Energy Sector Innovation within Absolute Zero

Business growth in a transformative journey to zero emissions

UK FIRES

Energy Sector Innovation within Absolute Zero

UK FIRES is a 5-year research programme funded by £5m of UKRI support and the subscriptions of an active and growing industrial consortium. With academics from six universities spanning from materials engineering through data science to economics, corporate strategy and policy and an industry consortium spanning from mining through construction and manufacturing to final goods.

UK FIRES stands for placing Resource Efficiency at the heart of the UK's Future Industrial Strategy. When we proposed UK FIRES, it was to focus on Resource Efficiency as the key means to reduce industrial emissions. However, in 2019, both houses of Parliament unanimously approved a change to the UK's climate change act to target zero emissions in 2050. This has been reinforced by recent Government targets for 2030 and 2035.

UK FIRES takes a pragmatic approach: we focus only on technologies that are available to us today and exclude those that have yet to be proven at meaningful scale, since they simply may not be ready in time. In 2050 we aim to meet the energy demand of UK society by non-emitting electricity generation.

We would like to thank the Energy Research Partnership, whose members were an essential sounding board for our researchers during the process of writing this report. ERP is a public-private partnership seeking to guide and accelerate innovation in the energy sector to achieve Net-Zero through enhancing dialogue and collaboration. With a diverse range of energy sector stakeholders they aim to provide a reasoned and independent view, underpinned by industry, government and academic insight. Through a highly engaged membership, they are an open forum that seeks to inform debate, and help shape the Energy and Industrial strategy.

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Executive Summary

The UK's legal commitment to zero emissions by 2050 requires substantial growth in renewable electricity generation, but rapidly expanding demand is likely to exceed supply. In parallel to a £23bn/year supply-side opportunity, this report reveals nearly £200bn/year worth of largely untapped opportunities for energy sector business growth in efficiency improvement, time-shifting demand, electrification, and decommissioning.

Since 2010, the UK's non-emitting electricity supply has doubled, and with current commitments, the same linear rate of expansion is likely to continue to 2030 and beyond. This growth will be sufficient to replace all today's gas-powered generation, but will not be enough to meet future demand. As transport, space-heating and industrial processes are electrified, demand for emissions-free electricity will soon outstrip supply, and by 2050 we will have around 60% of what we would otherwise want.

This report reveals four substantial business growth opportunities created by this likely shortage.

Delivering energy efficiency in products and services will create a market of at least £37bn per year. This is dominated by the market for retrofitting 28 million homes in the next 28 years, to reduce their total demand through better insulation and other efficiency measures. Further opportunities for business growth from efficiency arise from the delivery of smaller, lighter electric vehicles, clustering local delivery services, and industrial energy efficiency improvements.

The greater reliance on renewable electricity generation means that electricity supply is increasingly intermittent, creating lucrative opportunities for time-switching demand. An annual market worth £109bn would be available if demand could perfectly shift to meet intermittent supply. This incentivises new systems for optimising the purchase of variable supply, time-shifting demand at domestic, commercial, and industrial scales and novel contracts for securing priority access to energy.

A further lucrative £42bn per year opportunity for electrifying the 75% of final energy demand that is currently directly met by fossil fuels is dominated by electrifying the two main scale uses of fossil fuels: cars (£34bn) and domestic heating (£5.5bn). Other key opportunities for electrification include electrifying the remaining 62% of the rail network that is not yet electrified, installing an overhead pantograph network to electrify long haul freight and installing induction hobs for domestic cooking.

The legacy of the fossil-fuel era has created a raft of redundant assets and infrastructure whose decommissioning or adaptation creates a market of around £8bn per year. The business growth opportunities include decommissioning assets with no further value such as power stations and the petrol/diesel supply chain, adapting existing assets, for example retrofitting electric powertrains and vintage cars with high attachment value, and re-conditioning the new assets of the emissions-free era, such as old wind turbines.

These new market opportunities occur in parallel with £23bn per year market for non-emitting electricity generation, operation, and maintenance.

The report draws attention to the reality that non-emitting electrical supply is unlikely to grow fast enough to match growing demand on our journey to zero emissions. The democratic processes of public consultation, negotiations on public finance, land acquisition, legal, environmental, health & safety and financial compliance all extend the already complex projects of installing large energy infrastructure and limit their rate of growth. Rather than hoping blindly that emissions-free electricity supply will expand to match any future demand, the report reveals how much opportunity there is for businesses to grow the products and services that are compatible with likely future restraint.

New markets worth £222bn

All energy electrified

Energy shortages

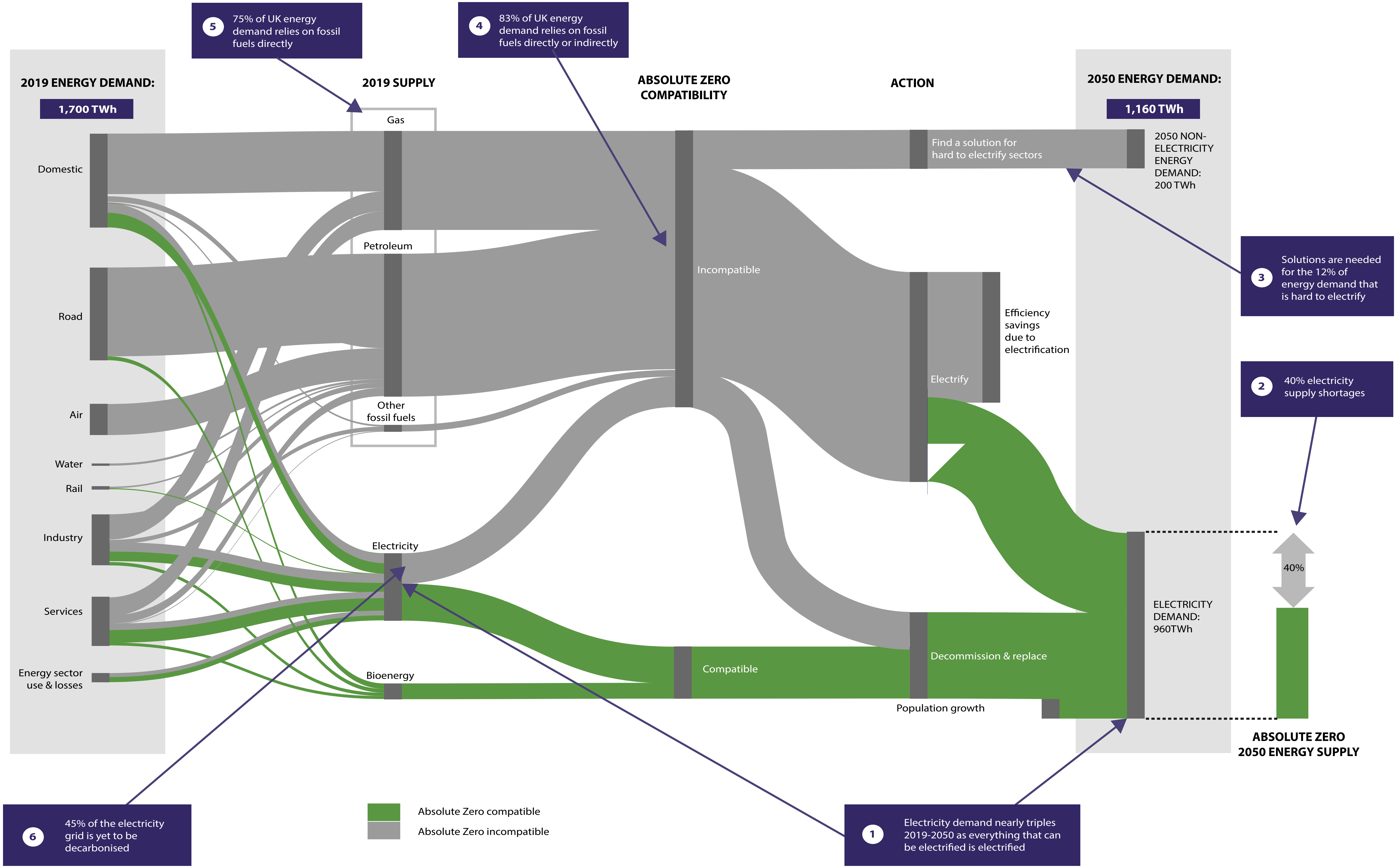


Figure 1: Overview of the energy sector transition to Absolute Zero

Overview of the Energy Sector transition to Absolute Zero

Absolute Zero Challenge

- No Carbon Capture & Storage (CCS) & hydrogen at scale
- Electricity demand triples as everything that can be electrified is electrified
- Unprecedented expansion in electricity generation capacity
- 40% efficiency improvement
- Any available CCS & hydrogen capacity prioritised for hard to electrify sectors

Market Trends

- High, time varying electricity price
- Intermittent supply and risk of outages especially in winter
- Customers value efficiency & embodied energy

Strategic Opportunities

- Efficiency
- Time-switching demand
- Decommissioning
- Electrification
- Generation

The Nature of the Transition

Over-reliance on uncertain carbon capture and storage (CCS) technologies increases the likelihood that net zero targets will be missed. Rather than relying on these breakthrough technologies, this report explores the energy transition to Absolute Zero (Allwood et al. 2019), finding business opportunities that use known technologies to meet needs within carbon constraints.

Without CCS at scale, demand for electricity is expected to almost triple as all energy demand that can be electrified must be electrified (See Point 1, Figure 1). Ambitious plans to increase renewable energy supply would meet 60% of Absolute Zero electricity demand in 2050 (Point 2, Figure 1).

This means that, as well as finding solutions for hard to electrify sectors (aviation, shipping, freight and high-grade heat in industry – currently responsible for 12% of energy demand (Point 3, Figure 1)), a 40% efficiency improvement is needed, on average across all applications, in the way that energy is used to meet needs (Point 2, Figure 1).

The transition to net zero calls for a direct change in the goods and practices that govern 83% of current energy generation and use in the UK (Point 4, Figure 1). This includes electrifying the three quarters of energy demand that is currently directly fuelled by fossil fuels (mainly transport and heating buildings (Point 5, Figure 1)) and decarbonising the remaining 45% of electricity generation (Point 6, Figure 1).

No aspect of current business practices will be unaffected by this transition and the resultant disruption to markets will see lucrative opportunities for companies that are able to anticipate these fundamental market shifts. Together the required changes will see markets worth at least £222bn per year expanding in the years to 2050.

Strategic Opportunities

Energy efficiency

Build & retrofit efficient homes; clustered local services; efficient electric vehicles; industrial energy efficiency

£40bn pa

Time-shifting demand

Match demand with intermittent supply via variable price contracts, SMART technology, priority access contracts and seasonal shifts in production.

£109bn pa

Electrification

Maximum electrification including electric cars, rail, pantographs, heat pumps, and industrial processes.

£42bn pa

Decommissioning

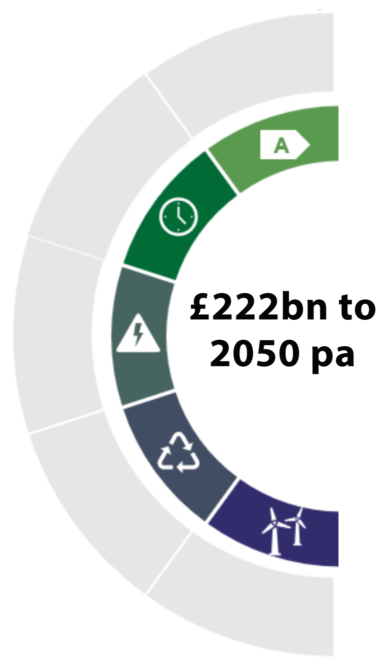
Decommissioning fossil fuel infrastructure; adapting vintage cars; reusing where possible.

£8bn pa

Generation

Zero carbon generation capacity, home/community level generation, AI optimised generation v. battery use

£23bn pa



Strategic Opportunities for the Energy Sector revealed by the Absolute Zero analysis

Energy Efficient Service Delivery

The Absolute Zero challenge:

- Energy efficiency, material efficiency and product service efficiency improvement measures must balance the 40% shortfall between supply and demand of electricity (Point 2, Figure 1).
- Efficiency and demand-reduction measures are needed to eliminate emissions from hard to electrify energy applications – shipping, aviation and high grade heat in industry – that currently account for 12% of energy demand (Point 3, Figure 1).

Resultant market trends:

- Shortages in zero carbon electricity increase prices, strengthening incentives for efficiency improvements across supply chains.
- Emphasis shifts from selling products to selling product services e.g. mobility not cars.
- Energy efficiency becomes a priority for customers buying houses, cars and appliances.
- Data and communication systems allow greater coordination reducing inefficiencies.
- International goods and passenger transport becomes a high-value, scare resource, increasing incentives to meet needs and use resources locally.
- Hybrid services emerge across traditional sector boundaries to exploit inefficiencies e.g. combined logistics, passenger services.

Analysis: Why does the Energy White Paper not foresee energy shortage?

Absolute Zero (Allwood et al. 2019) anticipates a 40% shortfall in zero carbon electricity supply in 2050. By contrast, the analysis underlying the Government's Energy White Paper (BEIS 2020) finds 3,360 unique low carbon deployment mixes that meet its electricity demand projections for 2050, with no mention of potential electricity supply shortages. Figure 2 shows the difference in the 2050 supply and demand projections across the two pieces of analysis. The figure shows that the greatest difference is on the demand- rather than the supply-side, with the Absolute Zero 2050 electricity demand projection 43% higher than the BEIS high demand scenario.

The Absolute Zero analysis assumes electrification of all energy demand apart from hard to decarbonise sectors, and projects current per capita demand forward to 2050 using population growth (See Figure 1). As electric devices are more efficient than their hydrocarbon-fuelled counterparts, a 60% efficiency saving is applied to processes that are electrified. This results in projected electricity demand of 960TWh in 2050.

The electricity demand projections underlying the Energy White Paper come from the UK TIMES model which is an optimisation model that allows for supply and demand-side responses. The demand projections are lower than the Absolute Zero demand projections as they assume incomplete electrification of industry, transport and heating and as they may also include a degree of demand-side response. The Energy White paper analysis looks at the balance between projected electricity supply and demand. This means that Energy White Paper scenarios that claim to exclude Carbon Capture and Storage (CCS) and hydrogen, implicitly assume that these technologies are available to decarbonise the remaining share of energy demand.

Instead, Absolute Zero assumes that all energy demand that can be electrified, is electrified in the absence of CCS at scale, and that solutions must be found for the remaining 12% of energy demand that is hard to electrify. This results in a clear statement on the magnitude of shortages to be addressed by demand and supply-side measures in the absence of CCS and hydrogen at scale: everything that can be electrified must be electrified, and electricity demand must be reduced by 40% in the absence of CCS at scale.

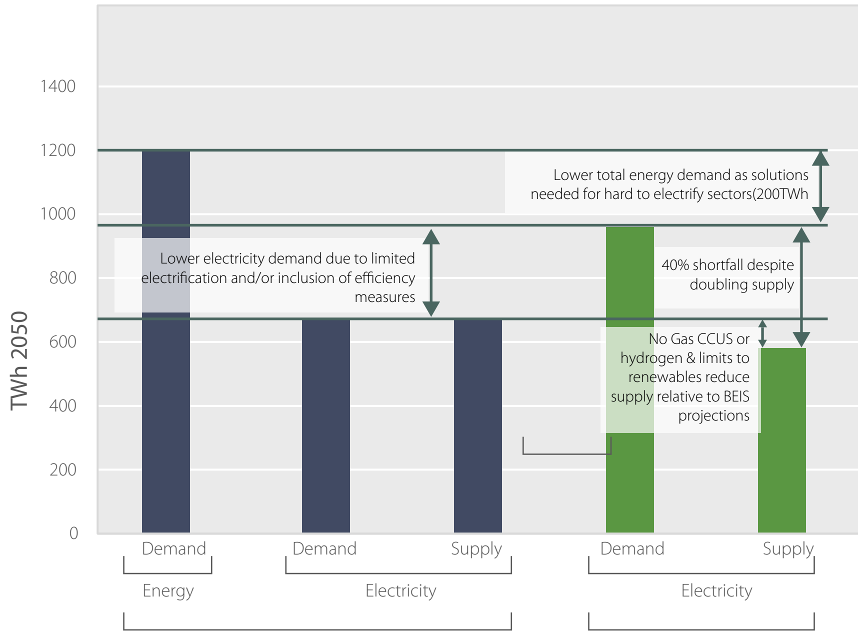


Figure 2: Comparison of electricity supply and demand projections

Strategic opportunity: Energy efficient product service delivery

1. Shelter and Comfort

Improving the energy efficiency of housing is key as it reduces winter peak energy demand when electricity supply shortages are most likely. This involves:

£1.6bn pa

expenditure on energy efficiency measures, passive cooling measures, water efficiency measures and flood resilience measures for the 5m new homes to be built by 2050

£17.7bn pa

expenditure on retrofitting the 28 million homes to at least EPC B

£763

savings in energy costs for the average household per year

23 yr

payback period for the average home retrofit project

For more on this see the UK Fires Construction Report

2. Mobility

Truly Efficient Electric Cars:

The average car is driven for 14 years before it is scrapped meaning that cars driven on UK roads are likely to be replaced twice before 2050. 99% of these cars are currently fueled by petrol or diesel. Each vehicle replacement is an opportunity not just for electrification but for energy efficiency:

45%

efficiency saving shifting from the least efficient to the most efficient electric car currently on the market

25%

further efficiency improvement possible by designing lightweight cars that focus specifically on efficiency

£14bn

annual fuel cost saving shifting the entire vehicle fleet from average efficiency electric cars to new lightweight cars designed for efficiency

Clustering local service deliveries:

Certain services, such as waste collection and postal services, are routinely organised so that particular local areas receive the service at set times/days to improve efficiency compared to serving each household on demand. Applying this principle more widely would mean:

40%

efficiency improvement in supermarket deliveries by clustering deliveries by postcode

£2.7bn

annual saving in last mile delivery costs

For more information on efficient mobility see the UK Fires Transport Report

3. Industry

Improving efficiency in industry through greater connectivity and smart automation could achieve:

30%

improvement in the energy efficiency of industry by 2050 resulting in a

£3.7bn

pa saving in industrial fuel costs

For more information on energy and material efficiency in industry see the UK Fires Materials and Manufacturing Report

EXAMPLE: HiyaCar

HiyaCar is a peer-to-peer car sharing website. Car owners register their cars and install a virtual car locking system (that also acts as a tracker). The platform allows vetted drivers to hire cars and provides insurance and road-side assistance. Car owners set the price and there is an option to set 'mates rates' to provide discounted hire (insured via the platform) to friends and family.

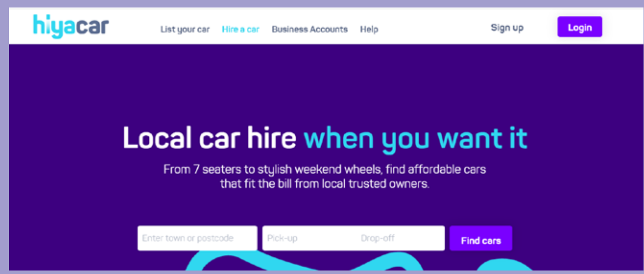


Image: www.hiyacar.co.uk

Managing a Scarce & Intermittent Energy Supply

The Absolute Zero challenge:

- Without the possibility to generate electricity from gas and store the carbon, there are fewer base load electricity generation options. Supply becomes more intermittent as the share of electricity generated by wind increases from 20% now to over 50% in an Absolute Zero compatible grid.
- The UK's transmission and distribution capacity will constrain supply, creating electricity shortages, particularly across seasons.
- Hydrogen supply is limited and prioritised for hard to decarbonise sectors.

Resultant market trends:

- With energy a scarce resource, and supply more intermittent, energy prices rise and time-varying energy contracts become more widespread.
- Real time communication of electricity prices and planned outages allows customers and SMART devices to optimise energy use relative to intermittent supply.
- A market emerges to secure priority access to electricity via transmission network clusters of priority energy users that are protected from rolling grid black outs.
- New contracts encourage seasonal shifts in industrial production to increase energy demand in summer and reduce energy demand.

Analysis: Will hydrogen solve the problem?

Hydrogen features heavily in the Government's Net Zero Strategy (HM Government 2021) and Energy White Paper (HM Government 2020), with the ambition to install 5GW of hydrogen capacity, delivering 42TWh by 2030. Hard to electrify sectors – including aviation, shipping and high-grade heat in industry – currently demand 200 TWh of energy (12% of total energy demand). If the current ambition for hydrogen capacity is delivered on time and target it would only meet a fifth of the demand from these hard to decarbonise sectors (equal to a 2.4% of total energy demand) in a third of the time from now until 2050.

Even this relatively modest ambition is unlikely to be met due to underfunding. The Net Zero Strategy commits £100m in 2023 to award contracts of up to 0.25GW of hydrogen capacity i.e. 5% of the total 5GW 2030 ambition. If this were an annual commitment (which it is not) it would take 20 years (i.e. until 2043) to deliver enough hydrogen capacity to meet the government 5GW ambition. Clearly there is no plan for delivering hydrogen for scale activities, such as domestic heating, and it is questionable whether there will be sufficient hydrogen capacity to meet energy demand from hard to decarbonise sectors from hydrogen by 2050 in the UK.

Even if hydrogen deployment could be dramatically increased after 2030, the potential role of hydrogen is limited in the absence of CCS due to the energy intensity of hydrogen production. Although there are many methods for producing hydrogen, all bar one, using electrolysis powered by renewable energy to split hydrogen from water, rely on CCS. This method, sometimes referred to as 'green hydrogen', is highly energy intensive. The IEA write 'Producing all of today's dedicated hydrogen output (69MtH2) [used mainly for fertiliser and applications in methanol and steel production] from electricity would result in an electricity demand of 3600TWh, more than the total annual electricity generation in the European Union' (IEA 2019).

Using hydrogen as an energy carrier to store excess electricity supply also carries a high energy penalty: less than a third of the original electricity input is conserved after converting electricity to hydrogen, shipping it, storing it, and then converting it back to electricity in a fuel cell (IEA 2019). Hydrogen production is tied to CCS either directly or indirectly as in presupposes abundant zero carbon electricity supply. In the absence of CCS at scale there is no Hydrogen at scale. To the extent that CCS and hydrogen capacity is available by 2050 they should be targeted for use in hard to decarbonise sectors that are required for the energy transition.

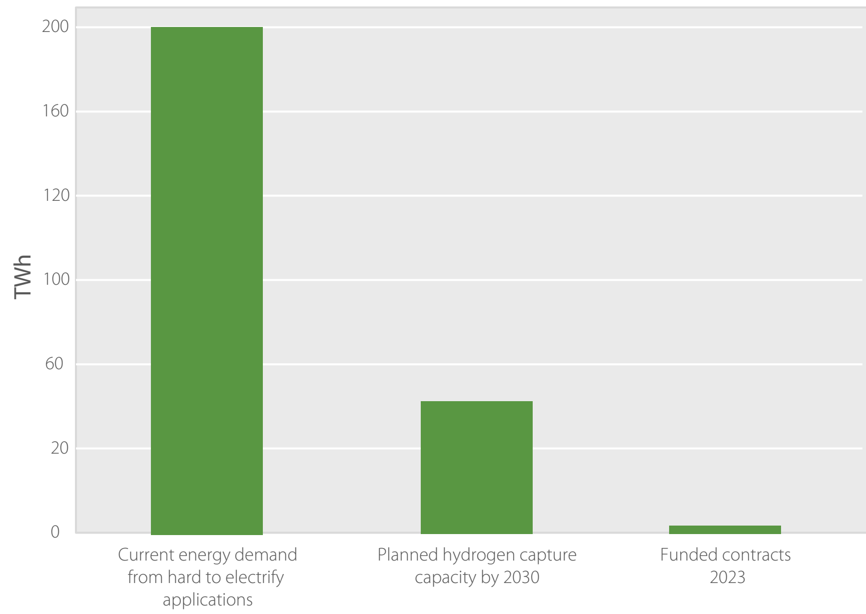


Figure 3: Planned hydrogen capacity relative to demand from hard to electrify sectors

Strategic opportunities: Managing scarce & intermittent energy supply

Total market opportunity

Wind farm operators are paid to stop generating electricity when demand is low. The potential market value of current excess ('curtailed') supply of wind energy over the course of the year is £1bn at current electricity prices. Operators are compensated £0.3bn for their lost output which could increase supply by 6%. As the grid shifts towards more intermittent electricity sources, curtailment increases disproportionately. By 2050, curtailed energy supply is likely to exceed 380TWh with a market value of £109bn all else being equal. This would be enough to cover the expected 2050 electricity supply shortage if demand could perfectly match intermittent supply patterns.

£109 bn pa

If energy-users could perfectly shift demand to meet intermittent supply, £109bn worth of excess energy could be sold.

Strategic opportunities that exploit this market include:

1. Time-shifting industrial production

EAF steelmaking plants operate 64% of the time

A side benefit of the electrification of steelmaking is that shifting from blast furnaces to electric arc furnaces (EAF) changes steelmaking from a continuous to a batch process. There are currently 5 operational EAF plants in the UK, but the UK generates enough scrap to justify 7-13 furnaces in total. Blast furnaces typically run continuously for 4-10 years, whilst electric arc furnaces run in 90min batches. Electric arc furnace could be operated more flexibly to take advantage of variable electricity prices, scheduling regular maintenance during peak energy demand times (17:00-19:00) and planning for more extensive maintenance during winter months and so reducing electricity costs that currently account for 8% of electric arc furnace steelmaking costs. Current EAF plants in the UK operate at 64% of full capacity (with 2.5Mt capacity installed, producing 1.6Mt in 2018) suggesting that there is a significant amount of downtime in steelmaking that could be used to help balance the grid.

2. Time-shifting household energy demand

Variable price contracts allow households to benefit from shifting energy-use to off-peak times, helping to balance the grid. SMART meters such as Nest can automatically make small adjustments to temperature settings to reduce peak electricity demand, saving 5-10% on heating costs. SMART home systems such as Home Connect can automatically take advantage of time varying prices e.g. by allowing householders to set a time that a laundry load has to be ready and using the software to cost-optimise the timing of when the machine should run.

The downside of variable energy price contracts is that they also expose customers to high energy prices at peak times. Greater energy shortages in the transition to Absolute Zero coupled with a more intermittent grid, could see a trend towards fixed price tariffs with variable incentives for time-switching. This would allow households to offer flexibility to capacity markets without fully exposing them to wholesale energy price fluctuations.

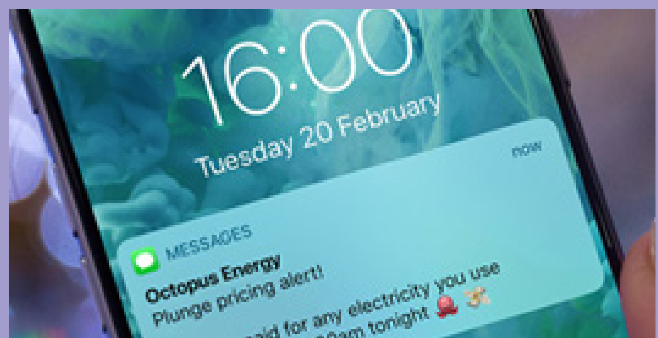
3. Planned outages and priority access

Planning and communication are key to managing the social and economic disruption caused by power shortages. Selective power cuts including rolling black outs (when power is temporarily cut in one area at a time to limit the duration of outages) and brownouts (when the voltage temporarily reduced) are used to avoid widespread power failure when demand for electricity exceeds supply. More frequent, systemic shortages under Absolute Zero increase incentives to cluster priority energy users on the same network circuit. Novel contracts could be used to allow energy-users to pre-book electricity supply, paying a premium to ensure that they are protected from power outages for a specified period.

The 'value of lost load' (VoLL) reflects willingness to pay to avoid energy shortages. The VoLL can exceed the energy price as it reflects the full value of activities that cannot take place in the absence of energy i.e. the cost of complementary inputs of production and the utility associated with energy services. Evidence that highest VoLL does not necessarily correspond with peak demand is promising in that it shows that energy use is not necessarily most valued at the times of peak demand (when shortages are most likely). A study of households in Ireland found winter peak demand at 5pm but VoLL twice as high at 8-9am as at the peak time on the same day.

EXAMPLE: OCTOPUS TARIFFS

Contracts such as the Agile Octopus tariff pay customers to use electricity when renewable energy supply exceeds demand.



EXAMPLE: PAPERMILL PROJECT

Centrica worked with a paper mill to install SMART wireless sensor technology to identify energy efficiency measures and manage flexible power loads to capture real-time wholesale market opportunities. The system identified energy intensive, time-flexible processes (in this case de-inking) that could be avoided during capacity market stress or at peak-time pricing. Clearly defined operating guidelines ensured that negative impacts on productivity and safety during capacity market stress were avoided.

In 2020 National Grid opened the Optional Downward Flexibility Management (ODFM) service to allow small scale renewable generators to reduce supply, and industrial producers to increase demand for energy in summer months. To date the paper mill has provided 50MW of flexibility to the capacity market and it is forecast that to generate over £3m through demand-side response over the 5 year contract.

Decommissioning

The Absolute Zero challenge:

- With no carbon capture and storage technology available at scale, there is no option to continue generating energy from fossil fuels, be it in power stations, cars, or domestic boilers. This means that all fossil fuel infrastructure, that currently directly or indirectly meets 83% of energy demand (Point 4, Figure 1), must be decommissioned, converted or mothballed until carbon capture and storage options become available at scale after 2050.
- Shortages in zero carbon energy supply preclude the use of energy intensive hydrogen for large scale applications such as domestic heating. This rules out repurposing the gas grid to supply hydrogen to households for heating before 2050.

Resultant market trends:

- Energy shortages increase the value of embodied energy, increasing incentives for remanufacturing and reuse of components, sub-assemblies and products.
- High electricity prices increase pressures to return to fossil-fuel-based energy sources. Actively decommissioning fossil fuel infrastructure acts as a commitment device, reducing options to renege on climate commitments.

Analysis: Forced or natural replacement cycles?

Part of the UK government approach to the net zero transition is to set regulations that ban certain goods or practices. This provides clarity on the nature of the transition required and catalyses change. Examples include the closure of coal-fired electricity generation, the ban on gas connections (for heating and cooking) in new build, and the ban on new petrol and diesel cars. The potential reach of regulations that apply to additions to stock (i.e. regulations that apply to new cars/new houses rather than all cars/all houses) depends on stock dynamics (i.e. the age profile of existing goods, the rate of replacement and the growth rate).

Figure 4 uses stock dynamics information to show the potential reach of a range of regulations. It helps to explain why the ban on new petrol and diesel cars was brought forward from 2035 (when it would be expected to cover 91% of cars in 2050) to 2030 (when it would be expected to cover 98% of cars in 2050). The figure shows that the upcoming ban on petrol and diesel vehicles will cover 98% of the stock of vehicles in 2050 through the natural cycle of replacing vehicles at the end of their useful lives. This is not the case for long-lived buildings where policies that apply to the existing stock are required.

Future legislation will have to force retrofit/replacement for long-lived assets that will not naturally be replaced before 2050.

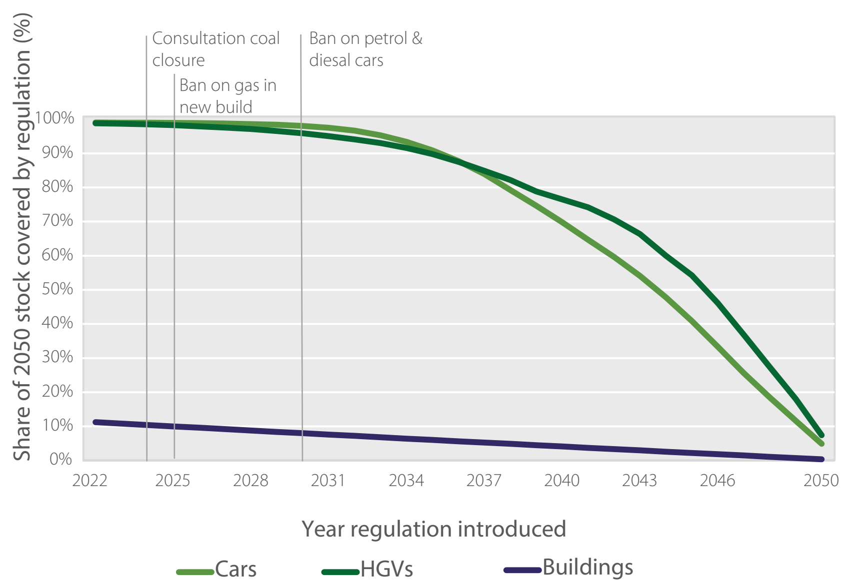


Figure 4: The reach of regulations that apply to additions to stock (UK Fires analysis)

Strategic opportunities: Decommissioning

1. Decommissioning fossil fuel infrastructure

High electricity prices due to supply shortages in the transition to Absolute Zero will increase pressures to return to fossil-fuel-based energy sources. Actively decommissioning of fossil fuel infrastructure acts as a commitment device, reducing options to renegue on climate commitments. This involves:

Power Stations

£4.7bn pa on decommissioning the existing nuclear and fossil fuel fleet of power stations.

Boilers and Gas Grid

£456m annual spending on decommissioning boilers in the 88% of homes that are currently heated with gas.

Petrol Stations

£18m per year spending on decommissioning storage tanks at the 8,380 petrol stations in the UK.

North Sea

£1.4bn-1.8bn annual spending on decommissioning oil and gas infrastructure in the North Sea.

2. Adapting Infrastructure

£690m pa

2% of vehicles are not expected to be replaced before 2050 (see page 17). These are long-lived vintage cars that carry a high attachment and cultural value. Retrofitting these cars with electric motors creates a market worth £690m pa from now until 2050.

3. Reusing Infrastructure

770 wind turbines are expected to be decommissioned over the next four years in the UK. Wind turbines are typically decommissioned after 20-25 years at a cost of 3-4% of total CAPEX. This equates to a total spend of approximately £173m per year on decommissioning wind turbines. Instead, offshore wind farms could be re-powered using new or reconditioned turbines and existing towers. Innovative companies such as Renewable Parts ltd work to remanufacture wind turbine components.

EXAMPLE: RETROELECTRIC

Retro Electrics fit electric motors to vintage cars charging £25,000 to retrofit a Beetle or £47,000 for a newly converted Electric Beetle.

Electrification

The Absolute Zero challenge:

- The key areas of energy demand that are currently directly fuelled by gas, petrol, diesel, and coal, including domestic heating, car travel and freight, must be electrified by 2050. This means electrifying the 75% of final energy demand that currently directly uses fossil fuels (Point 5, Figure 1).
- Solutions must be found to power hard to electrify energy applications, in particular high-grade heat for industry, aviation and shipping. Together, these applications account for 12% of current final energy demand (Point 3, Figure 1).

Resultant market trends:

- Electric devices are on average 60% more efficient than their fossil fuel powered equivalents, but in the past gas prices have typically been a fifth of electricity prices. How these relative prices evolve as electricity prices decouple from fossil fuel prices will be key to incentivising electrification.
- Key tipping points must be reached - e.g. in the installation of electric vehicle charging facilities and uptake of retrofit energy efficiency measures in homes – to enable widespread adoption of electric cars and heat pumps.
- With electricity prices high due to electricity shortages, and fossil fuels to be phased out by 2050, each purchasing and replacement decision (e.g. of a car, boiler or piece of industrial machinery) is an opportunity not just for electrification, but for switching to energy efficient options within the range of electric devices offered.

Analysis: The market penetration challenge

On the demand-side, the transition to Absolute Zero requires many disparate individuals to replace products with alternatives that are compatible with Absolute Zero. The current market share of these solutions is low: the share of current housing stock with an energy performance (EPC) rating of A or B is 1.4%, electric vehicles account for 1.1% of the vehicle fleet and heat pumps are installed in 0.8% of UK homes. Figure 5 puts the required change to 2050 in the context of past energy transitions.

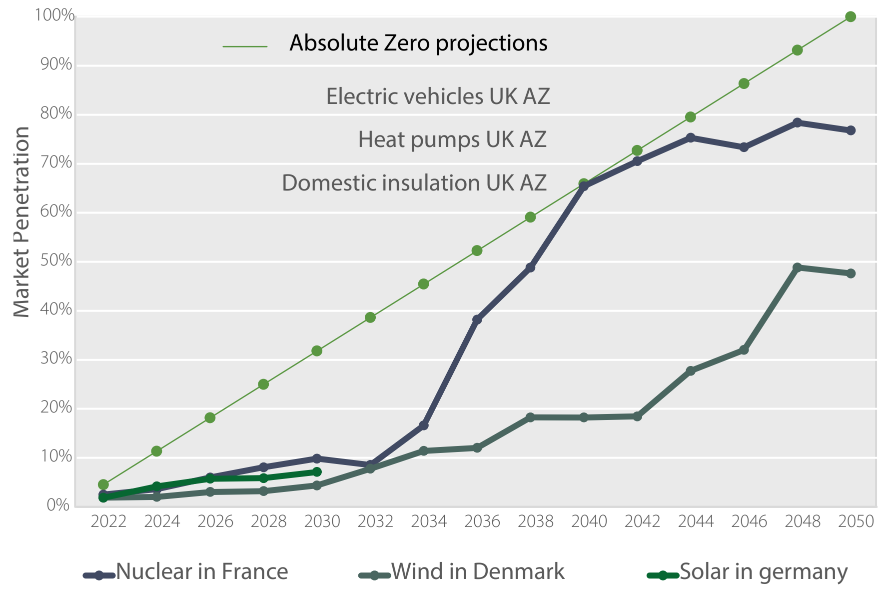


Figure 5: Past energy sector market penetration rates from 1% compared to Absolute Zero projections

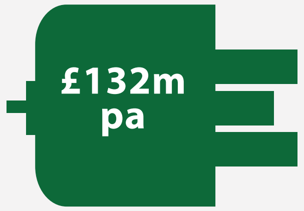
Strategic opportunities: Electrification

1. Maximum electrification of transport

There are nearly 40 million petrol and diesel cars on UK roads. Electric vehicles currently account for 1.1% of the total stock of vehicles registered in the UK. New cars, bought in the last year, account for 5% of the total stock of vehicles, and of these, 8.5% were electric vehicles. The average car is scrapped 14 years after it is manufactured meaning that there are at most 2 cycles of vehicle replacement between now and 2050 for the current vehicle fleet. Each vehicle replacement is an opportunity to switch to an electric drivetrain and to switch to as efficient a car as possible. The ban on sales of petrol and diesel cars in 2030 will cover 98% of the stock of vehicles in 2050 through the natural cycle of replacing cars as they get older (see page 17).

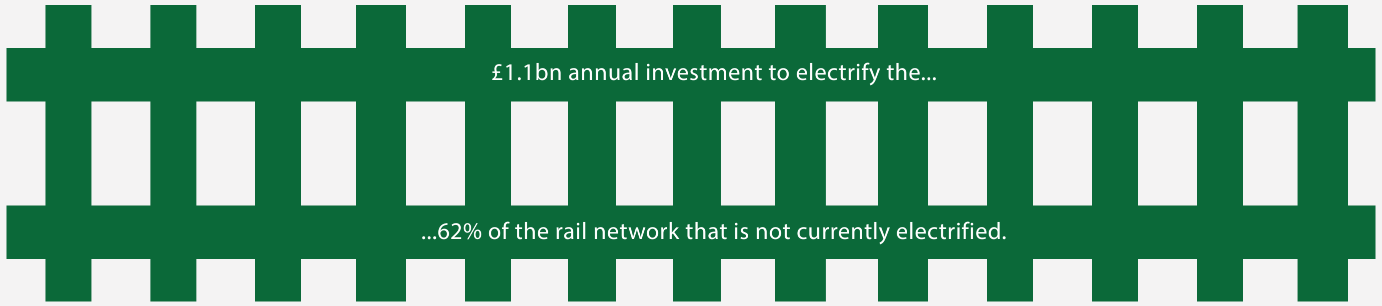
Electric Vehicles:

Replacing all current petrol and diesel cars with entry level electric vehicles values the electric car market at £954bn from now until 2050, equal to £34bn pa



£3.7bn investment in public charging points would power a fully electric vehicle fleet by 2050.

Rail Network Electrification



38% of the 15,900km rail network route length is currently electrified. The unit cost of rail electrification schemes varies greatly depending on the amount of clearance work required (typically accounting for 30-40% of costs) and on other factors such as power and signalling requirements. Past costs (excluding clearance) have varied from £350,000 per single track kilometre to £2.5m per single track kilometre. This demonstrates the potential cost reductions of learning-by-doing and exploiting economies of scale.

Overhead pantographs for freight

£700m pa

investment in overhead pantographs to electrify the...

65%

of freight that is classed as long haul.

£19.3bn total investment would electrify the 65% of freight that is long hauled using overhead cables to supply lorries with electricity. Pantographs are the only viable option for decarbonising long haul freight given the expected shortages in hydrogen availability (see page 13). The investment in pantograph-electric vehicles by fleet operators is estimated to pay back within 18 months due to lower energy costs. Investment in electrification infrastructure including catenary cables and substations is expected to pay back in 15 years making the system self-sustaining with private finance.

Electrifying Domestic Energy Use

Moving away from fossil fuels means replacing heating systems and cooking appliances in most UK homes. This includes:

£5.5bn

annual expenditure on replacing heating systems in the...

92%

of homes that are currently heated with fossil fuels.

£196m

annual expenditure on induction hobs by the...

61%

of households that cook with gas.

Electrification of industry

£857m pa

To supply high and moderate temperature electric industrial heat through specialised plasma-based or electrode-based heating, industrial heat pumps and other low temperature process heat solutions.

For more on this see the UK Fires Materials Report

EXAMPLE: Riding Sunbeams

Riding sunbeams aim to power railways with direct-wired renewable energy. This saves on the conversion from direct to alternating current (for grid distribution) and makes use of the existing rail distribution network reducing connection costs for distributed renewable energy generators.

EXAMPLE: CES / Siemens

A collaboration between Continental Engineering Services (CES) and Siemens Mobility is testing overhead pantographs for freight on three public highways in Germany.

Generation

The Absolute Zero challenge:

- Available carbon capture and storage capacity is prioritised for hard to decarbonise core activities that are key to the transition to zero emissions. This means that there is no CCS capacity available for electricity generation and that generating electricity from fossil fuels must stop by 2050.
- Electricity demand nearly triples (Point 1, Figure 1) as all applications that can be electrified must be electrified in the absence of other decarbonisation options.

Resultant market trends:

- With electricity prices rising and availability limited, households and communities seek to generate their own electricity.
- New investment instruments emerge to finance the unprecedented expansion of electricity capacity to 2050.
- Technology enabled contracts help to optimise home generation/battery use/ grid imports to capitalise on time-varying electricity prices.

Analysis: Can we build more zero carbon electricity capacity?

Nobody wants to prescribe a precise energy mix for 2050 for fear of 'picking winners' in a sector where levelised costs have defied expectations over the last decades. Nevertheless, it is helpful to describe particular zero carbon electricity deployment mixes, in order to explore the physical implications of the energy transition and to put the transition in the context of past changes. Figure 6 puts the scenario from the BEIS Energy White Paper analysis that is closest to the Absolute Zero scenario, in the context of past annual additions to capacity and highlights the unprecedented scale of the transition required.

The recently published Net Zero Strategy (HM Government 2021) failed to set out how a transition of this magnitude will be achieved. For example, the strategy anticipates that emissions-free electricity generation in the UK will more than double between 2030 and 2035 (from 229 to 505 TWh/yr p.325) with no description of how this will happen. Even if the government plan to approve a new nuclear power station by the end of the parliament is successful, and it is deployed and built faster than the similarly sized Hinkley C (14 years from the grant of licence to generation (expected in 2026)), then the new 3.2GW nuclear plant will generate 24TWh zero carbon electricity/year, less than 9% of the assumed increase in zero carbon capacity 2030-2035.

Given this lack of clarity and funding constraints, the Absolute Zero analysis takes a more conservative approach, assuming that current linear rates of growth of renewable energy are continued (Allwood et al. 2019) resulting in sufficient electricity supply to meet 60% of demand. The additions to electricity generation capacity outlined in Figure 6 would meet 70% of Absolute Zero projected electricity demand in 2050. Given the unprecedented scale of the transition required, and the time take to plan, approve, fund and build large scale energy generation infrastructure, it is highly unlikely that that energy shortages foreseen by the Absolute Zero analysis can be bridged through supply-side generation expansion in addition to that already set out in government policy.

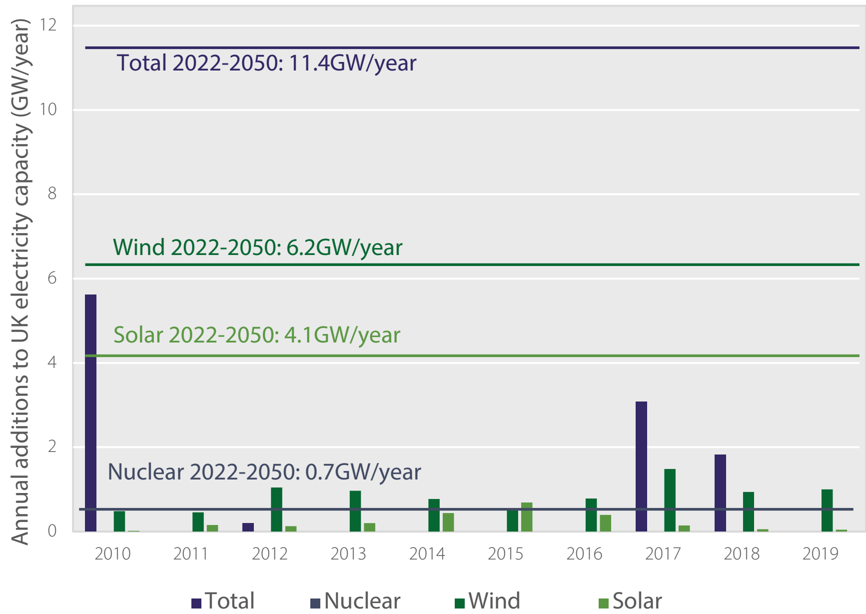


Figure 6: BEIS Min Firm Low Carbon 2050 Scenario capacity assumptions compared to past capacity additions

Strategic opportunities: Generation

Overall capacity requirements

Zero Carbon Energy Supply

Unprecedented growth in renewable and nuclear electricity generation in the UK is required in the 28 years to 2050. By way of example, this could include £22.8bn pa investment made up of:

£3.7bn pa

investment in nuclear capacity equal to 5.2 times Hinkley C capacity to supply 20% of electricity in 2020

£1bn pa

in planning and pre-devlopment of wind infrastructure

£8.3bn pa

in construction of offshore wind

£2.1bn pa

in construction of onshore wind

£7.7bn pa

in wind operations and maintenance costs

EXAMPLE: SIEMENS GAMESA

The UK is the largest producer of offshore wind globally. The Siemens Gamesa offshore wind factory in Hull is at the forefront of this effort, and is currently building the 165, 8MW turbines for the nearby Hornsea Two project.

Image: Siemens Gamesa

Strategic opportunities to deliver these capacity requirements include:

1. New financing methods to secure future zero carbon energy supply

Even with the expansion of zero carbon electricity generation capacity outlined above, as demand for electricity nearly triples there will be electricity shortage in 2050 (Point 2, Figure 1). Currently there is no futures market for zero carbon electricity to 2050 that reveals this shortage. This means that companies can reach for convenient solutions in their net zero strategies – including switching to zero carbon electricity – without considering the aggregate availability of these resources at scale. Creating a market for long term (15-30 year) Zero Emission Resource Purchasing Agreements (ZERPA) would provide price certainty for investors and would allow purchasers to secure access to future zero carbon resource (Nelson, Low, and Allwood 2021). This proposal effectively allows demand-side competition into current Contract for Difference auctions and so serves as a better mechanism for revealing future shortages.

For more on this see the UK Fires ZERPAs Report

2. Technology enabled distributed generation

Rising electricity prices as future scarcity becomes apparent to the market incentivise householders and communities to take electricity supply into their own hands. Domestic scale solar generation currently accounts for 92% of installations and a fifth of current UK solar output.

Bulk purchasing schemes, such as the Cambridgeshire Council Solar Together scheme, that allow householders to register to bulk buy solar panels from accredited suppliers, reducing search costs and information barriers.

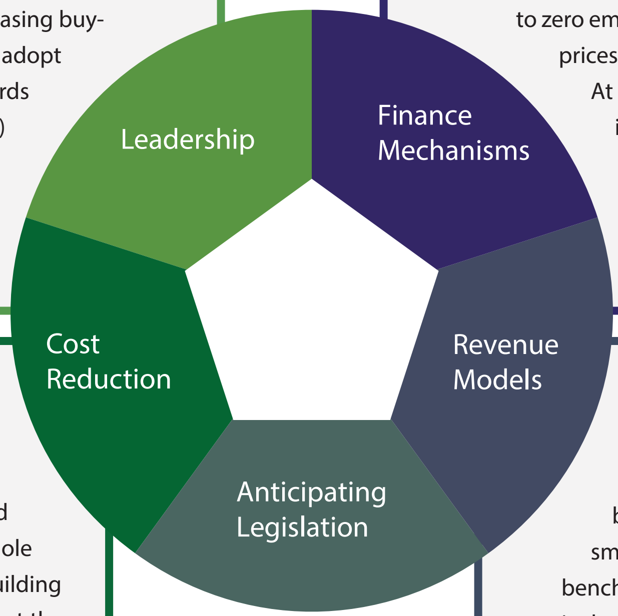
70%

Energy Local Clubs that allow communities to save the 70% price difference between the price typically paid to households for supplying energy to the grid, and the price paid by households to buy electricity back from the grid, by selling each other energy and encouraging matching supply and demand locally.

4x ££

Novel contracts such as those offered by the Social Energy Hub, that use AI to learn household energy use patterns and optimise household battery use, pay 4 times as much as standard contracts for every unit of electricity sold back to the grid.

Exploiting the Opportunity



Leadership

Tesla led the electric car market with **aspirational** cars, weathering 18 years of losses before becoming one of the highest valued companies. Could aspirational products lead the Absolute Zero transition in other sectors? Energy users tend to be divided into two groups: those who **don't care** about energy efficiency and those who **can't afford** energy efficiency measures. To the extent that household energy-using goods are differentiated by status, more aspirational options tend to be more energy intensive (e.g. over-powered hoovers and American-style fridges) marketed to the 'don't care' customer segment. Leadership from the entertainment industry – running climate change **storylines** in soap operas and Grand Designs style **retrofit programmes** - helps to **shift the narrative**, increasing buy-in to action from those who can afford it and raising awareness of options, just as the Archers encouraged farmers to adopt modern farming methods in the 1950s. Home energy efficiency could become aspirational, even to the rich, as it affords **autonomy** in the face of constrained energy markets (recent fuel shortages saw drivers (regardless of spending power) in long queues at petrol stations). Mass buy-in from those who can afford these measures would reduce costs for those who care about energy efficiency but are currently priced out of the market. SMART meter **benchmarking** between households and even **social media sharing** options could be used to demonstrate energy efficiency leadership by householders with a competitive nature and eagerness to share (in the style of Wordle scores).

Finance mechanisms

Like the transition to Net Zero, the transition to Absolute Zero requires billions of pounds worth of investment in zero carbon electricity. Funding mechanisms such as the **Contract for Difference and the Regulated Asset Base (RAB)** model are being used to de-risk renewable and nuclear electricity generation projects, lowering the cost of capital, and so stimulating investment. The concern is that the resulting investment will deliver insufficient zero carbon electricity supply to meet demand in 2050. A market for **Zero Emissions Resource Purchasing Agreements (ZERPAs)** would reveal any future scarcity to the market, by allowing buyers to secure future access to zero emissions resources (zero carbon electricity, biomass and negative emissions) at a price agreed at auction. Higher auction prices would indicate shortages stimulating further investment and incentivising a coordinated demand-side response. At the household and industrial level, the Absolute Zero transition involves many disparate individuals making upfront investments in energy efficiency and electrification. **Energy Service Companies (ESCOs)** enable customers to pay for today's upgrade with tomorrow's savings through **shared savings or guaranteed savings contracts** that either offer finance directly or help to arrange finance (at a reduced cost due to guaranteed savings).

Cost reduction

The cost of wind energy has halved over the last five years and solar energy has seen similar cost reductions. **Economies of scale** of this magnitude are less likely for less standardised applications such as housing retrofit and rail electrification, however, **mass customisation** techniques could be used to reduce costs e.g. by identifying a whole system retrofit solution for a particular type of building, actively marketing this solution to owners of this type of building and exploring **bulk purchasing agreements.** Intermittent energy supply in the transition to Absolute Zero means that there are times of energy abundance as well as shortages. This presents an opportunity for **cost reduction through time-switching demand**, with variable contracts paying energy users to use electricity at peak supply times in order to reduce pressure on the grid. Software and AI can help to automate time switching as well as learning energy habits and cost-optimising decisions such as grid v. battery use.

Revenue models

Due to high gas prices and energy price caps, energy companies are currently losing money for every unit of electricity sold. This incentivises companies to help their customers invest in energy efficiency measures, effectively becoming **suppliers of comfort rather than of energy**. Many energy companies already provide their customers with smart meters, including more sophisticated models that can be used to alert customers to higher than usual bills and benchmark the efficiency of devices helping to identify potential savings. These types of schemes could be extended to include other efficiency measures such as retrofit. In the face of the high energy prices expected in the transition to Absolute Zero, this would help **energy providers position themselves as part of the solution** (providing comfort) rather than the problem (charging high energy prices). More generally, service models including **conventional and distributed (e.g. Airbnb) leasing** can help to improve product service efficiency by selling underutilised resources (spare rooms, parked cars, unused holiday homes, spare seats in car journeys) and so generating revenues whilst improving efficiency and displacing purchases that carry high embodied energy.

Anticipating legislation

The current approach to dealing with fuel poverty due to high energy prices involves using deferral mechanisms to spread high costs over multiple years. The structural (long term) energy shortages expected over the enxt 30 years mean that these types of **deferral mechanisms** cannot be used. Energy companies can avoid **exposure to fuel poverty measures** by helping customers install energy efficiency measures and so reducing their **regulatory risk**. The UK government has introduced a series of bans, set ahead of time to warn industry of the planned transition. Examples include the ban on coal-fired electricity generation, the ban on petrol and diesel vehicles, and the ban on gas connection in new build. These policies align with the natural replacement rates of assets or apply to new purchases, however additional policies will be required for long-lived assets such as the 80% of buildings in 2050 that have already been built. Here deep changes in **energy performance requirements** are inevitable if climate change commitments are to be met. **Early action** on energy efficiency means more years with lower energy costs. Mortgage providers may also be implicated as increased costs (both direct energy costs, and the cost of retrofit measures) increase the likelihood of defaults. This could incentivise **green mortgages** with preferential rates for those who have already met efficiency standards.

Absolute v. Net Zero policy

The Net Zero policy narrative tends to switch from supply-side optimism (that sees many different possible technology-led transition scenarios to reach net zero in 2050) to defeatism (without these technologies the target cannot be met, and the Climate Change Act will be revoked). Absolute Zero opens-up a discussion between these two extremes, exploring the opportunity for a coordinated demand-side response, that reimagines the way that we harness natural phenomena to meet human need, using existing technologies and novel combinations of the assemblages that make up these technologies (Arthur 2009). In the energy sector, the required transition is effectively two-fold: moving to zero carbon energy sources (for the 80% of UK energy demand that is currently fuelled by fossil fuels) and reducing demand for these resources to align with available supply. Government policy must tackle these dual objectives simultaneously, encouraging efficiency improvements alongside shifts in energy source and accounting for aggregate supply-side constraints. Implementing Absolute Zero across energy-using supply chains will require several policy interventions in addition to the current Net Zero strategy:

Policy mechanism	**Current Net Zero Strategy**	**Additional actions to support Absolute Zero**
Public finance mecha-nisms and subsidies	Contract for difference for renewable energy; Regulated Asset Base model for nuclear power; industrial funds for CCS & hydrogen	Create ZERPA market to fund and allow trade in future zero emissions resource capacity and reveal any future shortages early Focus available public sector CCS and hydrogen funding on sec-tors that have no other options and are key to the transition Subsidies to support the introduction of newly electrified heat Innovation funding for high grade EAF steelmaking Government-held ZERPAs to secure access to energy for fuel poor households National bulk purchasing and mass customisation plan for retrofit of social housing Incentives for energy companies to co-fund home retrofit for fuel-poor households
Markets & taxation	New UK ETS to be aligned with net zero	Ensure that primary and secondary steelmaking face the same carbon price Border adjustments to replace the free allocation of ETS permits to avoid carbon leakage and strengthen incentives for down-stream material efficiency and energy efficiency Re-balance VAT to favour asset maintenance over replacement Export duties to match landfill tax to encourage domestic recycling and use of steel scrap Fuel duty on air travel to be raised in the first instance through a frequent flyer tax
Regulation & standards	ICE car ban, ban on gas connection new build, ban on coal fired electricity generation	Add efficiency standards to the internal combustion engine car ban Phased in EPC retrofit standards applied at point of change in ownership/tenancy Rules on changing energy supplier if supplier has part-funded retrofit Phased ban of non-electric heating systems Non-linear energy price caps to promote energy efficiency Product efficiency standards in line with or ahead of EU Right to repair standards Product disassembly standards to allow separation of copper and tin from steel recycling streams Ban on short haul flights that compete with train connections (as in France and Austria) Specification of Best Available Technology for electrification of industry Part Z building regulations on embodied emissions
Crisis management	BAU bailouts	Bail-outs conditional on credible Net Zero transition plan that takes into account aggregate availability of zero emissions electricity, biomass & CCS Steel industry transition plan to EAF steelmaking Promotion of domestic production in anticipation of shortages in international shipping and freight
Monitoring, reporting & verification	International MRV	Report UK zero emissions electricity, carbon capture and stor-age, biomass and hydrogen capacity compared to total energy demand annually as well as projections (stating share that is funded) Corporate net zero reporting to state share of emissions reductions that come from each of the three zero carbon emissions resources and efficiency improvements Material flow mapping of key materials to inform material efficiency strategy
Planning & Permissions	Various policies	Fast track planning for rail electrification as part of 'Project Speed' No more airport expansion No more coal mining justified by coke for steelmaking
Local government	Various policies	Conservation area guidance to allow for solar panels and insulation cladding Coordinate neighbourhood led retrofit bulk purchasing agreements and ESCOs Revisit rules on heat pumps distance to property boundary (1m from boundary in England and Scotland, 3m in Wales and 30m in Northern Ireland) Community heat networks and energy generation

Supplementary Information

Energy efficient service delivery			
New builds:			
Measure	**Value**	**Units**	**Source**
New homes to be built by 2050 [1]	5	M homes	UK Fires analysis
New build heating system cost: space heating demand 15kWh/m2/year; passive cooling; water efficiency; flood resilience [2]	8,900	£/home	CCC (2019)
Cost of efficiency measures in new build [3]	45	£bn	[1]*[2]/1,000
Years to 2050	28	years	
Market for efficiency measures in new build	1.6	£bn/yr	[3]/[4]
Retrofit Housing Stock:			
Share of dwellings energy rating A/B [1]	2%	Share dwellings	English Housing Survey 2020-2021 Table DA7104
UK housing stock [2]	28.5	M dwellings	[2]*(1-[1])
Dwellings to be improved [3]	28	M dwellings	
Cost to upgrade to EPC B [4]	17,700	£/home	Environmental Audit Committee (2021) cost per home of pilot in Leeds
Cost of retrofitting to EPC B [5]	495	£bn	[3]*[4]/1,000
Current average heating demand [6]	145	kWh/m2/year	Mitchell & Natarajan (2020)
Heating demand retrofitted house [7]	15	kWh/m2/year	CCC (2019)
Average dwelling size [8]	80	M2	Property Reporter (2021)
Household gas price 2021 [9]	7.37	p/kWh	British Gas (2022)
Average saving per year of retrofit [10]	763	£/year	([6]-[7])*[8]*[9]/100
Payback period	23	years	[5]/[10]
Years to 2050 [11]	28	years	
Annual market for retrofit	17.7	£bn/yr	[5]/[11]
Efficient Electric Cars:			
Least efficient electric car currently available [1]	430	Wh/mile	Electric Vehicle Database (n.d.)
Most efficient electric car currently available [2]	235	Wh/mile	Electric Vehicle Database (n.d.)
Average efficiency electric cars UK [3]	313	Wh/mile	Electric Vehicle Database (n.d.)
Possible efficiency lightweight electric car [4]	177	Wh/mile	UK Fires Transport report
Additional saving due to lightweighting	25%	Share of current max efficiency	([2]-[4])/[2]
Miles driven on GB roads [5]	357	bn miles	Department for Transport (2020)
Electricity price [6]	0.28	£/kWh	British Gas (2022)
Fuel saving shifting fleet from average efficiency to efficient lightweight car	14	£bn/yr	([3]-[4])*[5]*[6]/1000
Grouped Deliveries:			
Reduction in CO2 emissions due to supermarket deliveries with slots randomly assigned relative to hh driving to the supermarket [1]	45	%	(Wygonik and Goodchild 2012)
Reduction in CO2 emissions due to supermarket deliveries with slots assigned by postcode relative to hh driving to the supermarket [2]	86	%	(Wygonik and Goodchild 2012)
Additional savings due to assigning postcodes [3]	41	%	[2]-[1]
Value of UK courier and express delivery market [4]	12.6	£bn	Mintel (2019)
Share of delivery costs due to last mile [5]	53	%	Business Insider (2022)
Cost savings last mile delivery by allocating postcodes	2.7	£bn	[4]*[5]*[3] assuming other cost savings are proportional to emissions savings
Industry:			
Global industrial energy demand 2050 [1]	260	EJ	IEA (2021) p56
Savings due to efficiency improvements & behaviour change 2050 [2]	80	EJ	IEA (2021) p56
Efficiency saving [3]	30	%	[2]/[1]
Annual industrial energy expenditure UK 2019 [4]	12.2	£bn	UK Fires analysis based on ONS (2021) and ECUK (2020)
Annual fuel cost savings	3.7	£bn	[3]*[4]

Intermittency & shortages			
Excess supply:			
Curtailed excess wind output 2019 [1]	3.8	TWh	Electric Insights (2020)
Household electricity price [2]	0.28	£/kWh	British Gas (2022)
Current value of curtailed supply	1	£bn	[1]*[2]
Minimum expected curtailment under Absolute Zero all else being equal [3]	380	TWh	(BEIS 2020b) curtailment expected in BEIS scenario closest to Absolute Zero constraints: BEIS High demand, 5g/kWh, 2 GW Gas CCUS, 25GW nuclear
Value curtailed excess supply under Absolute Zero 2050	109	£bn	[3]*[2]
Electricity demand Absolute Zero [4]	960	TWh	Figure 1
Share of demand that could be met if curtailed supply fully exploited	40%	Share of 2050 demand	[3]/[4]*100%
Time-shifting steelmaking			
UK steel production 2018 [1]	1.6	Mt	
UK steelmaking installed capacity 2018 [1]	2.4	Mt	
UK steelmaking capacity utilisations	64%	Share of installed capacity	[1]/[2]*100%
Priority access			
Value of lost load 8-9am compared to peak time on the day of highest electricity demand in Ireland	2	Multiplication factor	(Leahy and Toll 2011)

Electrification			
Electric cars:			
Vehicle stock 2020 [1]	38.6	M vehicles	Department for Transport (2021)
Stock of ultra low emissions vehicles (ULEV) registered UK [2]	432,000	vehicles	Department for Transport (2021)
ULEV share of vehicle stock [3]	1.1%	Share of stock	(ULEV stock/total vehicle stock)*100%
Entry level electric car price [4]	25,000	£/car	https://www.edfenergy.com/for-home/energywise/cheapest-electric-cars-to-buy
Value of replacing all current petrol & diesel cars with electric cars [5]	954	£bn	[1]*(1-[3])*[4]
Years to 2050 [6]	28	years	
Annual electric car market to 2050	34	£bn	[5]/[6]
Charging facilities:			
Vehicle stock 2020 [1]	38.6	M vehicles	Department for Transport (2021)
Public charging points required per car [2]	0.06	Points/vehicles	UK Fires analysis based on (Nicholas and Lutsey 2020)
Charging points required if all vehicles electric [3]	2.45	M charging points	[1]*[2]
Cost per charging point [4]	1,500	£/charging point	Spirit Energy (n.d.)
Cost of charging points 100% fleet electrification [5]	3.7	£bn	[3]*[4]
Years to 2050 [6]	28	years	
Annual electric charging point market	132	£mn	[5]/[6]
Electric rail:			
Share of UK rail network electrified [1]	38%	Share of route length	OBR (2020)
Size of UK rail network 2019-2020 [2]	31,200	Single track km	OBR (2020)
Single track to be electrified [3]	19,300	Single track km	[2]*(1-[1])
RIA electrification cost target for future projects [4]	1	£M/single track km	Railway Industry Association (2019) for 'simple' route, excludes clearance
Clearance cost [5]	40%	Share of project costs	High end of range – this is very project specific (Railway Industry Association 2019)
Total cost [6]	32.2	£bn	[3]*[4]/(1-[5])
Years to 2050 [7]	28	years	
Annual rail electrification opportunity	1.1	£bn	[6]/[7]
Freight pantographs:			
Share of freight long haul	65%	Share of journeys	Ainalis, Thorne, and Cebon (2020)
Investment required to electrify long haul freight [1]	19.3	£bn	Ainalis, Thorne, and Cebon (2020)
Payback period	18	Months	Ainalis, Thorne, and Cebon (2020)
Years to 2050 [2]	28	years	
Annual investment in pantographs	0.7	£bn	[1]/[2]
Domestic heating:			
UK housing stock [1]	28.5	M dwellings	BRE Trust (2020)
Share electric heated [2]	8%	Share of dwellings	English Housing Survey Table DA6101
Heat pump costs [3]	5,800	£	Scottish Government (2020)
Total cost [4]	154	£bn	[1]*(1-[2])*[3]

Years to 2050 [5]	28	years	
Annual heat pump market	5.5	£bn	[4]/[5]
Cooking:			
Share of households with gas hobs [1]	61%	Share of households	BRE (2013)
UK housing stock [2]	28.5	M dwellings	BRE Trust (2020)
Price cooker/hob [3]	315	£/unit	Scottish Government (2020)
Total cost replacing gas hobs with induction [4]	5.5	£bn	[1]*[2]*[3]
Years to 2050 [5]	28	years	
Annual induction hob market to 2050	196	£bn	[4]/[5]
Industry:			
Cost of electrification of the materials sector [1]	16.5	£bn	UK Fires Materials & Manufacturing report
Years to 2050 [2]	28	years	
Annual industrial electrification market	860	£mn	[1]/[2]
Decommissioning			
Current power stations:			
Total fossil fuel and nuclear power stations UK [1]	83	Number	Statista (n.d. a)
Coal capacity	7.9	GW	DUKES Table 5.12
Oil capacity	1.2	GW	
Gas capacity	35	GW	
Power station decommissioning costs:			
Unit costs: [2]			
Coal	158	£m/GW	Raimi (2017)) Table 1. Exchange rate 1.35 £/$ 2016
Oil	42	£m/GW	
Gas	20	£m/GW	
Absolute costs:			
Coal capacity	1.2	£bn	{1]*[2]/1000
Oil capacity	0.05	£bn	
Gas capacity	0.7	£bn	
Total fossil fuel [3]	2	£bn	
Total nuclear [4]	129	£bn	NDA (2019)
Years to 2050 [5]	28	years	
Annual decommissioning market	4.7	£bn	([3]+[4])/[5]
North Sea:			
North Sea oil & gas decommissioning costs [1]	39-51	£bn	Oil & Gas Authority (2020) Current cost estimate £51bn but there is a cost-cutting initiative underway to reduce costs to £39bn
Annual north sea decommissioning market	1.4-1.8	£bn	[1]/28 years to 2050
Petrol stations:			
Number of petrol stations [1]	8,380	Number	Statista (n.d. b)
Cost of decommissioning [2]	10%	Share of purchase price	US Department of Energy (n.d.)

Petrol station purchase price median [3]	0.6	£m/petrol station	Daltons Business (n.d.)
Total cost [4]	0.5	£bn	[1]*[2]*[3]/1000
Annual cost to 2050	18	£m	[4]/28 years to 2050
Boilers:			
UK housing stock [1]	28.5	M dwellings	BRE Trust (2020)
Share of dwellings currently gas-heated [2]	88%	Share of dwellings	English Housing Survey Table DA6101
UK dwellings with boilers [3]	25.2	M dwellings	[1]*[2]
Cost decommissioning boiler [4]	509	£/boiler	Scottish Government (2020)
Total cost decommissioning boilers [5]	13	£bn	[3]*[4]/1000
Annual market for decommissioning boilers	465	£m	[5]/28 years to 2050
Adapting cars:			
Share of 2050 vehicle stock covered by 2030 ban on petrol & diesel cars [1]	98%	Share of stock of cars 2050	UK Fires analysis based on Dft (2021) Vehicles Licensing Statistics Table VEH0124
Cost to retrofit classic Beetle with electric motor [2]	25,000	£	Retro Electrics (n.d.)
Vehicle stock 2020 [3]	38.6	M vehicles	Department for Transport (2021)
Retrofitting classic cars with electric motors [4]	19.3	£bn	[3]*(1-[1])*[2]/1000
Annual market retrofitting classic cars with electric motors	690	£m	[4]/28 years to 2050
Reusing turbines			
Wind turbine decommissioning costs 500MW wind farm [1]	132-229	£m	Adedipe & Shafiee (2021)
Average wind turbine capacity [2]	2.5	MW	
Decommissioning cost per turbine [3]	900,000	£/turbine	Mid range [1]/(500/[2])
Turbines to be decommissioned per year [4]	193	Turbines	770 to be decommissioned over the next 4 years
Annual expenditure on wind turbine decommissioning	173	£M	
Generation			
Share of UK energy demand currently met by fossil fuels	83	%	UK Fires analysis based on ECUK (2020) Energy Consumption UK & DUKES
Share of electricity grid generated by fossil fuels	45	%	
Share current electricity from nuclear power	20	%	
Infrastructure requirements:			
Energy capacity: [1]			
Nuclear	20	GW	(BEIS 2020b) Scenario: High demand, 5g/kWh, 2GW Gas CCUS
Wind	180	GW	
Solar	120	GW	
Interconnectors	18	GW	
Load factors: [2]			
Solar	11	%	Figure 11 (BEIS 2020b)
Wind	26	%	
Nuclear	86	%	
Energy generation: [3]			

Nuclear	150	TWh	[1]*8760 hours in year*[2]/1000
Wind	415	TWh	
Solar	120	TWh	
Unit costs renewables:			
Pre-development: [4]			
Large-scale solar	3	£m/TWh	Average levelised cost 2025-2040 (BEIS 2020a)
Offshore wind	2.5	£m/TWh	
Onshore wind	3	£m/TWh	
Construction:			
Large-scale solar	25	£m/TWh	Average levelised cost 2025-2040 (BEIS 2020a)
Offshore wind	25	£m/TWh	
Onshore wind	25	£m/TWh	
Operations & maintenance:			
Large-scale solar	10	£m/TWh	Average levelised cost 2025-2040 (BEIS 2020a)
Offshore wind	19	£m/TWh	
Onshore wind	16	£m/TWh	
Absolute costs renewables:			
Pre-development:			
Large-scale solar	0.4	£bn	[3]*[4]/1000
Offshore wind	0.8	£bn	
Onshore wind	0.2	£bn	
Total	1.4	£bn	
Construction:			
Large-scale solar	3	£bn	[3]*[4]/1000
Offshore wind	8.3	£bn	
Onshore wind	2.1	£bn	
Total	13.4	£bn	
Operations & maintenance:			
Large-scale solar	1.2	£bn	[3]*[4]/1000
Offshore wind	6.3	£bn	
Onshore wind	1.3	£bn	
Total	8.9	£bn	
Nuclear capacity:			
Hinkley Point C build cost	23	£bn	BBC (2021)
Hinkley Point C capacity [5]	3.26	GW	EDF (n.d.)
Sizewell C cost [6]	20	£bn	BBC (2021b)
Sizewell C capacity [7]	3.2	GW	EDF (n.d. b)
Additional capacity required [8]	16.7	GW	Nuclear capacity requirement [1] - [5]
Number of Sizewell C -sized plants required to deliver additional capacity [9]	5.2		[8]/[7]
Cost of additional capacity	104	£bn	[9]*[6]
Novel contracts:			
Household electricity price [1]	28	p/kWh	British Gas (2022)
Price paid for electricity sold back to the grid via the Smart Export Guarantee [2]	1.5-5.6	p/kW	Dobson-Smith (2021)
Difference price paid by households for electricity sold to v. bought from grid	80%	Share of price to buy	(1- [2]/[1])*100%

Tesla Energy Plan – 'symmetrical' 24/7 import/export tariff offered in partnership between Octopus Energy/Tesla for households with solar panels and Tesla Powerwall battery	8-11	p/kW	Dobson-Smith (2021)
Social Energy Hub – software optimises how and when energy is stored, used and sold	20	p/kW	Social Energy (n.d.)

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