scenes take on lithium-ion battery prices https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/
[27] Internetofbusiness (2018). Ricardo and partners get major UK EV battery tech project underway https://internetofbusiness.com/ricardo-partners-uk-ev-battery-tech-project/
[28] Innovate UK (2017). The Faraday Challenge https://innovateuk.blog.gov.uk/2017/07/24/the-faraday-challenge-part-of-the-industrial-strategy-challenge-fund/
[29] Reformers are vessels which allow for a catalytic reaction between e.g. steam and methane to produce (amongst other things) hydrogen and CO_2. For a technical explanation of a reformer, please see: https://www.sciencedirect.com/topics/engineering/methane-steam-reforming
[30] Delivering Clean Growth: CCUS Cost Challenge Taskforce Report (2018). https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/727040/CCUS_Cost_Challenge_Taskforce_Report.pdf

CCS is in the early stages, with only four international demonstration projects in the US, Canada, Japan, and France[31].

Automation and robotics, with specific applications in nuclear, industry and offshore wind

Denmark and Germany are each funding and trialling autonomous robotics for the operation and maintenance (O&M) of offshore wind[32],[33],[34]. However, the UK is also active in this area with, for example, £26.6m of funding committed to robotics technology for offshore wind applications[35]. The UK's large offshore wind fleet, combined with its existing robotics expertise, suggests the UK is one of the potential leaders in this area.

Major innovation efforts in China, the US, France, Japan, and the UK are underway to utilise robots in nuclear power, especially at the decommissioning stage[36][37][38]. Given strong international efforts, the UK is unlikely to be a first mover. However early stage research strength can enable the UK to play an important innovative role in a global effort. For example, the UK's National Centre for Nuclear Robotics, which has received £42m in funding, seeks to unite experts in artificial intelligence, robotics, sensors, radiation, and resilient embedded systems[39].

There are widespread international efforts to increase the integration of robotics in industry globally, including in Japan, China, and the US. The Made in China 2025 plan highlights industrial robotics as one of the priority innovation areas for China[40]. Similarly, the UK's Industrial Strategy seeks to drive uptake of robotics and AI[41]. This

[31] IEA (2017). IEAGHG Technical Review, Reference data and supporting literature reviews for SMR-Based Hydrogen production with CCS. https://ieaghg.org/exco_docs/2017-TR3.pdf
[32] Offshorewind.biz website https://www.offshorewind.biz/2018/12/21/denmark-backs-blade-repair-robot-with-eur-2-million/
33 PRnewswire (2018). Ørsted partners with SkySpecs to conduct automated robotic inspection on world's largest offshore wind turbine blades https://www.prnewswire.com/news-releases/orsted-partners-with-skyspecs-to-conduct-automated-robotic-inspection-on-worlds-largest-offshore-wind-turbine-blades-300682548.html
[34] Anybotics (2018). World's first autonomous offshore robot https://www.anybotics.com/2018/10/25/worlds-first-autonomous-offshore-robot/
[35] Offshore wind journal (2019). Funding for robots and AI could help reduce offshore wind costs https://www.owjonline.com/news/view,funding-for-robots-and-ai-could-help-reduce-offshore-wind-costs_56309.htm
[36] CBS (2018). Robots come to the rescue after Fukishima Daiichi nuclear disaster https://www.cbsnews.com/news/robots-come-to-the-rescue-after-fukushima-daiichi-nuclear-disaster-60-minutes/
[37] Foro nuclear website https://www.foronuclear.org/en/ask-the-expert/122300-the-latest-generation-of-robots-for-nuclear-dismantling
[38] *The Global Times* (2018). China's specialised robots are ready to counter potential nuclear leaks, military threats http://www.globaltimes.cn/content/1116555.shtml
[39] NCNR website https://www.ncnr.org.uk/
[40] China Briefing (2018). The Robotics Industry in China https://www.china-briefing.com/news/chinas-robot-industry/
[41] HM Government (2017). Industrial Strategy https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/664563/industrial-strategy-white-paper-web-ready-version.pdf

early stage activity and support can enable the UK to be part of a global effort for industrial robotics use.

Nuclear modularisation (SMRs) and simplification (Gen III and AMR), and use of heat

Major innovation efforts in SMRs are underway in China, US, Canada and the UK. These programmes are relatively early stage, and no deployment has been achieved yet. The UK is therefore a meaningful player in the international ecosystem.

If the UK were to pursue AMRs, it would seize a potential first-mover advantage, as these are currently not being developed elsewhere. The potential for AMR technologies to be rolled out by 2050 is, however, limited.

Advanced materials and manufacture of low cost electrolysers for hydrogen production

There are ongoing innovation efforts globally, including Germany, the US, and the UK, to reduce the capital cost of electrolysers. Although electrolysers have been commercialised, capital cost reductions are imperative to enable widespread deployment of electrolysers in a hydrogen economy.

UK companies are currently involved, along with international partners, in producing the world's largest electrolysis plant in Germany[42]. Early stage expertise in electrochemistry, coupled with deep UK strength in material science, can enable the UK to be in the leading group of countries for innovation in electrolysers and their components.

Advanced materials and manufacture of low cost fuel cells for use of hydrogen

There are major innovation efforts to deliver low-cost fuel cells globally, including in China, South Korea, Japan, the US, and the UK. Although global innovation efforts are widespread, the UK can leverage early stage strength in solid oxide fuel cells and PEM fuel cells and actively contribute to a global innovation effort. There is evidence of this already, with UK suppliers signing strategic agreements to license solid oxide fuel cell technology and collaborate with international partners in its development[43].

[42] Gasworld (2018). World's largest hydrogen electrolysis plant https://www.gasworld.com/worlds-largest-hydrogen-electrolysis-plant/2014068.article
[43] Ceres Power website http://www.cerespower.com/news/latest-news/strategic-partnership-with-bosch/

Innovations for offshore wind such as new blade technologies and turbine components

Innovation has driven strong deployment of fixed-bottom offshore wind in recent years, with 11 European countries contributing 84% of overall deployment[44]. As of 2017, the UK is the world's largest offshore wind market, with over a third of global deployment[45].

The Offshore Renewable Energy (ORE) Catapult, the UK supply chain, and international partners are collaborating to deliver new and larger wind turbine blades[46]. The UK can leverage this innovation to open new export markets and gain a first-mover advantage, along with Denmark and Germany.

Develop floating or long-reach foundations for offshore wind to access deeper waters

Innovation efforts are underway in multiple territories to either increase the water depth that piled foundations can be used at or bring floating offshore wind to market. Trial projects have taken place in Portugal, Japan, and the UK[47]. Floating wind turbines lag substantially behind fixed-bottom turbines and there has been no wide-scale deployment globally. Therefore, the UK maintains a strong international position.

Given the UK deployed the world's first floating wind farm, there is a good opportunity to gain a first-mover advantage and lead global innovation in floating wind turbines[48].

A set of innovations for heat pumps including sorption, new compressors and expanders

Major heat pump innovations are underway in China, the US, and the EU. Although heat pumps have reached mass-scale adoption in several countries, there are efforts to bring new heat pump systems to market. With some exceptions in heat pump technologies, the UK does not have strength in this area and is likely to lag behind other countries.

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[44] GWEC (2018). Offshore Wind https://gwec.net/wp-content/uploads/2018/04/offshore.pdf
[45] Ibid.
[46] Offshore Renewable Energy (ORE) Catapult (2017). https://ore.catapult.org.uk/blog/blade-stunners-testing-next-generation-wind-turbine-blades/
[47] ORE Catapult (2017). Foundation Innovation Supporting Next Generation Offshore Wind Farms https://ore.catapult.org.uk/app/uploads/2017/12/Circuit-Magazine-Autumn-Winter-2017.pdf
[48] BBC (2017). World's first floating wind farm starts generation electricity https://www.bbc.co.uk/news/uk-scotland-41652707

However, innovative heat pump solutions found in leading global markets, e.g. China and the US, may not be applicable in Europe because of regional variations in heating demands. Therefore, given there is some early stage UK heat pump innovation, the UK can be part of a regional effort to innovate in new heat pump systems applicable to the European market.

Post-combustion CCUS, new solvents and absorption processes

Clear international leaders in CCUS are the UK, US, Canada, China, Japan, and Norway[49]. As a country with a large oil and gas sector and expertise, and significant storage capacity, the UK is one of the few countries with a natural route into developing and innovating in CCUS.

[49] CCS Policy Indicators (2018). Global CCS Institute. http://decarboni.se/sites/default/files/publications/202109/ccs-policy-indicatorglobal-ccs-institute-2018digital.pdf

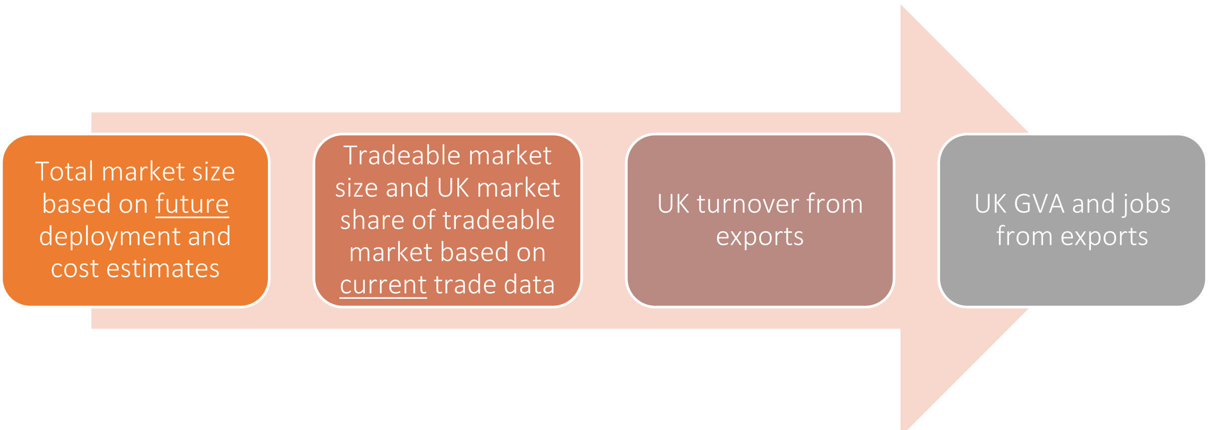
Appendix 5: Business opportunities methodology

Methodology for export business opportunity analysis

In identifying export opportunities for the UK, the EINA process uses a common methodology to ensure comparability of results:

- The **global and regional markets** to 2050 are sized based on deployment forecasts, which come from the IEA when available. For example, deployment of nuclear power is multiplied by costs to obtain annual turnover for the nuclear market.
- The **tradability** of the market is estimated based on current trade data, where available, and informed by expert judgement. This determines how much of the global market is likely to be accessible to exports and gives a figure for the tradeable market.
- The UK's **market share** under a high-innovation scenario is estimated based on current trade data, research, and expert consultation. The determination of these shares is discussed in more detail below.
- The tradeable market is multiplied by the market shares to give an estimate for **UK-captured turnover**.
- The captured turnover figure is multiplied by a GVA / turnover multiplier which most closely resembles the market to obtain **GVA**. The GVA figure is divided by productivity figures for that sector to obtain **jobs created**.

Figure 1 **Methodology for assessing export opportunities**



Source: Vivid Economics

For all EINA sub-themes, the assessment of the UK's future competitive position is informed by the UK's existing market share of goods and services, the market share of competitors, industry trends, and workshop feedback.

Export business opportunities for goods

- Current market shares of UK goods are evaluated based on existing trade data, where available. If the technology is immature or export levels are low, UK shares are based on trade data from trade in related goods.
- Based on the importance of innovation in unlocking markets, the UK is projected to reach a market share in the EU and RoW by 2050. The potential future market share is intended as an ambitious, but realistic, scenario. It is triangulated using:
  - Market shares of competitor countries, as a benchmark for what is a realistic share if a country is 'world leading'.
  - The maturity of the existing market, which affects the likelihood of market shares changing significantly.
  - The importance of innovation in the technology.
- Market share assumptions are validated at a workshop with expert stakeholders and adjusted based on stakeholder input.

Export business opportunities for services

- The EINA focus on service exports directly associated with the technology and innovations considered within the sub-theme. For example, this could include EPCm services around the construction of an innovative CCS plant, but it will not include more generic service strengths of the UK, such as financial services.
- The EINA methodology does not quantify opportunities associated with installation and operation and maintenance as these are typically performed locally. Exceptions are made if these types of services are specialised, such as in offshore wind.
- The key services to consider are based on desk research and verified through an expert workshop.
- The services considered in the CCUS EINA export analysis are EPCm services, transport and storage services.

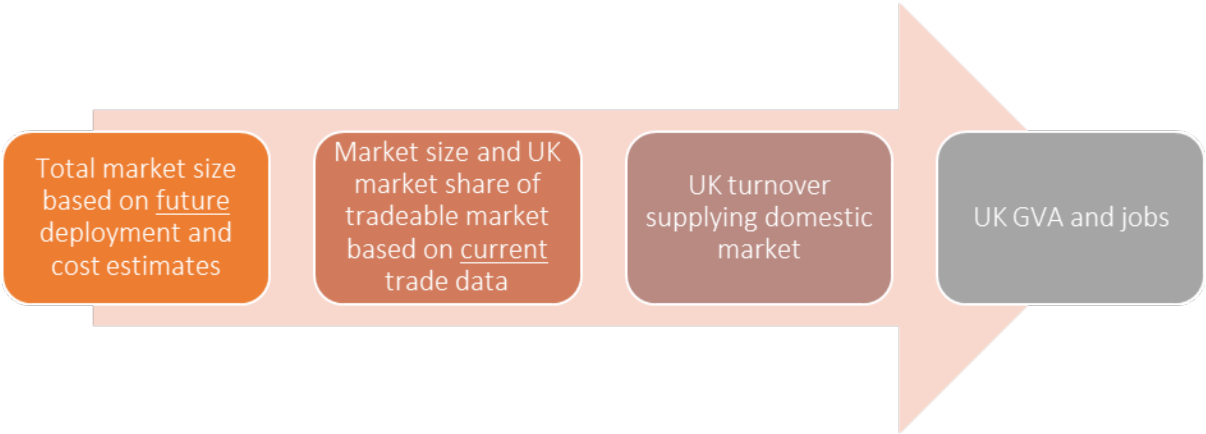
Methodology for domestic business opportunity analysis

To estimate the size of domestic business opportunities for the UK, the EINA methodology, as developed to size export opportunities, is adapted. The domestic analysis leans heavily on insight gleaned from the export analysis, particularly in estimating UK competitiveness and ability to capture market share in its domestic market. To estimate the domestic opportunity, the following methodology is used:

- The **domestic market** to 2050 is sized based on deployment and cost estimates. Deployment estimates are based on ESME modelling used for the EINAs and cost estimates are equal to those from the export work, and based on analysis for each of the EINA sub-themes.[50] For example, deployment of nuclear power is multiplied by costs to obtain annual turnover for the nuclear market.
- The **tradability** of the market is estimated based on current trade data, where available, and informed by expert judgement. This determines how much of the UK's market is likely accessible for foreign firms (e.g. electric vehicles), and how much is likely to be exclusively provided by UK companies (e.g. heat pump installation).
- For the traded share of the UK market, the UK's **market share** under a high-innovation scenario is estimated based on current trade data, research, and expert consultation. The determination of these shares is discussed in more detail below.
- To estimate **UK captured turnover** the traded and non-traded markets are summed.
  - The UK's captured turnover of the UK traded market is estimated by multiplying the tradeable market by the UK's market share.
  - The UK's turnover from the non-traded market is equal to the size of the non-traded market.
- The captured turnover figure is multiplied by a GVA / turnover multiplier which most closely resembles the market to obtain **GVA**. The GVA figure is divided by productivity figures for that sector to obtain **jobs supported**.

[50] For detail on cost estimates used, please refer to the Excel calculators provided for each sub-theme, and the individual sub-theme reports.

Figure 2 **Methodology for assessing domestic business opportunities**



Source: Vivid Economics

For all EINA sub-themes, the assessment of the UK's future competitive position is informed by the UK's existing market share of goods and services, the market share of competitors, industry trends, and workshop feedback.

Domestic business opportunities for goods

- Current market shares of UK goods are evaluated based on existing trade (import) and domestic production data, where available. If the technology is immature, UK shares are based on trade data from trade in related goods.
- Based on the importance of innovation in unlocking markets, the UK is projected to potentially increase its market share in its domestic market. This estimate is informed by the previously performed export analysis. It is triangulated using:
    - Market shares of competitor countries, as a benchmark for what is a realistic share if a country is 'world leading'.
    - The maturity of the existing market, which affects the likelihood of market shares changing significantly.
    - The importance of innovation in the technology.

Domestic business opportunities for services

- The EINA focus on service exports directly associated with the technology and innovations considered within the sub-theme. For example, this could include EPCm services around the construction of an innovative CCS plant, but it will not include more generic service strengths of the UK, such as financial services.
- The domestic assessment explicitly quantifies services such as O&M and installation, which are typically not traded but can support a large number of jobs associated with e.g. heat pumps. For these services, the estimate of potential service jobs supported is based on:

- An estimate of the total turnover and GVA associated with the service
- A ratio of GVA/jobs (adjusted for productivity increases) in analogous existing service sectors based on ONS data.

- The key services to consider are based on desk research, verified through stakeholder workshops.

Worked example

1. The **global and regional markets** to 2050 are sized based on illustrative deployment forecasts, which come from ESME when available.[51] For example, deployment of nuclear power (37 GW by 2050) is multiplied by O&M costs (~12% of total plant costs) to obtain annual turnover for the nuclear O&M market (~£2.5 billion by 2050).
2. The **tradability** of the market is estimated based on current trade data, where available, and informed by expert judgement. This determines how much of the global market is likely to be accessible to exports and gives a figure for the tradeable market. In the case of nuclear O&M, tradability is 0% being as it is not tradeable. For the domestic analysis, tradability does not directly feed into our model, but is vital to provide insight on the share of the domestic market UK firms will capture.
3. The UK's **market share** under a high-innovation scenario is estimated based on current trade data, research, and expert consultation. The determination of these shares is discussed in more detail below. For example, for nuclear O&M the UK domestic market share is 100% because the component is not tradeable and therefore foreign firms do not capture some of the value.
4. The tradeable market is multiplied by the market shares to give an estimate for **UK-captured turnover**. For nuclear O&M, market turnover (~£2.5 billion) is multiplied by the UK market share (95%) of O&M to obtain UK-captured turnover (~£2.5 billion by 2050).
5. The captured turnover figure is multiplied by a GVA / turnover multiplier which most closely resembles the market to obtain **GVA**. The GVA figure is divided by labour productivity figures for that sector to obtain **jobs supported**. For example, appropriate Standard Industrial Classification (SIC) codes are chosen for nuclear O&M. This leads to a GVA / turnover multiplier (49%) that is multiplied by market turnover (~£2.5 billion) to isolate GVA (~£1 billion by 2050), which is then divided by labour productivity (~70,000 GVA / worker by 2050) to isolate jobs supported (~16,000 jobs by 2050).

[51] If deployment information is not available from the IEA, alternative projections from, for example, Bloomberg are used. Please see individual sub-theme reports for further detail.

Appendix 6: Assessment of business opportunities uncertainty

The assessment of business opportunities in the long term, associated with new technologies is uncertain. This assessment does not attempt to forecast what *will* happen. Instead, the business opportunity assessment attempts to provide a realistic and consistent assessment, based on current information, on the business opportunities that *could* be captured by the UK. Whether these opportunities are indeed realised depends on domestic and international developments, political decisions, macro-economic conditions, and numerous other complex variables.

As this assessment is not intended as a full forecast, a formal quantitative sensitivity analysis has not been performed. the below provides a high-level qualitative assessment of the uncertainty associated with the sized opportunity. Note, this is *not* an assessment of how likely the UK is to capture the opportunity, rather it is an assessment of the uncertainty range around the size of the opportunity. The assessment is based on three key factors driving the assessment

1. *The level of future deployment of the technology*. Technologies such as offshore wind are deployed at scale across different energy system modelling scenarios and hence considered relatively certain. In contrast, there is more uncertainty for e.g. hydrogen related technologies. The export analysis is based on 3 IEA scenarios (with numbers provided for the IEA ETP 2 degree scenario). Domestic analysis is based on a single ESME run used across the EINA process.
2. *The potential domestic market share* the UK can capture. This assessment attempts to estimate a plausible market share for the UK across relevant markets. Where this can be based on longstanding trade relationships and industries, this assessment is considered more robust.
3. *Future technology costs and production techniques* are a key driver of the future turnover, gross value added and jobs associated with a technology. For immature technologies for which manufacturing techniques may, for example, become highly automated in future, future costs and jobs supported by the technology may be significantly lower than assessed.

The ratings in the table below are the judgement of Vivid analysts based on the above considerations. The analysts have worked across all sub-themes and the ratings should be considered as a judgement of the uncertainty around the size of the opportunity relative to other sub-themes. As a rough guide, we judge the uncertainty bands around the opportunity estimates as follows:

- **Green**: Size of the opportunity is clear (+/- 20%). Note, this does not imply the UK will indeed capture the opportunity.
- **Amber:** Size of the opportunity is clear, but there are significant uncertainties (+/- 50%).
- **Red:** There are large uncertainties around market structure and whether the technology will be taken up at all in major markets. The opportunity could be a factor 2-3 larger or smaller than presented.

Table 7. **Assessment of uncertainty in business opportunities across sub-themes**

Sub-theme	Uncertainty rating	Comments
Biomass and bioenergy		• **Deployment**: Moderate deployment uncertainty; BECCS can produce negative emissions that have high value to the energy system under a deep decarbonisation pathway; there is moderate uncertainty as to whether BECCS will be used for hydrogen production, as in the ESME modelling, or for power generation. • **UK market share:** Speculative market share for immature traded equipment, but majority of business opportunities associated with certain untraded services and feedstocks. • **Costs and production techniques:** Relatively certain costs with most opportunities associated with labour input rather than immature technologies.
Building fabric		• **Deployment:** Depends on levels of retrofit that greatly exceed those seen to date. • **Market share:** Speculative for traded. However, majority of market untraded, highly likely captured domestically. • **Costs and production techniques:** High share of labour costs (independent of uncertain tech cost).
CCUS		• **Deployment:** Moderate deployment uncertainty; decarbonisation scenarios anticipate rapid uptake of CCUS, though there are few large-scale facilities today. • **Market share:** Moderate market share uncertainty; the UK is likely to be competitive in the storage of CO2 and EPCm services while component market shares are less certain given numerous technology choices and lack of clear competitors. • **Costs and production techniques:** Moderate cost uncertainty; the lack of large-scale facilities today makes estimating future costs difficult.
Heating and cooling		• **Deployment**: Expected to be deployed in most UK buildings by 2050. • **Market share:** some uncertainties, immaturity in markets such as for hydrogen boilers. • **Costs and production techniques:** Relatively certain given relative maturity of boilers and heat pumps. • **Deployment of hydrogen boilers or heat pumps** lead to similar opportunities for UK businesses, while heat networks present a 50 per cent smaller opportunity per household.

Hydrogen and fuel cells		• **Deployment**: Highly uncertain future deployment with a wide-range of 2050 hydrogen demand estimates across scenarios, particularly for export markets. • **UK market share**: Speculative market share for immature traded equipment, but majority of business opportunities associated with certain untraded services. • **Costs and production techniques:** Although deep uncertainty in future hydrogen production costs, for example electrolysis, most domestic costs are associated with labour input rather than equipment.
Industry		• **Deployment**: Relative certainty in deployment as it is based on the 2050 Roadmaps • **UK market share**: Some uncertainty due to poor quality of trade data that may not be representative of technologies within scope. • **Costs and production techniques:** Some uncertainty in costs, particularly for less mature technologies.
Light duty transport		• **Deployment**: Certainty in deployment; low-carbon vehicles will be required in any deep decarbonisation scenario. • **UK market share**: Speculative market share for a relatively immature market; a small number of uncertain future FDI investment decisions generates high uncertainty in overall business opportunities. • **Costs and production techniques:** Highly uncertain future costs, with substantial falls in battery costs a key enabler of BEV uptake.
Nuclear fission		• **Deployment**: Moderate uncertainty in future deployment with some proposed nuclear plants recently cancelled • **UK market share**: Relatively certain market shares based on robust estimates of current nuclear activity; market share growth is dependent on uncertain development of UK reactor IP; however, most business opportunities are associated with untraded activity or areas where the UK has existing strength • **Costs and production techniques:** Uncertain costs for nuclear new build, with dangers of construction overrun; deep uncertainty in costs for immature nuclear technologies, for example SMRs and AMRs.
Offshore wind		• **Deployment**: Offshore wind will be required in any deep decarbonisation scenario, with clear government commitments. • **UK market share**: Expected growth in current market shares given commitments and progress to date. • **Costs and production techniques:** Costs are relatively certain, with clear pathways to 2050.
Smart systems		• **Deployment**: High deployment uncertainty given immaturity of smart system market today and evolving business models and regulatory framework. • **UK market share**: Moderate uncertainty given immaturity of the market today and scalable nature of digital smart technologies, though there is UK leadership in aggregation services and V2G charging. • **Costs and production techniques**: Moderate uncertainty of cost reductions of batteries and V2G and smart chargers, though costs are expected to continue to fall.

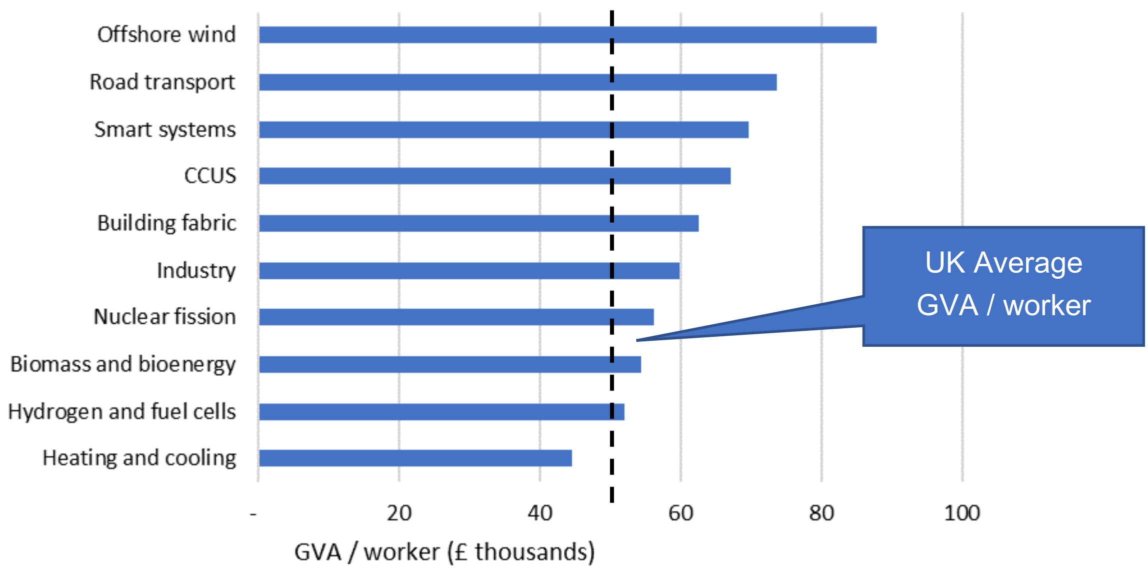
Source: *Vivid Economics*

Appendix 7: Quality of jobs supported

The differences in GVA/worker provide an indication of the potential quality of jobs created. For example, while smart systems rank third in GVA, they support relatively fewer jobs given the high GVA/worker in the sector, but these jobs could potentially be characterised by higher productivity and higher earning potential. It should be noted however that GVA/worker across a sector is a poor indicator of the typical quality of job within the sector as it does not account for the distribution of GVA across the workforce.

GVA per worker across sub-themes varies significantly in the sub-themes. The figure below shows *current* differences in GVA/worker. Our analysis assumes constant productivity growth across all sub-themes, which implies that productivity differences increase further between the sub-themes over time. To reflect observed higher productivity in ‘green sectors’, the manufacture of technologies within sub-themes which have a clear green element (e.g. offshore wind turbines) have been given a green productivity uplift in the jobs estimation. In effect, this makes our jobs estimates slightly more conservative.

Figure 13. **Current GVA per worker across sub-themes**



Source: Vivid Economics analysis based on ONS Annual Business Survey data

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