Energy Innovation Needs Assessment

Sub-theme report: Disruptive technologies

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Contents

The views expressed in this report are the authors' and do not necessarily reflect those of the Department for Business, Energy and Industrial Strategy.

Acronyms and abbreviations

Table 1. **Key acronyms and abbreviations**

Acronym/abbreviation	Definition
AI	Artificial Intelligence
BEIS	Department for Business, Energy & Industrial Strategy
BEMS	Building Energy Management System
BEV	Battery Electric Vehicle
BioSNG	Bio-Synthetic Natural Gas
CAPEX	Capital Expenditure
CCC	The Committee on Climate Change
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation, and Storage
CDM	Clean Development Mechanism
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
DACCS	Direct Air Capture with Carbon Storage
DSR	Demand-Side Response
DSO	Distribution System Operators
EINA	Energy Innovation Needs Assessment
ESME	Energy System Modelling Environment
EV	Electric Vehicles
FCEV	Fuel cell Electric Vehicles
GDP	Gross Domestic Product
GGR	Greenhouse Gas Removal
GHG	Greenhouse Gas
GVA	Gross Value Added
GW	Gigawatt
HDV	Heavy-Duty Vehicle

HEMS	Home Energy Management System
ICE	Internal Combustion Engine
IEA	International Energy Agency
IP	Intellectual Property
KWh	Kilowatt-Hour
LCOE	Levelised Cost of Energy
LDV	Light-Duty Vehicles
MDV	Medium-Duty Vehicle
MMV	Measuring, Monitoring, and Verification
P2G	Power-to-gas
P2P	Peer-to-peer
PEMFC	Polymer Innovation Electrolyte Membrane Fuel Cells
PHEV	Plug-In Hybrid Electric Vehicle
PV	Photovoltaic
RD&D	Research, development, and demonstration
SAE	Society for Automotive Engineers
TINA	Technology Innovation Needs Assessment
TRL	Technology Readiness Level
TSO	Transmission System Operator
TWh	Terawatt-Hour
V2G	Vehicle-to-grid
VPP	Virtual Power Plant

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 and are therefore grouped into the heating and cooling sub-theme.
System value and Innovation value	Estimates of change in total system cost (measured in GBP) 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 Add	Gross Value Add (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.

Introduction

Box 1. **Background to the Energy Innovation Needs Assessment**

The Energy Innovation Needs Assessment (EINA) aims to identify the key innovation needs across the UK's energy system, to inform the prioritisation of public sector investment in low-carbon innovation. Using an analytical methodology developed by the Department for Business, Energy & Industrial Strategy (BEIS), the EINA takes a system-level approach, and values innovations in a technology in terms of the system-level benefits a technology innovation provides.[1] This whole system modelling in line with BEIS's EINA methodology was delivered by the Energy Systems Catapult (ESC) using the Energy System Modelling Environment (ESME™) as the primary modelling tool.

To support the overall prioritisation of innovation activity, the EINA process analyses key technologies in more detail. These technologies are grouped together into sub-themes, according to the primary role they fulfil in the energy system. For key technologies within a sub-theme, innovations and business opportunities are identified. The main findings, at the technology level, are summarised in sub-theme reports. An overview report will combine the findings from each sub-theme to provide a broad system-level perspective and prioritisation.

This EINA analysis is based on a combination of desk research by a consortium of economic and engineering consultants, and stakeholder engagement. The prioritisation of innovation and business opportunities presented is informed by a workshop organised for each sub-theme, assembling key stakeholders from the academic community, industry, and government.

This report on disruptive technologies does not use ESME modelling in the same way as the other EINA sub-themes. It is intended to capture possible disruptions which are typically not well captured in a system model such as ESME and sets out how the innovation prioritisation set out across other sub-themes could be affected by large disruptions.

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 overall. Further work is required to assess detailed implications.

The disruptive technologies sub-theme report

The disruptive technologies EINA sub-theme is intended to highlight technologies and options that may significantly disrupt the energy system. By their nature, disruptive innovations are difficult to anticipate, and this report is therefore an exercise in exploring ranges of uncertainty. This EINA report follows a different structure and has a different purpose to the other sub-themes. Instead of prioritising 'disruptive' innovations, the report highlights potential sources of disruption and how these could significantly change the innovation priorities across the energy system. The report provides two key outputs:

- A description of potentially disruptive innovations and their impact on the energy system.
- An analysis of the impact of disruptions on our innovation prioritisation, highlighting where innovations are likely to become significantly more or less important.

We define disruptive innovations as any innovation or other shock which moves the UK energy system substantially away from our central scenario. Throughout the EINA sub-themes, innovations are prioritised to reflect their importance to the energy system to 2050. Using a central scenario as an anchor, the EINA sub-themes can estimate the importance of innovation in a given technology. For example, the system benefits of innovation (and cost reductions) in hydrogen fuel cells are quantified given a central expectation of the cost of hydrogen in the energy system.[2] If hydrogen costs turn out much lower than expected (and hence fuel cells are more widely deployed) innovation in fuel cells could become significantly more valuable than expected in our central scenario. As a rough benchmark, any innovation which shifts 10% of primary energy demand (or reduces energy demand altogether) is considered as disruptive.

Unlike other EINA sub-themes, this disruptive sub-theme is not anchored in system modelling. As described in Box 1 and Box 3, the ESME system model has been used to define the central scenario and identify the technologies where innovation creates the greatest UK system benefit across other EINA sub-themes. While the ESME model provides a valuable frame for the EINA work, the nature of a cost-optimising model such as ESME means it is better suited to modelling evolutionary rather than disruptive change.[3] To ensure the EINA as a whole captures potential revolutionary changes, this disruptive sub-theme takes a qualitative

[1] The system-level value of a technology innovation is defined in the EINA methodology as the reduction in energy system transition cost that arises from the inclusion of an innovation compared to the energy system transition cost without that innovation.
[2] Which itself depends on central input assumptions around the cost of electrolysers, steam methane reforming, etc.
[3] ESME requires the modeller to provide expected cost reductions as inputs, and hence is not able to model self-reinforcing cost reductions or feedback loops, which often drive large disruptions.

approach, setting out potentially disruptive worlds and the technologies which could spur this disruption.

A significant change in the expected makeup of the 2050 energy system could affect the priority of innovations now. For example, in a future energy system scenario which is very highly electrified and uses no hydrogen, innovation in hydrogen technologies is not very valuable from a UK energy system perspective. The purpose of this report is to highlight possible disruptions and indicate the impact on the innovation prioritisation across the EINA sub-themes.

The report has five sections:

- **The central scenario and potential disruptions:** This section describes the central EINA scenario and defines the key potentially *disrupted worlds*.
- **Innovation opportunities for disruptive technologies:** Describes the main areas of innovation in disruptive technologies.
- **Impact of disruptive technologies on innovation priorities:** Describes how disruptive technologies may shift innovation priorities across sub-themes.
- **Business opportunities:** Briefly highlights the impact of UK energy system disruption on export opportunities in other sub-themes, and potential export opportunities arising from disruption.
- **Policy opportunities:** Describes considerations for creating an enabling environment for innovation in disruptive technologies.

Key findings

Priority innovation areas in energy system disruptions

The innovation priorities identified across EINA sub-themes could shift as a result of highly disruptive innovation. The below sets out four possible disrupted energy systems and the key changes these imply for the innovation prioritisation set out in the EINA sub-themes.

- **An 'automated' scenario**, with extremely flexible demand. This scenario shifts innovation priorities to smart technologies across heating, industry, transport and smart systems. Innovations in centralised consumers platforms, demand-side response (DSR) business models, autonomous technologies, and sensors can optimise household energy consumption and grid optimisation and enable this scenario.

- **A 'decentralised' scenario,** with (nearly) full energy system electrification and highly decentralised electricity generation. Widespread distributed generators reduce the innovation need in large-scale generators, including nuclear, whilst high battery electric vehicle (BEV) penetration reduces fuel cell innovation needs (in transport). This scenario shifts innovation priorities to smart system storage and electrified transport. Solar photovoltaics (PV) or thin film innovation, coupled with sharp improvements in electric battery density, enable the decentralised scenario and independence from the grid.

- **A 'new energy carrier' scenario** where hydrogen and synthetic fuels are widespread. Cheap hydrogen, storage solutions, and widespread combined heat and power (CHP) fuel cells reduce innovation prioritisation in nuclear generation, BEV in heavy-duty transport, and electric heat pumps. This scenario shifts innovation priorities to hydrogen and synthetic fuel production technologies, including electrolysers and steam methane reforming, and final use technologies, such as hydrogen-based furnaces. Wider energy system innovation, such as offshore wind, is also necessary to deliver cheap electricity for electrolysis.

- **A 'reduced emission reduction needs' scenario,** with extensive greenhouse gas removal (GGR) deployment or large international offsets. Large-scale GGR lessens the stringency of UK carbon budgets and reduces innovation prioritisation in the most difficult-to-decarbonise sectors, including industry and heavy-duty road transport. This scenario increases the innovation priority of carbon storage to enable carbon dioxide. Furthermore, it increases the benefits of hydrogen innovation, given the abundance of high purity captured carbon dioxide (CO_2) to be used as an input to synthetic fuel production. Innovations in direct air capture with carbon storage (DACCS) technology, coupled with the creation of a robust of international offsetting scheme, is vital to deliver the requisite greenhouse gas removals in this scenario.

Business opportunities to the UK

Note, business opportunities for disruptive technologies were not assessed using the consistent EINA methodology as used in the other EINA sub-themes.

Significant energy system disruption in the UK is likely to affect UK business opportunities from energy innovation through two channels:

- **Business opportunities in other EINA sub-themes will shift.** Disruptive scenarios can affect the export market size available to UK firms, and their international competitiveness. For example, the new energy carrier scenario may increase UK business opportunities in hydrogen production technologies because of a larger global market. It can also increase UK competitiveness because the domestic energy system may be more suited to hydrogen than key competitors and enable UK firms to gain higher learning-by-doing benefits because of stronger domestic deployment.

- **New business opportunities** will arise from exporting goods and services associated with disruptive technologies. This includes technologies, such as DACCS, that are not included in the central scenario.

Policy opportunities

Key policy opportunities to support innovation in disruptive technologies are:

- Adaptive regulation and sufficiently flexible standards ensure that emerging technologies and their application are enabled in the regulatory framework.
- Clear long-term policy signals enable innovators to direct innovation towards meeting the needs of future consumers.
- Innovators need to be able to access finance to innovate and deploy at scale.
- Government can support the availability of high-quality data, including through data sharing frameworks, privacy and cyber security protocols, and engaging in a dialogue with industry to identify and make available government-held data that would support disruptive innovation.

Box 2. **Industry workshop**

A workshop was held on 13th March 2019 with key delegates from the government, and industry (see Appendix). Key aspects of the EINA analysis were subjected to scrutiny, including innovation opportunity assessment and business and policy opportunities assessment. The views of the attendees and the evidence that they provided has been included throughout this report.

Given the invitees of the workshop, the scope focussed on automated and decentralised technologies. New energy carrier and lower emission reduction needs were also discussed, but to a lesser extent.

The central scenario and potential disruptions

The following sets out key aspects of the EINA's central scenario and four possible disrupted scenarios.[4] The central scenario is described as a reference case, with the disrupted worlds described in terms of key changes from the central scenario. The four key scenarios considered are intended to be illustrative. They are not predictions, but instead act as tools to understand how disruptive innovations could affect the innovation prioritisation in other sub-themes (set out in Table 8. The described scenarios are:

- **Automated scenario** in which demand is extremely flexible.
- **Decentralised scenario** in which the energy system is fully electrified and electricity production is highly decentralised.
- **New energy carriers scenario** in which hydrogen and synthetic fuels are large energy vectors.
- **Low emissions reduction needs scenario** where innovations in greenhouse gas removal reduce the stringency of UK carbon budgets.

[4] The EINA's ESME modelling includes several hundred innovation runs. Each run will create slight changes in the scenario as an individual technology becomes cheaper through innovation. The description of the central scenario below captures the broad outlines of the scenario, but in, for example, an innovation run for heat pumps, the balance between heat pumps and hydrogen boilers does shift.

Central scenario

Under the central scenario, the UK decarbonises through a mix of energy-efficiency improvements and low-carbon technologies. The scenario includes significant hydrogen use, large-scale offshore wind, and nuclear capacity in the electricity system. It also includes a combination of energy efficiency, fuel switching, and carbon capture and storage (CCS) in industry, transport, and buildings. The scenario is calibrated so that the UK meets its greenhouse gas (GHG) target (80% below 1990 levels in 2050). Table 3 sets out the characteristics of the central scenario energy system in 2050.

Table 3. **Central scenario energy system overview**

Sector	Central scenario characteristics in 2050
Electricity 	• Annual electricity demand increases nearly 50% to 440 terawatt-hours (TWh) • Offshore wind provides 40% of generation, nuclear 30%, and onshore wind 10% • Solar PV and gas CCS generate 10% and other renewables (biomass, energy from waste, hydro, and tidal) generate the remaining 10% • 140 gigawatts (GW) 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[5] • 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

[5] 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.

	• Remaining space heating demand is met from near equal parts hydrogen boilers (15%), gas boilers (15%) and, district heating (15%)
Industry 	• Industry emissions decline 55% from today to 33 metric tonnes (Mt) of carbon dioxide (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 (all with CCS)[6] • 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

Partial electrification of transport and space heating increases total electricity demand to 440TWh annually by 2050. Nuclear and wind power generation meet 80% of this increased electricity demand, with solar PV, gas CCS, and other renewables supplying the rest.[7] Flexibility is required to meet challenging levels of intermittency from the high level of variable renewables in the electricity system. Hydrogen turbines and gas CCS are used to meet daily and seasonal demand peaks. Further flexibility is provided by 8 gigawatt (GW) of storage, 10 GW of interconnection, and 16GW of unabated gas back-up capacity. The UK also deploys digital technologies to enable flexibility, such as demand-side response (DSR), vehicle-to-grid (V2G) chargers, and flexible market platforms. As a result, by 2050, one-third of peak demand is flexible.

In transport, electric vehicles displace ICEs and outcompete FCEVs. By 2050, EVs make up more than a third of the light-duty vehicle fleet. FCEV uptake is low as investment in related fuelling infrastructure fails to materialise. Hard-to-treat

[6] Natural gas reforming with CCS provides an alternative hydrogen generation option. This is not selected in ESME due to input cost assumptions, but the central scenario would not change meaningfully if this is the main mode of gas generation rather than e.g. coal gasification.
[7] Biomass, energy-from-waste, hydroelectric, and tidal.

transport, such as aviation, shipping, and HDVs, continues to rely on conventional fuels, though.

Building space heating demands are met using hybrid heating systems, which deploy heat pumps alongside gas boilers. Deploying heat pumps alongside gas boilers allows for the installation of medium-size heat pumps to operate as baseload, while ensuring gas boilers provide back-up capacity to supplement heat pumps on exceptionally cold days. By 2050, this hybrid system results in heat pumps providing 50% of annual space heat production, while only accounting for 20% of space heating capacity. In order to accommodate heat pumps, building thermal efficiency improves as eight million new thermally efficient homes are added to 2050 and ten million homes are retrofitted (improving thermal performance by 20-30%). A mix of district heating and hydrogen boilers, using 100% hydrogen green gas grids, meet the remaining space heating demand.

Industrial energy demand declines and the fuel mix diversifies by 2050. Industrial energy demand declines 12% by 2050 compared to today. Industrial CCS is deployed, capturing 7Mt of CO_2 annually. Around 50TWh of hydrogen is consumed by industry annually, while natural gas and electricity continue to provide most of the industrial fuel.

Annual hydrogen production reaches 160TWh by 2050. Hydrogen is prioritised for use in spacing heating and, consequently, 2TWh of geological storage is built to ensure security of supply for hydrogen boilers during winter months. Hydrogen is mostly produced from coal and biomass gasification, with CCS to capture emissions from these processes, with limited production of hydrogen from electrolysis.

Disruptive technology: Automated scenario

The key characteristic of the automated scenario is enhanced energy system flexibility from autonomous operation of DSR. The automated scenario reflects an increase in digitalisation and deployment of smart systems compared to the central scenario with, for example, a highly autonomous vehicle fleet which is always available for DSR when not used for transportation. Similarly, in order to reach extremely high levels of flexibility, substantial deployment of autonomous optimisation technologies is required to facilitate ubiquitous consumer participation in demand-side response programmes. In addition to the increased electricity system flexibility this provides, overall energy efficiency would also increase significantly as automated systems outperform human operators (e.g. a self-driving car is more fuel-efficient than a human driver).[8]

Table 4. **Automated scenario 2050 outlook**

Sector	Change from central scenario in 2050
Electricity	• The electricity system is highly flexible and coordinated • There is autonomous real-time electricity trading at the transmission and distribution levels • Electricity system capacity is lower, particularly back-up capacity that is displaced with DSR • Renewable load factors are higher • Lower levels of distribution and transmission infrastructure (per TWh)
Transport	• V2G smart charging for EVs • Autonomous vehicles • New vehicle ownership models • The number of light-duty EVs increases as charging congestion declines • Increased MDV and HDV efficiency from autonomous vehicles and optimised scheduling
Buildings	• Deployment of home and building energy management systems (HEMS and BEMS) • Heat pump capacity and generation increases • Gas boiler capacity and generation declines • Smart heat pumps likely outcompete hydrogen grids • Buildings provide high levels of DSR
Industry	• Energy efficiency in industry increases from autonomous manufacturing • Total industrial energy demand decreases • Industry provides high levels of DSR
Hydrogen	• Moderately higher levels of hydrogen production from electrolysis in flexible power-to-gas (P2G) projects

[8] Self-driving cars: will they reduce energy use? University of Leeds. Available from: http://www.its.leeds.ac.uk/fileadmin/documents/research/MobilityEnergyFutures_-_SelfDrivingCars.pdf

Source: Vivid Economics

The automated scenario goes beyond the level of digitalisation in the central scenario, with possibly 50-60% of peak demand delivered through flexibility solutions.[9] Autonomous vehicles are highly efficient and reduce energy consumption in transport. Furthermore, they are capable of self-driving to chargers and provide flexibility services. Advanced home and building energy management systems autonomously optimise electricity consumption. By 2050, the widespread uptake of demand-side response technologies, such as V2G chargers, smart heat pumps, and industry DSR, allows 50% or more of peak demand to be shifted. Nearly all electricity consumers subscribe to autonomous DSR services to optimise their electricity consumption throughout the day. Energy trading takes place at all levels of the energy system, including peer-to-peer (P2P), virtual power plant (VPP), distribution system operator (DSO)-to-DSO and DSO-to-transmission system operator (TSO), and new business models proliferate.

Reduced grid congestion, through increased efficiency and flexibility, allows for greater electrification with less generating capacity. Digitalisation optimises electricity consumption across power, heat, and transport. There is reduced electricity grid congestion during peak times as electricity demand is optimised throughout the day across sectors. Real-time electricity supply and demand signals enable dynamic tariffs that incentivise off-peak electricity consumption for EV charging and electric home heating. The reduction in EV charging congestion from smart V2G chargers and self-driving-self-charging vehicles lowers electricity prices for consumers, spurring increased EV uptake. The ability for most households to autonomously heat their homes at optimal times also enables greater levels of electrification as autonomous heating increases efficiency and allows households to be rewarded for their flexibility. This would come at the expense of district heating, natural gas, and hydrogen boilers.

The automated scenario requires key innovations in technologies capable of encouraging mass consumer participation in demand-side response. Figure 1 shows an indicative automated scenario pathway with benchmarks for two key innovations. The future realisation of these benchmarks strongly suggests that the electricity system is heading towards the automated scenario. These innovations are:

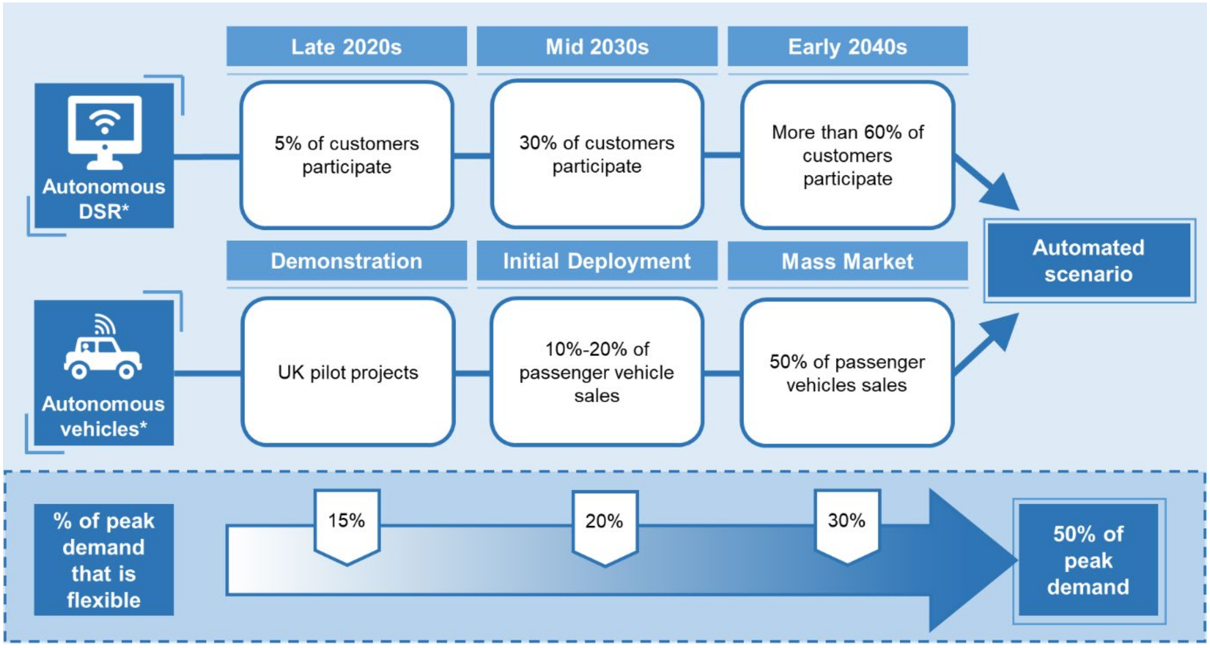
- **Autonomous DSR** is needed to facilitate the participation of all electricity customers in DSR. Autonomous consumer platforms are essential as they

[9] Smart charging alone could provide 12.6GW of turn-up and 29.7GW of turn-down flexibility by 2040. This would increase significantly further with V2G and vehicles autonomously connecting to the grid and could plausibly reach ~70GW of flexibility. See 'What National Grid Latest Forecasts Mean for EV Flexibility' (2019). Open energi. Available from: https://www.openenergi.com/ev-flexibility-national-grid-forecasts/

reduce the amount of customer input required to participate in DSR. From the customer's perspective, autonomous consumer platforms are 'fire and forget' optimisation, allowing even the most indifferent consumers to participate.

- **Autonomous (self-driving-self-charging) vehicles** are needed to increase energy efficiency and reduce EV charging congestion by allowing the vehicle to charge at optimal times and places without consumer input. These vehicles require autonomous operation equivalent to Society for Automotive Engineers (SAE) level 5 (autonomy without driver input).[10] In the digital world, EV chargers are assumed to be V2G-enabled, allowing EVs to provide substantial grid balancing benefits in conjunction with the autonomous consumer platforms identified above.

Figure 1. **Indicative automated scenario pathway**



Note: **Indicative disruptive breakthrough technology. Other technologies with similar characteristics are also possible disruptors.*

Source: *Vivid Economics*

Disruptive technology: Decentralised energy production and consumption scenario

The decentralisation scenario is characterised by widespread decentralised production and consumption of (electrical) energy. A decline in distributed generation costs results in inexpensive 'behind-the-meter' electricity. Combined with

[10] Note, lower levels of autonomy would suffice to bring significant energy-efficiency improvements.

inexpensive storage, this promotes significant uptake of these technologies at the household, commercial, and industrial levels. This leads to 20% (or more) of customers defecting from the electricity grid and becoming self-sufficient 'prosumers'.

Table 5. **Decentralised scenario 2050 outlook**

Sector	Change from central scenario in 2050
Electricity	• Installed distributed solar PV capacity increases substantially, supplying the bulk of residential and commercial electricity demand • Distributed storage increases accordingly, with around 50% of households owning a stationary battery pack • Total generation capacity increases as households and business deploy distributed generation • Annual electricity generation increases • The installed capacity of large-scale centralised generators, such as offshore wind, gas CCS, and nuclear declines • 20% or more of customers defect from the grid • Reduced need for flexibility from DSR
Transport	• The light-duty vehicle (LDV) fleet completely electrifies • MDVs and HDVs also electrify • Electricity becomes almost all road transport energy consumption • The annual number of EV miles driven increases • Hard-to-treat transport, such as aviation and shipping, remain conventionally powered
Buildings	• Increase in electric resistance heaters • Reduction in gas or hydrogen boilers compared to central scenario • Reduction in district heating compared to central scenario • Widespread uptake of home batteries
Industry	• Increase in electricity use with decentralised additive manufacturing co-located with decentralised electricity generation
Hydrogen	• Reduced need for hydrogen to balance the electricity system • Reduced need for hydrogen in heating and transport, due to highly competitive battery technology

Source: Vivid Economics

Low-cost and locally abundant electricity further electrifies transport and heat. Distributed generation outcompetes large centralised generators as the cost of electricity falls due to inexpensive and ubiquitous behind-the-meter solar. The decline in electricity costs facilitates higher levels of electrification throughout the economy as electrified transport and heat outcompete the hydrogen alternatives. Decentralised generation also reduces transmission grid congestion, allowing for higher levels of electrification than would be possible under centralised generation without improved grid capacity or flexibility. Although overall hydrogen use is likely to decrease (particularly in buildings), inexpensive decentralised electricity is likely to lead to an increase in the production of hydrogen from electrolysis (displacing other forms of hydrogen production).

Inexpensive and radically improved batteries enable electrification of hard-to-treat transport and substantial grid defections. Electricity storage costs plummet as battery energy density radically improves and production of batteries expands substantially, enabling cost-saving economies of scale. The low cost of storage prompts widespread uptake of battery storage by households with distributed generation. The combination of inexpensive storage and inexpensive electricity spurs at least 20% of households to become self-sufficient prosumers, undermining the economics of the electricity grid as widespread grid defections occur. Low-cost high-energy-density batteries also reduce the cost of light-duty EVs and facilitate the electrification of MDVs and HDVs. By 2050, nearly the entire light-duty fleet is comprised of EVs[11] and most MDVs and HDVs are EVs. FCEVs and ICEs become impractical as the associated infrastructure declines from a lack of investment.

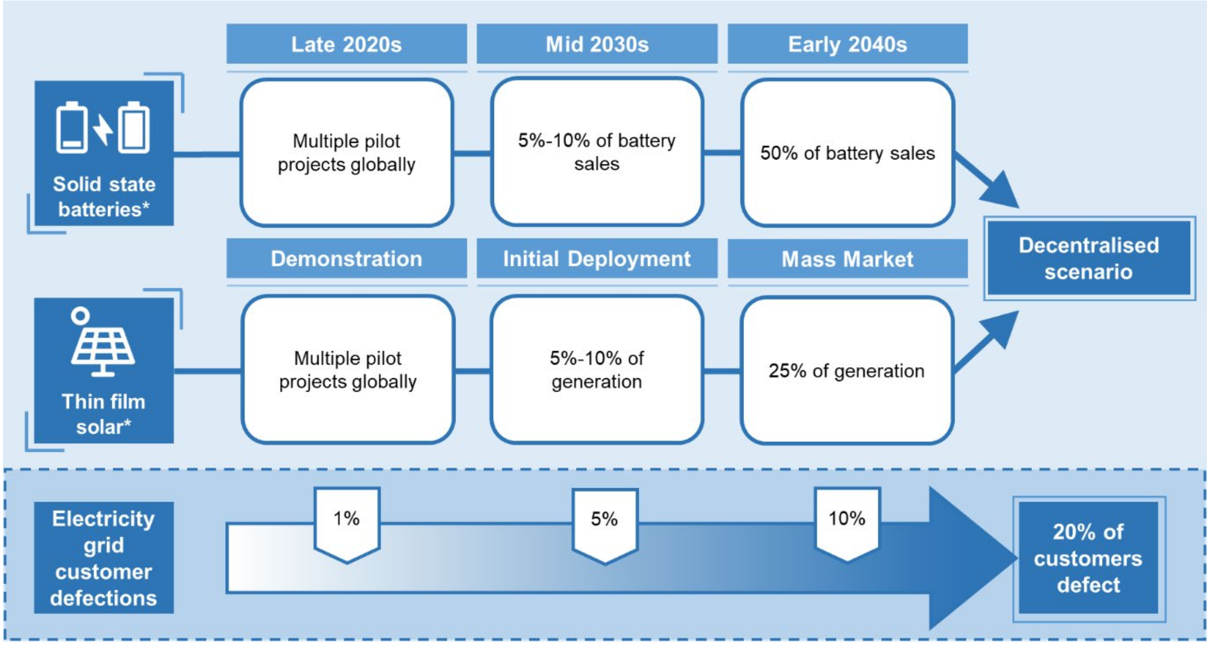
The decentralised scenario requires key innovations in distributed generation and electricity storage. Figure 2 depicts an indicative decentralised scenario pathway with benchmarks for two possible key innovations. The realisation of these benchmarks in the future strongly suggests that the electricity system is heading towards the decentralised scenario. These innovations are:

- **Very low-cost batteries[12]** to reduce the cost of electricity storage throughout the energy system. Innovation is needed to deliver very low-cost batteries. Solid-state batteries may provide this breakthrough, with radically higher energy densities than today. Coupling inexpensive energy-dense batteries with inexpensive distributed generation permits the widespread grid defections that characterise the decentralised scenario.
- **Low-cost solar** to reduce the cost, and barriers to installation, of distributed generation. Improvements in efficiency of thin film solar would allow for widespread installation (at low cost) of solar generation. Further innovation in

[11] Including BEVs and plug-in hybrid vehicles (PHEVs).
[12] The scenario as described would likely require costs below $50/kWh.

invertors, possibly in combination with domestic batteries, would help significantly reduce home system costs.

Figure 2. **Indicative decentralised scenario pathway**



Note: *Indicative disruptive breakthrough technology. Other technologies with similar characteristics are also possible disruptors*

Source: *Vivid Economics*

Disruptive technology: New energy carriers scenario

The new energy carrier scenario is characterised by the inexpensive and widespread availability of hydrogen and synthetic fuels. In a scenario with very high wind deployment, during periods of low demand or high wind, wind energy that would otherwise be curtailed provides an inexpensive supply of electricity. Electrolysis, using this cheap electricity, and natural gas reforming with CCS produce an abundant and inexpensive supply of hydrogen. Significant hydrogen volumes may also be imported.[13] The new energy carrier scenario moves substantially beyond hydrogen use in a narrow range of sectors, as in the central scenario. It has widespread hydrogen utilisation across the energy system (18% of final energy demand in 2050).[14] Synthetic fuel production ramps up as inexpensive hydrogen reduces production costs.[15] Net zero synthetic fuels meet 50% of final aviation fuel demand in 2050. Although other energy carriers could be considered, for example

[13] From, for example, production using solar electricity and electrolysers near the equator.
[14] Hydrogen Council (2017) Hydrogen scaling up http://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-Scaling-up_Hydrogen-Council_2017.compressed.pdf
[15] CO_2 required for this could be sourced from DACC or CCS.

bioenergy, the hydrogen and synthetic fuel focus is driven by their greater potential to disrupt the central scenario.

Table 6. **The new energy carrier scenario 2050 outlook**

Sector	Change from central scenario
Electricity	• Further deployment of offshore wind capacity to supply electricity for electrolysis • Hydrogen storage and hydrogen power plants are the main storage flexibility option, absorbing both seasonal variations in demand and providing peaking capacity
Transport	• LDVs, FCEVs, and synthetic fuel vehicles are the standard in highly utilised vehicles (e.g. taxis) • Substantial increase in FCEV and synthetic fuel usage in heavy-duty vehicles; by 2050 all HDV sales are either FCEV or synthetic fuel vehicles • Increased use of hydrogen fuel cells in shipping and aviation; extensive use of synthetic fuels in shipping and aviation; synthetic fuels comprise 50% of aviation fuels by 2050
Buildings	• Increased use of hydrogen boilers and reduced use of heat pumps • Reduced investment in retrofits
Industry	• Increased use of hydrogen in energy-intensive industry, including in the steel and chemical sectors
Hydrogen	• Substantial increase in electrolysis • Smaller increase in natural gas reforming routes to hydrogen • Reduction in biomass and coal gasification • Hydrogen is used across the energy system

Source: Vivid Economics

Compared to the central scenario, hydrogen and synthetic fuels will have the largest disruptive effect in transport and industry. Fuel cell vehicle penetration remains limited to high-use cases in light-duty vehicles because of cost-competitive BEVs. However, given the lack of alternatives, hydrogen and synthetic fuels are widely adopted in medium-duty and heavy-duty vehicles, shipping, and aviation. For these difficult-to-decarbonise transport sectors, hydrogen may be converted to electrical energy to power a fuel cell, or when used to produce synthetic fuels, be the energy input for an internal combustion engine.[16] In the new energy carrier scenario, over 50% of heavy-duty vehicle sales are FCEV in 2050, compared to minimal FCEV uptake in the central scenario. In addition to transport, hydrogen and synthetic fuels can strongly disrupt industry. In energy-intensive industries, such as steel and chemicals, low-carbon hydrogen can be vital to drive decarbonisation. For example, hydrogen could replace coal and coke in steel production.[17]

The disruptive effect of the new energy carrier scenario is smaller in buildings because of greater hydrogen utilisation in the central scenario. Unlike with transport and industry, the central scenario already includes significant hydrogen use in buildings. Accordingly, the new energy carrier scenario represents a less significant disruption to the buildings' energy mix. The inexpensive supply of hydrogen drives hydrogen boiler uptake at the expense of heating alternatives, including electric heat pumps. Very widespread hydrogen use would likely require upgrades to the UK existing gas infrastructure. Notably, this need could be significantly reduced if CO_2 is injected and synthetic methane (rather than hydrogen) is used. This would, like direct hydrogen use, significantly reduce the use of electric heating.

The new energy carrier scenario does not significantly disrupt electricity generation, but is disruptive to energy storage. Hydrogen is unlikely to compete against the inexpensive supply of renewable electricity in the new energy carrier scenario. Indeed, installed capacity of renewable electricity is likely to increase to supply electricity for electrolysis-produced hydrogen. This hydrogen could be stored to meet peak intra-day electricity demand or peak winter heating demand. Availability of hydrogen as a means of storing energy would reduce the need for bulk battery (and other forms) of storage.

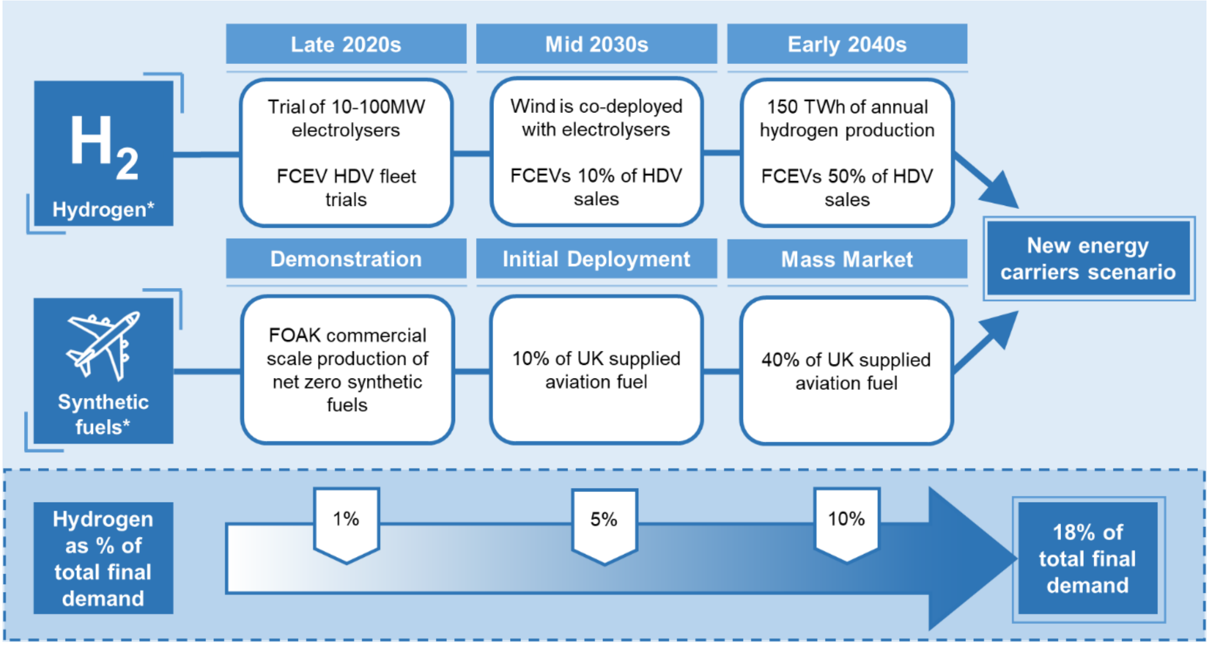
The new energy carrier scenario requires key innovations in hydrogen and synthetic fuel technologies. Figure 3 shows an indicative new energy carrier scenario pathway with benchmarks for two key innovations. The realisation of these benchmarks in the future strongly suggests that the electricity system is heading towards the new energy carrier scenario. These innovations are:

- **Hydrogen technologies** to reduce the cost of production and utilisation of hydrogen. Innovation is required throughout the hydrogen value chain, including for electrolysers and fuel cells, to ensure an abundant low-carbon hydrogen supply and a strong final demand market.
- **Synthetic fuel technologies** to reduce the cost of production and utilisation of synthetic fuels. Coupled with an inexpensive supply of hydrogen, innovation

[16] It may also be used directly in a combustion engine, although innovation in the engine would be required.
[17] Hydrogen Europe website https://hydrogeneurope.eu/decarbonise-industry

in synthetic fuel production can enable deep penetration of synthetic fuels in aviation.

Figure 3. **Indicative new energy carriers scenario pathway**



Note: *Indicative disruptive breakthrough technology. Other technologies with similar characteristics are also possible disruptors

Source: *Vivid Economics, hydrogen as a percent of final demand based on Hydrogen Council (2017)*

Disruptive technology: Reduced emission reduction needs scenario

The reduced emission reduction needs scenario is characterised by widespread greenhouse gas removal from the atmosphere. In this scenario, DACCS, or potentially other negative emissions technologies, scales up to capture 100Mt of atmospheric carbon by 2050.[18] Alternatively, a robust international offsetting scheme would allow UK emitters to offset emissions against international greenhouse gas removal. This scheme overcomes the climate issues prevalent in existing international offsetting schemes, such as the Clean Development Mechanism (CDM), to enable industrialised countries to robustly offset emissions in

[18] Note, this would be **in addition to** negative emission levels already commonly modelled in UK (possibly net zero) scenarios) such as BECCS and afforestation.

land-abundant countries.[19] The additional 'headroom' created in the UK's carbon budget from large-scale GGR reduces the need to decarbonise hard-to-treat sectors.

Table 7. **Reduced emission reduction needs scenario 2050 outlook**

Sector	Change from central scenario
Electricity	• No significant change from the central scenario; power is the cheapest sector to decarbonise and will still (nearly) fully decarbonise

Transport	• The decarbonisation of light-duty vehicles and aviation and shipping follow the central scenario
	  ◦ LDVs will mostly decarbonise by 2050
	  ◦ Aviation and shipping will not decarbonise by 2050
	• HDVs do not decarbonise at all.

Buildings	• No hydrogen boilers • Reduction in electric heat pumps use, with continued use of gas boilers in places • Reduction in building retrofits
Industry	• Substantial reduction in industry decarbonisation because the availability of offsets enables industry to avoid decarbonising some of the most difficult processes
Hydrogen	• No widespread hydrogen use in the economy

Source: Vivid Economics

Widespread greenhouse gas removal will slow the decarbonisation of heavy-duty transport, buildings, and industry. According to the Committee on Climate Change (CCC), high decarbonisation costs lead to some emissions remaining in heavy-duty transport, buildings, and industry in 2050 in all scenarios.[20] Under the reduced emission reduction needs scenario, widespread GGR can substitute for emissions reductions in the most difficult-to-decarbonise sectors to achieve net zero.

[19] Carbon Market Watch (2018) The Clean Development Mechanism: Local Impacts of a Global System https://carbonmarketwatch.org/wp/wp-content/uploads/2018/10/CMW-THE-CLEAN-DEVELOPMENT-MECHANISM-LOCAL-IMPACTS-OF-A-GLOBAL-SYSTEM-FINAL-SPREAD-WEB.pdf

[20] Committee on Climate Change (2016) UK climate action following the Paris Agreement.

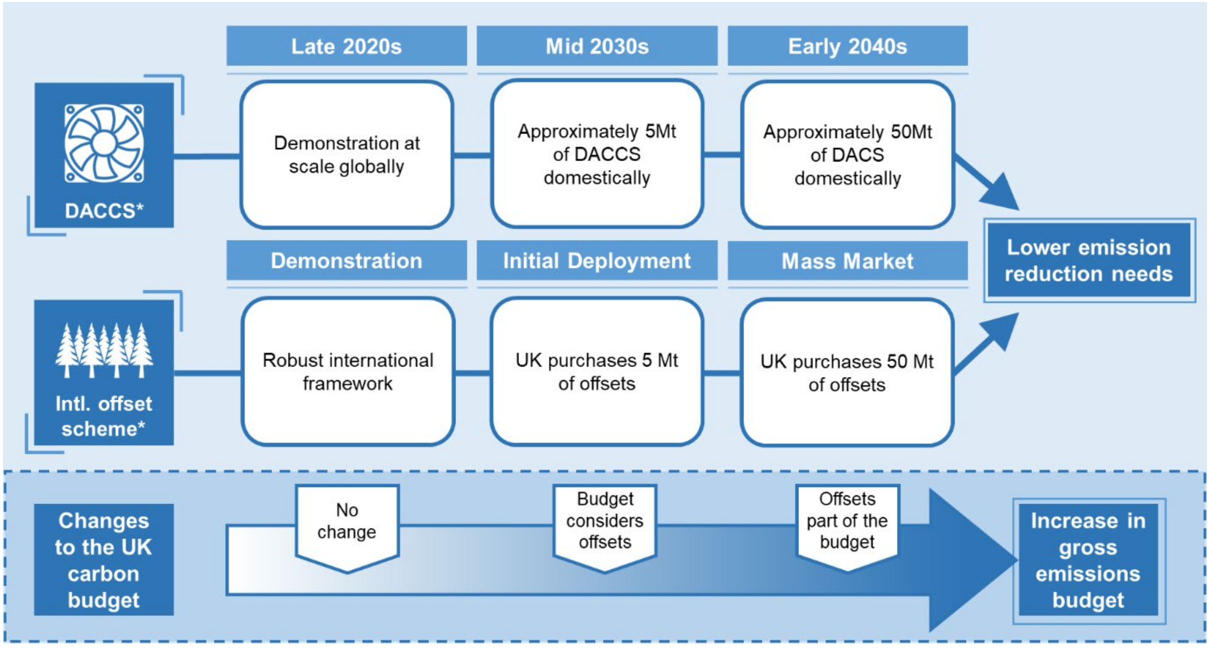
This GGR availability slows the decarbonisation of heavy-duty transport, buildings, and industry.

The decarbonisation of power and light-duty transport continues in the reduced emission reduction needs scenario, as in the central scenario. Renewable power and LDV BEVs will be the most cost-competitive technologies under all disruptive scenarios. Therefore, the decarbonisation pathway of power and light-duty transport in this scenario follows that of the central scenario.

The reduced emission reduction needs scenario requires key innovations in technologies capable of removing greenhouse gases from the atmosphere. Figure 4 shows an indicative reduced emission reduction needs pathway with benchmarks for two key innovations. The realisation of these benchmarks in the future strongly suggests that the electricity system is heading towards the reduced emission reduction needs scenario. These innovations are:

- **DACCS** to reduce the need for the more difficult and higher cost emission reduction activities, particularly in industry and buildings. It is possible that DACCS scales up to supply the indicative 100 $MtCO_2$ of negative emissions, removing the need for an offsetting scheme to make this scenario plausible.
- **Robust international offsetting scheme** to enable UK firms to purchase emission-offsetting credits in developing countries. The scheme's design must be robust and allow for substantial scale up in tradeable credits while minimising negative impacts in countries selling offsets.

Figure 4. **Indicative reduced emission reduction needs scenario pathway**



Note: **Indicative disruptive breakthrough technology. Other technologies with similar characteristics are also possible disruptors*

Source: *Vivid Economics*

Potential disruptive technologies

By their nature, disruptive innovations are hard to predict. This section provides an indication of innovations which could prove disruptive. It is, however, not a comprehensive horizon-scanning exercise. Crucially, the listed innovations are not the only route to a disrupted world. For example, the 'new energy carriers' scenario could be enabled by large-scale hydrogen imports, rather than innovations which spur large-scale domestic production. The purpose of this section is hence twofold, namely to:

- Provide an indicative horizon scan to highlight possible disruptions at the innovation level (e.g. innovation needs in air contactors for DACCS). This is provided in Table 8.
- Provide a higher-level description of innovations required from technologies, and the types of services for which these are required. This is intended to provide an indication of the substitutability of different innovations. For example, instead of cheap thin film solar, the disruptive decentralised scenario could be reached through innovation in small-scale wind turbines.

Table 8. **Brief horizon scan of disruptive technologies enabling each scenario**

Sector	Disruptive technologies

Automated	• Innovations in smart markets and DSR as discussed in the Smart Systems sub-theme
	• Additional innovations include:
	  ○ Deep-learning algorithms for domestic appliances
	  ○ Development of autonomous decision-making capability for appliances and home hubs
	  ○ Metering for individual appliances
	  ○ Artificial intelligence for autonomous vehicles up to SAE level 5
	  ○ Inductive charging to enable autonomous charging
	  ○ Universal 5G network availability to enable vehicles and appliances to autonomously communicate with each other and the cloud

Decentralised	• Innovations in battery storage, as described in the Smart Systems sub-theme, including in battery management and invertors
	• In addition, further battery innovations required are:
	  ○ Significant improvements in $/kWh available from battery chemistries. This may include commercialisation of solid-stage
	  ○ Business model innovations combining storage, solar, and flexibility offerings
	• Disruptive Innovations in decentralised generation are mostly likely to come from solar technologies and include:

	○ Thin film efficiency increases to reduce area requirements through, for example, new materials such as copper indium gallium diselenide (CIGS)[21] ○ Thin film cost reductions through improved manufacturing processes such as solar panel 'printing'[22] ○ Thin film solar using nanowires
New energy carriers	● Innovation will be required across hydrogen production and use technologies ○ Innovations in hydrogen production do not necessarily need to go beyond those identified in the CCUS and Hydrogen sub-themes, but will all need to come to materialise together to enable large-scale low-cost hydrogen production. ○ Similarly, innovations in hydrogen-use technologies do not need to go significantly beyond those considered in the Hydrogen, Smart Systems, Industry, Transport, and Heating and Cooling sub-themes, but would all need to materialise
Reduced emission reduction needs	● Technological innovations which could unlock this scenario include need to move beyond established GGRs, such as afforestation and BECCS, and could include: ○ Innovations in DACC costs. These include innovations in materials (solvents and sorbents), opportunities of using low-carbon (waste) heat sources, and air contactors[23] ○ Innovations to enable large-scale deployment of very immature GGR technologies such as blue carbon or an electrochemical acidification cell[24,25]

Source: Vivid Economics

Automated scenario

The automated scenario requires a broad range of innovations to transform data into flexibility for the energy system. Although disruptive innovation is uncertain and difficult to predict, a set of innovations are identified as likely enablers of the automated scenario. These innovations overlap with innovations identified in the Smart Systems EINA. The automated scenario requires higher levels of innovation than those identified in smart systems in order to increase consumer uptake of technologies that increase system flexibility. Identified innovations include:

[21] Other materials may also may also provide the increased efficiency required. See NREL (2019). Research. Available from: https://www.nrel.gov/pv/research.html
[22] See for example, http://www.nanosolar.com/
[23] ICEF (2018). Direct air capture of carbon dioxide. Available from: https://www.icef-forum.org/pdf2018/roadmap/ICEF2018_DAC_Roadmap_20181210.pdf
[24] The Royal Society and Royal Academy of Engineering (2018). Greenhouse Gas Removal. Available from: https://royalsociety.org/~/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf
[25] Willauer et al. (2012). Development of an Electrochemical Acidification Cell for the Recovery of CO_2 and H_2 from Seawater II. Evaluation of the Cell by Natural Seawater. Available from: https://pubs.acs.org/doi/abs/10.1021/ie301006y

- **High adoption of centralised consumer platforms** to aggregate consumer interactions with the grid in order to manage household electricity demand. These platforms could take the consumer's electricity demand choices as an input and autonomously optimise them in conjunction with smart appliances across space and water heating, vehicle charging, appliances, and home storage. The increase in flexibility could be substantial. For example, a trial study in Denmark has demonstrated that peak load could be reduced by a range of 47% to 61% using EVs and heat pumps controlled by smart devices.[26] The introduction of autonomously operating software for these platforms is a key innovation. It could allow for higher levels of participation in demand response and system balancing than non-autonomous platforms that require higher levels of consumer interaction. The digital scenario requires virtually all consumers to participate in DSR.
- **High adoption of DSR business models** that incentivise participation of residential, commercial, and industrial customers. These innovative business models could increase DSR uptake by reducing upfront capital costs to consumers and offering incentives that make participation in DSR worthwhile. It is likely that any innovative DSR business model would require dynamic tariffs in order to properly incentivise consumer behaviour to participate or outsource participation to an autonomous platform (discussed above). For example, business models could offer separate dynamic tariffs by end use (e.g. separate tariffs for appliances, EV charging, spacing heating, and water heating).
- **Widespread use of autonomous technologies** to optimise consumption of energy and utilisation of DSR technologies without active consumer participation. In transport, development of self-driving vehicles capable of driving to charging points at off-peak times could reduce charger congestion, lowering electricity costs to EV owners. To enable self-charging, these vehicles require autonomous operation equivalent to SAE level 5 or above (autonomy without driver input). In industry, digital manufacturing and offers the potential for greater energy efficiency in industry, reducing electricity demand. Autonomous operation of DSR, potentially on a platform as identified above, is another key innovation to create a more flexible energy system.
- **Innovative applications of artificial intelligence** to optimise electricity system and generator operation. AI-assisted grid operation could improve balancing, scheduling, dispatch, and voltage management. For example, AI can be used to predict future grid constraints and increase dispatch to stationary storage to facilitate future system balancing. Generator operation and maintenance can also be improved by AI as AI can adjust generator

[26] IRENA (2019) Innovation Landscape for a Renewable-Powered Future: Solutions to Integrate Variable Renewables https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Feb/IRENA_Innovation_Landscape_2019_report.pdf

operation in real- time to optimise output and use predictive analytics for asset maintenance. Industry estimates suggest that digital systems and data analytics could reduce operating and maintenance costs by 10%, increase generation by 8%, and reduce curtailment by 25%.[27] Under the digital scenario, AI-assisted digital systems and analytics are expected to, at minimum, deliver these benefits throughout the electricity system. To enable AI, the creation and sharing of 'golden' data sets is essential to train and test AI systems.

- **Pervasive use of low-cost sensors and associated cloud services** to support digital communication throughout the energy system. The optimal level of cloud-connected sensor deployment and frequency of communication for a digital scenario is uncertain. Trials and testing of cloud-connected sensors at different points in the electricity system, from the generator to the household levels, are needed to better understand optimal levels of deployment and functionality. There is also a need for improved energy-specific data compression to facilitate higher levels of data sharing without a substantial expansion of communication infrastructure. Crucially, further development in cyber security and data sharing, without unnecessarily compromising privacy, is a crucial enabler (as described in the Smart Systems sub-theme).
- **Fully flexible and coupled energy system** to provide enhanced energy system flexibility. The innovations associated with disruptive vector coupling innovations are discussed in the new energy carriers section.

Box 3. **Industry workshop feedback**

- Workshop attendees suggested innovation in technologies that forecast demand and supply is critical to delivering the automated scenario and the required smart energy system.
- The disrupted scenario requires an efficient marriage of power, heat, and transport to support household energy independence from the grid.

Decentralised scenario

The decentralised scenario is enabled by inexpensive distributed generation and inexpensive and improved battery storage. The combination of inexpensive local generation and inexpensive local storage reduces the demand for centralised

[27] IRENA (2019) Innovation Landscape for a Renewable-Powered Future: Solutions to Integrate Variable Renewables https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Feb/IRENA_Innovation_Landscape_2019_report.pdf

generation and transmission capacity. This scenario delivers the greatest degree of electrification across the energy system. EVs benefit from both reduced electricity and battery costs and improved battery energy density. For this scenario to be plausible, innovations improving key performance characteristics and cost profiles are required across distributed generation and battery storage.

The main innovation in the decentralised scenario is inexpensive battery storage. Inexpensive battery storage is necessary to align consumer electricity demand and distributed generation supply profiles, enabling widespread grid defections. This scenario envisages innovations that radically improve battery energy density, moving substantially beyond the Smart Systems sub-theme. The lithium-ion (Li-ion) battery family could drive this transformative battery density improvement, with innovations in silica anodes, advanced cathodes, and solid-state electrolytes. Additionally, a solid-state electrolyte could facilitate the use of pure lithium anodes, which could increase battery cell energy density by 40%.[28] There are options beyond Li-ion, such as lithium air and vanadium flow batteries.

Inexpensive batteries will require a combination of economies of scale, advanced manufacturing techniques, total system cost reductions, and innovative business models. Economies of scale in cell and pack production are necessary to drive down battery costs. The expansion of the EV industry, in conjunction with stationary batteries, could drive a substantial increase in battery output under the decentralised scenario.[29] Automated manufacturing and more flexible production could offer further cost reductions and reducing the quantity of rare earth metals, such as lithium or cobalt, used in battery manufacturing would yield moderate price declines. In combination with advances in battery cells and packs, further cost reductions in battery management, invertors, rectifiers, and installation are required to drive down costs of the total battery system. Innovative consumer financing or leasing models could reduce upfront battery storage costs for the consumer and lead to wider adoption of home storage.

A reduction in distributed generation costs would unlock the decentralised scenario. Thin film solar is the most likely candidate today for inexpensive distributed generation in 2050 given the potential for ease of installation on various surfaces. Solar PV costs have reduced by 84% since 2010; solar costs could decline

[28]Arthur D Little (2018) Future of batteries: Winner takes all? http://www.adlittle.com/sites/default/files/viewpoints/adl_future_of_batteries-min.pdf

[29] The scale of the EV industry, and the large economies of scale associated with battery production, are expected to rapidly drive costs down compared to more niche storage options. Battery cost reduction in the decentralised scenario would exceed existing cost projections of $100/kWh by 2030, which are not uncommon today. See MIT (2018) Energy Storage for the grid: Policy options for sustaining innovation http://energy.mit.edu/wp-content/uploads/2018/04/MITEI-WP-2018-04.pdf

another 70% or more by 2050.[30,31] This could reduce the cost of solar to one to two pence per kilowatt-hour (kWh). Economies of scale in manufacturing and improvement in solar efficiency could deliver these prices. There is also scope for innovation in solar installation and ownership models. The latter, for example, could include new financing and leasing models to facilitate wider uptake. Further, inexpensive wind or commercialised small modular reactors could unlock the decentralised scenario, though these technologies face lower public acceptance than solar.

New energy carriers scenario

Cheap hydrogen and synthetic fuels are the key enabling innovations for the new energy carrier scenario. Inexpensive hydrogen and synthetic fuels can incentivise their widespread uptake across the energy system. Cheap hydrogen can unlock cheap synthetic fuels because hydrogen is a key input to produce net zero synthetic fuels.[32] Captured carbon dioxide could be converted to carbon monoxide, or used directly, and combined with hydrogen to produce synthetic fuels using the Fischer-Tropsch process.[33] Key innovations to unlock cheap hydrogen production from a variety of sources include further cost reductions in electrolysers, and innovation across natural gas reforming, coal gasification, and CCS (as described in the Hydrogen and CCUS sub-themes).

Innovation is required throughout the value chain to produce cheap low-carbon hydrogen and synthetic fuels. To access the new energy carrier scenario, innovation in hydrogen and synthetic fuel production must be accompanied by wider energy system innovations. For example, electrolyser innovation is insufficient for electrolysis to produce cheap hydrogen; cheap electrolysers must be coupled with broader low-carbon power innovations that deliver inexpensive electricity because energy input comprises most of electrolysis' costs.[34]

[30] BNEF (2019) Battery Power's Latest Plunge in Costs Threatens Coal, Gas https://about.bnef.com/blog/battery-powers-latest-plunge-costs-threatens-coal-gas/?utm_medium=Newsletter&utm_campaign=BNEF&utm_source=Email&utm_content=wirapril2&mpam=21051&bbgsum=DM-EM-04-19-M21051&elqTrackId=5c51379d3c9d4ad18f72571ef437f905&elq=a0a4fb73f0b840a9b90f475cbcf9ef59&elqaid=17630&elqat=1&elqCampaignId=9584

[31] BNEF (2018) New Energy Outlook 2018 https://about.bnef.com/new-energy-outlook/

[32] Agora (2018) The Future Cost of Electricity Based Synthetic Fuels: Conclusions Drawn https://www.agora-energiewende.de/fileadmin2/Projekte/2017/SynKost_2050/Agora_SynCost_Webinar_slides_Deutsch_and_Maier_20180516.pdf

[33] *The Economist* (2018) Synthetic fuels could help low-carbon aviation take-off https://www.economist.com/technology-quarterly/2018/12/01/synthetic-fuels-could-help-low-carbon-aviation-take-off

[34] Committee on Climate Change (2018) Hydrogen in a low-carbon economy https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf

Recognised final hydrogen and synthetic fuel demand is crucial to incentivise business investment. Uncertain final hydrogen and synthetic fuel demand may restrict business investment in key technologies because of rate of return concerns. If production is not scaled up, many key innovations in hydrogen and synthetic fuel production may not be accessed. For example, the Hydrogen and fuel cell sub-theme EINA report states that scale can drive important innovations in hydrogen production, including autothermal reforming. Without a clear demand signal, limited investment and scale production may inhibit overall innovation in hydrogen and synthetic fuel technologies and prevent the production cost reductions required to access the new energy carrier scenario. To overcome these final demand uncertainties, demonstration projects at significant scale are likely to be required, in coordination with projects which provide demand for the hydrogen produced.

The new energy carrier scenario requires high investment and innovation in energy infrastructure. If hydrogen is to meet peak intra-day electricity demand and peak winter heating demand, there must be further infrastructure investments and innovations in hydrogen storage. As discussed in the Hydrogen and fuel cells EINA sub-theme report, innovation in hydrogen tankers and novel material-based storage technologies are key innovation priorities to support this. Furthermore, to support demand, innovation in appliances, such as hydrogen boilers, and the gas grid will increase in importance.

A range of innovations will be required in end-use hydrogen and synthetic fuel technologies to establish high final demand. Along with cheap hydrogen and a mature hydrogen refuelling network, innovations that reduce the capital cost and lifetime of fuel cell systems are critical enablers of deep penetration of hydrogen power in FCEVs, shipping, stationary CHIP, and aviation. For example, innovation in polymer innovation electrolyte membrane fuel cells (PEMFC) can reduce FCEV costs and encourage their widespread uptake in heavy-duty vehicles. In shipping and aviation, synthetic fuels could be in high demand because of the weight of batteries and fuel cells and the ability of synthetic fuels to substitute for fossil alternatives in existing technologies.[35] Evidently, the new energy scenario requires innovation across a broad range of sectors and stages of the hydrogen and synthetic fuel value chains.

[35] *The Economist* (2018) Synthetic fuels could help low-carbon aviation take-off https://www.economist.com/technology-quarterly/2018/12/01/synthetic-fuels-could-help-low-carbon-aviation-take-off

Reduced emission reduction needs scenario

The most likely enabling innovations for the reduced emission reduction needs scenario are DACCS and a robust international offsetting mechanism. According to the Royal Society, in partnership with the Royal Academy of Engineering, GGR technologies, including DACCS, will be vital to achieving carbon neutrality by 2050.[36] Without high innovation and good mechanism design, DACCS and a robust international offsetting scheme are unlikely to be commercially realised. This will substantially limit the UK's greenhouse gas removal and prevent the lowering of emission reduction needs.

A range of innovations will be needed to drive the commercialisation of DACCS. There are pilot DACCS projects already in operation, with some processes, such as amine absorption, closer to commercialisation than others.[37] Continued innovation is essential if DACCS technologies can be practically applied and costs are to be reduced. Additionally, innovation that reduces or mitigates the high energy and heat requirements of DACCS technology will be vital to enable its widespread use.[38]

Investment in carbon storage must be coupled with innovation in DACCS technology to access the reduced emission reduction needs scenario. If the costs and feasibility of carbon storage remain too high, DACCS adoption could be restricted even if there is high innovation in DACCS technology itself. There is strong potential for innovation to reduce storage costs, for example by re-characterising abandoned old wells in the North Sea (see CCUS EINA). If storage costs reduce, this can reduce overall DACCS deployment costs, and help enable the reduced emissions reduction needs scenario.

Along with DACCS, the development of a robust international offsetting scheme can enable the reduced emission reduction needs scenario. The CDM under the Kyoto Protocol already allows industrialised countries to offset emissions by buying certified emission reduction credits in developing countries.[39] However, the CDM has been criticised because of a lack of climate benefits and the issuing of many credits for projects that would have happened anyway.[40] Therefore, there is a need for a more robust international offsetting mechanism that does have climate benefits and ensures good land management practices. Although a robust offsetting scheme will primarily rely on strong emissions accounting principles and monitoring,

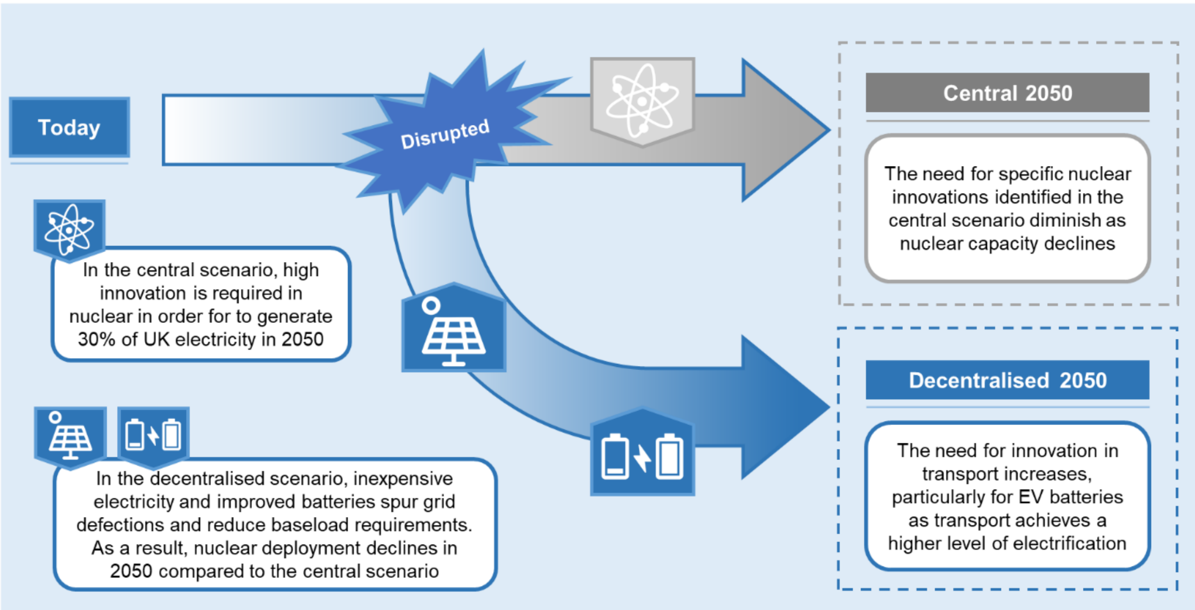
[36] The Royal Society (2018) Greenhouse gas removal https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf
[37] Ibid.
[38] Ibid.
[39] CDM website https://cdm.unfccc.int/about/index.html
[40] Carbon Market Watch (2018) The Clean Development Mechanism: Local Impacts of a Global System https://carbonmarketwatch.org/wp/wp-content/uploads/2018/10/CMW-THE-CLEAN-DEVELOPMENT-MECHANISM-LOCAL-IMPACTS-OF-A-GLOBAL-SYSTEM-FINAL-SPREAD-WEB.pdf

reporting, and verification processes, technical innovations such as the use of distributed ledgers for certification issuance are possible.

Impact of disruptive technologies on innovation priorities

Disruptive innovation affects the prioritisation of innovations across EINA sub-themes. This section considers how innovations identified in other EINA sub-themes may change priority as a result of disruptive innovation. For example, Figure 5 depicts how innovation in the decentralised scenario impacts innovation priorities in the Nuclear sub-theme.

Figure 5. **Example innovation disrupting EINA sub-theme prioritisation**



Source: Vivid Economics

This section considers how deployment levels are impacted in a disruptive scenario and how innovation priorities change in response. Table 8 ranks impacts from low to high for each scenario across sub-themes. A high impact rating indicates a substantial positive (↑↑) or negative (↓↓) impact on the need for innovation in a specific sub-theme as 2050 deployment increases or decreases. A low impact rating (→) indicates low impacts on the sub-theme as deployment remains essentially unchanged and a medium impact (↑ or ↓) rating indicates some impact on a sub-theme from a change in deployment.

When energy system disruption likely to highly affects a sub-theme, a description of the probable impacts is provided. For each of the four disrupted scenarios, a brief description is provided of the change in innovation priorities for key innovations in a sub-theme.

Table 9. **Impact of disruptive innovation on the EINA sub-themes**

Sub-theme	Automation	Decentralised	New energy carriers	Reduced emission reduction needs
Nuclear	↓	↓↓	→	→
Offshore Wind	↑	↓↓	↑	→
Tidal	↑	↓↓	↓	→
Heating & Cooling	↑	↓	↑↑	↓↓
CCUS	↓	↓	↑↑	↑↑
Bioenergy	→	↓	↑	↓
Hydrogen & fuel cells	→	↓↓	↑↑	↑↑
Building fabric	→	→	↓↓	↓
Industry	→	→	↑↑	↓↓
Transport (road)	↑↑	↑↑	↑↑	↓↓
Transport (marine and aviation) *	→	→	↑↑	→
Smart systems	↑↑	↑↑	↑	→

Note: **Marine and aviation is out of scope for the EINAs (and therefore not a sub-theme) but innovation could become significantly more valuable in the new energy carriers scenario, and hence a row is added*

Source: *Vivid Economics*

Automated scenario

Autonomous digital technologies increase the need for innovation in smart systems and aspects of heating and cooling, transport, and industry.

- **Heating and cooling:** A greater need for smart electrified heating, such as smart heat pumps, in the digital scenario.
- **Industry:** Greater innovation is needed in industrial DSR in order to improve electricity system flexibility. Autonomous vehicle technologies are also likely to lead to innovation spillovers that assist the automation of industry, ultimately increasing industry efficiency.
- **Transport:** Innovation is required in transport, particularly in autonomous vehicles capable of self-driving and self-charging. Innovations that improve battery energy density, such as next generation chemistries or advanced lithium ion improvements, are also a high priority in order to facilitate the electrification of MDV and HDVs.
- **Smart systems:** A digital scenario requires greater innovation throughout the technologies in the Smart Systems sub-theme, including flexible market platforms, aggregation services, demand-side response, battery storage, and vector coupling. Increasing learning by doing innovation efforts to trial and test consumer participation in flexible market platforms and V2G charging is crucial to reaching the levels of flexibility set out in the digital scenario.

Autonomous digital technologies decrease the need for innovation across generation technologies, particularly back-up generators.

- **Nuclear fission:** The need for innovation in nuclear declines as less nuclear capacity is required in the digital scenario.
- **Offshore wind:** The need for innovation in offshore wind, such as floating foundations, declines as less offshore wind capacity is required in 2050 with increased capacity available from decentralised sources.
- **Tidal stream:** The need for innovation in tidal is greatly diminished in the digital scenario as power generation capacity is lower.
- **Heating and cooling:** Smart heat pumps capable of heating during off-peak times likely reduce the need for innovation in decarbonised alternatives such as hydrogen boilers and hybrid heating systems.
- **CCUS (power):** Innovation in gas CCS is lower priority as the demand for seasonal balancing generation is reduced.

- **Industry:** The need for innovation in low-carbon substitutes is diminished as industry becomes more efficient from automation. This could also have a knock-on effect for the priority of innovation in low-carbon fuel production, such as bioenergy or hydrogen, consumed by industry.

Decentralised scenario

Disruptive decentralised technologies increase the need for innovation in smart systems and electrified transport.

- **Transport:** Innovation in mobile batteries is a higher priority in the decentralised scenario. Mobile battery innovations are likely to spill over to storage and vice versa. Key mobile battery innovations include solid-state technology and next generation chemistries**.** Innovations in the manufacturing of batteries at scale are also crucial to supplying radically improved mobile batteries at low cost**.** To take advantage of plentiful electricity in the decentralised scenario, battery innovations, and practically improved energy density to weight ratios, are higher priority for electric MDVs and HDVs. Innovation in advanced load-bearing structures is diminished as a result of the higher battery energy densities.

- **Smart systems:** A decentralised scenario requires greater innovation throughout the technologies in the smart systems sub-theme, including flexible market platforms, aggregation services, demand-side response, and battery storage.

Disruptive decentralised technologies decrease the need for innovation in large-scale generators and fuel cells. As distributed generators displace large-scale generators by 2050, innovations in large-scale generators become less important. This reduces the level of innovation need in the Nuclear, Offshore wind, Tidal and CCUS (power only) sub-themes.

- **Nuclear:** The need for innovation in nuclear declines as nuclear is outcompeted by inexpensive distributed generation.

- **Offshore wind:** Innovation in offshore wind, such as floating foundations, becomes a lower priority as the costs of distributed generation decline.

- **Tidal:** Innovation in tidal technologies is no longer necessary as tidal is outcompeted by distributed generation.

- **Heating and cooling:** Innovation in hybrid boiler systems and hydrogen boilers becomes a lower priority as electric heating (resistance heaters or heat pumps) coupled with home batteries outcompetes gas and hydrogen boilers.
- **CCUS (power):** The need for innovation in power CCS is greatly diminished.
- **Hydrogen and fuel cells:** The need for innovation in hydrogen fuel cells declines as high levels of electric light-, medium- and heavy-duty vehicles are deployed.

New energy carriers scenario

The new energy carrier scenario increases the need for innovation in the production of hydrogen and synthetic fuels and key final use technologies. Fuel cells have the greatest increase in innovation priority because heavy-duty FCEVs expand from minimal uptake in the central scenario to over 50% uptake in the new energy carrier scenario by 2050. However, widespread hydrogen and synthetic fuel demand substantially disrupt many sectors, and lead to increased innovation priorities across EINA sub-themes, as shown in Table 9, and below in more detail:

- **Offshore wind**: Innovation in offshore wind, such as deep-water wind turbine and fixed bottom, becomes a greater priority as electricity generation substantially increases to enable widespread electrolysis for hydrogen production.
- **Heating and cooling**: Innovation in hydrogen boilers, including burner technology, becomes a greater priority as cheap hydrogen enables widespread hydrogen boiler deployment using existing natural gas infrastructure.
- **CCUS**: Innovations across CCUS become more important, as the large-scale hydrogen production envisioned in this scenario will include significant hydrogen production from fossil and biomass feedstocks, requiring CCUS to ensure the hydrogen is low-carbon.
- **Hydrogen and fuel cells:** Innovation in CHP fuel cells and hydrogen storage becomes a greater priority as hydrogen is stored to meet peaks in heating and electricity demand.
- **Industry:** Innovation in industry to enable fuel-switching to hydrogen in, for example, the steel, cement, and chemical sectors, becomes a greater priority as widespread and cheap hydrogen contributes to industry decarbonisation.

- **Transport (road):** Innovation in PEMFC becomes a greater priority as FCEVs comprise over 50% of heavy-duty vehicle sales.
- **Transport (marine and aviation):** Innovation in synthetic fuel production becomes a greater priority as cheap synthetic fuels drive high uptake in shipping and aviation.

The energy carrier scenario decreases the need for baseload power and substitutes for hydrogen boilers, as set out in Table 9, and below.

- **Nuclear:** Innovation in nuclear power becomes a lower priority as high availability of hydrogen storage and CHP fuel cells reduces the need for baseload electricity capacity.
- **Heating and cooling:** Innovation in electric heat pumps becomes a lower priority as hydrogen boilers are widely adopted.
- **Building fabric:** Innovation in building thermal efficiency becomes a lower priority because lower electric heat pump uptake reduces thermal efficiency needs.

Reduced emissions reduction needs scenario

The reduced emission reduction needs scenario increases the requirement for innovation in carbon storage solutions and hydrogen production technologies. The greatest increase in innovation priority in the reduced emission reduction needs scenario is in CCUS because carbon captured from DACCS will need to be stored. The EINA sub-themes which have increased innovation priorities in the reduced emissions reduction needs scenario are:

- **CCUS:** Innovation in carbon storage, including post-closure Measuring, Monitoring, and Verification (MMV) and re-characterising legacy wells, becomes a lower priority as DACCS increases the needs for carbon storage.
- **Hydrogen and fuel cells:** Innovation in the Fischer-Tropsch process becomes a greater priority. This is because captured carbon dioxide from DACCS can, once combined with hydrogen, provide a route to synthetic fuels.

The reduced emission reduction needs scenario decreases the requirement for innovation in difficult-to-decarbonise sectors.

- **Industry:** Innovation in industry to decarbonise becomes a lower priority because DACCS and a robust international offsetting scheme can substitute for the most expensive and difficult decarbonisation activities.

- **Transport (road):** Innovation in low-carbon HDVs slows because DACCS and a robust international offsetting scheme can substitute for the most expensive and difficult decarbonisation activities in heavy-duty transport.

Business opportunities

Box 4. **Objective of the business opportunities analysis across the EINAs**

The primary objective is to provide a sense of the *relative* business opportunities against other energy technologies. Across other sub-themes, the analysis provides quantitative estimates of business opportunities from exports of innovative energy technologies and services.

Global energy system disruption can shift the business opportunities quantified in other EINAs sub-themes. Technologies that disrupt the UK's energy system are likely to be available internationally. For example, innovative low-cost DACCS can be exported globally as countries seek to meet net-zero targets. Therefore, disruption to the UK's energy system is expected to be replicated in other countries. This global disruption may drastically alter the market sizing of low-carbon energy technologies, and the export value available to the UK. In the case of the new energy carrier scenario, UK business opportunities may increase compared to the Hydrogen and fuel cells sub-theme because of strong fuel cell demand. However, UK business opportunities may also fall compared to the Heating and Cooling sub-theme due to lower electric heat pump demand.

Domestic deployment of disruptive technologies can shift the UK's international competitiveness. If disruptive technologies, e.g. hydrogen production and utilisation, are relatively more suited to the UK, these technologies can be more extensively deployed domestically than elsewhere. UK firms can leverage this greater domestic deployment to access further economies of scale and learning-by-doing effects, and gain a stronger competitive position compared to the central scenario. However, UK energy system disruption could also reduce domestic deployment of some technologies e.g. heavy-duty FCEVs in the reduced emission reductions needs scenario. This could lower UK international competitiveness.

Disruptive technologies can unlock business opportunities not available in the central scenario. For example, in the reduced emission reduction needs scenario, the export of DACCS represents a new business opportunity available to UK firms. Any business opportunities that shift in a disruptive scenario compared to the central scenario are not considered new opportunities. This distinction is made in Table 9, which sets out the two key channels that affect the change in business opportunities in a disruptive scenario. These channels are the new business opportunities created, and the shift in business opportunities in the disruptive scenario compared to the central one.

Table 10. **Business opportunity impacts**

Scenario	Business opportunity	
Automated	New opportunities	• Autonomous equipment, software and services and licensing of artificial intelligence intellectual property (IP)
	Key changes to other sub-themes	• Increase in opportunities across smart systems, including smarter markets, DSR, energy storage, vector coupling, and networks
Decentralised	New opportunities	• Solar PV panels and thin film, including components and IP
	Key changes to other sub-themes	• Increase in electric battery and electrolyser opportunities • Decrease in opportunities for FCEVs, and large-scale generators, including nuclear and tidal components
New energy carriers	New opportunities	• IP and expert advisory service opportunities in synthetic fuel production
	Key changes to other sub-themes	• Increase in opportunities for fuel cell components and expert advisory services in transport, and hydrogen boilers
Reduced emission reduction needs	New opportunities	• High-value DACCS technology and associated IP
	Key changes to other sub-themes	• Decrease in opportunities for both industry decarbonisation e.g. hydrogen-based furnaces, and building fabric, including pre-fabrication and services, as greenhouse gas removal mitigates the requirement for the most expensive retrofits of old buildings

Source: Vivid Economics and the Energy Systems Catapult

Policy opportunities

By their nature, disruptive innovations are generally hard to anticipate. As such, it is difficult to provide a list of market barriers and associated policy opportunities. However, there are broad policy principles which help enable positive disruptions.

Box 5. **The role of government in supporting innovation in disruptive technologies**

- Adaptive regulation ensures innovation activities are not obstructed and that emerging technologies and their application are covered by the regulatory framework. This often requires defined opportunities to reassess existing regulation and trail new disruptive business models. For example, in fintech, a 'regulatory sandbox' is used to introduce new products, free from some regulation, to a set of sample consumers.[41] Ofgem's Innovation Link is an example of a 'one stop shop' offering support on energy regulation to businesses looking to launch new products, services, or business models.[42]
- Clear long-term policy signals enable innovators to direct innovation towards meeting the needs of future consumers.
- Innovators need to be able to access finance to innovate and deploy at scale. By their nature, disruptive innovation processes are uncertain, iterative, and have the potential to fail, which conflicts with the short and predictable life spans of traditional private finance instruments.
- Government can improve the availability of high-quality data. Data supports innovation, but industry has limited understanding about individual benefits to data collection and sharing. Coordination failure means there is a role for government to establish frameworks, to ensure privacy and cyber security protocols are in place and to make relevant government-held data available.

[41] FCA (2015) Regulatory Sandbox https://www.fca.org.uk/firms/regulatory-sandbox
[42] See: Ofgem (n.d.) The Innovation Link https://www.ofgem.gov.uk/about-us/how-we-engage/innovation-link

Appendix 1: Organisations at expert workshop

- Deepmind
- Department for Business, Energy & Industrial Strategy
- IBM
- Imperial College London
- Oxford Martin, Programme on Integrating Renewable Energy
- The Alan Turing Institute
- University College London, Energy Institute
- Welsh Government

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