ENGINEERING A NET ZERO ENERGY SYSTEM.

Institution of MECHANICAL ENGINEERS

Improving the world through engineering

IMechE 175 1847–2022

“”

The Net Zero Project could be viewed as the most ambitious engineering project ever undertaken. I rather envy young engineers who have more than enough challenges over the coming years to keep themselves gainfully employed.

Peter Flinn MA MBA CEng FIMechE
Past President, Institution of Mechanical Engineers

Elevator Pitch

The world we have created over the lifetime of our institution, and its unprecedented standard of living, is based on energy derived from fossil fuels – coal, oil, and natural gas – which we currently consume at a rate of around 15 gigatonnes per annum and, in the process, unfortunately creates climate-changing greenhouse gases. To meet global and UK Government climate change objectives set for 2050, we need to reduce energy consumption significantly and switch to low-carbon sources of energy – primarily wind, nuclear, solar and bioresources –and for any continuing hydrocarbon sources to be produced sustainably or to include carbon capture. This is arguably the biggest engineering project ever undertaken by mankind. It requires funding on an unprecedented scale. In this report, the progress to date, especially in the UK, is reviewed from an engineering standpoint, and eight issues are identified that are critical to the success of the ‘Net Zero’ enterprise, paving the way for a series of more detailed policy outputs from IMechE and its partners.

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Introduction

This paper is less concerned with the science or politics of climate change than it is with the practical development of engineering solutions to the objective of achieving 'Net Zero' – the situation in which mankind adds no more greenhouse gases (GHG's) to the earth's atmosphere than are taken out, either naturally or by human means (see **Figure 1**). This strategy, if implemented by 2050, would achieve the objective of the 2015 Paris Agreement: limiting global warming to 1.5 °C above preindustrial levels.

The term 'Net Zero' is used in this paper in preference to 'climate change', which arguably is concerned more with the science of the earth's climate, or to 'sustainability', a broader concept.

The Net Zero Project could be viewed as the most ambitious engineering project ever undertaken. It seeks to break and eliminate a 200-year dependence on fossil fuels – coal, oil and natural gas – that have formed the basis of the world's current standard of living. Indeed, the first formative meetings of our Institution in 1846 and 1847 were concerned with the burning of coal to provide motive power. Energy conversion is arguably at the core of mechanical engineering.

Given that the purpose and strategy of the Institution of Mechanical Engineers is 'Improving the World Through Engineering', it is no surprise that many elements of the Institution's activities are already concerned with Net Zero, climate change and sustainability. This can be seen from the programme of seminars, lectures, conferences and learning and development courses.

Climate change and sustainability is one of our four key policy themes, alongside future transport, education and infectious disease control (see **Figure 2**).

The day-to-day jobs of many, if not most, of the Institution's members are linked in some way to climate change and Net Zero. Although the Institution itself does not have direct involvement in achieving Net Zero, it is very influential in this field through its membership and in its own right.

What is Net Zero?

Put simply, Net Zero means cutting greenhouse gas emissions to as close to zero as possible, with any remaining emissions re-absorbed from the atmosphere, by oceans and forests for instance.

United Nations

Figure 1: United Nations' definition of Net Zero

Impact

We will maximise the impact of our members in promoting engineering, informing opinion and stimulating innovation for the benefit of society.

Our work will:

1. Promote engineering as a career
2. Be a voice for engineerign in society
3. Shape public and engioneering debate on:
    a. Climate & Sustainability
    b. Future Transport
    c. Infectious Disease Control
    d. Education

Figure 2: Excerpt from the IMechE 2021 Annual Report

This paper sets out the Institution's views and approach to engineering the objective of Net Zero, which in the UK and many other countries has been set as the goal for 2050. Most of the specific examples quoted are from the UK, but the principles can be applied to a wide range of countries.

The perspective taken in this paper is consciously that of engineering, whose aim is, as I explained in my 2021 Presidential Address, is to develop practical, robust and cost-effective solutions to the world's needs.

Purpose of paper

Against this background, the aims of this paper are as follows:

- Set out a basis for potential collective action by the Professional Engineering Institutions of the UK for developing a common approach to the Net Zero requirements;
- Provide members with a framework for understanding this broad and complex subject;
- Draw attention to problem areas (and areas of success) to promote discussion about them; and
- Provide structured input to government and policy makers from one of the world's most respected professional engineering bodies.

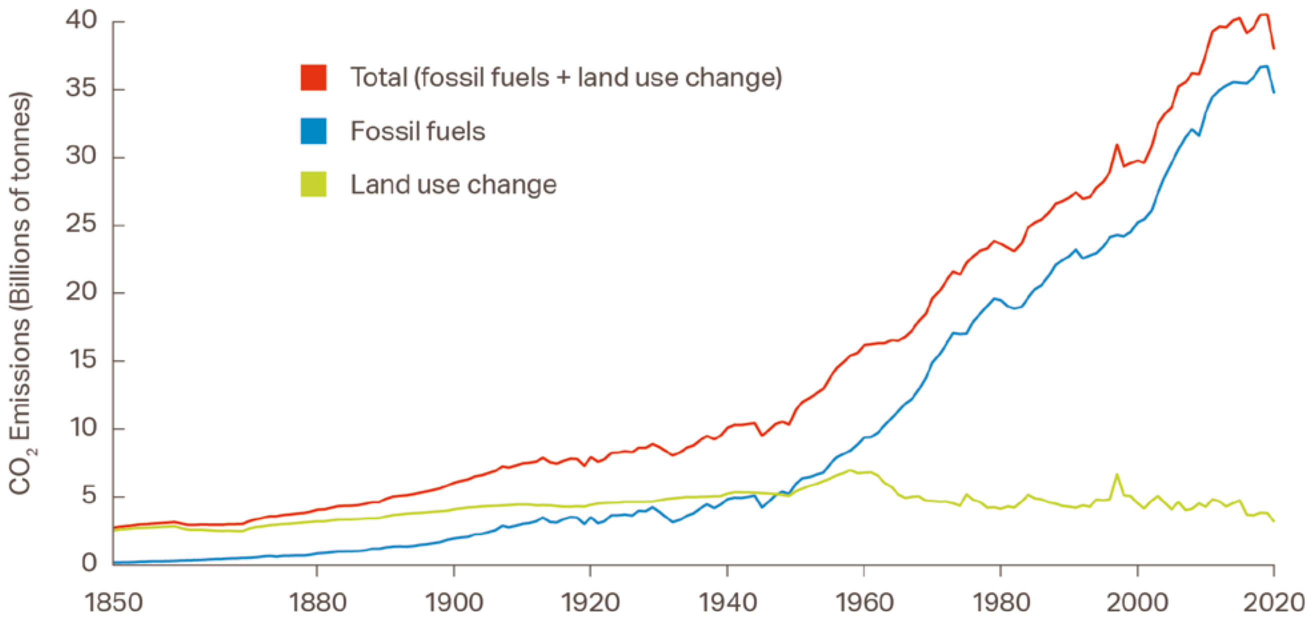
The Institution's future programme will continue to include separate papers and events concerned with the issues raised in this paper.

Climate change background

Summary of current global GHG annual output

At present, it is estimated that the total annual output of greenhouse gases is approximately 50 Gt pa CO_2 equivalent worldwide. This is primarily in the form of carbon dioxide itself (see **Figure 3**) but also includes methane, nitrous oxide and fluorinated gases, which also have a radiative forcing ('greenhouse') effect. As can be seen below, the output of greenhouse gases has continued to rise, even during the period following the 1980s, when climate change started to become a major concern.

Figure 3: Global carbon dioxide output since 1850[1]



The situation in the UK is somewhat better with a significant reduction of greenhouse gas output since 1990, as shown below in **Figure 4.** The same has been achieved in other countries, such as France, Germany, Italy, Spain, Sweden, and the United States. This has been achieved through the delivery of primary energy (ie reduction in the use of coal plus use and increase in renewables) and by efficiency improvements in manufacturing and transport.

In the UK and elsewhere, manufacturing has grown less than the economy overall; manufacturing has also seen a relative decline in carbon-intensive industries, such as steel and cement. Thus, it could be argued that some of the carbon reduction since 1990 has been achieved by 'exporting' the problem.

The origins of these emissions are usually broken down into 7–9 sectors, as illustrated in **Figure 5.** This is taken from sources in International Energy Agency (IEA), Global Carbon Project, Intergovernmental Panel on Climate Change (IPCC) and the World Resources Institute. These numbers include the effects of methane and other greenhouse gases.

Figure 4: UK carbon dioxide output since 1750[1]

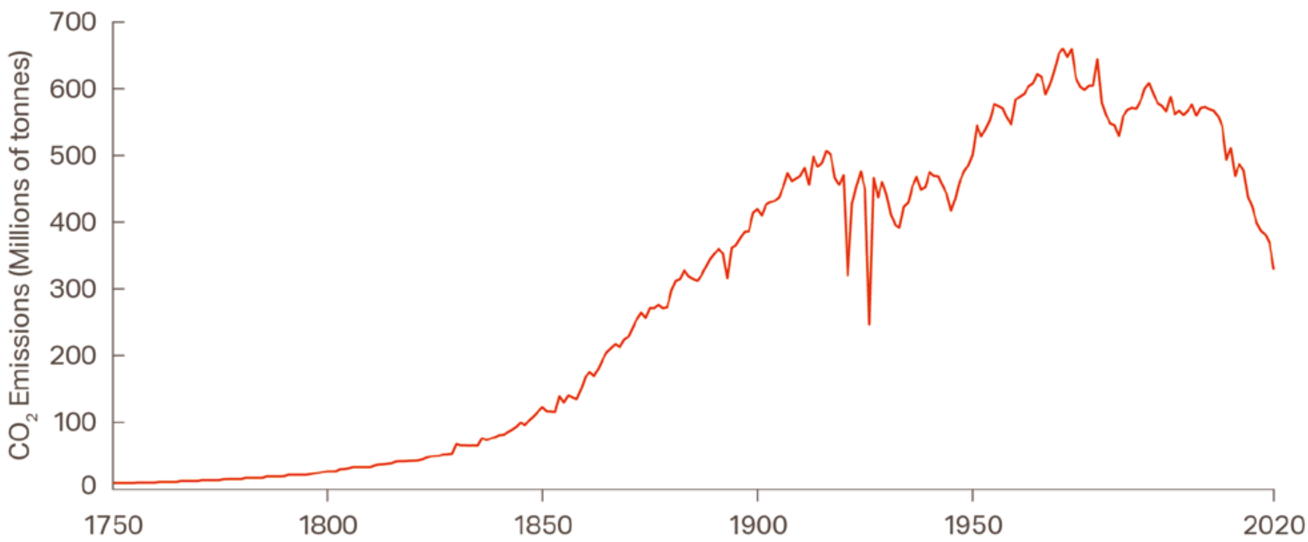


Figure 5: 2019 GHG total emissions – breakdown of gigatonnes per annum CO_2 equivalent

	Coal	Natural Gas	Oil	Land	Other	Total
Electricity	9.5	3.0	1.0			13.5
Industry	3.0	1.5	1.2		1.5	7.2
Chemicals	1.0				2.5	3.5
Transport			8.0			8.0
Heating		1.5	1.3			2.8
Agriculture			0.5	8.2		8.7
Fugitives					3.0	3.0
Other	1.0	1.0	0.7			2.7
Total	**14.5**	**7.0**	**12.7**	**8.2**	**7.0**	**49.4**

Effect on atmosphere – concentration of CO_2, methane and other GHG's

The overall effect of these emissions is a gradual increase in the atmospheric concentration of carbon dioxide, which has risen from 295 parts per million (ppm) in pre-industrial times to around 415 ppm currently. Concentrations of other GHG's have shown similar patterns; eg methane from 720 parts per billion (ppb) to 1,900 ppb.

Effect on climate

In summary, the principal effects of these increased atmospheric concentrations are as follows:

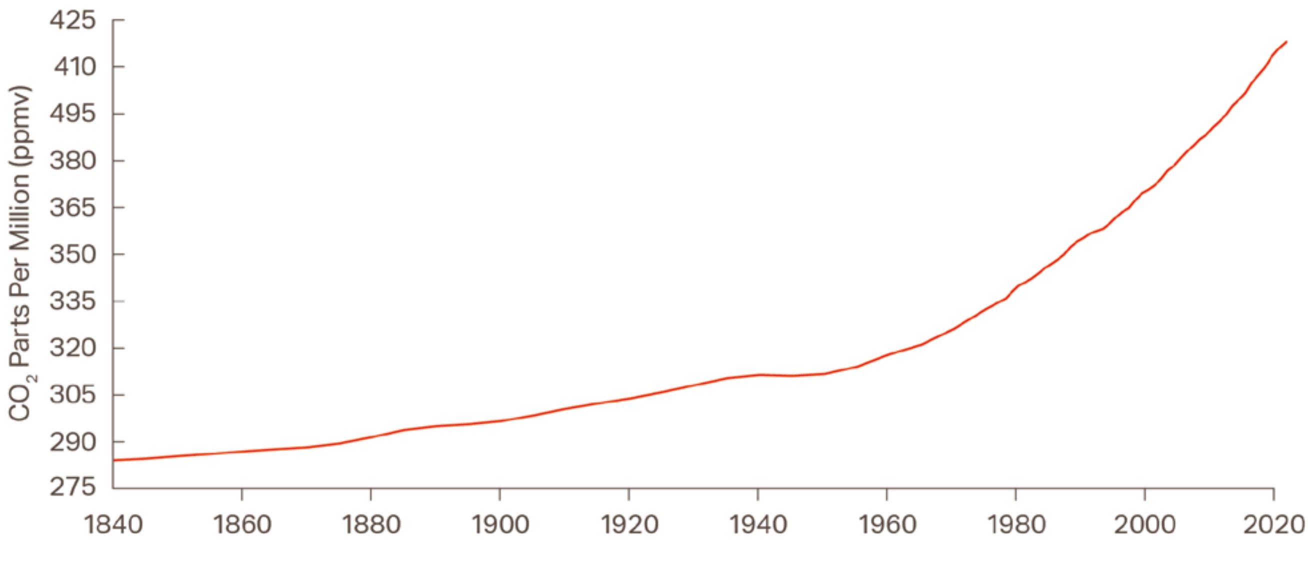
- Atmospheric temperatures – estimated to have risen by 1.1 °C since pre-industrial times and continue to rise at 0.15 °C per decade[3]
- Sea levels – estimated to have risen by 150mm to 200 mm since pre-industrial times and are rising at 3mm to 5mm per year[4]
- Sea ice reduction – most noticeable in the Arctic; sea ice levels are reduced by 13% per decade
- More frequent extreme weather events – precipitation, storms, heat waves, and hurricanes[5]

Urgency of response and scale of change

If the objective of limiting the temperature increase to no more than 1.5 °C above pre-industrial levels by 2050 (the 2015 Paris Agreement and the Paris Rulebook subsequently agreed at COP26 in 2021) is to be achieved, then the scale of change required is unprecedented. The scale can be appreciated by reference to the money involved – potentially of the order of $275 trillion[6] worth of investment in Net Zero technologies and infrastructure over 30 years, as indicated in the Scale of investment required section on page 29. Translated into UK terms, this equates to $150 billion to $200 billion annually in an economy worth $2,700 billion GDP.

An important counterpoint is the cost of not acting. The UK Office for Budget Responsibility has estimated that unmitigated climate change would result in 'debt spiralling up to around 290% of GDP thanks to the cost of adapting to an ever-hotter climate and of more frequent and more costly economic shocks'.

Figure 6: Atmospheric concentration of CO_2 from 1840[2]



Energy flows now and in the future

Summary of current energy flows

The world is currently estimated to be consuming 160,000 terawatt-hours (TWh) of energy per year[7], of which electricity comprises 25,000 TWh. For the UK, the equivalent figures are just over 1,500 TWh total energy and 300 TWh electricity. Details are illustrated below for the year 2020, noting that these figures are annual totals; day-by-day or hour-by-hour figures will fluctuate substantially.

In summary, in the UK, at the present moment, natural gas is the largest single source of energy and is used directly for heating and indirectly, via electricity generation, for a range of applications. Liquid hydrocarbon fuels are the second largest source and electricity (from nuclear, wind, solar, gas and other renewables such as bioenergy and import) the third. Bioresources make up the bulk of the remainder. In 2020, approximately 78% of the UK's current energy was derived from fossil fuels.

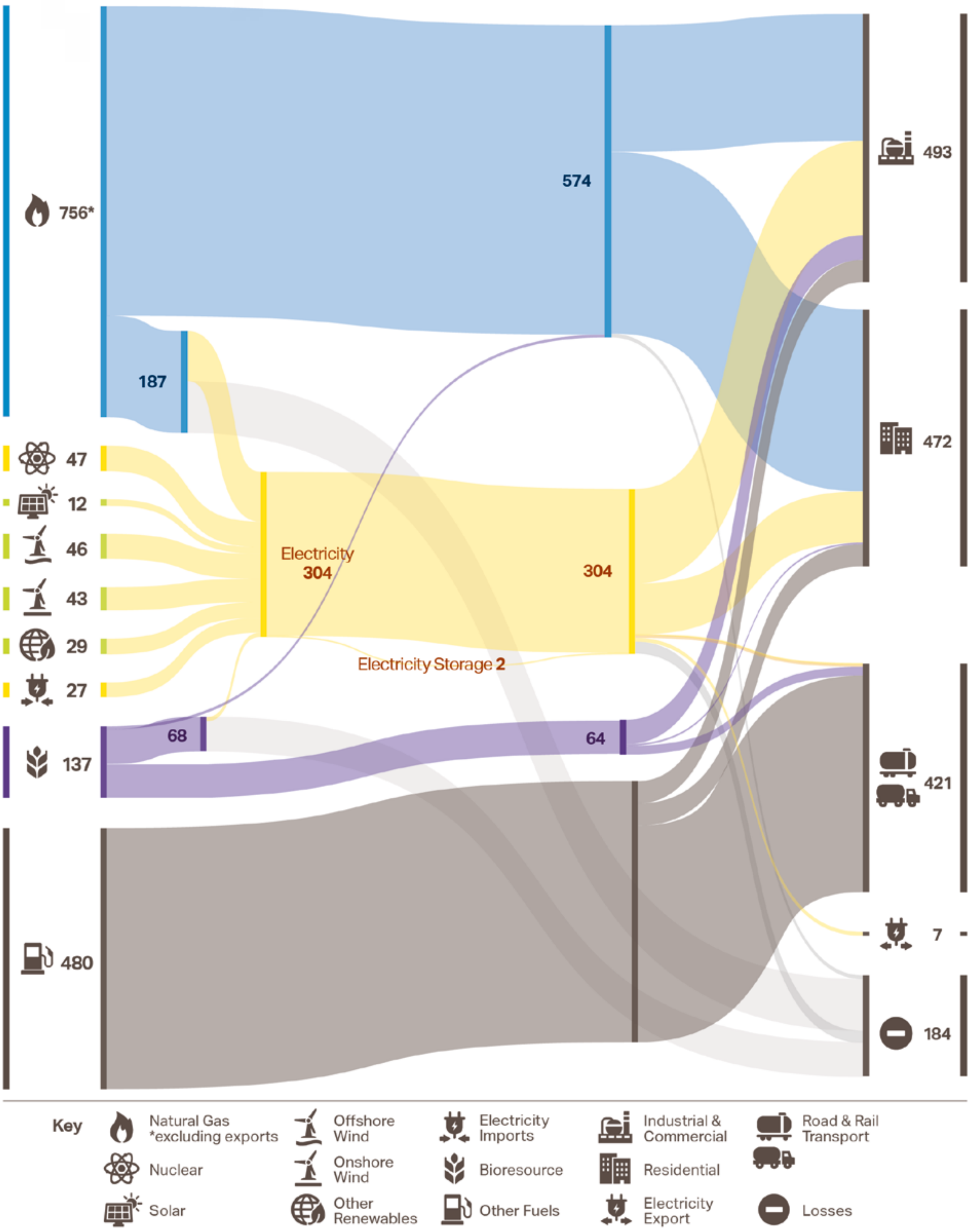
Approaches to decarbonisation

In very general terms, the decarbonisation of energy systems is achieved by:

- Energy reduction (eg building insulation, efficiency improvements and lifestyle/behavioural changes)
- Energy generation from low-carbon sources (eg wind, solar and nuclear)
- Electrification (eg of mobility and building heating, but noting the huge increase in electricity usage implied)
- Use of (liquid) synthetic or biofuels (eg for aviation and shipping)
- Use of gaseous fuels (eg hydrogen or ammonia as energy vectors or as storage media)
- Carbon capture, utilisation and storage
- The use of intelligent, two-way energy distribution and storage systems

All of these approaches, and more, are likely to be used in the future. But there is considerable debate about the exact mix of solutions that will eventually be employed. It could be argued that the situation will be resolved over time by a Darwinian process of natural selection based on the cost-effectiveness of the different solutions as they develop and are scaled up. Whether this is the most efficient approach is a matter of debate, as it runs the risk of false starts and of missing what is a very tight timescale. The latter point is especially important, given the maturity of the relevant technologies and the issues of deployment at scale.

Figure 7: UK energy flows 2020[8]



Future energy scenarios

Scenarios for the future have been developed by many organisations such as the International Energy Agency, Wood Mackenzie and, within the UK, the Energy Systems Catapult and National Grid. Taking the work of the National Grid as an example, it has recently updated (17th July 2022) four scenarios that, in effect, form an envelope within which most of the potential solutions could exist. Each scenario has a different mix of the solutions indicated in **Figure 7**.

In summary, the four National Grid scenarios are:

FS – Falling Short

Slowest credible decarbonisation, minimal behavioural change, power and transport decarbonised but not heating, GHG emissions reduced by 80% of 1990 levels (ie from 800 mega-tonnes (Mt) CO_2 equivalent to 200 Mt) but Net Zero not achieved – 1237 TWh total energy input compared with 1577 TWh in 2020.

ST – System Transformation

Changing the way that energy is generated and supplied, hydrogen used for heating, flexibility of supply, limited consumer behavioural change but Net Zero achieved – 1,406 TWh total energy, a 9% reduction from 2020.

CT – Consumer Transformation

Changing the way that energy is used, electrified heating, flexibility of energy usage and consumers willing to change behaviour, Net Zero achieved – 1,182TWh, a 25% reduction.

LW – Leading the Way

Significant lifestyle change, combined with world-leading technology and investment, hydrogen and electricity used for heating, power and transport decarbonised, Net Zero achieved – 1,123 TWh, a 29% reduction.

Range of solutions envisaged

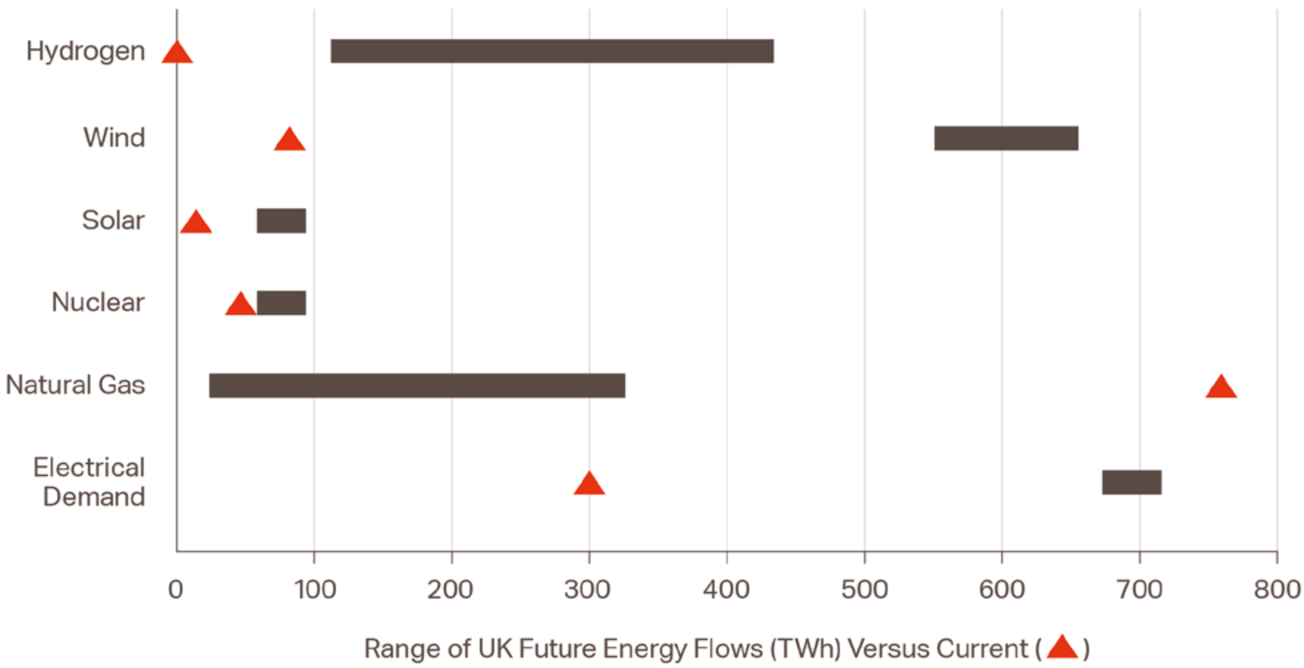
Three of the scenarios achieve the Net Zero goal, but they still define a wide range of potential solutions, although the direction of travel is clear.

The main likely characteristics for the future include the following:

- Increase in wind power by a factor of 6 or 7
- Increase in solar power by 5–8 times
- Increase in nuclear power generation by up to 2 times
- Natural gas consumption reduced by at least 60% and potentially almost eliminated
- Direct use of oil for energy eliminated
- At least double the use of electricity as a means of energy transmission
- Significant use of hydrogen, also for energy transmission, but with an almost 4:1 range in the quantities potentially used

These scenarios tend not to cover the growing use of synthetic or bio-derived hydrocarbon fuel or the use of carbon capture systems, at least as an interim measure.

Figure 8: Range of potential solutions[9]



Three perspectives on engineering Net Zero

The Institution takes a structured view of this complex subject with three distinct perspectives – a subject which effectively amounts to a complete redesign of the world's techno-economic system:

- Discrete technologies perspective – solutions to specific needs in specific situations, covering both energy generating technologies and energy-consuming technologies
- Complete systems perspective – end-to-end aggregations of specific solutions and their overall efficiency, plus whole-life considerations
- Commercial factors/affordability perspective – investments, operating costs, tariffs and government interventions

While the Institution will remain technology-agnostic (ie, not favouring any particular technologies or solutions to climate change), it will take an independent and rigorous view of potential solutions. The Institution also notes that all solutions at the discrete or system level will be very dependent on underpinning digital technologies. The so-called 'Fourth Industrial Revolution' is, in effect, running in parallel with the energy revolution.

Discrete technologies

The following is a brief review of the technologies that are being developed to support the achievement of the Net Zero goal.

Power generation technologies

Combined cycle gas turbine (CCGT) – CCGT power plants currently provide a third of the UK's electricity output from about 30 stations spread around the country within easy reach of centres of consumption. Capable of powering up and down quickly (ie 'dispatchable'), they are the main counters to the variability of renewable sources. and a 5:1 variation in output from day-to-day is not unusual. Combined with carbon capture utilisation and storage (CCUS), CCGT/CCUS stations appear in the mix of electricity sources in the future as one of the continuing means of countering this variability. The uncertainty here concerns the use of CCUS. Carbon capture systems, which mainly using amine scrubbing technology, have existed since the 1970s; however, they are small in number and in scale. The largest current unit is on a coal-fired station in Saskatchewan and has a demonstrated capacity of 730 kilo-tonnes of CO_2 per year/1 million tonnes capacity, which is significantly smaller than the requirements of a typical CCGT station of 2/3 Mtpa. The UK government has recently agreed to proceed to the next stage with a CCUS cluster with 30 Mtpa capacity in Humberside and Teesside and a similar programme (Hynet) in North-West England/North Wales. These will provide the main route by which CCUS technology is developed in the UK, noting that many of the applications are for industrial, hard-to-electrify activities rather than power. Worldwide, there are hundreds of CCUS projects in the pipeline. Other capture technologies exist (eg solid sorbents) but these are currently at low technology readiness levels (TRLs).

Wind – the UK has approximately 25 gigawatt (GW) of on- and off-shore wind capacity; about a quarter of electricity is currently produced this way. Future scenarios suggest that wind capacity could increase to 160 GW and that about 70% of electricity would come from this source. Although the technology itself is now quite mature (there are about 750 GW installed worldwide), this then raises the issue of variability, as well as the opposite effect of having excess capacity at times.

Solar – installed solar capacity in the UK is currently 13 GW, producing 12 TWh per year, equivalent to 4% of total electrical output. Future scenarios envision growth to be between 60 and 95 TWh, raising concerns about variability and seasonality.

Nuclear – the UK has used nuclear power since the 1950s and currently derives about 16% of its electricity, or 47 TWh per annum (p.a.), from this source, down from 26% in the 1990's. Current installed capacity is 7 GW, with Hinkley Point C and Sizewell C eventually adding 6 GW, plus 0.5 GW from each installed SMR; however, this is offset by the planned decommissioning of all but one existing station by 2030. The scenarios indicate up to doubling of current figures, which will require a corresponding increase in relevant industrial capacity. The UK Government has recently (6th April 2022) announced that it will promote 24 GW of nuclear capacity by 2050, almost twice that implied in the planning scenarios. A long-term solution to storing nuclear waste is also needed.

Bio-resources – bioenergy currently provides around 10% of the UK's energy, approximately 140 TWh, using a variety of fuels such as biomass (eg wood pellets), wood, waste, sewage and landfill gas. Future scenarios envisage this growth to be between 150 TWh and 250 TWh. The level of future use is dependent on a variety of factors: the success of other means of GHG reduction, the reliability of local sources of fuel supply, how much land can be accessed and relative costs. However, it could potentially provide a useful source of low-carbon dispatchable energy.

Power generation overall – the supply side of electricity has some uncertainties, but it is generally well defined. The main issue of concern is the dependence on variable or intermittent sources without there being a clear counterstrategy.

Storage & energy vector technologies

Liquid fuels – While the electrification of surface transport is likely to be the main route to decarbonising personal mobility, there will continue to be a place for liquid fuels in certain applications (heavier vehicles, legacy vehicles, ships and aircraft being potential examples). These fuels may also be used to dilute the carbon intensity of conventional fuels during the transition away from fossil fuels. Sustainable liquid fuels could be the most suitable fuel for long-haul aviation in the long term. More information is provided in an IMechE report published in January 2020[10].

Two types of sustainable liquid fuels are potentially available:

- **Biofuels –** those derived from organic biomass processed either by fermentation in the first stage to produce intermediate alcohols (methanol, ethanol and iso-butanol) that can then subsequently be processed by catalytic methods into gasoline or kerosene for use as 'drop-in' fuels or a number of other biofuel speciality processes (hydrotreatment or esterification) that take tallow, municipal waste, sewage, grease and oils and process them into fuels including biodiesel or hydro-treated vegetable oil (HVO).
- **Synthetic fuels –** produced by industrial processes initially by combining hydrogen and carbon dioxide (via syngas) through long-established gas-to-liquid/Fischer-Tropsch synthesis to produce longer-chain molecules. E-fuels are a specific subset of synthetic fuels that use renewable energy to make hydrogen.

These fuels can be regarded as 'sustainable' because the carbon in them was first captured from the atmosphere by photosynthesis or direct air.

There has always been concern about biofuels competing with food production, but so-called second-generation biofuels use non-food biomass, agricultural waste, straw or woody waste. There has also been concern expressed about the availability of sufficient biomass to satisfy demand, but a recent Imperial College report suggests otherwise.

A study by Sustainable Aviation[11] suggested that up to a third of fuel demand in 2050 could be met by sustainable aviation fuels.

The technology to produce these fuels is well established. Although quantities are currently small, costs are high and are likely to remain high given the number of process steps involved. Substantial investment is needed to produce them in quantity and to establish the supply chains. Confidence that demand will be there is needed ahead of this. Lastly, there is evidence in, for example, the aviation sector of demand crystallising and hence giving confidence to investors.

Overall, there would appear to be a place for sustainable liquid fuels, and it would make sense to encourage and develop them as a valuable option, especially as they can be applied to the vehicles already existing in the fleet.

Hydrogen – hydrogen is currently produced across the world at a rate of 70 Mt p.a., the equivalent of 2,800 TWh, and is used industrially in refining/hydro-cracking, methane, ammonia and fertiliser production. The UK produces and uses about 1% of this. It is produced mainly by steam methane reformation (SMR), gas partial oxidation (gas POX) or autothermal reforming using natural gas as the feedstock—all processes that produce significant amounts of carbon dioxide. The latter could be overcome in the future by adding carbon capture technologies—these processes plus carbon capture are one of two main routes to producing hydrogen in the future.

An alternative zero-carbon route is to produce hydrogen by electrolysis using power from renewable sources. The UK Government is encouraging the latter by setting a target of 10 GW installed electrolyser capacity by 2030 linked to a target for 40 GW of offshore wind capacity, also by 2030 but without specifying quantitatively the markets that would be served by the hydrogen thus produced. A major drawback of production by electrolysis is the inefficiencies of both the process of electrolysis itself and the subsequent processes of transmission, which result in a poor ratio between installed renewable power and useful output.

There is a wide range of possibilities for the future use of hydrogen with worldwide production levels up to 500Mt/20,000 TWh p.a. being projected. The most frequently mentioned are hard-to-electrify, high temperature processes such as steel production. It is being actively developed for use in fuel cells to power heavy vehicles where batteries will not provide adequate range, such as heavy goods vehicles, buses and trains. It also continues to be offered in passenger cars (eg Toyota Mirai) as an alternative to battery power. Hydrogen internal combustion engines are also being developed for heavy-duty excavators and commercial vehicles.

The further adoption of these examples will be driven by economic factors (onboard tanks for hydrogen are quite heavy and bulky) compared with other solutions and the availability of supporting infrastructure. Applications in aviation using cryogenic hydrogen are also being explored (eg ATI Fly Zero and Airbus ZEROe projects).

The most significant potential application of hydrogen in volume terms, however, concerns its use in domestic and commercial heating, partly replacing natural gas and providing an alternative to electrically powered heat pumps. Various trials are being conducted in the UK to assess the suitability of the natural gas network for hydrogen, and the UK Government is due to make a decision in 2026 on the principles of using hydrogen for domestic heating. This would open up a large direct market for hydrogen and also enable its use as a store against variability and seasonality (the geological storage of hydrogen has some history) and a means of absorbing excess or constrained renewable power generation, thus providing energy input at low marginal cost. Stored hydrogen could also be used directly in power stations as another means of countering variability, although the 'round trip' efficiency of such a route is low.

Overall, hydrogen could, on the one hand, be used in a number of specific applications. Setting aside cost and efficiency, hydrogen could also be a major resource to partially replace natural gas. With total UK demand potentially rising to more than 400 TWh, the production of renewable hydrogen would take up a substantial proportion of electrical capacity and/or would rely on established chemical processes + CCUS.

There is political momentum behind wider use of hydrogen in the UK with a Hydrogen Strategy[12] published by the UK Government in August 2021; however, there was limited recognition of the substantial inefficiencies, and hence the high costs, of the processes being advocated.

Energy usage technologies

Enormous efforts are being made to improve the efficiency of energy-consuming systems or, more importantly, to switch to different and sustainable energy sources, especially electricity. The following is a summary of the main trends:

- **Energy-intensive industrial processes –** The steel manufacturing industry is currently a major producer of CO_2, creating between 7% and 9% of global emissions, with each tonne of steel produced resulting in about 1.85 tonnes of carbon dioxide. Approaches to decarbonisation include the wider use of electric arc furnaces, application of CCUS, replacement of natural gas in downstream processes and, in the longer run, direct reduced iron (DRI), which removes oxygen from ores in a reducing atmosphere without melting. All are reliant on renewable electricity and hydrogen.
- **Built environment –** in the UK, the built environment (domestic housing, commercial buildings and infrastructure) accounts for 25% to 40% of total energy usage, depending on the method of analysis used. Carbon consumption has fallen by 30% since 2000. This usage is split evenly between operating energy and energy used in construction – 'embodied carbon'. Reducing energy use can therefore come from retrofitting existing building stock, of which there is a considerable quantity, constructing new housing or buildings with improved energy performance and adopting less carbon-intensive methods of construction. The UK Green Building Council has led a substantial, industry-wide planning activity, resulting in a roadmap to Net Zero in this sector by 2050.

- **Built environment (cont.) –** this is based around the points made above, with the reduced energy requirements that result being provided 80% by heat pumps, obviously electrically-powered supplemented by solar PV, and the remainder coming from district heating schemes and hydrogen where industrial clusters are in close proximity.
- **Passenger cars –** battery electric vehicles have become the de facto future standard, with some continuation in the use of hydrogen-fuel cell vehicles
- **Heavy goods vehicles (HGVs) –** HGVs cover higher mileages and have more arduous duty cycles than passenger cars; thus, battery-powered solutions tend to be less effective, although they are still being pursued for medium-distance operations. Hydrogen-fuel cell solutions or direct hydrogen combustion may be more suitable for long distances, and demonstrators are in active operation in small quantities. There may also be hybrid solutions with fuel range extenders or there may be battery charging catenary systems.
- **Rail –** railway systems, which produce less than 1% of global CO_2, have an advantage in that many high-utilisation routes being already electrified and therefore capable of being fed from renewable sources as they become available. For less intensively used routes, the alternatives are hydrogen/fuel cell or battery traction[13].
- **Shipping –** this industry, which produces 2% to 3% of global CO_2, conventionally uses heavy fuel oils in diesel engines, or natural gas. Three other options are under consideration: biodiesels from waste feedstocks (which may be limited in quantity), 'green' methanol from biomass and renewable electricity, and 'green' ammonia, which presents major toxicity issues, and of course hydrogen and nuclear propulsion. All options are being developed in relation to propulsion, storage and bunkering, with bio-methanol being slightly more advanced but still at an early stage in terms of production in quantity.
- **Aviation –** Net Zero targets are increasingly being adopted by aircraft manufacturers and their approach is coalescing around three technologies: sustainable aviation fuel (SAF), hydrogen in either cryogenic or compressed form, and electric power (for smaller/shorter range aircraft).

With the exception of battery electric vehicles, most of the technologies cited are at the demonstration phase rather than at the commercial exploitation stage.

Negative emissions technologies

The Net Zero scenarios suggested for the UK all include some level of GHG removal—negative emissions—to offset residual CO_2 emissions from sectors where full abatement is difficult to achieve. A capacity of between 9 and 14 $MtCO_2$ is proposed. On a global scale, IPCC has suggested that up to 10 Gt of removal might be required worldwide. Three approaches are being developed:

- **BECCS –** bioenergy combined with carbon capture, utilisation and storage is an approach which has the effect of withdrawing carbon dioxide from the atmosphere. The technology is based on producing energy from biomass, created by photosynthesis during growth, and then capturing the carbon dioxide produced by biomass combustion. A pilot scheme, with several extensions, has been running at the Drax Power Station in the UK since October 2018. There are some half-dozen similar schemes around the world. As with all bioresource-based technologies, the scale of the approach, and hence the ability to reach the target removal amounts, could be limited by the availability of biomass.

- **Direct air carbon capture & storage (DACCS) –** it is technically feasible to remove CO_2 directly from ambient air, despite its relatively low concentration at c.415 ppm. The technology is similar to CCUS, with CO_2 being absorbed into, or adsorbed onto, an intermediate substance from which the carbon dioxide is separated and piped to storage. Energy and substantial quantities of water are required to run such processes. There are some 20 small-scale projects globally demonstrating the basic feasibility of direct air capture, but also demonstrating the significant challenge of achieving acceptable operating costs.
- **Reforestation –** various plans exist to increase UK tree planting to between 30,000 and 50,000 hectares per year. Noting that the UK land area is 25 m hectares, the effect of such planting will not be significant, with carbon sequestration rates possibly improving by 10–15Mt p.a. versus the current greenhouse gas output of >400Mt p.a.

Overall, negative emissions technologies do exist and are being demonstrated, but with substantial limitations on what might be achieved in terms of scale and operating costs[14].

Overall situation

When reviewing the technologies considered to achieve the Net Zero goal, it is easy to be impressed by the scale of activity and the range of solutions being developed. However, a more sober assessment of the situation shows that relatively few technologies of the future are fully developed, competitive and commercially available, ie at the Technology Readiness Level (TRL) 9. Many, if not most, could be considered to be at TRL 7 or lower and require substantial scale-up investment, which is the only way by which competitive costs can be achieved. A successful Net Zero programme cannot therefore be envisaged without concerted contributions from the engineering community, business, investors and governments, as well as a dependence on a wide range of digital technologies.


Rexroth

Complete systems

Complete system viewpoint

It goes without saying that viewing each element of a complex system in isolation risks creating suboptimal solutions. For example, battery electric vehicles will only reduce greenhouse gas emissions to the extent that the electricity supply is decarbonised (in the UK currently, about half of electricity comes from non-fossil sources) and will only become accepted once recharging infrastructure is in place. Similar points can be made in relation to hydrogen-based solutions. Heat pumps will be accepted when practical solutions can be offered to householders and the skills for design and installation exist. In all cases, cost effectiveness is paramount.

It is also often overlooked that existing system resilience has been built up by empirical engineering development and tacit knowledge over many decades – especially the case with electricity and gas grids, which currently have an understated capability to react to changing circumstances with dispatchable energy and to maintain system stability when faults arise. The six industrial clusters currently being developed in the UK and similar local or regional projects will be critical in developing the practical engineering know-how that is needed for energy security in the future. As a broad principle, industrial-scale development of the type supported by the Catapult network will be critically important.

There is also the question of who is in charge. A national master plan and energy architect might have some merit, especially given that public scepticism will mount if elements of the plan are not synchronised.

Product system life cycle

The following section concentrates on the operating cycle and the greenhouse gas effects of energy-producing or energy-consuming systems without accounting for the effects of building those systems in the first place. In an ideal Net Zero world, industrial systems and processes would be decarbonised; hence there would be no carbon effect from building, for example, wind turbines or battery electric vehicles.

In the short term, however, there clearly is such an effect. As an example, Ricardo has estimated that a typical petrol-engined passenger car 'embodies' the equivalent of an extra 45 g/km of greenhouse gas during its construction (25% of in-use emissions) or 60 g/km in the case of a battery electric vehicle[15]. Hence, at least in the short term, the environmental benefits of such vehicles could be overstated by the amount of the embodied carbon. Similarly, for buildings, the embodied carbon can be approximately equal to the whole-life operating carbon.

Carbon accounting – scope 1, 2 and 3 emissions

Most of the previous analysis considers energy systems at the level of a country rather than more locally. However, as much progress can be achieved at the level of the firm or enterprise. The energy consumption levels, predicated in future energy scenarios on page 12, assume significant savings, which are generally accomplished on a company-by-company basis. The starting point for such work is understanding a company's current carbon footprint for which there are established methods originating from the Greenhouse Gas Protocol, which is widely used as a carbon-accounting standard[16]. The approach breaks down emissions into 3 'scopes':

- Scope 1 – emissions produced directly by a company in the course of its operations
- Scope 2 – emissions produced by others on behalf of the company, eg its electricity supplier
- Scope 3 – emissions produced indirectly by suppliers, of components, for example, or by customers using the company's products

An example of this approach for a medium-sized company, has been produced by AES Engineering Limited[17], including plans for the mitigation or offsetting of emissions to enable the company in question to achieve Net Zero. The results can be independently verified by certifying bodies. Furthermoer, progress can be tracked, and the process can be used to promote employee engagement or wider societal engagement. A similar approach, but on a much larger scale, has been adopted by the UK's National Health Service[18]

This approach is becoming increasingly mandated legally and is often now a requirement of funders who may need carbon footprint credentials when they dispose of a holding several years on.

Power grid

The demand for electricity is expected to rise by a factor of two worldwide (McKinsey Global Energy Perspective 2021) over the next 30 years as transport, home heating, building heating and industrial processes are electrified. Figures for the UK could be higher, with up to two and half times more electrical demand (National Grid Future Energy Scenarios 2021) expected and electricity rising from 20% to as much as 60% of total energy flow.

Much of the extra capacity will come, in the case of the UK and elsewhere, from renewable sources. The means of generating this energy are covered in power generation technologies on page 17 of this report. In terms of distributing power to end users, the needs are as follows:

- Country-to-country HVDC interconnectors to balance out variability and give access to a wider range of storage systems
- Offshore to onshore high-capacity HVDC connectors, possibly in addition to some hydrogen links and internal connectors (eg from Scotland to England)
- Reinforced high-voltage 400 kV transmission systems, particularly given that many generating sources will be remotely located from points of energy consumption
- Adaptable and reinforced local supplies to suit the local mix of solar, electric vehicles or heat pumps or to deal with local 'hotspots', such as bus depots
- Ability to cope with multiple local sources of power
- Grid-scale storage to an unspecified level to cope with variability and stabilise frequency and voltage
- Digitalising the network for status monitoring and control purposes, in addition the ability to manage and incentivise by price and consumption of energy during periods of high and low supply

The UK, as is probably typical of Western countries, has major investment plans in all these areas. However, it is probably fair to say that the plans are more mature and robust at the upper levels of the system, as outlined above, where the system and its needs are more easily defined. However, much more work at the local level, where there is more unpredictability and uncertainty.

Storage and variability or intermittency

With total electrical output in the UK likely to rise to c.700 TWh per year (ie 80 GW average power output with a majority (>60%) from renewable sources) a significant level of energy storage could be required. Estimates vary as to what storage is appropriate, with figures between 50 and 200 GWh being suggested. Even the latter would provide no more than 3 days' supply, which would hardly cover periods of the so-called 'dunkelflaute' (periods of low wind and solar output) affecting several countries. The four current pumped storage hydro systems in the UK provide 3 GW/27 GWh, and there are other schemes under development; such systems are well-proven ways of providing medium-term storage and should be part of the future mix.

Batteries seem an unlikely solution at the scale suggested (1 GWh of li-ion batteries would weigh about 7,000 tonnes), except for short-term supply/demand balancing. Access to electric vehicle batteries (V2G) would require 20,000 vehicles per 1 GWh, which is more plausible. Similarly, 1 GWh would require 30 tonnes of hydrogen, 1,300 m3 at 35 megapascals. Other solutions suggested include compressed air or liquid air energy storage, which do not have a track record at any scale. Overall, there does not appear to be a detailed and plausible plan to store energy at the grid scale and hence to overcome the variability of renewable energy supplies. There is, however, a good pipeline of more local storage projects.

Critical materials

The current industrial world has been built over a two-hundred-year period around coal (8 Gt p.a.), oil (4.2 Gt), natural gas (2.8 Gt), iron/steel (1.9 Gt), but obviously a much wider spectrum of materials at lower levels of consumption (for example, aluminium at 65 Mt p.a. and copper at 18 Mt p.a.). Geopolitically, the world has managed its way around the dependences and tensions that are created between producing and consuming countries, the two most obvious problems being the oil crisis of 1973 and the current crisis involving Russia and Ukraine. Smaller-scale crises have involved individual countries, but the availability of alternative sources of supply has undoubtedly helped (the three biggest oil producers in the world provide about 42% of the world's total supply) to avoid disruption.

The future energy system is more complex and is dependent on, amongst others (Canada has identified up to 30 critical minerals):

- Copper—electrical generating, transmission and consuming systems
- Lithium—EV batteries
- Nickel—EV batteries
- Graphite—Li-ion battery anodes
- Manganese—EV batteries
- Cobalt—EV batteries
- Rare earths—for example, neodymium, praseodymium, terbium and dysprosium in magnets, phosphors, catalysts, glass and alloys
- Platinum group metals

These materials tend to be more concentrated in their production. For example, three countries account for 86% of lithium production and one country, the Democratic Republic of Congo, accounts for about two-thirds of cobalt production. They are all required in combination for applications noted with bottlenecks arising if even a single material is missing.

Both governments and companies have recognised this situation. The UK government, to its credit, has a critical minerals strategy[19] and has set up a Critical Minerals Intelligence Centre (CMIC). Individual companies are acting to reduce their own dependence, eg schemes for eliminating cobalt from batteries.

Sustainability and the circular economy

Closely linked to materials, critical or otherwise, are the concepts of sustainability and 'circularity', whereby material usage, and all that is involved in their extraction and processing, is minimised. This is an important element of 21st-century engineering, possibly decoupling growth from sustainability. It is a substantial topic in its own right and an active part of the Institution's programme.

Methane emissions

Although most attention is given to carbon dioxide emissions, methane also has a significant GHG effect, albeit with a different residency time, and may account for up to half of the atmospheric temperature rise since pre-industrial times. Total worldwide emissions of methane are around 0.6 Gt per year, which has an effect equivalent to 9.4 Gt of carbon dioxide. The sources and sinks of methane are not well understood; however, there are natural sources of methane, such as wetland areas and there are man-made sources, such as energy production, landfills, farm animals, waste-water treatment and rice agriculture. At the COP26 summit, the Global Methane Pledge was signed, in which over 120 countries subsequently agreed to reduce manmade methane emissions by 30% by 2030. In engineering terms, the oil and gas sector can contribute the most to this; hence, this is the area where most activity is now concentrated.

Critical Skills

Clearly, new skills are needed to support technologies that achieve the Net Zero goal. According to the Engineering UK report 'Net Zero Workforce'[20] the UK could be 'sleepwalking towards a Net Zero engineering skills shortage without knowing how big the skills and educational gaps are. For example, we need more young people to take STEM subjects at school and in further education, but we are lacking the teachers and the infrastructure to make this happen. More needs to be done to encourage and enable young people across the UK to take up STEM-based qualifications with a view to tackling the climate crisis – if we don't have enough young people studying chemistry and physics now, for example, it could lead to a shortage of electrical and chemical engineers, which means we will not have the necessary skills in the future workforce.'

The UK's professional engineering institutions play a key role in embedding Net Zero principles and skills into degree courses, accreditation programmes and training courses. It could also be argued that we should be bringing more people into engineering from outside the traditional STEM sources, particularly given the need to engage society financially, politically and in terms of consumer behaviour.

Economic and cost factors

Funding of Net Zero engineering and economic factors

The third critical element of successful Net Zero solutions, alongside the discrete technologies providing those solutions, and the system engineering pulling them together, concerns their economics – specifically, the affordability of the solutions themselves in terms of their operational costs and the investment required to bring them into being. The world, by and large, operates on free market principles. History has shown that consumers will adopt new technologies and create new markets when products cross an affordability threshold, for example, cars, air travel, mobile phones and washing machines. Net Zero solutions will only be adopted widely if their operating costs are broadly on par with existing solutions using energy derived from fossil fuels. Investments to achieve this will only be made if the risks and returns are balanced. Bearing in mind that there are some 150–200 years of optimisation, cost reduction, market formation and subsidies behind the current fossil-fuel-based technologies, this is quite a challenge.

Scale of investment required

A number of organisations have estimated the total investment in energy infrastructure required over the next c. 30 years to achieve the Net Zero goal.

The UK's Committee on Climate Change[21] has estimated this as an additional 1% of GDP by 2050 above the normal annual investment spending in the UK of 15–24% of GDP. It believes that changes of a few percentage points in investment levels have previously been accommodated. There would also seem to be plenty of funding available, provided adequate returns can be achieved.

The McKinsey 'Net Zero Report'[6] estimates a worldwide infrastructure investment figure of $275 trillion over the next 30 years, ie $9.2 trillion per year worldwide over that period or about 13% of world 'GDP'. This represents a $3.5 trillion increase above today's investment levels, with much of it front-end loaded.

The OECD[22] takes a similar view, suggesting that the financing gap to achieve sustainable development goals is only 1% of the $380 trillion of assets held in global financial systems.

Hence, the overall picture is one of very large investments but at a level that seems feasible.

The scale of R&D investment needed in addition to infrastructure spend should be noted. The world's annual spending on R&D is around $2 trillion. Additional spending for Net Zero technologies will therefore not add significantly to the figures mentioned above.

Financing Net Zero is therefore quite a challenge; however, it seems to be surmountable.

Matching projects to funds and investment criteria

Most investments are funded by personal savings, pension funds, insurance funds, venture capital and sovereign wealth funds. All have slightly different investment criteria, but the bulk of investments of this type have rather conservative investment criteria. While there is no shortage of money in principle, investments will be made on the basis of business plans, market characteristics, prices, costs and similar parameters. Anecdotally, it would seem that investments in areas containing the words "technology, 'software', and 'information' are more attractive and command higher value than renewable energy.

This is an area for selective government intervention in terms of, for example:

- Providing subsidies in the early stages of new market development
- Contributing to early investments
- Acting as a guarantor for investments with higher uncertainty
- Underwriting market prices or investments (eg by contracts-for-difference or cap-and-floor mechanisms)
- Carbon pricing (to discourage CO_2 production)
- Continuing to fund early-stage Net Zero technology developments
- In the case of the UK, encouraging increased late-stage venture capital funding[23]

The overall aim is risk reduction, and hence, reduced cost of capital in non-established and uncertain markets. The stability and predictability of these support measures are as important as the interventions themselves and governments must strike a fine balance. Too frequent or unpredictable market interventions will have the opposite effect to that intended.

Operating affordability

The enormous improvement in living standards that have been achieved over the last century have been brought about by a virtuous circle of volume increases, investment, productivity improvement, wage increases and hence demand increases. However, all these improvements were built around fossil fuels as the main source of energy. It is easy to overlook what has been achieved and, hence, what needs to be replicated using renewable energy sources.

It is usually the case that critical unit costs are required to achieve Net Zero breakthroughs. For example, it has been suggested that batteries for automotive applications should be available at $100/kWh.

If a battery had a 50 kWh capacity, the cost would be c. $5k and the range about 200 miles, parameters that would make electric vehicles competitive with conventional vehicles, especially when fuel costs are taken into account. Current costs at the time of writing are some 30% above this target level[24] and show signs of rising due to shortages. Hence, electric vehicles currently have a degree of uncompetitiveness when considered by retail buyers.

Hydrogen is relevant to both retail and industrial customers. The US Department of Energy has set an 'Energy Earthshot' target of $1/kg for hydrogen production using renewable resources. The current costs are at least $5/kg, and the goal of the programme is to release applications such as steel production, energy storage and heavy-duty trucks. Costs in these industries must achieve international standards of competitiveness.

These two examples illustrate the general point about the criticality of costs, both of individual elements of systems and of systems overall.

Key points

The economics of Net Zero solutions are just as important as the technologies used. Huge capital expenditure in energy generation and use systems is required to achieve Net Zero goals. Funds are available to achieve this, but with much of it up-front, the 'investability' of projects is critical. With many technologies queuing up at TRL 7, industry, investors and governments need to work together to bring these solutions through to high-volume fruition, with **Figure 9** providing some examples of the maturity status of a sample of relevant technologies.

Progress to date/current state of play

The Gap Report of the United Nations Environment Programme of 2021, published before COP26, takes a rather dismal view of progress. It is concerned mainly with political rather than technological progress. In particular, it deals with targets to achieve climate change objectives via 'nationally determined contributions', so-called NDC's[25]. At the point of publication, the collective efforts of the world's nations seemed a long way short of the targets agreed upon in Paris in 2015. COP26 considerably improved the picture, albeit at a political level.

In terms of the development of the world's climate and related issues, the Climate change background section of this report, has already pointed out that GHG levels are still rising, CO_2 levels by about 2.5 ppm per year[26], for example, and sea levels by 3–5 mm per year.

However, at an engineering level, the situation is arguably one of considerable effort and progress.

Figure 9: Illustrative list of technology readiness levels in the energy sector

Maturity	Area
Success – TRL9 achieved	• Battery-electric passenger cars • Hydrogen/fuel cell passenger cars • Wind power • Solar PV • Large scale (>1GW) nuclear power • Electricity HVDC inter-connectors and HV transmission systems
Ripe for Development – Currently at c. TRL7	• Carbon capture, utilisation and storage • Battery-electric and/or hydrogen fuel cells for heavy vehicles, buses and trains • Bio-energy with carbon capture & storage • Small, modular nuclear power • Domestic heat pumps in substantial quantities • Flow batteries • Direct reduced iron
More work Required – Lower TRL's	• Domestic retrofit insulation & heating in quantity • Direct air capture of CO_2 • Compressed air, liquid air, and gravity energy storage • Nuclear fusion • Space-based solar power

Critical topics and engineering challenges

Based on the foregoing, the following are proposed as critical topics where the Institution and its partners could bring attention to and arrange expert inputs by way of papers or lectures:

- Overcoming the variability or seasonality of energy sources in an energy environment very dependent on wind and solar energy, including particular methods and costs of storing energy and providing dispatchable sources of energy that can be rapidly brought online.
- Intelligent energy grid management, automation, and stability, especially with very high numbers of sources and consumers, with two-way flows, matching short-term supply and demand and providing security against frequency instability and short-circuit performance.
- The future role of hydrogen both for specialised applications and/or, more widely, for heating.
- Supplies, availability, and geopolitics of critical materials, such as copper, lithium, cobalt, nickel, graphite, and rare earth elements.
- Carbon capture, utilisation, and storage systems, scale-up, widespread adoption, efficiency, and costs.
- Retrofitting existing housing and buildings to radically improve their energy performance and to provide them with Net Zero heating and cooling systems.
- Replicating quickly the empirical and practical engineering knowledge gathered over 150–200 years of running current fossil-fuel-based energy systems.
- Role of governments in market interventions, guarantees, subsidies, carbon pricing/credits and their effect on the flow of funds into scale-up processes.

Concluding points

In conclusion, we have less than 30 years to switch from fossil fuel to low-carbon energy sources. This is arguably the largest engineering project undertaken by mankind. Most of the technologies to achieve this transition already exist, and some existing energy technologies will still have a place. However, there are many challenges in making these technologies robust, reliable, and cost-effective. We need to accelerate our efforts, create market demand, release cash, build up new skills and engage in a massive scale-up programme for this to occur.

In support of this goal, we, the IMechE, will:

- Provide comprehensive, objective and balanced coverage of technologies, with particular reference to their development (TRL) status and the market opportunities created, drawing attention to critical topics;
- Provide convening leadership in the UK engineering community on power generation and distribution, critical materials, capture technologies, building systems and energy vectors to maximise the impact of this community;
- Work to develop the education, skills and qualifications needed to under-pin Net Zero;
- Stress the importance of whole system design, optimising the whole and not just elements of the whole, pointing to gaps or weaknesses that we are aware of;
- With agencies such as Innovate UK and the Catapult network, encourage the development of large-scale pilot projects; and
- Emphasise the scale of change and the investment necessary, the flow of money and the need to create new markets and, hence, business opportunities.

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