Chapter 2
State of Research

Sven Teske, Malte Meinshausen, and Kate Dooley

Abstract This chapter sets the context for the climate and energy scenario development. The first part summarizes the scientific status quo of climate change research and explains how the global climate has changed over recent decades and the likely outcomes if we continue with business as usual and fail to drastically reduce GHG emissions.

The second part reviews the development of the global energy markets during the past decade. Trends in the power-, transport- and heating sector in regard to technologies and investments are provided for the year of writing (2018). The developments put the energy scenarios presented in the following chapters into a global context.

2.1 Scientific Status Quo of Climate Change Research

A summary of the latest scientific publications explains how the global climate has changed in recent decades and the likely outcomes if we continue with 'business as usual' and fail to drastically reduce greenhouse gas emissions.

2.1.1 Basics of Climate Change and Radiative Forcing

The Earth's current climate is the result of a delicate balance between incoming short-wave solar radiation and outgoing long-wave radiation that moves back to space. Roughly half (165 W/m^2) the incoming short-wave radiation (340 W/m^2) reaches the

S. Teske (✉)
Institute for Sustainable Futures, University of Technology Sydney, Sydney, NSW, Australia
e-mail: sven.teske@uts.edu.au

M. Meinshausen · K. Dooley
Australian-German Climate and Energy College, University of Melbourne, Parkville, Victoria, Australia
e-mail: malte.meinshausen@unimelb.edu.au; kate.dooley@unimelb.edu.au

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surface of the Earth. The rest is reflected back to space by clouds, aerosol particles, or scattering gases, such as N_2 and O_2 (100 W/m^2) or is absorbed by the troposphere (75 W/m^2) (Stephens et al. 2012). With the exception of clouds and aerosols, this window to incoming solar radiation onto Earth's surface is relatively transparent, so that most of the Sun's energy that comes towards Earth is absorbed either in the atmosphere or on the Earth's surface. This window is our basic heating engine, and the incoming radiation that is our energy source is somewhat dimmed by aerosol emissions and by changes in the amount of sunlight reflected back to space by changes in land use. However, these are not humanity's greatest influences on the Earth's climate.

There is a second window for radiation, through which outgoing long-wave radiation passes, and we are much more effectively closing this window than the one for incoming solar radiation. We can imagine that this second atmospheric window already has a thick curtain across it, largely formed by water vapour. That curtain prevents surface long-wave radiation from going directly to space. In other words, that curtain acts like a thick blanket. The long-wave radiation that the Earth loses back into space originates not from its surface but from much higher atmospheric layers, which tend to be colder. Without absorbers of long-wave radiation in the atmosphere, the Earth's surface would be much colder and inhospitable to humans.

To the parts of the outgoing radiation window that are not yet covered by water vapour, humanity is now adding more layers of absorbers of other long-wave radiation in the form of GHGs. By adding an assortment of GHGs, we are thickening the existing curtain and closing the curtain further across the long-wave radiation window. Compared with the overall incoming solar radiation at 340 W/m^2, the 'curtain' generated by human-induced increases in the concentrations of long-lived greenhouse gases (CO_2, CH_4, halocarbons, N_2O and fluorinated gases) appears to be of little importance, as it "only" amounts to 2.83 W/m^2. The addition and subtraction of many other smaller human influences results in a slightly reduced net current (year 2011) forcing of 2.29 W/m^2.

2.1.1.1 Anthropogenic Contribution

Beyond reasonable doubt, climate change over the last 250 years has been driven by anthropogenic activities. In fact, the human-induced release of GHGs into the atmosphere has the potential to cause more than 100% of the currently observed climate change. The reason that climate change is not even greater than it is that some human-induced changes mask some of the warming attributable to elevated GHG concentrations. This masking effect arises from the emission of cooling aerosols and changes in land use that increase the reflectivity of the Earth's surface.

2.1.1.2 Carbon Budget and Future Warming

Although the anthropogenic contribution to climate change occurs via a large set of GHG emissions (the current emission scenarios that feed into CMIP6 include 43 GHG emission species), and multiple aerosols and land-use changes, there is one dominant influence: carbon dioxide (CO_2) emissions.

It is not only the magnitude of the anthropogenic emissions of CO_2 that makes it such a significant driver of human-induced climate change. There is also an inherent difference between CO_2 and almost all other GHGs and aerosols. Over the time scales of interest here, CO_2 does not have a finite lifetime in the atmosphere. All other gases react chemically, become photo-dissociated in the stratosphere, or are, for example, consumed by the bacteria in soils. However, once CO_2 is released from the near-permanent carbon pools of fossil fuel reservoirs, it only travels between a set of 'active' carbon pools. These active pools are the land biosphere, the ocean, and the atmosphere. Therefore, if CO_2 is added to one, the level in all three pools will rise and over time, a new, higher equilibrium concentration is reached. For example, whereas CO_2 is consumed by plants during the photosynthesis process and then built into plant tissue as carbon, this same carbon is released again as CO_2 when forests burn, when organic matter in the soil decomposes, and when humans and other animals oxidize the food they eat. Therefore, a kilogram of CO_2 emissions will increase the atmospheric CO_2 concentration for hundreds or even thousands of years. Initially, the average CO_2 concentration will shoot up by that kilogram, and then drop relatively quickly again before a new equilibrium is slowly re-established by the redistribution of carbon into the land biosphere and the ocean.

The IPCC Fifth Assessment Report highlighted this key difference between CO_2 and other GHGs. The airborne fraction of CO_2 emissions diminishes over time, as for other GHGs. However, the airborne CO_2 fraction does not decline to zero over 100 years, 1000 years, or even longer periods. Furthermore, carbon-cycle feedback mechanisms mean that higher CO_2 concentrations cause more carbon to remain in the atmosphere. Acting in the other direction, any extra amount of CO_2 in the atmosphere will have less and less effect on radiative forcing, i.e., how much each CO_2 molecule contributes to the warming of the planet. These factors act in concert with another feature of the climate system: the Earth's inertia to warming. When the thermostat of your kitchen oven is set to 220 °C, the oven will take a while to heat to that level. The situation is much the same with the Earth's climate. The IPCC Fifth Assessment Report notes that three effects (the carbon cycle and its feedbacks, the saturation effect of forcing, and the delayed response of the atmosphere to warming) combine to create what is almost a stepwise function in the warming caused by CO_2 emissions. In other words, every extra kilogram of CO_2 produces a slightly greater increase in temperature than the preceding kilogram, and the warming effect is much the same 10 years after the emission of that kilogram as it is after 100 or 500 years. Over time, less of the CO_2 will remain in the atmosphere, but the Earth's inertia will still cause the temperature to reflect the extra warmth arising from the initial emission.

This feature of the Earth's warming and the carbon cycle can be exploited to derive a very simple linear relationship between cumulative carbon emissions and warming. In fact, the resultant warming is a simple function of the sum of all the CO_2 that has ever been emitted, largely independent of when a certain amount of CO_2 was emitted in the past. Based on this understanding, we can compute the carbon budgets for specific levels of warming. As a complication, of course, an unknown amount of warming arises in response to other GHG emissions and aerosols. When deriving carbon budgets, this extra level of warming is normally derived from a range of future emission scenarios. Therefore, the ultimate level of warming is the sum of the linear CO_2-induced warming level (often described as the 'transient climate response to cumulative emissions of carbon') and a smaller and somewhat uncertain contribution that depends on the other GHGs and aerosols.

2.1.2 Carbon Budgets for 1.5 °C and 2.0 °C Warming

The IPCC Fifth Assessment Report used the results of earth system models to derive its carbon budgets. Earth system models are the most complex computer models we have of how the Earth, its atmosphere, oceans, and vegetation are interacting with each other. The IPCC investigated the amounts of cumulative carbon emissions (in a multi-gas world) that would be consistent with, for example, temperatures maintained below either 1.5 °C or 2.0 °C higher than to pre-industrial levels. The recently published IPCC Special Report on the 1.5 °C degree target cites different carbon budget numbers, depending on whether a low estimate of historical temperatures is assumed or surface air temperatures are consistently applied. Therefore, there is some complexity and uncertainty around the carbon budget, which is related to the fact that different interpretations can be made about how far we are still away from the 1.5 °C target (for example). If we assume that we are still 0.63 °C away from 1.5 °C warming (a very optimistic estimate, which is unfortunately based on a too optimistic account of historical emissions), from January 2018 onwards, we can still emit 1320 $GtCO_2$ before reaching 2.0 °C warming (66% chance) and 770 $GtCO_2$ before reaching 1.5 °C warming (50% chance). These figures must be reduced by a further 100 $GtCO_2$ to account for the additional Earth system feedback that has occurred over the twenty-first century. However, when a more realistic measure of historical temperature evolution is used (i.e., calculated by consistently using proxies for surface air temperatures over the land and ocean, rather than by mixing ocean surface water temperatures with air temperatures over land), the carbon budgets are no longer very high. Specifically, the carbon budget required to maintain the Earth's temperature below 2.0 °C, with 66% probability, then decreases to 1170 GtCO2 from 1 January 2018 onwards and to 560 GtCO2 for a 50% chance of staying below 1.5 °C (before the extra 100 GtCO2 that must be subtracted for additional Earth system feedbacks is taken into account; see Table 2.2 in the IPCC Special Report on 1.5 °C warming).

The substantial difference between these two sets of figures (and also their differences from earlier IPCC estimates of the carbon budget) is the focus of a current intense scientific debate, which is unlikely to be settled in the next few months (see e.g., Schurer et al. 2017, 2018; Hawkins et al. 2017). As already mentioned, one of the key factors in deriving a carbon budget is the estimated current level of warming. Among other reasons, the recent warming 'hiatus' in temperature may explain why the recently derived carbon budgets are more relaxed than expected. When the 'hiatus' period substantially influences the level of warming that is taken as a starting point, the ‘distance’ from 1.5 °C and 2.0 °C might seem larger than it is. The recent upswing in the global mean temperatures gives us an idea of how much natural variability is superimposed on the long-term warming trend. Other points for discussion in the determination of carbon budgets include the pre-industrial warming level and the already-mentioned amount of warming induced by non-CO_2 gases.

This study does not aim to resolve the differences in opinions about carbon budgets, but it does provide emissions pathways that can be considered to be consistent with both a target level of 1.5 °C warming in the case of the 1.5 °C scenario, and with a “well-below 2.0 °C” target level in the case of the 2.0 °C scenario.

Whatever the precise carbon budget, recent effects of climate change provide another set of stark reminders that it is more urgent than ever to replace fossil fuels. If we wait for the wild-fire seasons that will occur at global warming levels of 1.5 °C or 2.0 °C, with intensified droughts or ever-more intense hurricane, it might be much too late to avoid their widespread catastrophic impacts. Even at 1.5 °C warming, there is a risk that the continuous melting of the Greenland ice sheet will cause sea levels to rise by meters over the coming centuries. Fossil fuels have undoubtedly allowed great growth in prosperity across the globe, but their replacement with the cleaner, cheaper and emission-free technologies that are available today is overdue.

2.2 Development of Energy Markets—Past and Present

Renewable energy technologies have been developing rapidly since the beginning of the century, and they have emerged from niche markets to become mainstream. This section provides an overview of the development of renewable energy in the power, heating, and transport sectors up to the year of writing (2018). These developments will put the energy scenarios presented in the following chapters into a global context. The research and data in Sect. 2.2.1 are based on the REN21 Renewables 2018—Global Status Report Renewables.

2.2.1 Global Trends in Renewable Energy in 2018

In 2017, ongoing trends continued: solar photovoltaics (PV) and wind power dominated the global market for new power plants, the price of renewable energy technologies continued to decline, and fossil fuel prices remained low. A new benchmark was reached, in that the new renewable capacity began to compete favourably with existing fossil fuel power plants in some markets (Malik 2017). Electrification of the transport and heating sectors is gaining attention, and although the amount of electrification is currently small, the use of renewable technologies is expected to increase significantly.

The growth in solar PV has been remarkable, nearly double that of second-ranking wind power, and the capacity of new solar PV is greater than the combined increases in the coal, gas, and nuclear capacities (FS-UNEP 2018). Storage is increasingly used in combination with variable renewables as battery costs decline, and solar PV plus storage has started to compete with gas peaking plants (Carroll 2018). However, bioenergy (including traditional biomass) remains the leading renewable energy source in the heating (buildings and industry) and transport sectors.

Renewable energy's share of the total final energy consumption has increased only modestly in recent years, despite tremendous growth in the modern renewable energy sector. There are two main reasons for this. One is that the growth in the overall energy demand (except for the drop in 2009 after the global economic recession) has counteracted the strong forward momentum of modern renewable energy technologies. The other is the declining share of traditional biomass, as people switch to other forms of energy. Traditional biomass makes up nearly half of all renewable energy used, and its use has increased at a rate lower than the growth in total energy consumption.

Since 2013, the global energy-related CO_2 emissions from fossil fuels have remained relatively flat. Early estimates based on preliminary data suggest that this changed in 2017, with global CO_2 emissions growing by around 1.4% (REN21-GSR 2018). These increased emissions were primarily due to increased coal consumption in China, which grew by 3.7% in 2017 after a 3-year decline (ENERDATA 2018). This increased Chinese consumption, as well as steady growth of around 4% in India, is expected to lead to an upturn in global coal use, reversing the annual global decline observed from 2013 to 2016 (ENERDATA 2018).

In contrast to the upturn in global coal use, in 2017, 26 countries joined the Powering Past Coal Alliance, which is committed to phasing-out coal power by 2030, with new pledges from Angola, Denmark, Italy, Mexico, New Zealand, and the United Kingdom (Carrington 2017). An increasing number of companies who owned, developed or operated coal power plants have moved away from the coal business (Shearer 2017). Also in 2017, 26 of 28 European Union member states signed an agreement to build no more coal-fired power plants from 2020 onwards, and the Port of Amsterdam, which currently handles 16 million tonnes of coal per year, announced plans to become coal-free by 2030 (Campbell 2017).

The global oil price averaged USD 52.5 per barrel in 2017, equivalent to about half the record high prices that occurred between 2011 and 2014, although it was still almost double the prices from 1996 to 2005 (Statista 2018). Natural gas prices fell from 2013 to 2016, and early indicators suggest that prices remained low or decreased further in 2017 (BP 2017). Low fossil fuel prices have challenged renewable energy markets, especially in the heating and transport sectors (IEA-RE 2016).

The value of direct global fossil fuel consumption subsidies in 2016 was estimated to be about USD 360 billion, a 15% reduction since 2015—but still more than 20% higher than the total renewable industry turnover in 2017 (IEA-WEB

2018). The value of fossil fuel subsidies also increases by an order of magnitude if externalities are considered (IMF 2015). Although the Group of Twenty (G20) reaffirmed their 2009 commitment to phasing-out inefficient fossil fuel subsidies in 2017, progress has been slow and there are calls from large investors, insurers, and civil society to both increase transparency and accelerate the process (G20-2017). The main problems identified include that the G20 has not defined 'inefficient subsidies'; there is no mandatory reporting; and there are no timelines for phase-out commitments (Asmelash 2017).

At the global policy level, international climate negotiations have continued to influence energy markets. Following the 2015 Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC), a technical meeting on its implementation took place in Bonn, Germany, in November 2017 at the 23rd Conference of the Parties (COP23) (UNFCCC 2017). Although renewable energy figured prominently in a large proportion of the Nationally Determined Contributions (NDCs) that countries submitted in the lead-up to COP22 in 2016, the climate negotiations in 2017 were unable to resolve the question of how NDCs should be organized, delivered, and updated, leaving uncertainty about how national renewable energy commitments could be ramped up (Timberley 2017).

Despite these uncertainties, an increasing number of communities, cities, and regions have introduced 100% renewable energy targets. The number of cities powered by at least 70% renewable electricity has more than doubled in 2 years, from 42 in 2015 to 101 in 2017. These cities now include Auckland, Brasilia, Nairobi, and Oslo (CDP-WEB 2018).

Carbon pricing policies, which include carbon taxes and emission trading schemes, were in place in 64 jurisdictions around the world in 2017, up from 61 in 2016. In December 2017 (REN21-GSR 2018), China launched the first phase of its long-awaited nationwide carbon emissions trading scheme, which will focus on the power sector. Carbon trading will be based in Shanghai and will include about 1700 power companies emitting more than 3 billion tonnes of CO_2 annually (Xu and Mason 2017). For comparison, the emissions trading scheme of the European Union included around 1.7 billion tonnes of CO_2 in 2016 (EC 2017). Reforms to the European Union scheme were agreed upon at the end of 2017, which will reduce the number of emission certificates issued and accelerate the cancellation of surplus certificates (Agora 2018).

The global investment in renewable energy in 2017 (excluding hydropower plants larger than 50 megawatts [MW]) was USD 280 billion (REN21-GSR 2018), up by 2% from 2016, but 13% below the all-time high, which occurred in 2015. It is noteworthy that each dollar represents more capacity on the ground as prices per GW decrease. Nearly all the investment was in either solar PV (58%) or wind power (38%). Developing countries accounted for the largest share of investment for the third consecutive year, at 63% of the total investment. China alone accounted for 45% of global investment, with a 30% increase since 2016. The United States was next, with 14%, followed by Japan (5%) and India (4%). Investment remained steady or trended upwards in Latin America and the USA, but has been falling in Europe since about 2010, with a drop of 30% from 2016 to 2017 (UNEP-FS 2018).

Pressure to diversify and stable growth in the renewables sector over the past decade has increased the interest of the fossil fuel industry in renewables. Large oil corporations more than doubled their acquisitions, project investments, and venture capital stakes in renewable energy in 2016 relative to those in 2015. This increased the investment in clean energy companies to USD 6.2 billion over the past 15 years, with more than 70% of deals involving solar PV or wind, and 16% involving biofuels (Bloomberg 2017). However, this is dwarfed by the spending of these companies on fossil fuels. One estimate is that renewables account for about 3% of the total annual spending (around USD 100 billion) by the world's five biggest oil companies (Schneyer and Bousso 2018). Bank finance for fossil fuels increased in 2017 by 11% relative to that in 2016, after a significant decline in 2016 (RAN 2018).

In 2017, as in previous years, renewables saw the greatest increases in capacity in the power sector, whereas the growth of renewables in the heating, cooling, and transport sectors was comparatively slow. Sector coupling—the interconnection of power, heating, and transport, and particularly the electrification of heating and transport—is gaining increasing attention as a way to increase the uptake of renewables by the transport and thermal sectors. Sector coupling also allows the integration of large shares of variable renewable energy, although this is still at an early stage. For example, China is specifically encouraging the electrification of heating, manufacturing, and transport in high-renewable areas, including promoting the use of renewable electricity for heating to reduce the curtailment of wind, solar PV, and hydropower. Several USA states are examining options for electrification, specifically to increase the overall renewable energy share (NEEP 2017).

2.2.1.1 Trends in the Renewable Power Sector

The capacity for generating renewable power saw its largest annual increase ever in 2017, with an estimated 178 GW of capacity added. The total global renewable power capacity increased by almost 9% relative to that in 2016. Solar PV additions reached a record high and represented about 55% of newly installed renewable power capacity in 2017. The increase in the solar PV capacity was greater than the combined net additions to the fossil fuel and nuclear capacities. For the first time, the installed solar PV capacity surpassed the global operating capacity of nuclear power. Wind and hydropower installations were in second and third positions, contributing about 29% and 11% of the increase in renewable generation capacity, respectively (REN21-GSR 2018).

In 2017, renewables accounted for an estimated 70% of net additions to the global power-generating capacity, up from 63% in 2016 (REN21-GSR 2018). The cost-competitiveness of renewable power generation continued to improve. Wind power and solar PV are now competitive with the generation of new fossil fuel energy in many markets, and even with existing fossil fuel generation in some markets. The costs of bio-electricity, hydropower, and geothermal power projects commissioned in 2017 were mostly within the range of the cost of fossil-fuel-fired electricity generation. Offshore wind prices also fell significantly in 2017, as competitive tenders in Germany, the UK, and the Netherlands resulted in bids that were competitive with new conventional power generation.

By the end of 2017, the countries with the greatest total installed renewable electric capacities were China, the USA, Brazil, Germany, and Canada. When only solar and wind capacities are considered, the top countries were China, the USA, and Germany, followed by Japan, India, and Italy, and then by Spain and the UK, which had about equal amounts of capacity by the year's end.

Seventeen countries have more than 90% renewable electricity, with the majority supplied almost completely by hydropower. However, three of these, Uruguay, Costa Rica, and Ethiopia, also have significant contributions from wind power (32%, 10%, and 7%, respectively) (REN21-GSR 2018). Increasing proportions of variable renewable electricity (VRE) must be integrated into electricity systems, and VRE penetration reached locally significant levels in 2017. The countries leading the way with wind and solar penetration are Denmark (52%), Uruguay (32%), and Cape Verde (31%), with another three countries at or above the 25% VRE penetration mark. Several countries and regions integrated much higher shares of VRE into their energy systems as instantaneous shares of the total demand for short periods during 2017, e.g., South Australia (more than 100% of load from wind power alone, and 44% of load from solar PV alone on another occasion), Germany (66% of load from wind and solar combined), Texas (54% of load from wind alone), and Ireland (60% of load from wind alone) (Parkinson 2017).

Curtailment—the forced reduction of wind and solar generation—is an indicator of grid integration challenges. In six of the jurisdictions with the highest VRE penetration, the curtailment rates were low (0–6%) in 2016 (Wynn 2018). Although curtailment initially tends to increase as the VRE share increases, some jurisdictions have successfully introduced measures, such as transmission upgrades, that have significantly reduced curtailment (Wynn 2018). Integration challenges have led to high curtailment rates in China, the world's largest wind and solar PV market (ECNS.CN 2018). These were reduced in 2017, with the average curtailment of wind power for the year at around 12%, down from 17% in 2016, and the average curtailment of solar PV was 6–7%, down 4.3% relative to that in 2016 (Haugwitz 2018).

The ongoing increase in the growth and geographic expansion of renewable energy was driven by the continued decline in the prices for renewable energy technologies (in particular, for solar PV and wind power), caused by the increasing power demand in some countries and by targeted renewable energy support mechanisms.[44] Solar PV and onshore wind power are now competitive with new fossil fuel generation in an increasing number of locations, due in part to declines in system component prices and to improvements in generation efficiency. The bid prices for offshore wind power also dropped significantly in Europe during 2016 (FT 12.9.2017).

Such declines in cost are particularly important in developing and emerging economies, and in isolated electric systems (such as on islands or in isolated rural communities) where electricity prices tend to be high (if they are not heavily subsidized), where there is a shortage of generation, and where renewable energy resources are particularly plentiful, making renewable electricity more competitive relative to other options. Many developing countries are racing to bring new power-generating capacities online to meet rapidly increasing electricity demands, often turning to renewable technologies (which may be grid-connected or off-grid) through policies such as tendering or feed-in tariffs, in order to achieve the desired growth quickly.

Approximately 1.06 billion people, most in sub-Saharan Africa, lived without electricity in 2016, 223 million fewer than in 2012 (IEA-WEO 2016; IEA-EAO 2017). Distributed renewables for energy access (DREA) systems were serving an estimated 300 million people at the end of 2016, and they comprised about 6% of new electricity connections worldwide between 2012 and 2016 (IRENA-P 2017). In places where the electricity grid does not reach or is unreliable, DREA technologies provide a cost-effective option to improve energy access. For example, about 13% of the population of Bangladesh gained access to electricity through solar home systems (SHS), and more than 50% of the off-grid population in Kenya is served by DREA systems (Dahlberg 2018). Off-grid solar devices, such as solar lanterns and SHS, displayed annual growth rates of 60% between 2013 and 2017 (Dahlberg 2018).

2.2.1.2 Heating and Cooling

Energy use for heating and cooling is estimated to have accounted for just over half of the total world final energy consumption in 2017, with about half of that used for industrial process heat (IEA-RE 2017). Around 27% of this was supplied by renewables. The largest share of renewable heating was from traditional biomass, which continued to supply about 16.4% of the global heat demand, predominantly for cooking in the developing world (IEA-RE 2017). Renewable energy—excluding traditional biomass—supplied approximately 9% of the total global heat production in 2017, up from about 6% in 2008 (REN21-GSR 2018).

Renewable heating and cooling receives much less attention than renewable power generation, and has been identified as the 'sleeping giant of energy policy' for the past decade (IEA-Collier 2018). The use of modern renewable heat has increased at an average rate close to 3% per year since 2008, gradually increasing its share of heat supply, but it lags well behind the average annual increase of 17% in modern renewables for electricity (IEA-RE 2017). Renewable energy technologies for heating and cooling include a variety of solar thermal collectors for different temperature levels; geothermal and air-sourced heat pumps; bioenergy used in traditional combustion applications or converted to gaseous, liquid, or solid fuels and subsequently used for heat; and any type of renewable electricity used for heating. Heat may be supplied by on-site equipment or by a district heating network.

A wide range of temperature requirements exist, from temperatures of around 40–70 °C for space and water heating in buildings, to steam at several hundred degrees Celsius for some industrial processes (Averfalk et al. 2017; USA-EPA 2017). The variety in renewable heating systems and applications is much greater than in the renewable power sector, which makes standardization to reduce costs by economies of scale more challenging, and makes it difficult for policy makers to find effective mechanisms to increase the renewable share. Trends in the use of modern renewable energy for heating vary according to the technology, although the relative shares of the main renewable heat technologies have remained stable for the past few years. In 2017, bioenergy (excluding traditional biomass) accounted for the greatest share, providing an estimated 68% of renewable heat, followed by renewable electricity at 18%, solar thermal at around 7%, district heating at 4% (which was nearly all bioenergy), and geothermal at 2% (REN21-GSR 2018). Although additional bio-heat and solar thermal capacities were added in 2017, the growth in both markets continued to slow. The trends in direct geothermal heating are unclear.

Bioenergy systems provide individual heating in residential and medium-sized office buildings, either as stand-alone systems or in addition to an existing central heating system, and bioenergy also accounts for 95% of district heating (IEA-RE 2017). District heating systems are suitable for use in densely populated regions with an annual heating demand during ≥4 months of the year, such as in the northern part of China, Denmark, Germany, Japan, Poland, Russia, Sweden, the UK, and the northern United States (IRENA-RE-H 2017). However, district heating supplies a very small proportion of global heating needs. The majority of district heating systems are fuelled by either coal or gas, with the share of renewables ranging from 0% to 42% (IRENA-RE-H 2017). Switching existing districting heating systems from fossil fuels to renewables has considerable potential (IRENA-RE-H 2017). Since the 1980s, Sweden has progressively switched from an almost entirely fossil-fuelled heating supply to systems supplied by 90% renewables and recycled heat (Brown 2018). District heating can combine different sources of heat, and can play a positive role in the integration of VRE through the use of electric heat pumps.

Solar thermal collector installations continued to decline globally in 2017, with a reduction of 3% (REN21-GSR 2018) compared with 2016, but the markets in China and India remained strong. In Europe, hybrid systems, in which solar thermal systems are used in combination with gas-fired central heating or bioenergy, are becoming more common, with specialized companies offering standardized technology.

Electricity accounts for an estimated 6% of the total heating and cooling consumption in buildings and industry, with about half of that electricity estimated to be renewable (IEA-RE 2017). The further electrification of heating and cooling drew increasing attention in 2017, particularly in the United States and China. Residential solar PV systems are also increasingly connected to electricity-using heat pumps in buildings rather than feeding the energy into the public electricity grid, especially when feed-in tariffs for solar electricity are reduced or have been entirely phased out.

Space cooling accounts for about 2% (REN21-GSR 2018) of the total world final energy consumption, and is supplied almost entirely by electricity (IEA-RE 2017). Solar-based space-cooling systems are still in the minority compared with conventional air-conditioning systems.

2.2.1.3 Transport

The global energy demand for transport increased by an average of 2.1% between 2000 and 2016, and is responsible for approximately 29% of the final global energy use and 24% of GHG emissions (IEA-WEO 2017). The vast majority (92%) of global transport energy needs are met by oil, with small proportions met by biofuels (2.9%) and electricity (1.4%) (IEA-WEO 2017).

There are three main entry points for renewable energy in the transport sector: the use of 100% liquid biofuels or biofuels blended with conventional fuels; natural gas vehicles and infrastructure (these can run on upgraded biogas); and the electrification of transport (if the electricity is itself renewable), which can be via batteries or hydrogen in fuel cells.

Biofuels (bioethanol and biodiesel) make by far the greatest contribution to renewable transport. The overall renewable share of road transport energy use was estimated to be 4.2% in 2016, with nearly all of that from biofuels (IEA-RE 2017). In 2017, global bioethanol production increased by 2.5% relative to that in 2016, with a slight decline in Brazil offset by increases in the USA, Europe, and China (IEA OIL 2018). Biodiesel production remained relatively stable in 2017, following a 9% increase in 2016 relative to 2015 (IEA OIL 2018).

The technology for producing, purifying, and upgrading biogas for use in transport is relatively mature, and the numbers of natural gas vehicles (NGVs) and the associated infrastructure are increasing slowly but steadily internationally. Many countries have relatively well-developed NGV infrastructures, and NGVs provide a good entry point for biogas in the transport sector (IRENA-RV-2017). The largest producers of biogas for vehicle fuel in 2016 were Germany, Sweden, Switzerland, the UK, and the USA (IRENA-RV-2017). The main barriers to the further expansion of biogas for transport are economic, with supply costs of USD 0.22–1.55 per cubic metre (m^3), compared with natural gas prices, which are as low as USD 0.13 per m^3. However, the lack of consistent regulation and access to gas grids are also significant barriers (IRENA-RV-2017).

Historically, the electrification of the transport sector has been limited to trains, light rail, and some buses. In 2017, there were signs that the entire sector would open to electrification. Fully electric passenger cars, scooters, and bicycles are rapidly becoming common-place, and prototypes for heavy-duty trucks, planes, and ships were released in 2017 (Hawkins 2017).

The number of electric vehicles (EVs) on the road passed the three million mark in 2017 (Guardian 25.12.2017). Annual sales are still only a very small proportion of the global total (1%), but this is set to change. In 2017, partly influenced by the scandal over diesel emissions cheating, five countries announced their intention to ban sales of new diesel and petrol cars from 2030 (India, the Netherlands, and Slovenia) or 2040 (France and the UK) (Bloomberg 11.2017). The announcement of electric product lines by car manufacturers in 2017 was another breakthrough. However, the number of EVs on the road is dwarfed by the number of electric bikes.

The global fleet was estimated to be around 200 million at the end of 2016, most of them in China, and 30% of bicycles sold in the Netherlands were e-bikes in 2017 (Wang 2017). Electric two- and three-wheel vehicles account for less than 0.5% of all transport energy use, but they account for most of the remaining renewable share after biofuels (IEA-RE 2017).

Further electrification of the transport sector will potentially create a new market for renewable energy and ease the integration of variable renewable energy, if market and policy settings ensure that the charging patterns are effectively harmonized with the requirements of electricity systems. There are already examples of countries and cities supplying electricity for both heavy and light rail from renewable electricity, including the Netherlands (BI 2017), Delhi (Times of India 2017), and Santiago de Chile (CT 2017).

Road transport accounts for 67% of global transport energy use, and two-thirds of that is used for passenger transport.

Aviation accounts for around 11% of the total energy used in transport (US-EIA-2017). In October 2016, the International Civil Aviation Organization (ICAO), a UN agency, announced a landmark agreement to mitigate GHG emissions in the aviation sector. By the end of 2017, 106 states representing 90.8% of global air traffic had settled on a global emissions reduction scheme (Guardian 6.10.2016). Together with technical and operational improvements, this agreement will support the production and use of sustainable aviation fuels, specifically drop-in fuels produced from biomass and different types of waste (ICAO 2018). In 2017, Norway announced a target of 100% electric short-haul flights by 2040 (Guardian 18.1.2018).

Shipping consumes around 12% of the global energy used in transport (US-EIA-2017) and is responsible for approximately 2.0% of global CO_2 emissions. There are multiple entry points for renewable energy: ships can incorporate wind (sails) and solar energy directly, and can use biofuels, synthetic fuels, or hydrogen produced with renewable electricity for propulsion. China saw the launch of the world's first all-electric cargo ship in 2017, and in Sweden, two large ferries were converted from diesel to electricity in 2017 (China Daily 14.11.2017). In 2017, the International Maritime Organization's (IMO's) Marine Environment Protection Committee (MEPC) approved a roadmap (2017–2023) to develop a strategy for reducing GHG emissions from ships. The roadmap includes plans for an initial GHG strategy to be adopted in 2018 (IMO 2017).

Rail accounts for around 1.9% of the total energy used in transport and is the most highly electrified transport sector. The share of rail transport powered by electricity was estimated to be 39% in 2015, up from 29% in 2005 (IEA-UIC 2017). Just over a third of the electricity (9% of rail energy) is estimated to be derived from renewable sources (IEA-UIC 2017). Some jurisdictions are opting to ensure that the proportion of energy from renewable sources in their transport sectors is well above the share of renewable energy in their power sectors. For example, the Dutch railway company NS announced that its target to power all electric trains with 100% renewable electricity was achieved ahead of schedule in 2017 (Caughill 2017), and the New South Wales Government in Australia announced a renewable tender for the Sydney's light rail system.

Following the historic Paris Climate Agreement in December 2015, the international community has focused increasing attention on the decarbonisation of the transport sector. At the climate conference in November 2017 in Bonn, Germany, a multi-stakeholder alliance launched the Transport Decarbonisation Alliance (UN-P 2018). France, the Netherlands, Portugal, Costa Rica, and the Paris Process on Mobility and Climate (PPMC) are members of the Alliance, which includes countries, cities, regions, and private-sector companies committed to ambitious action on transport and climate change (UN-P 2018).

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