# Energy Sources and Supply Grids – The Growing Need for Storage

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## ABSTRACT

Efficiently exploiting renewable, sustainable and green energy resources is one of the most critical challenges facing our world today. For example, as part of this challenge, Germany aims to generate 65% of its electricity from renewable sources by 2020 and Ireland aims to generate 40%. Renewable energy sources, *e.g.* solar and wind energy, are plentiful and sufficient to power our ever-increasing demand for more devices, technology and transportation. However, the increased demand for electricity at peak times, the increased instantaneous penetration of the grid by energy from non-conventional generation systems (such as wind turbines and solar photovoltaic) and the intermittent and non-dispatchable nature of renewable energy sources are threatening the stability of the electricity grid and limiting the ability of the transmission system operator to respond to sudden changes in generation or demand. This is particularly an issue in isolated grids such as on the island of Ireland, where the failure of a single generator results in the loss of a significant fraction of the overall grid capacity in an instant. However, in mainland Europe, the electricity grid of each nation is interconnected and synchronised, allowing the loss of a single generator in one region to be compensated for by increasing the output of the many other generators on the continent by a small amount. In the future, there will be a need for significant grid-scale

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storage, load levelling and stabilisation of the grid. Electric vehicles will become more prevalent and the fraction of renewables on the grid will increase significantly. These technologies and the way in which they interact with the grid will greatly affect the stability of the electricity grid. Smart and innovative interaction of these technologies with the grid raises the possibility of optimising the level of energy storage required for stable and reliable grid operation. However, lack of planning in these areas could make future cost-effective, sustainable and reliable energy solutions hard to achieve.

## 1 Introduction

In the last 50 years, global anthropogenic greenhouse gas (GHG) emissions (see Figure 1a) have almost doubled as our farming, deforestation, industrialisation, transportation and population have expanded rapidly.[1] GHG emissions are composed primarily of $CO_2$, $CH_4$ and $N_2O$. Burning of fossil fuels, *e.g.* coal, natural gas and oil, is the largest single contributor to GHG emissions (see Figure 1b), accounting for 57% of all GHG emissions and over three-quarters of all anthropogenic $CO_2$ emissions.[2,3] Concerns regarding security of energy supply and the impact of humans on the sustainability of our planet have led to significant changes in policies that attempt to reduce our dependence on fossil fuels by increasing our harvesting of energy from renewable resources and increasing the use of electricity for transport and for heat supply *via* heat pumps.

Driven by our increased use of renewable energy, the demand for energy stability and electricity-balancing technology is growing rapidly.[4] Wind and

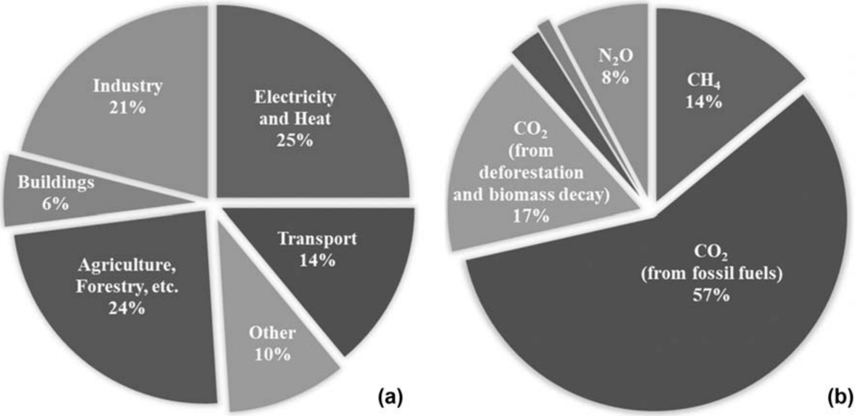

**Figure 1** Pie charts of the breakdown of global anthropogenic greenhouse gas emissions (a) by economic sector source (in 2010)[1] and (b) by gas emission type (in 2004).[3] Note that percentages are of $CO_2$ equivalent mass and the two minor percentages not indicated are 3% other $CO_2$ and 1% other gases.

solar power are non-synchronous and volatile, requiring the transmission system operator (TSO) to limit the instantaneous system non-synchronous penetration (SNSP), *e.g.* energy from wind and solar. Currently, sufficient synchronous 'inertia' and system services, necessary for grid stability and power quality management, are provided by conventional generation. The stability of the electricity grid is determined over several time scales. The fast reaction speeds of electrochemical systems and long operational life spans of many of these technologies make them ideal candidates for grid stabilisation and load levelling. However, such technologies cannot provide the stability currently provided by synchronous 'inertia' and, if they were to provide a large enough buffer for the variations in energy supply and demand, the cost of electricity would increase significantly. Therefore, a combination of smart grids and additional system services for the stabilisation of supply in conjunction with significant additional energy storage are required to facilitate the reduction in burning of fossil fuels and development of renewables as our source of energy for electricity, heat and transport.

## 2 Energy Sources

The transition to a lower carbon fuel mix, largely driven by the need to combat climate change, continues, with renewables being the largest source of energy growth.[5,6] The energy company BP's Energy Outlook estimates that by 2040 oil, coal, natural gas and non-fossil fuels will each provide around 25% of the world's energy.[6] That will be the most diversified fuel mix the world will have ever seen by a considerable margin. The expected increase in the standard of living worldwide will continue to drive an increase in global energy demand and, in order to mitigate the effects of climate change, this demand must be met by innovative clean energy solutions. Currently, this trend is being observed in the European Union, where renewables account for 80% of new capacity and wind power is predicted to become the leading source of electricity shortly after 2030.[7]

Coal and natural gas are the most used energy fuels for generating electricity. In 2014, the share of world energy consumption for electricity generation by source was coal at 40.8%, natural gas at 21.6%, nuclear at 10.6%, hydro at 16.4% and other sources (solar, wind, geothermal, biomass, *etc.*) at 6.3%. Oil accounts for only 4.3% of electricity generation, even though oil (petroleum and other liquids) provides the largest quantity of energy according to the World Energy Resources Report.[5]

### *2.1 Generation of Electricity from Combustion of Fossil Fuels*

In a thermal power plant, thermal energy from the combustion of fossil fuels, such as coal, oil and natural gas, is converted to electrical energy. Although there can be notable differences between different types of a given fuel in the level of emissions per unit energy (for example, differences in coal

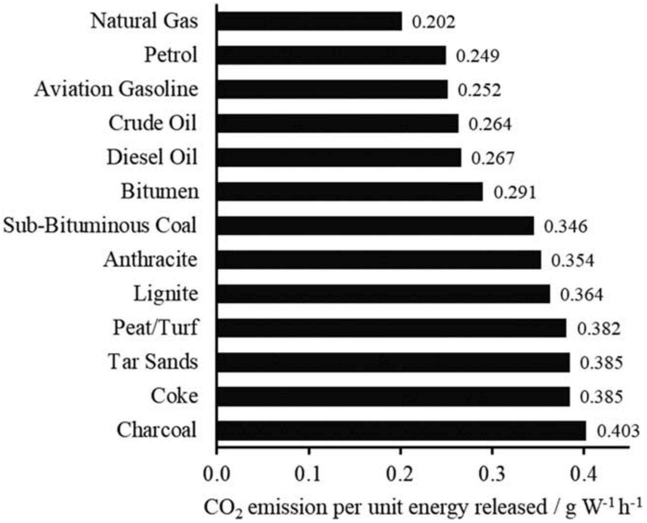

**Figure 2** Bar chart of the mass of carbon dioxide emitted per unit of total energy released by fully burning common fossil fuels.
Data from Intergovernmental Panel on Climate Change Report 2014.[1]

types; see Figure 2), there are some more general trends in the relative emissions between coal, oil and gas. Compared with oil and natural gas, coal produces the most $CO_2$ per unit of energy – $CO_2$ emissions from oil and natural gas are about 77 and 58%, respectively, of those from coal, as shown in Figure 2. This difference between the $CO_2$ emissions of different fossil fuels derives primarily from their carbon content – since coal consists primarily of carbon–carbon bonds the most significant product of its combustion is $CO_2$, whereas natural gas consists primarily of carbon–hydrogen bonds and therefore results in less $CO_2$ per kWh.

The combustion of any fossil fuel is damaging to the environment, but coal generally contains a small percentage of sulfur that, if released into the atmosphere as sulfur oxides, can lead to acid rain. However, oil is a small player in the power sector and therefore the following sections will focus on coal and gas, *i.e.* the major fossil fuels employed in the supply of electricity.

Coal-fired technology has a relatively low conversion efficiency of stored chemical energy to electrical energy compared with modern gas-fired combined cycle plants (of the order of 40% *versus* 58%), exacerbating coal's emissions problem. This gives gas-fired power plants a significant environmental advantage over both coal- and oil-fuelled generators. Nevertheless, coal remains a large fuel source in many countries, particularly in countries such as China and India where there are huge reserves.

*2.1.1 Coal.* Conventional power stations turn heat energy from fossil fuels into high-pressure and high-temperature steam that is then used to generate electricity. For example, in a typical coal-fired power plant, distillate oil is used to raise the temperature of a boiler's combustion chamber before admitting coal. When the chamber is at the correct temperature, coal ground to dust in ball mills is blown into the combustion chamber, where the pulverised fuel burns and generates heat. The design ensures good mixing of fuel and air to achieve complete combustion while ensuring that any bottom ash and fly ash produced as by-products of the process are captured. The gases from the combustion carry the heat to a boiler where water absorbs the heat and generates steam. The generated steam, when it reaches sufficient pressure and temperature, is admitted to the steam turbine, changing the internal energy of the steam into rotational kinetic energy (cooling the steam), which drives a synchronous electricity generator. (See the chapter Electrical Storage for more details on the operation of synchronous machines.) After this energy has been extracted, the steam is condensed and the water is circulated back to the boiler. As the plant output is increased by the plant operators at the request of a grid dispatch centre, the plant's control system increases the fuel feed to the combustion chamber, thereby delivering more steam to the steam turbine and generating more electricity. The overall thermal efficiency is typically between 35 and 40%, with some sophisticated systems achieving >40%.

In large-scale coal generation units (*ca.* 400 MW), the power is generated at around 15–20 kV, then enters a generator transformer and is stepped up to the local transmission voltage; this is typically in the hundreds of kilovolts. Coal plants generally have long start-up times, typically taking up to 6 h to go from cold to full load output. Of course, in situations where the plant is hot already, this delay can be significantly shortened to about 2 h.

Coal is currently still the most widely used fuel in the world for electricity generation, accounting for 37% of the total electricity generated.[8] In particular, some large economies, including China, the USA, India and Germany, use significant amounts of coal for electricity generation. With the emphasis in recent years on cleaner air, reduced emissions and combating climate change, there has been a shift away from coal, but progress has been slow. Data from the International Energy Agency (IEA) show that coal's share in electricity generation remained significant at 41% in 2014, but is estimated to have decreased since then.[7] Coal-fired power generation in the major developed countries is on a steep downward trajectory, in particular in the USA owing to competitive gas prices and the growth in renewables, whereas developing countries are still experiencing coal generation growth. In India, the third-largest coal consumer in the world, coal-fired power generation increased by 3.3% in 2015 as their economy continues to grow at a rapid pace. The widespread availability of coal in many countries makes it difficult for renewable energy technologies to compete.

In recent years, China has made policy decisions to reduce excess coal production. This has depressed global coal demand, particularly in the electricity sector, where it has typically been replaced by natural gas and renewable energy sources.[6] Britain's relationship with coal has almost come full circle, with the closure of Britain's last three underground coal mines and consumption decreasing to where it was roughly 200 years ago, around the time of the industrial revolution. Britain's electricity sector recorded its first-ever coal-free day in April 2017, thought to be the first time the nation had not used coal to generate electricity since the world's first centralised public coal-fired generator opened in 1882, at Holborn Viaduct in London.[9]

*2.1.2 Natural Gas.* Although coal is currently the primary source of electricity, it is likely that natural gas will soon take its place, as it is a much more environmentally friendly fuel. This is clear from the $CO_2$ data in Figure 2, where natural gas results in significantly less $CO_2$ emissions per unit of energy released. However, gas turbines often consume significant quantities of water, which is used in the reduction of $NO_x$ gas emissions.

As alluded to previously, gas, compared with coal or oil, has the additional advantage that a greater fraction of the chemical energy released during its combustion can be converted to electricity [in large-scale combined-cycle gas turbine (CCGT) plants]. Since products from the combustion of natural gas contain very few tars or particulates, it can be combusted in a gas turbine that is connected to a synchronous generator. The most common type of gas-fired plants are open-cycle gas turbines (OCGTs) that can be fuelled by gas or oil distillate. These plants are primarily designed for use during peaks in demand and as a backup to forecasting errors and rapid drops in generation from wind. Their design allows them to turn on quickly so as to take on a fraction of their maximum load and to ramp up to full load in less than half an hour. In addition, since the combustion of the fuel happens in the turbine, the response of such systems is much quicker than that of a conventional thermal power plant (where flow of steam can be controlled quickly but the ramp rate of heating of water in the boiler is much slower). However, flue gases that are exhausted from the gas turbine result in a huge loss of thermal energy to the atmosphere. The overall thermal efficiency of OCGT systems is typically less than 40%, *i.e.* similar to that of coal-fired systems.

CCGT plants capture a large quantity of this 'waste' heat from the flue-gases. These gases are passed through a waste-heat recovery boiler to generate steam, which is then used to drive a steam turbine and hence generate further electricity. The result is that the thermal efficiency of a CCGT plant can be close to 60%. However, a large decrease in efficiency occurs if the plant is operating at a fraction of its rated load or it switches over to operating as an open-cycle plant.

OCGT plants are normally used as peaking plants, *i.e.* to supply electricity for short durations when demand is high. Many system operators use OCGT plants during peak demand times or when some baseload plants trip out or fail to turn on when dispatched; in essence they frequently provide back-up power to the electricity grid and typically might run only a couple of hours daily, if at all. CCGT plants are extensively used as baseload plant, *i.e.* to meet the minimum load of the network. They typically run at full output for

16 h per day, so as to maximise the efficiency of the system, and at 80% load during the night so as to maximise stability.

Given the significantly greater thermal efficiency of CCGT plants, one would expect them to be the most common type of gas-fired power plant being constructed. However, CCGT plants, typically sized at 500 MW, are designed to run and deliver these high performances as baseload plant. It follows that, owing to the dramatic recent increase in intermittent generation – mainly wind turbine and solar photovoltaic – OCGT or other peaking plants with high part-load efficiency and flexibility are the most common type of new power plant being constructed. There is a growing need for and interest in 'wind-chasing' plants where there is a high penetration of intermittent generation. Wind chasers tend to be highly flexible, with good efficiency and high part-load performance. Indeed, large reciprocating gas engines with dual-fuel capability to burn back-up distillate fuel are becoming common. For example, a 160 MW power plant could be composed of 10 such gas engines and would therefore be able to turn on incrementally with relatively high efficiency.

*2.1.3 Oil.* Oil-fired generating plant lies in third place behind coal and gas, with only 4.3% according to world energy statistics.[6] Typically, oil is burned in conventional boilers with combustion chambers in the form of heavy fuel oil (HFO, termed 3000-second oil), light fuel oil (LFO, termed 200-second oil) and distillate or diesel oil. HFO and LFO must be heated prior to injection into the combustion chamber under pressure so that the atomised oil is completely and efficiently combusted. Distillate or diesel oil is normally used in conventional coal- and oil-fired plants during start-up, but these plants change over seamlessly to LFO or HFO (or coal in the case of coal-fired plant) when the HFO/LFO is sufficiently hot for use. The design of these oil-fired plants is similar to that of plants that burn coal, but oil-fired boilers are generally more efficient than similar-sized coal-fired plants as the latter have higher 'house loads' due to the additional power consumed in fuel handling, grinding and pulverising the coal prior to blowing it into the combustion chamber.

A more widespread use of distillate is as a fuel for OCGT plant where there is no gas transmission system. Distillate is also used widely as a back-up or secondary fuel for gas-fired power plants so that these plants are available for running if the gas supply is unavailable for any reason.

## 2.2 Nuclear Power

Nuclear power plants are normally steam-driven systems in which electrical energy is produced from splitting of atoms *via* nuclear fission.[10] More energy per mass of fuel can be produced in this way than by any other electricity generation system. The first large nuclear reactors were built in the 1940s as a method for producing plutonium for use in nuclear weapons. These plants used uranium as fuel, which had been shown to have fissile properties in

1938 by Otto Hahn, Fritz Strassman and Lise Meitner.[11] They showed that the mass of the products of the fission of uranium was less than the original mass – a verification of Einstein's theory of special relativity. In 1942, Enrico Fermi's team were the first to initiate a self-sustaining chain reaction as part of the Manhattan Project.[11]

For a nuclear reactor to sustain a chain reaction and produce atomic energy, atoms first have to be split, *i.e.* nuclear fission must occur. Uranium is the most commonly used fuel. In such reactors,[12] the fission of a small number of nuclei results in the release of neutrons capable of striking and splitting other nuclei within the fuel. The neutrons from this chain reaction are slowed by the moderator that encases the uranium fuel rods, optimising the probability of them splitting further atoms. Light water ($H_2O$), heavy water (deuterium oxide) and graphite are used as moderators.

The loss in mass, $m$, during these reactions corresponds to the release of energy, $E$, stored within the atom, where $E = mc^2$ and $c$ is the speed of light in a vacuum. Therefore, since $c^2$ is a large multiplier, a small loss of mass results in a large release of energy. In a nuclear power station, the heat generated from the splitting of the atoms is discharged through a cooling system that heats water, or some other coolant, that then is used to heat the water in a boiler, creating steam that drives a steam turbine. Therefore, in order to achieve high thermal efficiency, the coolant must operate at high temperatures and therefore high pressures. Furthermore, the nuclear reactions that occur in the reactor/pile produce radioactive products. Therefore, the reactor has to be encased in steel and concrete safety shields needed to contain the pressure and the reactive products, and a range of safety measures and protocols have to be closely followed to ensure safety.

Nuclear power stations have even longer ramp-up times than coal-fired and CCGT plants and therefore they are ideally suited to meeting the grid's baseload. Furthermore, nuclear plants operate most efficiently when run continuously at close to their rated output. However, in France, where 70–80% of electricity is generated from nuclear fission,[13] nuclear power plants are also used to meet peak demand, requiring plants to be designed so as to accommodate this ability without resulting in a significant loss of efficiency. This is a unique situation, resulting in very low off-peak electricity prices and encouragement of demand-side management through off-peak space and water heating and, more recently, charging of electric cars. However, the reliance on one source of energy has resulted in security of supply issues and price spikes, especially during cold weather; *e.g.* France's electricity demand rises by 2.3 GW per 1 °C drop in temperature, resulting in France changing from being a net exporter to a net importer of electricity during cold weather.[14]

In 2015, nuclear power provided 4.9% of total primary energy supply and 10.6% of electricity generation worldwide, requiring 65 000 tonnes of uranium.[15,16] Since nuclear power plants operate in a similar manner to conventional power plants, by boiling water to produce steam to drive a steam turbine, they also have similar efficiencies, *i.e.* 33% for a boiling water reactor and 30% for a pressurised water reactor, the two main reactor types in the USA.[10]

In addition to the energy efficiency, another important consideration is the fuel efficiency. The fuel in a nuclear reactor is made up of fissile material, *e.g.* U-233, U-235 or Pu-239, and fertile material, *e.g.* U-238 or Th-232.[12] The fissile material, when hit by neutrons, releases, in addition to a large amount of energy, at least two neutrons that can split other fissile material, resulting in a continued chain reaction. The fertile material, on the other hand, cannot undergo fission directly but must instead capture neutrons produced in the fission process, leading to it becoming fissile. This process is called breeding and it can replenish the concentration of fissile material. All nuclear reactors breed some fuel. In a typical reactor, the most common isotope formed is Pu-239 through the capture of a neutron by U-238 (the fertile material), which then undergoes beta decay to yield the fissile isotope. This isotope can then take part in the chain reaction, producing similar energy to that in the fission of U-235 (the main fissile material in a typical reactor).[17]

The risks associated with the operation of nuclear reactors are significant and the radioactive wastes produced can have very long half-lives and therefore require careful disposal. These concerns result in substantial political pressure that limits the adoption of nuclear power in many countries and has resulted in the decommissioning of nuclear plants (without replacement) in countries such as Germany.[14] These concerns are primarily driven by major accidents, *e.g.* at Chernobyl in 1986 and, most recently, at Fukushima–Daiichi in 2011.[18] However, nuclear reactors do have many safeguards, including intrinsic negative feedbacks such as a negative temperature coefficient of reactivity, and they do not cause air pollution or GHG emissions, making them an important alternative to fossil fuel-fired power stations, especially for meeting the electricity grid's baseload. Furthermore, there has been a resurgence in research in this area, with significant research into alternative nuclear reactor designs such as the liquid fluoride thorium reactor (LFTR).[19,20] Such reactor types promise several operational advantages, including a strong negative temperature coefficient of reactivity, very reliable failsafe mechanisms (owing to the liquid nature of the fuel, all the fissile material can be rapidly removed from the reactor though a plug in its base, quenching the chain reaction), high thermal efficiency and long fuel cycles between charges.[19] Since, compared with uranium, thorium is more abundant and proliferation resistant, and has a high fuel burnup (*i.e.* most of the fuel in an LFTR is consumed per fuel cycle as opposed to <1% in a typical uranium reactor) and short half-life products, LFTRs would result in increased security of supply, decreased costs and reduced damage to the environment.[19,20]

## 2.3 Renewables: Solar, Wind, Wave, Tidal and Hydro

*2.3.1 Solar.* The Sun pours energy onto the Earth's surface at rates that dwarf even the current rates of use of non-renewable fuels, including fossil and nuclear fuels. Only one part in 20 million of the Sun's radiation strikes our atmosphere and about half of that energy reaches the Earth's surface. This energy originates from nuclear reactions in the Sun, *i.e.* conversion of energy stored as mass in the nuclei in the Sun to energy. We typically convert solar energy into electrical energy in one of two ways, using photovoltaics (PV) or concentrated solar power (CSP).

In PV, the energy is harvested by large arrays of small solar cells, typically made of silicon. These cells convert light (photons from the Sun) into electricity. These cells typically operate at low efficiency, with less than 20% of the photons that strike the device leading to an excited electron. Although this low efficiency is undesirable in terms of land usage, the ubiquitous nature of solar energy makes any method of harvesting it desirable. As advanced semiconductor devices, PV cell arrays are both expensive and energy intensive to produce, which can significantly offset their green credentials.

In CSP, the energy is harvested in a similar manner to that in conventional thermal generators. Heat from the Sun is concentrated using specialised optics and used to heat water, which can generate steam and turn a turbine. This system can also be adapted to incorporate some thermal energy storage using a fluid from which heat can later be harvested (see the chapter Thermal and Thermochemical Storage for further details).

Solar power provided just 1% of total global electricity generation in 2016 but this is rising rapidly. In 2014, the International Energy Agency predicted that solar penetration could be as high as 27% by 2050, making it the world's largest source of renewable electricity.[21]

*2.3.2 Wind.* Solar energy absorbed in our atmosphere can reappear as lightning, wind, *etc.* Winds arise from different degrees of heating of the Earth's atmosphere by radiation from the Sun. Although windmills have made innumerable contributions to our industrial progress, the need to site them in often remote locations seriously limits their applications. However, the use of similar wind turbines for the generation of electricity has decoupled the need for colocation of generation and load, greatly increasing the usefulness of this energy source.

The harvesting of energy from the wind has seen explosive growth in recent decades. This is due to the many advantages that wind generators have over other sources of electrical energy. Wind energy is, in principle, available almost anywhere, produces no GHGs or other harmful emissions during operation and consumes no water and little land. However, large wind turbines may present a risk to certain species of birds and are often lamented for their impact on rural scenery.

As with most renewable sources, the major drawback of using wind energy to supply the electricity grid is the intermittent and non-synchronous (see the section on synchronous machines in the chapter Electrical Storage) nature of its output. Modern weather forecasting techniques allow the wind, and thus the amount of wind energy generated, to be predicted with reasonable accuracy. However, there are still discrepancies between forecasted and actual wind levels. Furthermore, even if the wind output is stable and matches forecasts, the output of a wind generator cannot be increased, except for short durations, to accommodate a shortfall in generation or an increase in demand, *i.e.* it is non-dispatchable. As a result, when the fraction of wind power (or other renewables) on the grid is high, a number of backup generators must keep burning fuel at low output, ready to come online should demand suddenly increase or should the wind suddenly decline. This has a negative impact on the overall efficiency of a grid with a high level of renewable penetration.

As with more traditional systems (*e.g.* thermal power plants), electrical energy is generated by converting the kinetic energy of the wind into rotational energy by having it turn a large electricity-generating turbine. In traditional power stations, the speed of rotation of the generator is fixed by the grid frequency (*e.g.* 50 Hz in Europe and 60 Hz in the USA) and all of these generators operate in a synchronous manner. Wind turbines can be operated in either a synchronous or non-synchronous manner.[22] Although synchronous wind turbines, operating at constant speed, were at one time more common, these have largely been supplanted by non-synchronous units, operating at variable speed.[23] While non-synchronous designs do not provide a synchronous inertial response to the grid, such designs can be used to maximise the energy harvested from the wind by operating at the optimum rotating speed for the current wind speed. In addition, depending on design, the rotational kinetic energy stored in the angular momentum of the turbine can deliver reserve power for short durations.[22,24–26]

Wind turbines can be located either on land or at sea. Offshore wind turbines have a number of advantages, including access to the more frequent and powerful winds often available offshore and the lack of objections, since local people are non-existent. However, the installation and maintenance costs are much higher than for land-based systems.

Wind penetration has increased considerably and is now estimated to account for 4% of total global electricity generation.[7] This increase is expected to continue for the foreseeable future and is largely driven by the move away from fossil fuels and the ubiquitous nature of wind energy.

#### 2.3.3 Wave.

Renewable energy can be harvested from the motion of water waves and converted into electricity. This can be done in many ways, including harvesting the kinetic energy of a floating body as it continuously rises and falls with the waves or forcing the rising water into an enclosed space, compressing air and using it to turn a turbine. This technology is promising as it is typically not visible to humans and would harvest an abundant and currently untapped source of renewable energy. This technology has seen relatively little deployment owing to the corrosive environment of the sea, resulting in a requirement for expensive materials and regular maintenance. These systems may also pose a hazard to various types of marine life, may encroach on productive fishing grounds and could provide a navigation hazard to seagoing vessels.[27] Several small- to medium-scale (<10 MW) commercial systems have been commissioned, but most systems that have been installed are still in the developmental stage and are not yet commercially viable.[28]

*2.3.4 Tidal.* Renewable electricity can be generated from the motion of the tides. This has the significant advantage that the tides (unlike wind or sunshine) can be accurately predicted, making tidal energy one of the few non-volatile forms of renewable electricity. Indeed, careful planning of the location and phase difference between tides across Europe or other similar regions could allow tidal energy to meet reliably some of the baseload of electricity grids.[29] However, only certain regions have sufficiently large tidal ranges to make this technology competitive.[30] Tidal generators can work in a number of ways but typically involve using the tide to turn hydroelectric turbines. One method of achieving this is by capturing the water at high tide in a reservoir or dam and slowly releasing this water through the turbines after the tide has fallen. In some regions where the flow of water is constricted (*e.g.* by natural straights or artificial bridges), the flow of water due to changing tides can reach a relatively high velocity and a strategically placed turbine can generate a significant amount of power.

Tidal generation has seen relatively little deployment. This is often due to the lack of suitable locations but these systems also potentially pose a threat to marine wildlife and suffer from the same corrosion issues as are experienced by wave generators. The nascent stage of the technology's development also contributes to the high up-front cost of these systems. A handful of plants have been commissioned worldwide, with the largest having outputs of a few hundred megawatts.[31]

*2.3.5 Hydro.* Water evaporated by energy from the Sun can condense on high land, converting solar energy to potential energy. As this water makes its way back to lower ground, hydroelectric generators can convert this energy to electricity. The flow of water rotates turbines in these generators. While these turbines can be used to harvest tidal energy, hydroelectric generation typically refers to large systems of dams and turbines in which the water is kept at an elevated level by the dam and slowly released through a tunnel containing a turbine. The motion of the water causes the turbine to rotate, generating electricity. These systems can be operated in a continuous manner or can hold their reserves for times of increased demand, *e.g.* pumped hydro storage (see the next chapter on Mechanical Systems for Energy Storage for further details).

Although there are some locations that provide a natural water drop which can be exploited for hydroelectric generation, typically the construction of large dams, along with the canals used to redirect water during and after the dam's construction, is necessary. This can lead to a very large up-front capital cost for these systems. However, once built, these systems generate very little emissions. Hydroelectric generation is one of the oldest types of electricity generation and 70% of all electrical energy from renewable sources was generated from hydroelectric sources in 2017, amounting to almost 16% of total electricity generation globally.[15] However, there are a number of drawbacks in addition to the high capital costs. The redirection of rivers and creation of large new lakes can lead to the displacement of large numbers of people in addition to disrupting the habitats of a wide range of flora and fauna.[32]

## *2.4 Geothermal, Combined Heat and Power, Biomass Combustion and Waste Incineration*

*2.4.1 Geothermal.* Geothermal energy is harvested from the heat of the Earth's molten interior. This heat originates from radioactive decay within the Earth and, to a much lesser extent, near the surface, from stored solar energy.[33] On average, the temperature increases at about 30 $^{\circ}\mathrm{C\,km^{-1}}$ towards the centre of the Earth, resulting in a total rate of heat flow to the Earth's surface of 42 TW or 82 $\mathrm{mW\,m^{-2}}$. This energy may be harnessed to provide energy for a variety of purposes, including direct heating to nearby communities or industries, or to generate electricity or provide heating using geothermal heat pumps.

Direct heating in the form of hot springs was used in ancient Roman and Chinese times for bathing and washing. Today, direct heating is employed in locations worldwide that have hot springs close to towns and communities in the form of district heating schemes. Additionally, the heat may be delivered as hot water or industrial steam to nearby process industries. The drive to combat climate change coupled with the availability of hot springs mean that district heating schemes are well developed in Iceland and are being looked at more closely in other countries.[34] These schemes can be augmented by fossil-fuel boilers and more recently by renewable sources such as wind and solar PV.[35]

Geothermal heat can be used for electricity generation. Energy can be extracted from the Earth by injecting water deep underground. The returning steam (or hot water, which is later converted to steam) drives turbines connected to generators. The depth of injection and location *inter alia* have a significant impact on both the return temperature of the water/steam and the quantity of energy extracted. If the steam is superheated and at sufficient temperature, it may be used to drive a steam turbine directly. In most cases, it is likely that the return geothermal steam or water will require routing through a boiler to bring the steam conditions up to those necessary for admission to the steam turbine. Although the capital cost can be enormous in extracting geothermal heat, the operating costs are generally low; these costs are largely the energy costs for continuous recirculation of water.

Geothermal energy contributes a significant share of electricity generation in several countries. There is 13.2 GW of geothermal power capacity worldwide, with 43% of this based on island nations and 72% of the installed capacity near tectonic plate boundaries or hotspots where the energy is more accessible.[5] The Philippines are the second-largest geothermal electricity producer after the USA, at about 10 TWh of electricity per annum, which equals approximately 14% of the Philippines' total electricity generation. Kenya is the seventh-largest producer of electricity from geothermal energy at about 5 TWh of electricity per annum, but it has the largest share of its total electricity generation from geothermal energy at about 44%.

In many areas of the world, particularly in Europe and the USA, buildings require heating during the winter and cooling during the summer, owing to fluctuations in ambient air temperatures. Although air temperatures above ground change throughout the day and with the seasons, temperatures 3 m below the Earth's surface are consistently between 10 and 15 °C. This consistent below-ground temperature can be used to heat and cool buildings by employing geothermal heat pumps. These transfer heat from the ground into buildings during the winter and reverse the process in the summer.

According to the US Environmental Protection Agency (EPA), geothermal heat pumps are the most energy-efficient, environmentally clean and cost-effective systems for heating and cooling buildings.[36] All types of buildings can use geothermal heat pumps but a limiting factor is the amount of heat transfer surface required to extract or dissipate the heat from/to the ground.

*2.4.2 Combined Heat and Power.* Combined heat and power (CHP) is the simultaneous production of utilisable heat and electricity from an integrated thermodynamic process. Usually this involves capturing and utilising the waste heat from the production of electricity and thereby increases the overall process operating efficiency. Waste heat recovery from power plants can provide steam and/or hot water to serve local requirements. This can include steam or hot water for industrial use, adsorption chilling and district heating schemes providing heated water for residential developments.

CHP plants are frequently given priority dispatch so that the plant generates electricity whenever supplying heat to contracted customers. If the plant is dispatched only in accordance with merit order then there may be significant periods when the plant would not be in operation and those relying on heat will have to provide their own back-up heat by less environmentally friendly means. There is an electricity cost to be borne when the CHP plant is given priority as more efficient plants are displaced, often resulting in the market operator applying a Public Service Obligation levy on all electricity users so as to recover the additional out-of-merit-order costs arising from the plant being given priority.

Governments have recognised the importance of CHPs in helping to achieve national emissions targets and combat climate change. The migration towards large-scale business parks with all services on site, including power and heat, is providing benefits to industrial steam users and nearby residential communities using district heating and is therefore a major boost to the CHP sector. Government policies may seek to attract more investment into this sector by enabling investors to qualify for certain capital and depreciation allowances in addition to not being liable for carbon taxes.

Although these may not appear significant, they may be just sufficient to enable some projects to reach financial viability.

*2.4.3 Combustion of Biomass.* Biomass is fuel that is developed from organic materials such as wood waste, forest trimmings, bagasse (*i.e.* dried pulp from sugar cane), straw and animal manure. Some crops, such as willow and *Miscanthus* grass, are specifically grown for biomass use. These renewable and arguably sustainable sources of energy are used to generate renewable electricity or create other forms of renewable energy. The combustion of biomass can be considered carbon neutral because the carbon dioxide produced when it is burned is offset by the carbon dioxide captured during its production. When the biomass waste material is used in the production of electricity, it produces GHG emissions, but if the waste was openly burned, dumped or allowed to rot into the soil, these emissions would still occur.

A key element that is often missed is that the combustion of biomass should be as close as possible to the source of the biomass, as fuel costs and carbon emissions due to long distance transportation can significantly increase carbon emissions from non-renewable sources, undermining the concept of biomass carbon neutrality, *e.g.* forest trimmings transported from the mid-western USA to Europe by ship and then transported further by road to a biomass-fired power plant. This has a serious impact on the biomass efficiency cycle. Another aspect that requires serious consideration is the need for drying or other processing. A harvested wet willow crop will have a very low heat/calorific value per tonne and hence low economic value until its moisture content is significantly reduced. Kiln drying of biomass should be avoided and atmospheric drying should be used where possible.

In biomass power plants, wood waste or other waste is burned to produce steam that drives a steam turbine, which generates electricity. Biomass is often burned at combined heat and power plants. In recent times, small isolated islands and remote communities have been looking at developing small biomass plants to generate and supply electricity into a mini or micro grid, *i.e.* a localised electricity network augmented by wind generation and solar PV. Energy storage, employing either batteries or flywheels coupled with load management techniques, is used to provide system stability and security in these new self-sufficient mini/micro grids around the globe.

Biomass is not without its challenges, not least a long-term and consistent feedstock supply. For this reason, governments may introduce REFIT (renewable feed-in tariff) schemes to ensure that potential projects achieve sufficient financial support from investors. However, even with a REFIT scheme in place, biomass investors will be reluctant to come into the market if there is a concern regarding a stop–start fuel supply or if no long-term supply contract can be negotiated.

*2.4.4 Waste Incineration.* High-technology waste incineration or waste-to-energy (WtE) with sophisticated environmental controls has come to the fore in recent years, particularly for municipal solid waste, hazardous waste and medical waste. With increasing focus on the environment and on the planet's finite resources, waste reduction, recycling, reusing and composting, together with awareness of the circular economy where waste is a feedstock for other industries, are all contributing to a reduction in the use of both landfill and waste incineration. These are now seen as the final links in the waste chain, with waste incineration nevertheless playing a reduced but important part in waste management. All of this has resulted in a depleting feedstock, with some exceptions, and a low-level increase in waste incineration.

Fortunately, a significant portion of municipal waste – consisting of paper, cardboard, plastics, metals, glass, wood, rubber and textiles – can be recycled and reused, leaving a depleted feedstock for waste incineration. Similarly, increased emphasis on composting has led to more environmentally friendly uses of household and organic waste. For example, food waste from households and the food processing industries is being increasingly used as a feedstock for anaerobic digesters for the production of biogas. In many countries, national gas grids provide injection points where scrubbed biogas can be injected and sold to renewable generation and CHP plants through GPAs (gas purchase agreements, similar in structure to power purchase agreements).

Medical and biomedical waste requires special waste disposal practices owing to the risk of infections and other public health concerns. The increasing emphasis on healthcare, in both developed and developing countries, means that this waste stream is increasing. Until new methodologies are developed for recycling and reusing infectious waste, waste incineration will be the preferred method of disposal.

Hazardous waste is defined by environmental authorities in most countries as waste material that can be classified as potentially dangerous to human health or the environment on the basis of a range of characteristics, including its toxicity, flammability or corrosiveness. In the past, much of this hazardous waste was sent to landfill but, with concerns about contamination of air, surface water and groundwater from uncontrolled land-disposal sites, tougher regulations for this waste disposal have come into operation. As a result, advanced technologies have been employed for managing hazardous waste, including stringently controlled incineration.

As discussed earlier, waste incineration is frequently used in conjunction with waste heat recovery for district heating. This arrangement enables the WtE plant to operate as a high-efficiency CHP and hence deliver the greatest possible benefit to the local community and the environment.

## 3 Operation of Electricity Networks

In the early nineteenth century, Volta's battery and Faraday's electric motor, along with several other key inventions and theories, allowed the controlled conversion of different forms of energy to and from electrical energy.

Through the advancement of research and development in this area by Bell, Edison, Kelvin, Parsons, Tesla and many others, electrification of industry was made possible, resulting in the second industrial revolution. This electrical energy was and still is remarkable for its flexibility. It can be produced from a variety of energy sources, *e.g.* wind, coal and nuclear, and can be transported hundreds of kilometres to the point of consumption. Hence the generation of electricity can be placed near the source of the energy even if that is a significant distance from the ultimate user, *i.e.* it became no longer necessary to place large industries beside hydro dams or to transport coal inland to fuel power-intensive, mining *etc.*

By connecting multiple energy sources and loads to a simple grid, a reliable supply of energy is provided without ever, from the point of view of the consumer, having to be ordered, delivered or topped up. These large electricity grids can ride through the turning on and off of large appliances and can even maintain operation in the event of a significant fault, such as the unexpected disconnection of a major generator. In addition, extra-large grids, such as the synchronous grid of Continental Europe, also benefit from the spread of peak loads, *e.g.* since peak loads occur in Warsaw and Lisbon at different times, the overall fluctuations of power on the grid are reduced. In a similar way, although the average wind speed at a particular site varies very little from year to year, the instantaneous wind speed varies significantly; but, a distributed network of wind turbines and other intermittent energy sources across Europe would produce a very stable source of power.

Although the structure of the electricity supply industry (ESI), comprising large-scale generation plants, transmission and distribution networks and a supply function, has remained largely the same over many decades, developments in recent years have resulted in a more complex arrangement. The growth in intermittent generation (wind and solar), grid-connected storage, distributed generation and distribution-connected storage has added to more complex market arrangements in different countries. However, the supply of electricity is considered as primarily four distinctive sectors, as shown in Figure 3, with distributed generation, *etc.*, connected at the supply and distribution level. Bulk electricity is transported from power

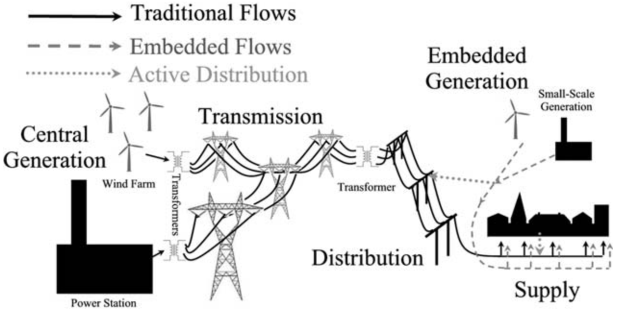

**Figure 3** Schematic of distinctive sectors of supply of electricity.

stations (generation) through the high-voltage national grid (transmission) and through the low-voltage network (distribution) to end customers (supply). Coal-, gas- and oil-fired power plants usually compete for the electricity supply whereas more modern technologies such as wind and solar often have priority for energy supply. Transmission is the term used for the bulk movement of electricity, often over long distances, at high voltage from generating stations mainly to transmission substations where the voltage is stepped down to the distribution level through transformers. Transmission and distribution are in most instances monopoly sectors. Supply is normally a competitive sector that interfaces with consumers through a supply contract with metering and tariffs. Some of these tariffs, such as the wire charges and consumer levies, are normally regulated whereas the energy consumption tariff may be a competitive element that is contracted between the customer and supplier, usually for a specific period.

### *3.1 Transmission Network*

A transmission system consists of a meshed network of high-voltage wires that transports bulk power from generation nodes to large demand centres (usually cities, towns and large consumers). The wires are normally arranged over a number of different voltages so that the grid may consist of three or four high-voltage (HV) voltages, *e.g.* 110, 220, 400 and maybe 700 kV; this meshed HV network is typically referred to as ‘the grid’. Large power plants normally feed into the grid at high voltages consistent with their megawatt output; the higher the voltage for a particular output, the lower is the current and hence the lower are the losses and size of the conducting wires. For example, a large 400 MW plant would connect at 220 kV or above whereas a smaller plant could connect at a lower voltage.

The wires of each voltage network, *e.g.* 220 kV, are linked, coupling them to the next highest and next lowest voltage through what are referred to as tie-transformers, normally located in transmission substations. In the past, power flows were thought of as flowing from higher to lower voltages, passing through step-down transformers, and eventually stepped down further to what is commonly referred to as the distribution network. However, with the growth of embedded generation, where medium-sized generators such as wind farms, CHP plants and solar PV farms are connected at distribution voltages or at the low transmission voltages, power flows can frequently be reversed.

Each voltage network can be thought of as a particular floor in a large building: to get to the floor above or below, one must use stairs; in the case of the grid, electricity flowing from one voltage level to the next highest or lowest must flow through a transformer. Although these can carry power in both directions, power normally flows from higher to lower voltage. Network voltages below 100 kV are normally deemed to be distribution networks, although this can vary in different countries around the globe.

## *3.2 Distribution Network*

A distribution system consists of a meshed network of low- and medium-voltage wires that transports power from large bulk nodes – referred to as substations – to individual customers. As with the transmission network, the wires are normally arranged over a number of different voltages so that the network may consist of three or four voltages, *e.g.* 38 kV, 20 kV and stepping down to 400 V three-phase supply to small business and 230 V single-phase supply to domestic customers. Again, in the past, power flows were thought of as flowing from higher to lower voltages, passing through step-down transformers and eventually connecting to the individual customer's meter point. In recent times, there have been several forms of micro generation from small, single-phase wind turbines, solar PV panels, micro CHPs or mini hydro schemes feeding into the distribution network at the lower distribution voltages, with medium-sized wind farms feeding in at the higher distribution voltages, resulting in reverse power flows.

Distribution networks encounter problems that are not normally seen in transmission networks. For example, because small generators do not have the same sophisticated protections as large conventional generators, there is an increased risk that they may feed into a 'dead' network during planned or forced outages of the network. This can prove to be a serious risk to maintenance crews working on the network, *e.g.* on 38 kV lines, as power fed in at low voltages, *e.g.* 230 V, can be stepped up to where repair crews are working. Distribution Codes normally require that all distribution-connected generators – large or small – are fitted with disconnection/trip mechanisms should the network voltage be lost. Another problem area is 'islanding' of distribution-connected generators, alone or while remaining connected to a small part of the network. For example, a circuit breaker connecting a part of the network where a small wind farm is located close to a factory could open/trip, leaving the wind farm as the sole feed to the factory. As these loads are unlikely to be matched exactly, the islanded frequency could increase or decrease dramatically, exposing equipment or personnel to risk. The need for reliable and sensitive detection and shutdown mechanisms is crucial to cope with such situations.

## *3.3 Distributed Generation*

Currently, there is no consistent definition of distributed generation (DG) within the electricity sector literature. However, the Office of Gas and Electricity Markets (Ofgem) in the UK aptly describes it as 'embedded or dispersed generation, where the electricity generating plant is connected to a distribution network rather than the transmission network'. There are many types and sizes of DG, including CHP plants, wind farms, hydroelectric power, solar PV or one of the new hybrid generation technologies. Depending how distribution voltages are quantified, DG sizes may vary from fairly large wind farms down to small generators of less than 10 kW; all connected at different distribution voltages.

Over recent years, we have witnessed a dramatic growth in the number of distributed generators seeking to connect to the distribution network. Many DG developers are first-timers to the electricity market and frequently encounter significant difficulties in navigating their way through the planning, licensing and connection processes. The development of DG requires governments and regulators to ensure that planning, licensing and connection to the distribution network are such as to treat DG fairly. DG is expected to become more important in future generation systems as countries and citizens seek to contribute to combating climate change. From a national perspective, DG can greatly increase awareness of the environment in addition to supporting the meeting of national emissions targets. Furthermore, energy losses are considerably reduced as the electricity is consumed closer to the point of generation.

The development and increased availability of small-scale battery storage systems coupled with advances in wind turbine and solar PV technology are encouraging many householders, farmers and small businesses to have their own DG, while remaining connected to the distribution network. Many consumers are now able to supply their own energy and export excess energy to the grid, although the former may be the better of the two, depending on the regulatory framework that applies. For example, where the regulations allow net metering, there is a significant benefit to the customer/generator as any excess electricity exported onto the network during off-peak times can effectively be drawn down and used later at peak times. The benefit arises because electricity, which is normally expensive to store, has a different value at every point in time. Hence, if a customer/generator can export a surplus unit of electricity during off-peak times with a value of only 1 penny or 1 cent, and then draw it down and use it later in the day when valued at 5 pence or 5 cents, then he/she has gained considerably. However, this benefit has not been gained for free; rather, there is a cost that is spread across all electricity consumers so that in effect it is cross-subsidisation from the many to the few.

It is worth highlighting that customers with their own generation (including domestic generation with roof PV) purchase far fewer units of electricity and hence pay much less to the supplier and hence to the distribution and transmission operators. Since the fixed tariffs are usually not cost-reflective, with much of the fixed infrastructure costs and fixed billing and payments costs covered in the unit rates rather than in the standing charge or other fixed charges, when customers pay for fewer units (because they are generating their own energy) they are no longer paying their fair share of the fixed costs. Often the poorer customers who cannot afford PV are subsidising the wealthier who can afford it, raising an issue for the long-term sustainability of, in particular, the distribution operators under such regimes.[37]

## 3.4 Mini Grids

The World Bank states that 87.3% of the world's population in 2016 had access to electricity.[38] At a global population of 7.44 billion, this means that approximately 1 billion people do not have access to electricity. It was only in 2018 that the last remaining village not connected to the grid in India was connected. However, many people in villages in India still do not have access to electricity.[39]

Mini grids are normally associated with developing countries or small isolated communities. Such mini grids may be a long-term solution, as in the case of a remote island, or they may serve as an interim solution pending the arrival of the main grid at a future date. Decisions regarding their development are driven as much by social and political considerations as by economics.

A mini grid can be defined as a combination of generators, possibly coupled with an energy storage system and load management system, all connected to a distribution network to supply electricity to a local group of customers. The generation mix in such a mini grid may involve dispatchable generation such as diesel generator sets coupled with some non-dispatchable solar and wind, with a total capacity normally of between 50 kW and 10 MW. System stability is provided through the control system, employing energy storage such as batteries and/or flywheels and a load management system.

The control system ensures that frequency and voltage are maintained within specified limits by utilising the energy storage and, if these limits are reached, load control is employed. The mini grid normally serves a limited number of customers *via* a localised distribution network, which is operated in isolation from the main grid.

With the push towards the greater use of renewables and the higher availability of solar and wind energy on islands and in remote locations, there is a shift away from diesel engines. Many locations are seeking an all-renewable mini/micro grid with, for example, dispatchable biomass and non-dispatchable wind/solar supported by storage. This storage may well be hybrid storage, incorporating high-cycling lithium-ion batteries or flywheels and low-cycling lead–acid batteries. Issues to be addressed in these grids include load matching and grid stability from both voltage and frequency perspectives. The latter must be managed during both continuous frequency regulation and ‘events’ due to loss of generation or demand. Other areas that require attention are power quality, fault conditions and associated protection.

A *micro grid* should be seen as a small mini grid, where a similar definition applies, namely that it supplies a small group of electricity customers through an isolated network, employing all the elements of a mini grid, but with a total load between 5 and 50 kW. *Nano grids* are a step below this, with loads normally in the range 500 W–5 kW. *Pico grids* are the smallest level of all, where the load is below 500 W, and would normally be associated with a remote stand-alone dwelling.

There is a strong social drive behind these small grids as remote, isolated or developing communities no longer want to wait for several more years for electricity supply to reach them. Global access to the Internet, the availability of mobile and smart phones and a greater awareness of comparative deprivation are all driving the need for sustainable electricity systems among even the most remote of communities across developing countries. Where there are no plans to build a main grid and associated distribution network, then the push for mini grids increases. Some key considerations include the following:

- Are policymakers and regulators driving the construction and operation of mini grids within their country with the appropriate incentives for investors? These will only come into the market if the rewards are in line with the risks profile.
- Are major development entities such as the World Bank, Asian Development Bank, African Development Bank and European Union actively encouraging and promoting such projects across developing communities through the provision of adequate funding? An adaptive and replicative approach must be adopted so that projects can be replicated 100 times, having been adapted to incorporate the local conditions and sources of energy.
- Will regulators adopt a business-like approach to tariff setting by making provision for a subsidy, or through a regulated tariff, guaranteeing an acceptable risk, or will they opt for a tariff that is cost-reflective plus a margin?
- Will there be a sufficient uptake of the electricity supplies, particularly as the cost per kWh may be significantly higher than the cost to those who are grid connected? Also, remote and island communities tend to be poorer than consumers in cities, hence the possible need for subsidies and the need to contain costs through proven replicable projects.
- The envisaged time frame for access to the national grid, even though several years away, is a critical factor in the ‘transfer’ of the mini grid assets to the national grid/distribution network. If investors believe that there is a considerable risk of grid access coming earlier than expected or of having their assets grossly undervalued when subsumed into the national grid/distribution network, then they will be reluctant to invest.

In summary, national governments, policymakers and regulators and development/funding agencies all have a key role to play in bringing electricity to remote communities and thereby opening up a whole new world to them. The knock-on effects can be enormous: for example, facilitating further education, remote learning with foreign universities, developing programming and software skills and facilitating remote work. In terms of addressing the inequitable access of people to enjoying a better standard of life, access to a sustainable electricity supply can be viewed as a critical step. Furthermore, designing these grids to supply energy from renewable and ubiquitous sources can greatly reduce the running costs to isolated communities and curtail the increase in global GHG emissions through a reduction in the use of imported fossil fuels.

## 4 Stabilisation of the Electricity Grid

Electricity supply grids are in a transitional period, driven by national and international objectives with respect to renewable energy. The current state of evolution of a particular electricity grid is dependent on many factors, including its current generation portfolio, the availability of non-fossil fuel generation alternatives and geographical considerations. Such transitions have resulted and will further result in fundamental changes to the power system generation portfolio, leading to changes in the operational characteristics of each system under both steady-state and transient conditions and requiring significant transformation of the composition of system services required for the reliable operation of the grid.

### 4.1 System Support Services

System support services, also referred to as ancillary services, are services other than the supply of energy that are required for the secure and reliable operation of an electricity system. As the maximum supply of energy from wind increases on a grid, the need for these service and newly defined services, *i.e.* services that would have previously been supplied as an intrinsic part of conventional power generation, increases. Frequency and voltage control are the key criteria for the TSO in maintaining a secure and stable system. Frequency control is maintained through spinning reserve and standby reserve whereas voltage control is maintained mainly through automatic voltage control on generators that are running (see the section on synchronous machines in the chapter Electrical Storage), supported by tap changing on transformers.

Security of supply may be of particular concern to large multinational businesses, data centres and other industries located in flagship business parks. The advanced electronic equipment found in modern working environments often requires a high degree of reliability from the incoming electricity supply. For example, many sophisticated manufacturing processes rely heavily on microcomputers, variable-speed drives and robotic devices to achieve high levels of product throughput and product quality. Other areas of business, such as data centres and the bio-pharmaceutical and IT industries, will only invest where the energy and telecommunications infrastructure is strong and quality of supply is assured. Even the most robust grids have some outages, so large customers with critical processes must have uninterruptible power supplies (UPS) to allow them to continue operation during short outage periods. Additional system services will be required to facilitate a secure electricity supply with large-scale wind and solar penetration.

*4.1.1 Spinning Reserve.* Spinning reserve is the increase in generating capacity that is available from generators that are running at times when the system frequency is below the normal operating level. This additional generation capacity is provided by dispatching a number of running plants below their full output so that in the event of the loss of a large generator and a consequential decrease in frequency, these plants can rapidly increase output to restore the frequency to normal.

The general rule that TSOs use for determining the level of spinning reserve required is that it should be equal to the largest infeed, *i.e.* generator or interconnector. Hence if the largest infeed was 400 MW then the total spinning reserves required would equal 400 MW to cover the loss of this infeed. An additional rule for prudent operation of the grid is that the largest infeed should be limited to 10% of the total demand. There can be a significant cost in providing spinning reserve as plants with low positions on the merit order must be dispatched to provide spinning reserve, displacing plants higher in the merit order (that are unable to provide the same level or type of spinning reserve).

Following an event on the system that leads to a sudden decrease in the voltage and/or frequency, the spinning reserve will slow the rate of change of frequency (RoCoF). The initial support to the grid is provided by an instantaneous synchronous inertia response where the RoCoF is determined by a combination of factors, including the magnitude of the supply/demand imbalance and the type of generators remaining on the grid after the event.[40–42] For such an event, the instantaneous response is augmented by the spinning reserve. Initially, the rotational kinetic energy (*i.e.* the 'inertia') of the synchronous generators coupled to the grid works to reduce the RoCoF. The next stage of the recovery comes from the primary reserve. This is provided by the ability of currently operating power plants to increase their output temporarily within a number of seconds, but this increased output is available for only a short period, of the order of minutes. Stage three in the recovery comes from the secondary reserve and is done by activating storage from hydro power plants or dispatching thermal plants from part-load to full-load output. This is done within minutes of the event and must remain in operation until the final stage of recovery can be activated, namely utilising the long-term reserve (*i.e.* at least one power plant that is shut down is brought on load), fully replacing the lost power plant with another one.

Spinning reserve rules would normally be more stringent for an isolated system to ensure that system security is not compromised. In large systems with ac interconnectors across several countries, such as in Europe, each country will provide spinning reserve at a level agreed between TSOs. However, this may be influenced as much by economic reasons as by system security; interconnection will prevent system collapse in any country across the system, but there are often penalty charges for excessive imports across interconnectors from neighbouring national grids.

The definitions of different reserves vary slightly between countries. The following definitions apply in Ireland, but are typical:

- *Primary Operating Reserve* (POR) is the additional power output (and/or reduction in demand) delivered compared with the pre-incident output (or demand), which is fully available and sustainable over the period from 5 to 15 s following an event. Note: the timing of the 'event' is defined in terms of the frequency nadir.

- *Secondary Operating Reserve* (SOR) is defined in a similar way, but it must be fully available and sustainable over the period from 15 to 90 s following an event.
- *Tertiary Operating Reserve* (TOR) is sometimes divided into two time frames, namely TOR1 and TOR2: TOR1 is from 90 s to 5 min and TOR2 is from 5 to 20 min following an event.
- *Replacement Reserve* is over the period from 20 min to 1 h following an event and it can be divided into synchronous reserve from plant that is running [Replacement Reserve Synchronised (RRS)] and desynchronised reserve from plant that is shut down [Replacement Reserve De-Synchronised (RRDS)].

## 4.2 Impact of Renewables on Operation of Electricity Grid

High penetration of renewable generation poses challenges for the TSO with regard to grid stability. The solution to managing these challenges will be met through the utilisation of traditional responses and reserves and a mixture of new system services, including backup from batteries and management of demand-side loads. As the maximum percentage of wind energy on the grid increases, the stability of the electricity grid can decrease significantly. This is primarily not due to the unpredictability of wind but rather is due to the displacement of conventional synchronous generators. All synchronous machines (generators, motors and condensers) provide instantaneous response to imbalances between electricity generation and load by using the rotational kinetic energy stored in the synchronous machines as a buffer. For example, if too little energy is generated, the rotational kinetic energy of the machines is converted to electricity, slowing their rotation and the frequency of the grid; if too much energy is generated, the reverse occurs. The instantaneous nature of this synchronous response cannot be replicated by batteries or other non-synchronous energy storage devices. However, the augmentation of synchronous response with conventional generators or synchronous condensers (*e.g.* generators spinning at synchronous speed with zero output but providing voltage support; see the chapter Electrical Storage for further details) increases the production of carbon dioxide and/or reduces the efficiency of the electricity grid.[41,42]

Up to penetrations of about 40% renewables, grid stability is provided by conventional plant with heavy steam turbines and/or generators, which are synchronised to the grid, rotating at synchronous frequency (3000 rpm, *i.e.* 50 Hz, across Europe) or a factor of that frequency. If a generator fails, causing the supply of energy to the grid to decrease rapidly, then the system frequency will fall as the synchronous machines slow and automatically convert their kinetic energy into electrical energy (see the section on synchronous machines in the chapter Electrical Storage). This stored energy is injected into the grid, reducing the rate at which the frequency of the grid falls. After a short duration, this recovery is supported by other running generators that increase output arising from governor response to the decrease in frequency.

As more and more renewable generators are connected to the grid, there is less and less room for heavy conventional synchronised generators to provide this stability. With the reduction in the number of large synchronous generators running, the system has considerably less 'inertia' and hence the trip of a large generator can cause a rapid decrease in frequency. For example, electricity systems often operate up to a RoCoF threshold of 0.5 Hz $s^{-1}$ measured over 500 ms, requiring all generators on the system to ride through any RoCoF of up to this level. However, if the instantaneous system non-synchronous penetration (SNSP) is high, *e.g.* >40% of energy originating from wind and solar, then there is an increased risk that the RoCoF threshold will be breached and some generators may fail to ride through the fault and trip out, making a bad situation worse. For this reason, operators that are increasing their instantaneous SNSP to >40% for the whole system are seeking to increase the RoCoF or fault ride-through capability of their generating plant to 1 Hz $s^{-1}$ measured over 500 ms.

RoCoF has been identified as an issue only in recent years, but it will become a bigger issue for system operators in the future as penetration levels of non-synchronous intermittent generation increase towards and above 40%. It is worth pointing out that this non-synchronous penetration is for a whole system rather than one national grid within the wider system.

From a grid stability perspective, synchronous inertia is currently the most proven method of mitigating high RoCoF events and will continue to be the most relied upon method as its reaction is instantaneous. Currently, up to 4% of fuel consumed by conventional plant connected to the electricity grid is dedicated to system service provision. As the penetration of renewable energy (non-synchronous generators) increases on the system, the requirement for additional services with faster response times, which can compensate to ensure system stability and reliability, will increase. The stability of the electricity grid is determined over several time scales, the most important of which is the first few seconds, since any decrease in the RoCoF increases the time that other systems have to react to imbalances between generation and consumption.[43–45] Currently, significant development work is being undertaken on non-synchronous technologies for the provision of synthetic inertia, particularly with batteries, flywheels and demand-side response. However, their capabilities and value as sources of synthetic inertia have yet to be demonstrated.

Although synthetic inertia has the potential to provide a power response to help prevent high RoCoF events, there are significant question marks regarding whether it can be delivered in the appropriate response time. First, the accuracy of detecting a RoCoF for the purpose of triggering the synthetic device and, second, the response and ramp rates of the specific non-synchronous device have a serious impact on the performance of these devices. If the synthetic inertia cannot be delivered in the appropriate time frame, it will not provide an alternative solution to maintaining the RoCoF standard at 0.5 $\mathrm{Hz\,s^{-1}}$ measured over 500 ms.

A significant concern for RoCoF alternative solutions is the commercial aspects of such projects. The revenue streams may not be sufficient to support the development of these emerging technologies in the mainstream electricity market. Serious thought needs to be given to this matter by regulators and system operators, otherwise none of these alternative solutions will materialise. Also, because these emerging technologies do not fit comfortably with existing distribution and grid codes (catering for conventional, hydro and wind generation plant), there is a need to develop an appropriate grid code for energy storage.[46]

## *4.3 Corrective Measures for Mitigating RoCoF*

Most conventional power plants continuously supply system inertia response that slows the RoCoF and they then provide increased output, referred to as primary operating reserve (POR), after 5 s following a system event; this would be regarded as a normal governor response to a decrease in frequency. However, a much more rapid response is needed to limit the RoCoF and assist in its restoration when there is a high penetration of non-synchronous generation on the system. For this reason, the concept of fast frequency response (FFR) – also referred to as enhanced frequency response (EFR) – has been developed so that rapid responses in 500 ms and less can be provided as a system service to the system operator to support the frequency. This rapid service can be provided by both synchronous and non-synchronous generators by responding rapidly to changes in frequency and supplement any intrinsic inertial response.

In particular, FFR or EFR provides a power response faster than the existing POR times and may, in the event of a sudden power imbalance, increase the time to reach the frequency nadir and mitigate the RoCoF in the same period, thus lessening the extent of the frequency excursion. Very fast-acting energy storage can provide such grid stability. This application requires high power over short durations but with a very high number of charging/discharging cycles, and can be provided by supercapacitors, batteries, flywheels or other energy storage technologies. Some types of storage are economic for long-duration storage whereas others are more suitable for high-power but low-energy storage capabilities. Some have a limited number of charge/discharge cycles whereas other technologies have almost unlimited cycling but higher capital costs. Although 2 s may appear to be a fast response, considerably faster response times, *i.e.* less than 0.5 s, will be required from these systems. The fast reaction speeds of flywheels and electrochemical systems and the long operational life spans of many of these technologies make them ideal candidates for grid stabilisation and load levelling.[4] These systems with the appropriate frequency detection and control systems can respond within times as short as 200 ms, but such technologies cannot provide the stability currently provided by synchronous 'inertia', *i.e.* electromagnetic coupling of rotational kinetic energy to the electricity grid through the use synchronous generators/motors. If sufficient system inertia is not present, *i.e.* the kinetic energy stored in the synchronous machines that are coupled to the grid is below a minimum level, the RoCoF may be rapid during this initial duration and the pseudo-synchronous responses not fast enough to protect the grid, thereby compromising its stability.

However, the wind generators on the grid have similar characteristics to conventional synchronous loads and generators in that they possess considerable rotational inertia. At present, the rotational inertia cannot be used to stabilise the grid since the generators are not synchronously coupled to the grid. Similarly, transport networks, pumps and other systems that have stored kinetic energy when in operation are usually run on non-synchronous motors or are not connected to the grid. Thus, if practical means were developed to run a fraction of these generators and motors synchronously with the grid, the stability of the grid would be improved. Currently, wind generators aim to maximise their energy efficiency, since they are paid per unit of energy produced, but in the future if they are also paid for the supply of auxiliary services, such as synchronous response, they may operate synchronously with the grid, increasing grid stability (but reducing their energy efficiency). Overall, the energy efficiency of the supply of electricity may be improved by such actions since currently this synchronous inertia response must be provided by conventional generators, some operating inefficiently and significantly below their rated output power.

### *4.4 Demand-side Solutions and Smart Grids*

A stable and efficient electricity grid requires precise matching of power supply and demand. This is typically achieved with the supply planned to respond to changing demand, where demand is modelled based on times when equivalent parameters were observed and the output of power plants is scheduled accordingly.

Traditionally, demand-side solutions have been employed to shift demand away from peak usage times in order to avoid the dispatch of expensive peaking plant and/or to relieve pressure on other grid infrastructure. These programs are all characterised by the use of incentives to promote favourable demand-side behaviour to support system operations. One such scheme involves contracts with large industrial users to reduce consumption at peak times during a particular season in return for preferable rates. From the user's perspective, this may be achieved by either reducing the load or turning on a local generator. For the same reasons, householders can have 'night rate' meters to incentivise them to shift their usage to times of reduced demand on the grid. This would typically be available to dwellings that use electricity for space and water heating.

Contracts are also available for companies that can reduce their demand at short notice in the event that, for example, unforeseen demand is present on the grid, a scheduled power plant will not be available or if wind energy forecasts have been inaccurate. More recently, networks have developed schemes that enable medium- to large-size electricity users to participate in demand management. Such a demand-side management unit consists of one or more demand sites that can reduce their demand when instructed by the TSO. For example, these units could have 1 h to reduce their demand and then be capable of maintaining the demand reduction for 2 h. Such units are usually operated by a third-party company that may contract with a number of demand sites and aggregate them together to operate as a single business unit, ensuring a high degree of implementation whenever the TSO issues instructions to reduce demand. Demand sites typically use on-site stand-by generation, plant shutdown or storage technology to deliver the demand reduction, and are required to be available 24 h per day, year-round. The ambition for demand-side management is that, in addition to it being a tool to promote behaviour conducive to the routine operation of the grid, it can evolve to the point that it can be used to form part of the response to frequency events on the grid.

A frequency event is typically caused by the unplanned loss of a power plant or part of the transmission or distribution network that causes an imbalance in the available supply and demand of power on the grid. The job for the TSO, as explained earlier, is to restore the grid frequency as quickly as possible.[47] However, as wind and solar electricity are increasing their penetration on the grid, this increase in asynchronous generation leads to less availability of all reserve types. This is a significant worry for the TSO in its role of maintaining a stable and efficient electric grid. Therefore, the role of demand response in emulating the current response to a frequency event is of great interest and significance in enabling the electric grid to allow greater penetration of low-carbon renewable energy.

The extent to which demand management can play a role in this is determined by how fast it can be deployed, in what magnitude and for what duration. To this end, different types of demand response should be mapped to their equivalent stage in the recovery mechanism from a frequency event based on the parameters with definitions similar to fast frequency response, primary operating reserve, *etc.* While a user's on-site, backup generation, for example at a data centre, will have an inherent delay in starting up and would likely map to primary or secondary reserve, the load reduction of a coordinated shutdown of large refrigeration warehouses should be deployable in a manner comparable to fast frequency response.

This will require the development of suitable technology, protocols and market mechanisms to do so, but none of this appears to be particularly challenging if demand management is pursued to achieve its greatest potential. Ultimately, it is possible to envisage a smart grid scenario where all appliances are cognisant of the operating conditions of the grid and can make choices to behave in a manner that supports a clean, stable and efficient electricity system (see the chapter Smart Energy Systems for further details).

## *4.5 Need for Energy Storage*

As mentioned before, a stable and efficient electricity grid requires precise matching of power supply and demand. As the level of renewable energy on the grid increases, its non-synchronous and intermittent nature will result in instability in the supply of energy by the grid and mismatch between supply and demand. Many of the technologies, system services, grid codes and smart operation of the grid can improve stability and reduce mismatch. For example, load levelling, demand-side management, use of untapped reserves and provision of auxiliary system services can support a future grid that encompasses less synchronously coupled energy (*i.e.* inertia). However, there will always be occasions when further reserves are required or traditional plant will have to be turned back on. Therefore, a key to stable operation of the future electricity grid depends on the connection of substantial extra reserves to, at a minimum, allow enough time for traditional plant to be turned on and possibly to allow the grid to be operated from energy reserves for longer durations.

The energy storage methods required to provide these reserves may include any technology that can transform electricity to a form of energy that can then be retrieved and transformed back into electricity at some later time. It follows that flywheels, batteries and capacitors can be used for the provision of such services, but also pumped hydro, hydrolysis of water and forestry can be part of the set of solutions. However, all of these systems have parameters that determine their suitability for a particular support service, including response times, life span, cyclability and inefficiencies associated with the building, holding and retrieving of energy.

Flywheels, turbines and other rotating masses coupled to synchronous machines store rotational kinetic energy that is automatically and instantaneously fed back to the electricity grid following a fault or frequency excursion, providing synchronous inertial response. However, such systems consume energy during their operation to overcome losses to friction and drag and they only provide response as a function of RoCoF (see the chapter Electrical Storage for more details). Capacitors, supercapacitors, asynchronous mechanical batteries (*e.g.* flywheels) and superconducting magnetic energy storage (see the chapter Electrical Storage for further details) can provide fast frequency response and operating reserves for several minutes but cannot respond in tens of milliseconds and are not designed to provide cost-efficient reserves for sustained durations. Batteries can also deliver fast frequency response and, in addition, are designed to deliver reserves for up to several hours, depending on the battery chemistry. However, as explained in the chapter Electrochemical Energy Storage, the cyclability, required capability and usage, life span, life cycle and other factors must be considered when deciding which battery chemistry and design to use. In addition, there is a range of other slower reacting technologies such as pumped hydro and compressed-air storage (see the chapter Mechanical Systems for Energy Storage for further details) that have very high cyclability and long life spans and can deliver operating reserves cost-effectively for long durations. Therefore, although storage is the key to reliable future grids, not all energy storage technologies are equal and not all storage applications will be best served by the same technology. Rather, a mix of technologies is required where the response times, capacities, $CO_2$ production, efficiencies, and financial and environmental costs can be balanced to deliver an efficient and reliable electricity grid for the supply of energy for a low-carbon economy.

## 5 Electric Vehicles and the Electricity Grids

Transportation accounts for 14% of current anthropogenic GHG emissions,[1] as shown in Figure 1. Transport is an increasingly large user and driver of electrical energy storage technologies. Conventional petrol- and diesel-powered engines already make use of energy storage in a limited way. For example, they incorporate flywheels for smooth engine operation (see the chapter Electrical Storage) and use electrochemical energy stored in their (usually lead–acid) batteries for engine starting (see the chapter Electrochemical Energy Storage). Significant progress has occurred over the last 10 years in the development of batteries for stop–start technology,[48] which allows engines to be turned off when the vehicle is stopped, and for traction technology where the energy of a (usually lithium-ion) battery is used to drive an electric motor.[49] The term electric vehicle (EV) covers a range of different technologies, ranging from hybrid to fully electric vehicles. The energy storage in these vehicles uses flywheels, capacitors, fuel cells and batteries (including lead–acid, nickel–metal hydride and lithium-ion batteries and others).

The electrification of transport provides both opportunities and challenges for the electrical grid.[50] The deployment of EVs is growing in many countries, driven by climate change targets and air quality concerns in major urban areas. For example, cities such as London and Paris are already signalling plans to ban combustion vehicles and China is already the leading adopter of EVs in terms of absolute numbers deployed.

The most desirable operating mode for battery EVs is for overnight charging at a moderate rate, typically C/4 to C/8 (*i.e.* 4 to 8 h of charging time), and a daily driving distance that is well within the vehicle range. Longer commutes may require workplace or destination charging. However, short trips represent the greatest proportion of vehicle usage, with a large-scale survey[51] in the USA showing an average journey length of 8.9 miles (14.2 km) per trip, 95% of trips less than 30 miles (48.2 km) and less than 1% of trips over 100 miles (161 km).

Long distance travel and slow recharge times have always been, and still are, the key limitations of fully electric vehicles. Much research and development effort has been expended over a long period of time to address these issues. Tremendous progress has been made, but inherent fundamental limitations make it a difficult problem.

Public perception and expectations have generated a mind-set whereby long-range battery EVs are considered a necessity for the adoption of EVs on a large scale. This has driven the desire for increasingly high energy densities in terms of both weight ($\mathrm{Wh\,kg^{-1}}$) and volume ($\mathrm{Wh\,dm^{-3}}$). However, such high densities bring both safety and environmental concerns. The highest energy density batteries to date involve lithium-ion chemistries with electrode materials containing cobalt compounds;[52] however, the price and environmental issues around cobalt mining have raised some concerns (see the chapter Electrochemical Energy Storage for greater detail on lithium-ion batteries).

Plug-in hybrids provide an interim solution, but most manufacturers of mainstream battery EVs have adopted fast-charging strategies to address the long-distance travel limitation. Other strategies such as battery swap and mechanical recharging with metal–air batteries have been proposed and tested, but so far have not been adopted on a larger scale, although they may be in the future. The deployment of public charging points with fast chargers is being undertaken in many countries and, together with a strong ICT support infrastructure, can support EV long-distance travel.[53] It may be the case that safer and more environmentally benign battery chemistries with lower energy densities, together with public fast charging or battery swap facilities, may be a solution for the mass adoption of EVs.

Alternatively, plug-in hybrids may become a permanent solution. This could possibly occur if electrification of motorways *via* overhead cables and pantographs or *via* electrified tracks facilitated an extended driving range while requiring only sufficient energy for the journey to and from the motorway to be stored in the vehicle.[54] This would have significant advantages since each EV would need only a small energy capacity in its battery, reducing supply and demand issues and, most importantly, reducing security issues that occur due to war over limited resources, *e.g.* for cobalt in the Congo.[55] Furthermore, smaller energy capacity requirements would mean that many battery chemistries would be capable of providing the necessary capacity, reducing the cost per kWh of storage and facilitating a change in focus in research and development from maximisation of energy density to other considerations, such as lifetime, recyclability, efficiency and cost. Furthermore, even if such electrification were applied only to trucks, it would greatly reduce the GHG emissions from transport since, although trucks account for only 9% of the total vehicle population, they account for 17% of vehicle distance travelled and 39% of life-cycle road transport GHG emisions.[54]

Battery storage in EVs, currently dominated by lithium-ion technology, ranges from a few kWh for plug-in hybrids to tens of kWh for mainstream battery EVs.[56] High-end vehicles and future models can have over 100 kWh of storage. The peak power available from such batteries is typically at the

100 kW level (3 to 5C) for mainstream battery EVs, with several hundred kilowatts for high-end models.

The interaction of such vehicles with the electricity grid occurs when the vehicle is connected to the grid for charging and two distinct modes of charging can be identified: slow (or time-insensitive) overnight or workplace charging and fast (or time-sensitive) charging where the user is waiting for charge completion.

### 5.1 Slow Charging

Overnight home charging and destination charging are normally achieved with an on-board charger (OBC), built into the vehicle, and typically range up to 7.2 kW, *i.e.* 240 V single phase at 32 A. Such chargers are normally unidirectional and connect to the residential grid connection, typically through dedicated electric vehicle supply equipment (EVSE).

Bidirectional on-board charging equipment is technically readily achievable, with some additional complexity and cost in the associated power electronics. Often termed vehicle-to-grid (V2G), such equipment could provide a similar power level back to the electricity grid for load balancing or emergency stabilisation of the grid. Currently most EV manufacturers do not provide this as an option as there has been little demand from customers and an economic model to justify the additional cost and inconvenience to the vehicle owner has not yet been made.

Electricity utilities have identified potential capacity issues on legacy low-voltage distribution networks with future mass adoption of EVs along with mass adoption of electric heat systems, such as heat pumps. However, installation of smart grid support in domestic EVSE units could allow for smart charging algorithms to achieve maximum utilisation of local distribution networks without overload.[57] EV storage batteries and on-board chargers can readily support such variable charge rates and timing, but state-of-charge determination for the batteries may need to be improved to optimise charging rates.

With peak demand for electricity being normally in the daytime and early evening, the use of overnight charging is seen as a desirable feature, with many electric utilities already providing reduced tariffs for night-time electricity usage. Overnight or off-peak charging can directly contribute to a better load balance for electric utilities and effectively increase the utilisation of existing grid and distribution infrastructure.

The economics of EVs with overnight home charging are favourable, with capital and running costs for EVs in this mode being attractive, particularly in countries with high petroleum prices, *e.g.* in the European Union.

### 5.2 Fast Charging

The fast charging options available come in a number of standards and are listed under a range of terms such as rapid, quick or fast charge, but are probably best described as dc charging (although there is also a fast ac charge option from at least one manufacturer). Such dc charging options, in effect, present a port on the vehicle with direct connection to the terminals of the main traction battery, and also a signalling channel through which information such as battery voltage and current ranges and status can be exchanged.

The power electronics for conversion from the ac electricity grid to the dc source required for charging is then situated outside the vehicle and can be sized to a high power level. Power levels for mainstream battery EVs are typically up to 50 kW with proprietary systems available in excess of 100 kW. Increasing power levels up to and above 100 kW are being supported by existing standards and power levels of 350 kW are available as technical demonstrators.

As a direct connection to the main traction battery terminals is provided, it is possible to draw energy from the battery. With the power electronics conversion being done outside the vehicle, the additional cost and complexity of bidirectional power circuits are less of an issue and, for example, might be borne by the electric utility rather than the vehicle owner. In this manner, there is potential for the use of EVs as a distributed storage resource, subject to the development of a viable economic model. Indeed, if such chargers were used for slow charging whenever an EV was parked, the batteries would have longer life spans (compared with batteries that are always fast charged) and the batteries would be available for FFR and POR support of the electricity grid.

The fast charging capability of EVs was primarily intended as a method of mitigating their range limitation. To this end, the typical manufacturer claim is a 30 min period to fast charge the battery to an 80% state of charge from empty. For mainstream battery EVs, this requires a source and charger power of typically 50 kW with levels up to 100 kW expected. The expectation is that with increasing EV adoption, banks of such chargers would be located regularly along main transport arteries, typically every 50 to 100 km. Figure 4 shows an example of an eight-bay EV charge site located in Birdhill, Ireland. Each set of two bays has a power delivery capacity of 120 kW.

**Figure 4** Eight-bay Tesla super charge site in Birdhill, Ireland, requiring 4×135 kVA grid connections, *i.e.* in excess of 0.5 MVA of grid connection. Photographer: Thomas Conway.

There is increasing research into higher recharge speeds, with claims such as 5 min recharge times. To charge a 50 kWh vehicle to 80% state of charge from empty in 5 min would require 500 kW per individual vehicle.

In the context of fast charging, the effect on the grid is potentially severe, as such loads represent a high load level with highly variable usage patterns and poor load factors. The demand for high power availability along major transport routes, where grid infrastructure may not have been provisioned, may also present a challenge for current electricity grids.

However, the demand for fast charging could be viewed as a high-value product with EV users prepared to pay a premium for energy availability at a high power level at a suitable public location. Such observation has led some to propose that such locations could be an ideal location for dual-purpose, grid-level, energy storage facilities.

The premium available for supply of energy to EV users may improve the economic viability of such deployments and the distributed nature of such locations may provide a synergy with the distributed nature of many renewable energy sources. The demand for high-power sources can then be met from local storage, reducing the need for upgrading of the existing electricity grid. Some fast charger facilities already incorporate local battery storage and local renewable energy sources such as solar panels.

## 5.3 End-of-life Usage

A further way in which EVs may impact the grid and electric energy storage is in the area of second use for EV battery packs. As the battery packs age through use in EVs, their energy storage capacity degrades and at some point may become too low for the users' range demands, or the vehicle may reach its end of life. Although battery material recycling may become realisable for EV battery packs, there are currently several factors – including a range of chemistries, structure of the electrodes and location of the active materials within other supporting materials – that contribute to making lithium-ion battery recycling more complicated than lead–acid or nickel–metal hydride battery recycling.[49,58,59] Furthermore, collection rates are currently very low, with only 5% of lithium-ion batteries being collected in 2010 in the European Union.[60] However, the cells of used EV battery packs still have a useful energy storage capacity and can be utilised for stationary storage.[61] It is too early at present to assess the impact of these effects and issues, but over the next several years a more significant number of vehicles are expected to reach their end of useful life and a battery pack reuse industry is expected to emerge.

## 5.4 Implications of Connecting Electric Vehicles to the Electricity Grid

The mass embracing of EVs will be a transformative change for the electricity grid. Their adoption, if not carefully managed, will require significant reinforcement of the grid and lead to further peaks in energy demand. These demands on the grid will require greater power generation and may lead to greater grid instability. However, the energy storage technology in EVs can also be viewed as a distributed network of energy storage devices that can be used for grid stabilisation, load levelling and smart operation of the grid. Furthermore, if this technology can be operated smartly, *e.g.* if EVs are charged slowly during the night, the variation in electricity supply during day-time peaks and night-time troughs will be reduced, increasing the use of wind energy whenever it is available and reducing the need for the electricity grid to invest in and own energy storage. However, since these EVs will probably be operating during day-time hours, their energy storage capacity will not be connected during peak operation times of the electricity grid.

If EVs are directly connected to the grid during operation *via* overhead cables or in-road tracks, they will require only small batteries and for significant durations, particularly in the case of freight transport, the motors in these vehicles could run directly from the grid. Although such systems will require significant investment,[62] this investment may reduce the need to reinforce existing grids to accommodate energy harvesting from renewables, charging of EVs and smart grid operation. Such a transport fleet would add stability to electricity supply at all times of the day since the batteries could be used for shedding of loads and backup of the grid, *i.e.* making them an integral and flexible part of a future smart grid. Therefore, the average power and number of generators connected to the grid would increase, increasing the reliability and stability of the grid. Furthermore, if the motors were synchronously coupled to the grid, the increased level of stored kinetic energy, and therefore the increased synchronous inertial response, would reduce the RoCoF and thereby increase the reliability of the overall grid. The increase in synchronous inertial response that could be achieved by such an approach would be small. However, as with synchronous inertial response delivered from any demand-side synchronous machine, where the energy losses to friction and drag occur regardless of whether or not the machine's operation is synchronised to the grid, support to the grid does not cost any additional energy.

The increasing adoption of EVs worldwide inherently provides a large electricity storage capability, and helps to load-level the grid by providing an off-peak demand for electric power. With more than 2 million fully electric vehicles on the roads already,[63] representing in the order of 40 GWh of storage, the widespread adoption of electricity storage is already under way.

## 6 Conclusion

The stored energy in coal, wood and hydrocarbon oils and gases originates from nuclear reactions in the Sun. This reaches the Earth as solar energy and has been stored in the form of chemical energy by living flora and fauna. Indeed, the energy in the wind originates from the Sun and, therefore, with the notable exceptions of geothermal, tidal and nuclear energy, most of the energy we utilise originates from solar energy.

The drive to harness and control energy is an inherent characteristic of the human race. From our ancient use of tools, fire and animals to today, every new technological advance has involved some new way of controlling energy. Each advance by itself may not have been ground-breaking at the time, but our history seems to be divided up into periods dominated by a new form of control of energy. Today it would seem that we are at the beginning of a new era where energy is no longer harnessed primarily from the burning of fossil fuels but from renewable sources of energy.

Stored forms of solar energy are being used up at a rapid rate and many of the most prosperous nations in the world now rely on significant imports of fossil fuels to ensure a continuous supply of energy so as to support their economies and maintain their ways of life. It follows that for many countries the burning of fossil fuels can be seen not just as depleting finite natural resources and producing significant anthropogenic GHGs and pollution but also as an extremely significant security-of-supply and political concern. For instance, 54% of the European Union's energy originated from fossil-fuel imports from non-EU countries in 2015, and the main supplier of oil, gas and solid fuels to Germany and Poland was Russia, on which these countries are therefore highly dependent for heat, transport and electricity.[64] It follows that the use of solar, wind and other ubiquitous energy sources to offset the use of fossil fuel imports is not only advisable for the care of our planet but also for increasing security of supply and possibly reducing international tensions.

However, the technologies that will support a future based on energy from such sources are not obvious and the transition from our current regime – supported by combustion engines and conventional electricity generators – is fraught with problems and technological obstacles. Nevertheless, these challenges present opportunities for individuals, companies and nations that can successfully transition to smart and reliable electricity grids powered by renewables. In such an ever-changing world, it is important for nations to be nimble and to peruse multiple new ideas. This is particularly true in the area of energy where renewable energy, energy storage and smart grids may greatly increase both our energy and political stability.

Reliable and stable electricity supply at a time of increased renewable energy penetration of the electrical grid has been highlighted as one of the key challenges in the drive for future prosperity and development. International agreements on reduction of carbon emissions and increase in the use of renewable energy sources mean that we will require technologies to mitigate the difficulties related to the supply of energy in this changing environment.

As smart grids are developed, large fluctuations between day-time and night-time electricity load can be greatly reduced, for example by charging EVs and performing other non-urgent tasks at night. Overall, although the fluctuations in consumption of electricity may be reduced, the total electricity consumed seems destined to increase, placing significant strain on existing electricity grid infrastructure. The expansion of the grid due to both distribution of generation, particularly to geographically isolated locations, and increased flows of electricity will require significant reinforcement of the existing grid infrastructure and may lead to the return of local grids. Such a transition will be helped by EVs, *etc.*, which, in addition to increasing average load, may lead to increased stability and significant changes in the operation of electricity grids.

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