11

Sustainable energy options

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Abstract

Photovoltaics (PV) and wind are overwhelmingly dominant in terms of new, low emissions generation technology because they cost less than alternatives. PV and wind constitute half of the world's new generation capacity installed each year. Wind and PV are essentially unconstrained by resource, environmental, materials supply, water supply, or security issues. Their prices are now competitive with new fossil and nuclear power plants. Conventional hydro cannot keep pace with wind and PV due to lack of rivers to dam, and biomass availability is severely limited. Heroic growth rates are required for nuclear, carbon capture and storage (CCS), concentrating solar thermal, ocean, and geothermal to span the 20- to 200-fold difference in scale to catch wind and PV—which are themselves moving targets since both are growing rapidly and both access massive economies of scale. Pumped hydro energy storage (PHES) constitutes 99 per cent of all storage for the electrical supply industry. The combination of PV, wind, and PHES, each of which has more than 150 gigawatts (GW) deployed, allows high (80–100 per cent) renewable energy penetration of electricity markets. The conversation of land transport and urban heating to electrical supply may allow renewable electricity to supply more than three-quarters of end-use energy in the medium term.

Energy options

Energy and greenhouse gas emissions

About three-quarters of global greenhouse gas emissions arise from use of fossil fuels in the energy sector, as illustrated in Figure 11.1. In order to avoid dangerous climate change, it is necessary to replace this fossil fuel use with energy sources that do not emit greenhouse gases.

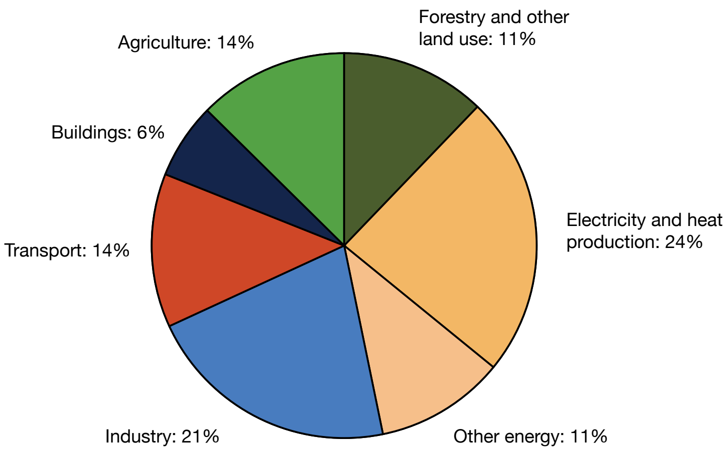

Figure 11.1 Global warming potential of greenhouse gases by economic sector over a 100-year time frame

Source: IPCC (2014: 88).

Energy technologies

The energy sources that are available and potentially have low greenhouse gas emissions comprise:

- solar—both directly from the Sun (photovoltaics (PV) and solar thermal) and indirectly (such as wind, hydro, biomass, and wave energy);
- fossil fuels (coal, oil, and gas) with carbon capture and storage (CCS);
- nuclear (fission and fusion);
- geothermal; and
- tidal.

The focus of this chapter is on pathways to deep reductions in energy-related greenhouse gas emissions over the next two decades. The energy technologies that can meet this goal must have large resource bases, should not introduce other serious problems, and must be at a point in their technology and economic development that does not require heroic assumptions in relation to future deployment rates and cost reductions. Wind and PV are likely to be the dominant low-emission energy technologies deployed over the next two decades. Some of the other energy technologies listed above will have significant supporting roles.

The worldwide PV and wind industries are being deployed on a large scale (>100 gigawatts (GW) of new plant constructed per year combined), and are likely to grow into enormous industries over the next decade. In 2015, renewable energy (primarily hydro, wind, and PV) provided 64 per cent of net new electricity generation capacity worldwide, with fossil fuel (primarily gas and coal) power stations providing most of the balance (see Figure 11.2). On current trends, wind and PV will both pass fossil and nuclear combined in 2018 in terms of annual new generation capacity. PV and wind presently constitute nearly all new generation capacity in Australia and several other countries.

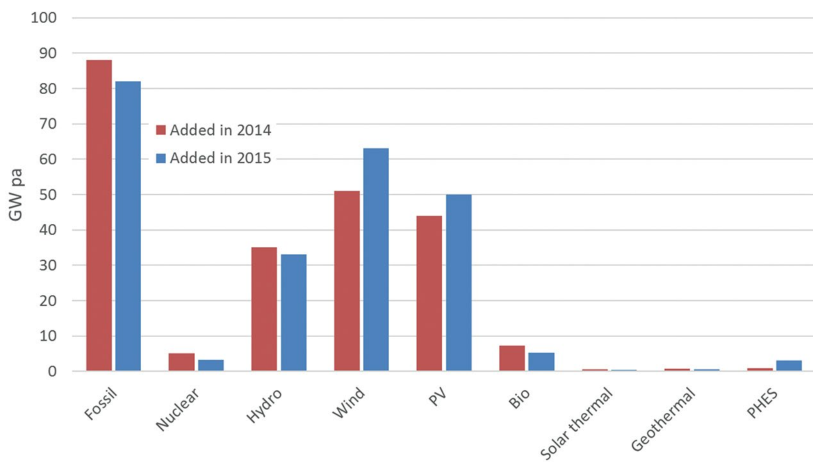

Figure 11.2 New generation capacity added in 2014 and 2015 by technology type

In 2015, 113 GW of net new wind and PV were deployed, which is nearly as much as everything else combined.

Source: REN21 (2016); Frankfurt School–UNEP Collaborating Centre (2014); IRENA (2016).

In 2015, new additions of PV and wind capacity combined grew 19 per cent over the previous year. Installation rates of the other generation technologies stayed steady or declined. Wind and PV are unconstrained by resource, environmental, material supply, or security issues.

Hydro cannot keep pace due to lack of rivers to dam, and biomass availability is severely limited. Heroic growth rates are required for the other potential low-emission technologies (nuclear, CCS, concentrating solar thermal, ocean, and geothermal) to span the 20- to 100-fold difference in scale to catch wind and PV—which are themselves moving targets since both are growing rapidly and both access massive economies of scale.

It appears that PV and wind have 'won' the race to dominate the low-emission generation sector. It will be difficult for another low-emission technology to catch PV and wind before they saturate the electricity market. Since their marginal cost of energy production is nearly zero (as with hydro), it will be difficult for another renewable electricity technology subsequently to undercut PV and wind in the market.

In the discussion below of the various energy technologies, the focus is upon those that have the potential for large-scale deployment (>100 GW per year by 2030). Current world electricity production is about 23 million gigawatt hours (GWh) per year. Of this, 22 per cent is derived from renewable energy (mostly hydro). To set this in context, deployment of 175 GW per year of each of wind and PV capacity would be sufficient to achieve a 23 million GWh per year renewable electricity target by 2035. This is obviously possible since it only requires a threefold increase in annual deployment rates of wind and PV compared with current practice (2015). Of course, demand for electricity is likely to grow because the world population is increasing, affluence is increasing, and it is probable that much of the fossil fuels used for motor transport, heating, and industry will be replaced by electricity from low-emission sources.

Fossil fuels

The carbon dioxide (CO_2) emitted from combustion of fossil fuels can be captured and stored underground. In practice, this has proved to be challenging and expensive on a large scale. It is necessary to separate CO_2 from other gases (nitrogen, argon, oxygen, and water vapour), transport it to a suitable site, pressurise it to form a liquid, and inject it into a secure location deep (kilometres) underground. Parasitic energy use by CCS reduces the overall efficiency of a coal- or gas-fired power station, and CCS adds substantially to the capital and operating costs. Because it is difficult and expensive to retrofit existing power stations with CCS equipment, widespread deployment of CCS would therefore require that future fossil fuel power stations be fitted with CCS.

The Boundary Dam project in Saskatchewan, Canada, is the first large CCS project in the power sector (Global CCS Institute 2014). About 1 million tonnes per annum of CO_2 will be captured and stored underground. For comparison, this amount of avoided CO_2 emissions could also be achieved by deploying about 0.3 GW of wind or 0.6 GW of PV. To provide context, in 2016, 60–70 GW each of wind and PV will be deployed worldwide.

Carbon dioxide is sometimes used for enhanced oil recovery by pressurising underground oil reserves in order to extract more oil. Whilst this is economically desirable, and does sequester significant amounts of CO_2, the resulting oil adds to greenhouse gas emissions.

Prospects for widespread deployment of new fossil fuel power stations fitted with CCS are poor due to immature technology, high cost, high risk, and strong competition from hydro, wind, and PV, which are being deployed at vastly larger scale and lower cost than the prototype CCS systems (Frankfurt School–UNEP Collaborating Centre 2014).

Nuclear energy

All nuclear reactors obtain energy from the fission of heavy elements, usually uranium. Nuclear energy is well-established and produces about 11 per cent of the world's electricity. Nuclear energy is associated with problems such as nuclear weapons technology proliferation, potential for fissile material production, reactor accidents, and waste disposal. Nuclear reactors are characterised by strong local opposition, long lead-times, substantial security requirements, and perceptions of high risk. This strongly constrains rapid deployment of nuclear energy. Current net deployment rates of nuclear energy (new reactors minus retiring reactors) are 15 times smaller than each of wind and PV.

Fusion energy drives the Sun. Magnetic and inertial confinement of deuterium and tritium (isotopes of hydrogen) can be used to achieve the temperatures and times required for net release of fusion energy. However, fusion reactors are a very challenging endeavour and are unlikely to be commercially available before 2050.

Geothermal and tidal

Geothermal and tidal energy are significant in some countries. However, economically harvestable global resources are too small to make a difference at a global level, although they could be important in some regions. Geothermal energy is derived from heat within the Earth. In volcanic regions, hot rocks are available near the Earth's surface—for example, in Iceland and Indonesia. Steam can be harvested for use directly or to generate electricity.

In some regions, masses of slightly radioactive rock buried kilometres below the surface become hot, allowing harvesting of heat at a temperature of around 300 degrees Celsius. Cold water is injected under pressure to fracture the rock, and allow steam to be extracted. This hot dry rock technology is challenging, and is only applicable in certain regions with the right geology. There has been no significant deployment to date.

Energy can be extracted from tidal flows using standard hydro technology. In a typical system, a weir is constructed across an estuary, and water flows through turbines as the tides rise and fall. Suitable sites with large tidal ranges and sufficiently low environmental impact are rare.

Solar energy supply

Solar energy is vast, ubiquitous, and indefinitely sustainable. Its utilisation generally has minimal environmental, social, and security impacts over unlimited timescales. Recent large-cost reductions now place solar-derived energy in the same cost range as fossil and nuclear energy. Renewable energy derived from the Sun, principally comprising solar, wind, and hydro energy, now constitutes most new electricity generation capacity constructed worldwide each year.

The Sun will continue to shine for billions of years. Each year the Earth receives about four orders of magnitude more solar energy than human commercial energy consumption. After accounting for conversion losses (only 15–50 per cent of solar energy incident on a solar collector is successfully collected and converted to a useable form) and inaccessible regions (oceans, the poles, mountains, and forests), there is hundreds of times more available solar energy than human commercial energy consumption.

The two major direct solar energy conversion technologies are PV and solar thermal. The former directly converts sunlight into electricity. The latter includes solar collection for heat in buildings and industrial processes (such as solar hot water and solar heating of buildings), solar thermal electricity (produced by concentrating sunlight onto a receiver to create high-temperature steam), and solar-assisted thermochemical production.

Solar energy drives world energy systems, which yield indirect energy in the form of wind energy, hydro energy, wave energy, ocean thermal energy, and biomass energy.

The solar resource

The Sun provides about 1.3 kilowatts (kW) per square metre (1.3 kW/m^2) to the upper atmosphere of the illuminated half of the Earth. Most is transmitted though the atmosphere to the surface of the Earth, while some is absorbed and reflected by the atmosphere. The solar intensity at noon on a sunny day at the Earth's surface is about 1 kW/m^2. Each year, the Earth receives about 3.8×10^{24} joules of solar energy. This is about 50,000 times more than current worldwide electricity consumption. Much of this energy is in the form of direct beam radiation; that is, it comes directly from the visible disc of the Sun. At ground level, a sizeable fraction appears as indirect (diffuse) radiation due to scattering from clouds, aerosols, and other atmospheric constituents, plus reflected light from the ground. A relatively small fraction of the solar energy is converted into energy forms that can be harvested as wind energy, hydroelectricity, ocean energy, and biomass.

The sum of the direct and diffuse radiation received by a solar collector is termed global radiation. Some collector systems such as non-concentrating PV panels respond to both the direct and diffuse components of sunlight. Other collectors, such as concentrating PV (CPV) and solar thermal systems, respond primarily to the direct beam component—fundamental physical laws limit concentration of the scattered diffuse light. For this reason, concentrating systems are best suited to dry locations with low levels of cloud and air pollution. For example, the proportion of annual radiation in Australian cities that is diffuse is about one-third, meaning that one-third of the available solar power will be discarded in a solar concentrating system. Tropical cities and desert regions have annual diffuse radiation amounting to about half and one-quarter of the incoming solar radiation, respectively.

The available solar radiation depends upon latitude, weather patterns, and air pollution levels. The seasonal variation in solar radiation is important because it is expensive to store energy harvested in summer for use in winter. In general, low latitudes have much less seasonality in both solar energy availability and energy demand (for heating and cooling).

About two-thirds of the world's population live in the latitude range +/-35° where there is generally good solar availability and moderate seasonal variation of both solar energy supply and energy demand compared with higher latitudes. This latitude range is home to most of the populations of Africa, Central and South America, Australasia and Oceania, Southeast Asia, India and South Asia, and the Middle East. However, a group of highly influential countries with energy-intensive economies lie at higher latitudes, including European countries, South Korea, Russia, Canada and much of the United States, China, and Japan. Perceptions of the availability and suitability of solar energy are sometimes skewed by the current economic and political power of these countries.

Environmental and social aspects of solar and wind energy

Solar and wind energy collection utilises only very common materials, with few exceptions. For example, PV systems utilise silicon (for the solar cells); silicon, oxygen, and sodium (for the cover glass of the solar module); oxygen, carbon, and hydrogen (for the encapsulating plastic); aluminium (for the frame of the solar module); iron (for the steel support posts); plus some metals in small quantities such as phosphorus, boron, copper, and silver. These elements are ubiquitous in the Earth's crust and atmosphere, and it is difficult to envisage ever running out of them. The amount of rock that needs to be moved during mining, for a given level of solar energy production, is orders of magnitude smaller than the equivalent for fossil and nuclear energy systems, principally because of the absence of mined or extracted fuel.

Solar and wind energy are available nearly everywhere in vast quantities; it is unlikely that people will ever go to war over access to solar and wind energy, in contrast to the situation with fossil fuels. Utilisation of solar and wind energy entails minimal security and military risks. The highly dispersed locations of millions of solar and wind energy collectors entails a robust and resilient energy system with limited utility for warfare and terrorist activity.

Less than 1 per cent of the world's land area would be required to supply all of the world's commercial energy requirements from PV using current technology. A large segment of the world's energy can be supplied from roof-mounted solar collectors, which effectively alienate no land. Another large segment of the world's energy can be supplied from solar collectors in arid regions, in conjunction with long-distance high voltage direct current (HVDC) transmission of electricity. Wind generators alienate only a few square metres per megawatt (MW) of capacity (the site of the tower) and farming operations can continue around the base of the tower. Relatively little alienation of productive farmland, forests, and ecosystems is required to achieve a world economy where most of the commercially traded energy is derived from solar and wind energy.

Solar and wind energy systems do not emit greenhouse gases during operation. However, greenhouse gases, principally CO_2, are emitted during the manufacturing phase. The time required to generate enough electricity to displace the CO_2 emissions equivalent to that invested in construction of a solar or wind energy system is currently in the range 0.5–2 years, compared with typical system lifetimes of 20 to 30 years. CO_2 manufacturing intensity and price are directly linked (via material consumption and efficiency), and so CO_2 payback times continue to fall as prices fall. CO_2 payback times are also falling as the proportion of low-emission generators in electricity systems increase. CO_2 payback times will eventually fall to a small fraction of one year.

Solar and wind energy system manufacturing and operation entails minimal pollution and noise. Social acceptance is generally high, although there is opposition to wind generators by some people, primarily based on aesthetic considerations. Both the risk and consequences of accidents are very low compared with fossil fuel and nuclear energy systems.

The future of solar and wind energy

Renewable energy technologies can eliminate fossil fuel use within a few decades at low cost, allowing a fully sustainable and zero carbon energy future. Roof-mounted solar energy systems can provide PV electricity, hot water for domestic and industrial use, and thermal energy to heat and cool buildings. Grid parity for PV at a retail level has already been achieved for much of the world's population. This is leading to rapid growth in sales in the residential and commercial sectors without the need for subsidies.

Large PV and solar thermal concentrator power stations, in conjunction with wind and hydro energy, can provide most of the world's industrial energy. In addition to direct solar energy collection, indirect forms of solar energy such as wind, biomass, wave, and hydro can make important contributions.

Solar- and wind-generated electricity, coupled with a shift to electrically powered cars and public transport, can provide most of the world's transport energy.

Photovoltaics

PV is likely to eventually dominate energy production worldwide because the solar resource utilised by PV is much larger and more ubiquitous than wind energy. PV is an elegant technology for the direct production of electricity from sunlight without moving parts. Most of the world's PV market is serviced by crystalline silicon solar cells (Reinders at al. 2015). Sunlight is absorbed by the solar cell and the solar power is converted to electrical power with a conversion efficiency of 15–25 per cent. The remaining solar power (75–85 per cent) becomes heat. This process of conversion is called photovoltaics (photo = light, voltaics = voltage).

In a silicon solar cell, sunlight causes electrons to become detached from their host silicon atoms. Near the upper surface is a 'one-way membrane' called a pn-junction. When an electron crosses this junction it cannot easily return, causing a negative voltage to appear on the sunward surface (and a positive voltage on the rear surface). The sunward and rear surfaces are connected via an external circuit containing a battery or a load in order to extract current, voltage, and power from the solar cell (see Figure 11.3).

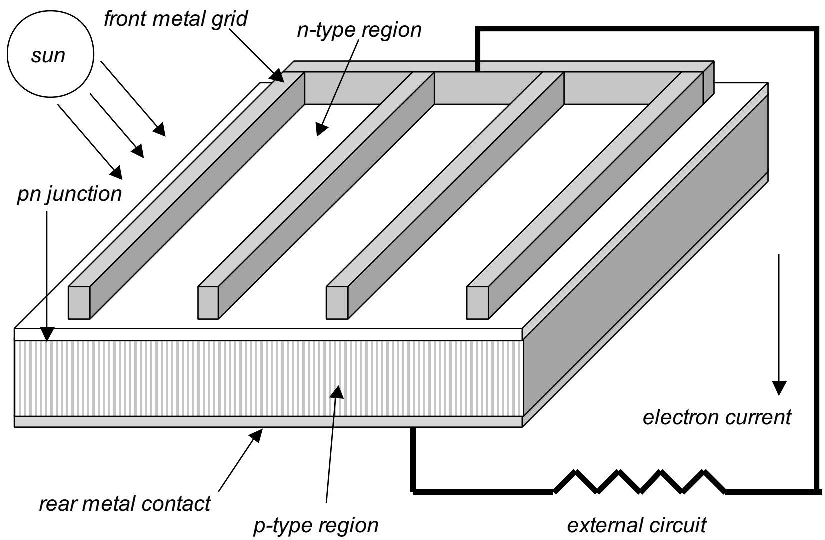

Figure 11.3 Schematic of a typical solar cell
Source: Author.

More than 90 per cent of the world's photovoltaic market is serviced by mono- and multi-crystalline silicon solar cells, and this will continue for the foreseeable future. Silicon has important advantages including elemental abundance (number two in the Earth's crust), moderate cost, non-toxicity, high efficiency, device performance stability, simplicity (it is a mono-elemental semiconductor), physical toughness, a highly advanced state of knowledge of silicon material and technology, and the advantages of incumbency. The latter comprises extensive and sophisticated supply chains, large-scale investment in mass production facilities, deep understanding of silicon PV technology and markets, and the presence of thousands of highly trained silicon specialists—scientists, engineers, and technicians.

In order to produce solar cells, silicon crystalline ingots are grown from a silicon melt at 1400 degrees Celsius. Many thin (0.15–0.2 mm) wafers with diameters of 156 mm are cut from the ingots using a saw, followed by wafers saw damage removed in a silicon etch. The next step is to diffuse a tiny amount of phosphorus into the sunward surface of the wafer to a depth of about 0.001 mm to create the pn-junction. Then follows deposition of a thin sheet of metal on the rear surface and a grid of metal on the sunward surface to allow extraction of electricity.

Groups of 60–80 solar cells are electrically connected and encapsulated in thin layers of plastic and laminated behind a tough, 3 mm thick glass cover to form solar modules, each with a power of about 300 watts (W). A junction box is added to house the electrical terminals. Dozens to millions of solar modules are mounted together and electrically interconnected to form a solar power system.

Some PV systems are mounted on fixed support structures that are tilted up to face the equator, with a tilt equal to the angle of latitude. This maximises annual electricity production. Large PV systems are usually mounted on sun-tracking systems to maximise annual output. Electricity produced by PV modules is conducted to a power conditioning unit that optimises voltages, converts the direct current produced by solar cells to the alternating current used in electrical grids, transforms the voltage to match that of the local grid, and manages interfacing with the local grid.

Photovoltaic systems have unmatched reliability and low maintenance cost due to the lack of moving parts. Manufacturers typically warrant PV modules for 25 years, and in dry locations they may continue to operate for 50 or more years. Specimen modules are exposed to severe accelerated failure testing in order to elucidate and prevent failure mechanisms. Degradation modes of PV modules include physical destruction caused by human action or violent hailstorms; slow chemical changes leading to yellowing of transparent encapsulation materials; and slow ingress of moisture causing corrosion of metallic components.

Photovoltaic technologies

Crystalline silicon solar cells constitute more than 90 per cent of the world PV market. The leading commercial crystalline silicon PV solar cell technology is based upon screen printing of the metallic contacts. Commercial solar cell efficiencies of 14–20 per cent are achieved with this technology. Interdigitated back contact and Heterostructure with Intrinsic Thin Layer silicon solar cells have commercial efficiencies of 22–24 per cent, albeit at a premium price, and are typically deployed where space is limited. The best laboratory cells have efficiency of 25–26 per cent, compared with the theoretical maximum efficiency of 29 per cent. The Passivated Emitter and Rear Cell design (Blakers et al. 1989) is likely to achieve dominance in world markets by 2020 due to improved efficiency (Reinders et al. 2015).

Currently, the leading non-silicon PV technology utilises cadmium telluride, with about 4 per cent market share primarily due to the commercial success of the company First Solar. A material called CIGS (comprising copper, indium, gallium, and selenium), and another called amorphous silicon, have market shares of 1–2 per cent each. Solar cells based on many other materials are under development but not yet in significant commercial production, notably perovskite materials. The latter has created substantial interest due to rapid improvement of efficiencies to above 20 per cent for small area laboratory cells, and the possibility of creating tandem solar cells in conjunction with crystalline silicon.

A potentially important branch of photovoltaics is CPV. Tracking of the Sun is required for concentrator systems. Mirrors or Fresnel lenses are used to concentrate light by 100 to 1,000 times onto a small number of highly efficient (and expensive) solar cells. Typically, active cooling of the solar cells is required to remove excessive heat. The best concentrator solar cells have conversion efficiencies approaching 50 per cent, and comprise three or more layers of different semiconductor materials drawn from the group 3 and group 5 columns of the periodic table. Such cells are very expensive per square centimetre compared with conventional silicon solar cells. However, concentration greatly reduces the effective cost per square metre of collector area—essentially most of the solar cells are replaced by cheaper lenses and mirrors. CPV may become important in the future but has only small market share at present, and will be restricted to areas with plenty of sunshine and low pollution because only direct beam light can be concentrated. CPV technology has much in common with concentrating solar thermal power, since much of the system infrastructure (such as trackers, controllers, lenses, and mirrors) could be used for either.

Photovoltaic markets

PV is unusual in that the unit cost of energy is similar for large (MW) and small (kW) systems—large systems have lower capital costs but higher financing costs and vice versa. Virtually all other energy sources have strong economies of scale. This confers a major advantage on PV, since it has markets at every scale from W to GW for the same basic product—the silicon solar cell.

In earlier decades, PV found widespread use in niche markets such as consumer electronics, remote-area power supplies, and satellites. Throughout the world, remote-area energy solutions are based upon various combinations of PV, wind, diesel, and batteries. Active load management is an important additional feature to minimise the requirement for diesel and batteries. In recent years, the industry has expanded (see Figure 11.4) and costs have declined very rapidly. PV systems are now installed on tens of millions of house roofs in cities, and also in large ground-mounted power stations. Mass production is causing rapid reductions in cost.

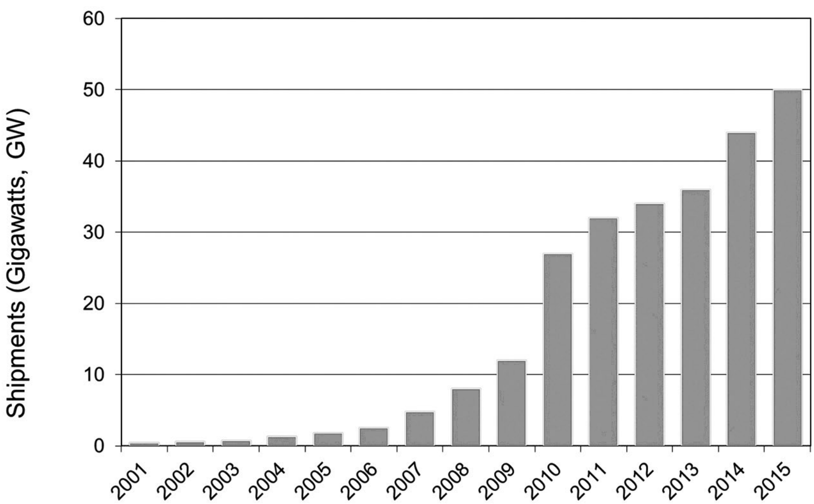

Figure 11.4 Shipments of photovoltaics since 2001

Source: Author data.

PV electricity is now less expensive than domestic and commercial retail electricity from the grid throughout much of the world, and is approaching cost-competitiveness with wholesale conventional electricity (IRENA 2015; Breyer and Gerlach 2013). This fact is the reason for the rapid growth in deployment of PV worldwide. Direct competitiveness with fossil fuels for wholesale energy supply is assisted by carbon pricing and the removal or equalisation of hidden support for fossil fuels. The cost of PV systems can be confidently expected to continue to decline for decades.

Solar energy has much to offer developing countries since nearly all are in low latitudes with good solar resources and low seasonal variability of both energy demand and solar availability. Small amounts of PV electricity can make dramatic differences to living standards, through the enabling of electric services such as lighting, computing, telecommunications, refrigeration, grain grinding, and water pumping.

Developing countries generally lack a widespread and robust electricity distribution grid. There are good prospects for organic development of thousands and millions of small solar- and wind-powered systems, which gradually merge to become a national grid. These countries may bypass the centralised electricity distribution systems of high-income countries. An analogy is telephony, for which low- and middle-income countries will rely heavily upon distributed mobile telecommunications rather than fixed lines.

Wind energy

Modern MW-scale wind generators located at good sites are amongst the lowest cost electricity generation technologies available. It is likely that wind and PV will have the largest deployment rates of electricity generation technologies in many countries for the next several decades. Wind and PV are often a good combination in that they counter-produce; it is often windy when not sunny, and vice versa. A modern wind generator comprises a tower, a rotating nacelle atop the tower housing a generator and control electronics, and three blades facing into the wind. Fields of hundreds of wind generators spaced apart from each other constitutes a wind farm. Typically, wind generators are located in farmland, and farming continues around the towers. The generators are located 5–10 rotor diameters apart. Wind farms located in shallow offshore waters are likely to become widespread in the future, both because it expands the available space for wind farms and because wind speeds are generally higher over water. However, there are significant technical and economic impediments to be overcome.

Commercial wind generators have power ratings of 1–8 MW. The largest currently available wind turbine is the Vestas V164, which is designed for offshore use and has a rated capacity of 8 MW (Wikipedia 2015), a maximum blade-tip height of 220 metres, and a rotor diameter of 164 metres. Even larger turbines are under development. Although costs increase rapidly with turbine scale due to the engineering required for such massive machines, the greater height of the rotors means that energy production also increases rapidly.

The power available from a wind generator is approximately proportional to the cube of the average wind speed at the top of the tower. This means that there is a strong incentive to find windy sites and to utilise tall towers. Accurate methods are available for assessing wind speeds as a function of location and height above ground. This is supported by sophisticated modelling to allow selection of the best sites for each wind generator in a wind farm.

The capacity factor refers to the annual output of a wind generator compared with the output that would be achieved were a generator to operate at its maximum power for the entire year. Higher average wind speed correlates with higher capacity factor. As larger machines become available, and as more offshore windfarms are constructed, they capture the stronger and more consistent winds blowing at greater heights from the ground and at sea, and the capacity factor rises. The cost of wind energy is inversely proportional to the capacity factor. Larger and more modern machines are gradually replacing older and smaller machines in good sites on land, and this is also leading to increased capacity factor.

Increases in machine size, and capacity factor, are leading to a decreasing cost of wind energy. It is unlikely that the bottom of the cost curve will be reached in the near future. Wind electricity is now fully competitive with fossil and nuclear electricity in many places throughout the world (IRENA 2015). This fact is the reason for the rapid growth in deployment of wind energy worldwide (see Figure 11.5).

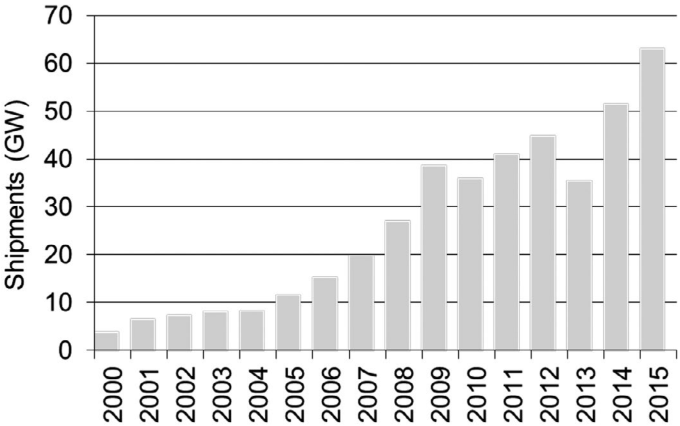

Figure 11.5 Wind energy shipments since 2000

Source: Global Wind Energy Council (2015).

Other solar energy technologies

Hydroelectric energy

Hydroelectric energy is a highly developed technology and accounts for about 16 per cent of worldwide electricity production. Hydro, wind, and PV constitute almost all current renewable electricity production. Generally, hydro involves construction of a dam on a river impounding a lake; construction of pipes or tunnels; and installation of an electrical turbine and power lines. Some hydro systems are 'run-of-river', which means that only small offtake weirs are needed. Most developed countries have utilised most potential hydro sites. Developing countries have many opportunities. Strong environmental and social opposition to hydro is often encountered, due to extensive flooding of sensitive river valleys, farmlands, and even cities.

Solar thermal

Good building design, which allows the use of natural solar heat and light, together with good insulation, minimises the requirement for space heating. Solar water heaters are directly competitive with electricity or gas in many parts of the world. Solar thermal electricity technologies use fields of sun-tracking mirrors to concentrate sunlight onto a receiver. The resulting heat is ultimately used to generate steam, which passes through a turbine to produce electricity. Concentrator methods are equally applicable to CPV systems. The commercially established methods of concentrating sunlight are line focus concentrators (troughs, both reflective and refractive) and central receivers (heliostats and power towers).

A potential application of concentrated sunlight is the generation of thermochemicals and the storage of heat at high temperature in molten salt to allow for 24-hour power production. Concentrated solar energy can achieve the same temperatures as fossil and nuclear fuels, either directly (using mirrors) or through the use of chemicals created using concentrated solar energy.

Solar thermal concentrators only utilise direct beam sunlight, and must be sited in dry locations with low levels of diffuse radiation in order to achieve economical application. Solar thermal electricity addresses a similar market to PV, but must be used at large scale in order to obtain competitive costs. Thus, there is a substantial cost barrier and financial risk factor compared with PV, for which energy costs from small and large systems are similar. Furthermore, the city market for which PV is well suited is unsuitable for solar thermal concentrators. Presently, new PV systems are being constructed 100 times faster than solar thermal. It is unclear whether solar thermal with thermal storage can become competitive with PV in conjunction with load management and storage (batteries and pumped hydro energy storage (PHES)).

Bio and ocean energy

Bio energy is obtained when sunlight allows growth and accumulation of biomass. Conversion of sunlight into chemical energy (i.e. biomass) is a very inefficient process compared with the PV and solar thermal energy collection. Bio energy conversion efficiency is generally much less than 1 per cent, while solar thermal and PV is 15–50 per cent efficient. Furthermore, growth of biomass requires large amounts of land, water, fertilisers, and pesticides, and competes with food and timber production.

Burning of waste biomass is a significant contributor to commercial energy production in many countries. However, the inherent limitations of bio energy production mean that it can never be more than a small fraction of commercial energy in an advanced economy. Bio energy is very widely used for heating and cooking in developing countries. It is observed in many countries that bio energy is gradually replaced by electricity or gas as incomes rise. The great flexibility of PV systems in terms of scale of deployment is likely to make a large impact in this respect.

Ocean energy comprises energy from waves, ocean currents, temperature gradients within the deep ocean, and gradients of salt concentration. In some countries with exposure to high levels of wave action and suitable seafloor conditions, wave energy could become significant when the technology is further developed. However, it is likely to be a small source of energy at a global scale.

Large-scale deployment of renewable energy

Large-scale energy storage

Wind and solar are likely to take an ever-expanding share of electricity markets. This raises questions about how to manage the variability of wind and solar power. It is observed that high penetration of electricity grids does not necessarily lead to unstable grids and the consequent need for substantial storage until quite high penetration is reached (Fraunhofer Institute for Solar Energy Systems 2015). For example, the state of South Australia obtains about half of its annual electrical energy from wind and PV, has no significant hydro or other storage, and is weakly connected electrically to other parts of Australia.

A key point in relation to storage is that a few hours of storage is sufficient to facilitate high penetration of wind and solar. Both power supply and demand are constantly fluctuating, but must remain in balance. Typically, this requirement is met through traditional hydro and low-duty cycle gas plants due to their rapid response time.

Short-term storage (4–24 hours) covers the day/night cycle, extreme demand events such as hot summer afternoons and cold winter mornings and evenings, offsets periods of low supply such as wind lulls and cloud, offsets plant and transmission line failure, and covers the time required to bring a low-duty cycle biomass, coal, or gas-fired power station online if the demand shortfall is likely to be extended. Additionally, short-term storage improves the capacity factor of constrained power lines; for example, those connecting wind and solar farms in remote windy and sunny regions to national grids. Owners of storage facilities can engage in arbitrage (buying energy when prices are low and selling when prices are higher).

PHES constitutes 99 per cent of all energy storage around the world (155 GW; see IRENA 2016: 17) because it is cheap compared with alternatives such as batteries. It is likely to continue its dominance in the wholesale storage market. PHES can provide excellent inertial energy, spinning reserve, and rapid start and black start capability. PHES involves pumping water to an upper reservoir when there is excess electricity, and later recovering that energy by allowing the water to flow back to a lower reservoir through a turbine. Response time (from off to fully on) is less than one minute. The operational lifetime is more than 50 years, with low operational costs. Round-trip energy storage efficiencies of 80 per cent are possible for well-designed systems, accounting for losses in the pumps, pipes, and turbines; i.e. 20 per cent of the stored energy is lost. The amount of energy stored in a PHES system is proportional to both the elevation difference ('head') between upper and lower reservoirs (typically 100–1,000 metres) and to the volume of water stored in the upper reservoir.

Most existing PHES is integrated with hydroelectric generation systems on rivers. In contrast, in a closed PHES system, the same water circulates indefinitely between upper and lower reservoirs, thus eliminating the need for a river ('off-river PHES'). There is limited capacity to build new hydroelectric dams in many countries. Constraints include limited, undeveloped economical dam sites, the environmental impact of the added power generation infrastructure, and the need to create additional power line easements, frequently in remote mountainous national parks. However, there is large scope to construct off-river PHES as the lowest cost mass storage option. Low costs for off-river PHES are facilitated by large heads (400–1,000 metres), absence of the need for flood control, short and steep pipelines, small reservoirs (1–20 hectares), and co-location with loads, power lines, and wind/solar farms—which are available at thousands of sites around the world.

Off-river PHES takes advantage of the vastly larger area of land that is off-river compared with on-river, which provides the opportunity to find numerous good sites close to loads and transmission infrastructure. Importantly, the upper reservoir can be on top of a hill rather than in a river valley, allowing three to five times larger head. This is a major advantage since energy storage capacity and power capacity both scale with head, and therefore cost scales inversely with head.

Off-river PHES sites comprise pairs of small, hectare-scale 'turkey nest' reservoirs, for which the walls are made from spoil scooped from the centre. There is no net generation. They can be located in hilly country near loads and power transmission networks, and connected by pipes or tunnels incorporating a pump/turbine. An off-river PHES system can deliver 1 GW for five hours utilising twin 15-hectare reservoirs with an average depth of 20 metres and an altitude difference of 750 metres. In contrast, typical conventional hydroelectric systems have lake areas of thousands of hectares, expensive flood control, and much smaller heads. Indicative costs of off-river PHES are US$0.8 million per MW for four hours of storage.

Several other large-scale energy storage technologies may be available by 2025. These include compressed air in caverns, advanced batteries, and solar thermal storage by means of molten salt. Should the cost of these technologies decline rapidly then they may become competitive with pumped hydro. Thermal storage would be a key element of any large-scale solar thermal electric generation at significant scale. However, none of these storage technologies have been deployed at significant scale compared with PHES, and future costs and technical feasibility are more speculative than for PHES.

Long-distance transmission of electricity

Transmission grids within industrialised countries are based around a relatively small number of large fossil, nuclear, and hydro power stations. Load management is practised by offering reduced prices at times of low demand. Increasing scale of interconnection confers robustness of supply, allows smoothing of total demand by increasing the variety and timing of loads, and allows the incorporation of more varied power sources including pumped hydroelectric storage. Additionally, wide geographical spread of generators connected with high voltage cables reduces the chance of simultaneous absence of sufficient sun and wind. Continent-wide transmission grids are emerging and are being strengthened. Long-distance transmission increases competition within markets, as well as allowing 'time shifting' through several time zones from one side of a continent to the other.

Greater penetration of variable renewable electricity sources is occurring. Although PV allows distributed generation of electricity including in cities, renewable energy generation is often far removed from cities. Examples include offshore wind generation and solar generation in desert regions. Transmission of electricity over long distances generally utilises HVDC technology. Since the power transmission capacity scales with the square of the transmission voltage, voltages in the range of hundreds of kilovolts (kV) up to a megavolt are used. High power alternating current transmission is technically infeasible over long distances. HVDC has additional advantages relating to reduced transmission easements and reduced induced current flowing through people living and working near direct current overhead transmission lines (Andersen 2006; Hammons 2008; Hammons et al. 2011; Kutuzova 2011).

HVDC technology was first used to link Gotland with mainland Sweden in 1954. This link was capable of transporting 20 MW, at 100 kV, over a 98 km underwater cable (Peake 2010). Since this installation, distances spanned, voltages attained, and power transmitted have all experienced massive increases. The longest HVDC line to date is in China, connecting the Xiangjiaba Dam to Shanghai, spanning a distance of 2,071 km and transmitting up to 6.4 GW at ±800 kV (Hammons et al. 2011).

The right of way needed for HVDC is substantial. On land, corridors of around 60 metres wide are necessary for the installation of a 5 GW cable (Kutuzova 2011). Obtaining access rights is a significant impediment to HVDC transmission. Underground cables require a much narrower corridor, but are more expensive and less capable of transmitting large amounts of power.

Transmission losses associated with an 800 kV DC power line with 5 GW capacity is quoted by Siemens as 3 per cent per 1,000 km (Siemens 2012). In addition, there is a few per cent conversion loss at the two ends of the cable. Costs of large HVDC cables can be expected to decline substantially as many more are constructed in coming decades. Costs below US$300 per MW kilometre are likely (Blakers, Luther, and Nadolny 2012).

Solar energy systems in cities

Tens of millions of roof-mounted PV systems have been deployed around the world. These systems have a power capacity of 0.1–10 kW for an individual dwelling, and tens to thousands of kW for commercial buildings. The roof area required amounts to 7–10 m^2 per kW. Low-density suburban housing generally has ample roof area to yield enough energy over the course of the year to equal the annual end-use energy of the dwelling. Low-rise commercial and light-industrial building roofs can yield substantial excess quantities of PV electricity for export to the electricity grid. However, in high-density regions of cities there is insufficient unshaded roof space for high penetration of PV electricity into the building energy requirement.

Roof-mounted PV systems generally compete with the retail price of electricity, which is typically two to four times larger than the wholesale price. The levelised cost of obtaining PV electricity from building roofs in moderate latitudes (<35 degrees Celsius) is well below the retail electricity tariff in many cities (Breyer and Gerlach 2013). This is driving strong growth in deployment of roof-mounted PV systems; for example, about one in six Australian houses had a roof-mounted PV system in 2015.

The deployment of millions of roof-mounted PV systems is causing a large shift in demand profiles of the distribution networks. Large increases in deployment of thermal and electrical storage will allow high penetration of PV electricity in urban areas, which will cause a dramatic shift in the economics of the electricity distribution industry. Storage is required because energy demand is often out of phase with solar energy availability. When teamed with effective energy management and control strategies, combined electrical and thermal storage is attractive both for the building owner and the electricity grid operator.

Battery storage can be used to increase self-consumption of roof-mounted PV generation, and effectively manage the electrical network and power system, by taking advantage of the fast response, power-on-demand nature of batteries. However, the high (but declining) costs of batteries means that using battery storage alone to match PV generation to building demand is costly compared with other methods of energy storage.

Storage of energy in the form of hot water in an insulated tank is very widely deployed. Conventional solar, gas, and electric hot water systems are under commercial pressure from the rapidly declining price of electricity from PV systems on building roofs. PV, combined with advances in highly efficient air-to-water heat pumps, allows PV-driven heat-pump hot water to become a cost-effective hot water supply option. Heat pumps use electrical energy to move heat from one place (outside the building) to another at a higher temperature (hot water tank). Several units of thermal energy can be delivered per unit of electricity. Heat-pump hot water storage can be easily controlled alongside other storage elements in conjunction with roof-mounted PV generation rates and household energy loads.

Thermal storage to provide space heating and cooling in buildings can be accomplished by raising or lowering the temperature of a building when low-cost energy is available, relying on thermal mass to store heat, and good insulation to reduce thermal losses. Reverse-cycle air conditioners (which are also heat pumps) are increasingly cost-effective in this application, and can be powered using roof-mounted PV. Heat banks rely on ceramic bricks to store at a high temperature and fans to circulate heat as required. They can be charged using PV electricity during the day for use at night. Cold storage can be accomplished using PV-driven heat pumps to produce cold water and ice during the day. Thermal energy storage via building space heating and cooling can be controlled, along with hot water and battery storage, to optimise the use of PV generation and to manage net household demand.

Reduction in the retail use of gas, and its replacement with PV-driven delivery of thermal energy in conjunction with heat pumps, is an emerging trend in urban buildings. Gas burning in domestic dwellings for delivery of hot water and space heating is relatively expensive and inefficient compared with PV. Additionally, gas appliances for water and space heating are relatively expensive. Hotplate cooking, a minor but highly valued use of gas, can be replaced by induction cooktops.

Generation of medium-temperature (>100 degrees Celsius) heat in cities for industrial purposes is usually achieved with gas for substantial applications. This temperature range is beyond the supply capacity of conventional thermosiphon and evacuated solar collectors. However, provision of 100–150 degrees Celsius heat is within reach of PV-driven heat pumps and resistive elements and is expected to rapidly increase.

Transport systems and solar fuels

Fossil fuels used for transport typically account for about 20 per cent of a developed country's greenhouse gas emissions. Cars, buses, and commercial vehicles comprise most of this, which can be avoided by moving to electric vehicles and electrically powered public transport, provided that electricity comes predominantly from renewable energy. Electric vehicle sales are rising rapidly, due to cost reductions in vehicles and improvements in automotive systems and batteries. For a driving distance of 8,000 km per year, a 1 kW photovoltaic panel is sufficient to provide the annual electricity requirements. The panel will occupy space of about 7 m^2, and would preferably be mounted in a sunny place such as a rooftop. The fully installed cost of the PV panels will be US$1,500–$2,000, and typically they will last 25 years—twice the typical lifetime of the car. Thus an outlay of a few thousand dollars provides the electricity requirements of an electric car for its whole lifetime, at a cost of about one cent per km.

Conversion of most land transport (vehicles and trains) to electricity derived from renewable energy sources appears to be feasible, which will greatly reduce the requirement for fossil transport fuels. However, some transport functions, such as ships, aircraft, and heavy machinery, cannot be met from electrical sources because of the impracticable size, weight, and cost of the required battery storage. Some industrial processes may also be difficult to service with (renewable) electricity. Cost-effective renewable energy-driven fuel synthesis, in competition with fossil fuels, is still some time away from large-scale utilisation, not least because there are many energy losses along the way.

Synthesis of chemical fuels, utilising solar energy to drive the chemical reactions, allows solar and other renewable electricity sources to substitute for fossil fuels for both transport and as an industrial fuel. There are a limited number of suitable chemical fuels, taking account of material abundance, toxicity, storability, and other factors. Notable candidates are carbon-based compounds (methane CH_4, diesel $C_{12}H_{23}$, kerosene $C_{12}H_{26}$), hydrogen (H_2), and ammonia (NH_3). The likelihood is that most synthetic fuels will be 'drop-in' replacements for existing fuels to avoid the need to redesign existing engines, i.e. based upon carbon.

Synthesis of carbon fuels will require an energy source derived from a low-emission technology. A renewable source of carbon is also required, and the two candidates are direct extraction of CO_2 from air or seawater, and biomass. In the latter case, provided that the biomass is merely the source of carbon, rather than additionally the source of energy, then the amount of biomass required is reduced. This is important because biomass has very low efficiency of solar energy collection and conversion (less than 1 per cent) and requires large amounts of land, water, pesticides, and fertilisers.

Chemical fuel synthesis utilising solar energy can be driven either by heat or electricity. It is not possible to transfer heat over long distances—it must be generated and used locally. Additionally, land for solar collectors is expensive in industrial areas. Thus direct (local) utilisation of high-temperature solar heat in industry requires locations that have high direct beam irradiation and low land cost. This is problematical for nearly all current manufacturing localities around the world, including much of China and India (severe air pollution), much of Southeast Asia (tropical cloudiness), and much of Europe and North America (substantial cloudiness and substantial seasonality of solar insolation). Loss of 50 per cent or more of the global radiation because it is diffuse makes solar concentrators considerably less economic.

Electric-driven fuel synthesis takes advantage of rapid reductions in the price of electricity from renewable wind and PV. PV and wind collectors can be located remotely in windy/sunny locations to transmit electricity to an industrial centre. Thus, renewable electricity has a significant advantage over solar concentrator heat for heavy industry. A key requirement in fuel synthesis and other industrial chemical processes such as ammonia production is to obtain hydrogen. Currently, most hydrogen used in industry comes from natural gas (CH_4). Renewable fuel synthesis can, however, obtain hydrogen from electrolysis of water. If renewable carbon fuel synthesis relies upon extraction of CO_2 from the air, then by far the largest energy requirement is electrolysis of water to obtain hydrogen, which is an electrical process.

100 per cent renewable energy

Recent work at The Australian National University (Blakers, Lu, and Stocks 2016) shows that 100 per cent renewable electricity is feasible at low cost in Australia, and by extension in similar countries and regions. The analysis avoids heroic assumptions about future technology development, and only includes technology that has already been deployed in large quantities (>150 GW), namely PV, wind, HVDC, and PHES.

In the modelling, wind and PV contribute 90 per cent of annual electricity, while existing hydroelectricity and biomass contributes about 10 per cent. PV and wind are overwhelmingly dominant in terms of new, low emissions generation technology because of their low cost: they constitute half of the world's new generation capacity installed each year, and all new generation capacity installed in Australia. The modelling uses historical data for wind, sun, and demand for every hour of the years 2006–10, and maintains energy balance between supply and demand by adding sufficient PHES, HVDC, and excess wind and PV capacity.

The key outcome of the modelling is that the cost of balancing energy on an hourly basis for 100 per cent renewable penetration is relatively small, in the range US$15 per megawatt hour (MWh). This covers the cost of PHES, HVDC, and spillage of wind and PV electricity when supply exceeds demand and the storages are full. The total cost of a fully renewable electricity supply in Australia is estimated at US$50 per MWh (in the post-2020 time frame), including the cost of wind and PV as well as the cost of energy balancing mentioned above. A large fraction of the cost of electricity balancing relates to periods of several days of overcast and windless weather that occur once every few years. Substantial reductions in electricity cost are possible through contractual load shedding, the occasional use of coal and gas generators to charge the PHES reservoirs, and management of the charging times of batteries in electric cars.

Wholesale movement of transport and low temperature heat to electric vehicles and electric-driven heat pumps, respectively, will add to electricity demand but can sharply reduce greenhouse gas emissions at low net cost. In the longer term, complete electrification of the entire energy system in a developed country results in an approximate tripling of electricity demand after taking account of the greater efficiency of electric devices in most applications (in terms of joules of energy required to deliver an energy service). There is far more than enough availability of solar and wind resources to achieve this outcome, and the overall cost is likely to be little different from the cost of the current fossil fuel–dominated energy system.

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