1

Setting the Energy Scene

1.1 Introduction

Humankind has embarked on the third energy transition (see Figure 1.1). In the pre-industrial time, biomass, for example in the form of wood and peat, was used as the main source of energy with limited use of fossil fuels. The introduction of steam engines, which heralded the start of the first industrial revolution, increased the demand for easily transportable energy carriers, such as coal. For a long time, coal remained the main energy carrier (and in various countries still is by far the main energy carrier) but was gradually replaced by oil as an energy carrier when the need for transportation fuels increased. Going into the energy-demanding fourth industrial revolution, fossil fuels are being replaced with energy carriers derived from renewable resources. It is often argued that the driving force for the replacement of fossil fuels as the main energy carrier is driven by the depletion of these resources. However, this is incorrect. It has been stated in various forms: '*The Stone Age came to an end, not because we had a* ***lack of stones****, and the oil age will come to an end not because we have a* ***lack of oil***' [1] implying that the change is brought about by alternative technologies becoming more attractive than the continued use of existing technologies. This may be brought about by lowering the cost of alternative technologies but also by changing the view of costs associated with existing technologies (through implementation of environmental laws or through carbon tax).

The demand for primary energy has increased dramatically in the period 1820–2018 (see Figure 1.2), which can be ascribed in part to the growing world population, but also to the increased energy usage per person. It can be estimated that annual primary energy demand per person increased almost sixfold in that period from 16.7 GJ per person per annum (0.5 kW per person) in 1820 to 95.3 GJ per person per annum (3.0 kW) in 2018. The increase in the primary energy demand between 1850 and 2020 is stronger than would be expected based on a simple exponential growth pattern, possibly due to the presence of two independent factors driving the energy demand, viz. the increased population as well as the higher energy demand per capita. The power demand varies widely across the world, with developed countries having higher-than-average power consumption (though it should be noted that comparing the energy demand at a national level is difficult

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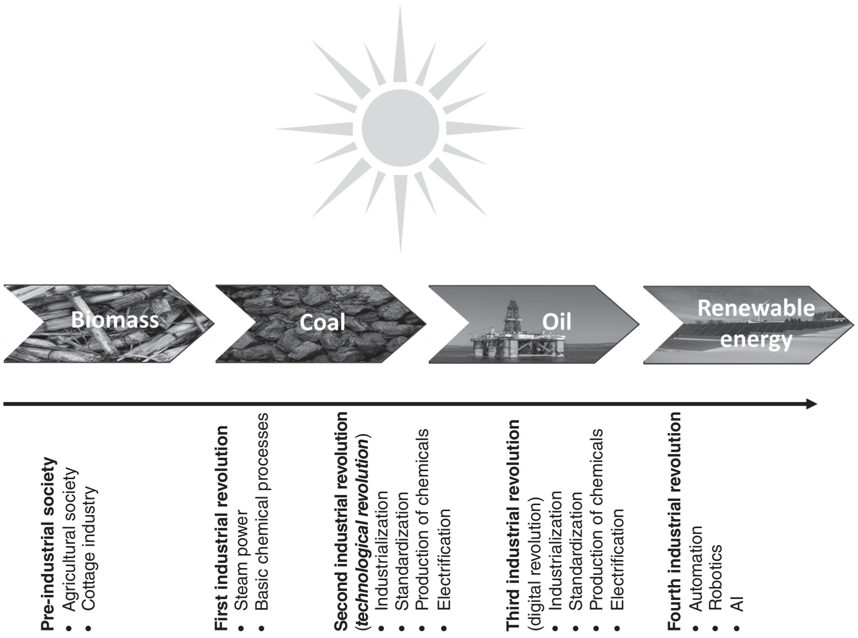

Figure 1.1 Energy carriers used in human history with the main technological areas associated with them (image by Pixabay).

due to the local differences in energy consumption and energy accounting, which often ignores the import/export of goods with their respective energy contents). The global average demand for primary energy per capita is still comparatively low at 2.4–3.0 kW per person. If it is assumed that the worldwide primary power demand per capita will come in line with that of the EU (4.6 ± 0.3 kW per person), the global primary energy demand will double by 2086 (1515 EJ per annum vs. ca. 719 EJ [2] or 604 EJ [3] per annum in 2018; note that different resources may yield different values for the total energy demand due to the different conversion factors used [10]). The change in the primary energy mix, which is currently taking place, would reduce the primary energy demand via improved efficiency for power generation from renewable resources. However, novel technologies such as AI may push the energy demand higher [11].

The industrialisation and population growth over the past decades have been accompanied by a steady increase in the emission of carbon dioxide (CO_2) into the atmosphere as a logical consequence of the dominance of fossil fuels as the energy carrier in this period, whose energy is being released by its combustion with CO_2 being the final product. The COVID-19 pandemic resulted in a (small) dip in the rate of CO_2 emissions, most likely because of a decrease in energy use for transportation, but the rate of emission has been climbing ever since then. The emission of other greenhouse gases such as methane has also steadily increased, although the emission of methane does not show the same rapid increase as seen for the CO_2 emission from 1950 onwards. Methane emissions into the atmosphere are

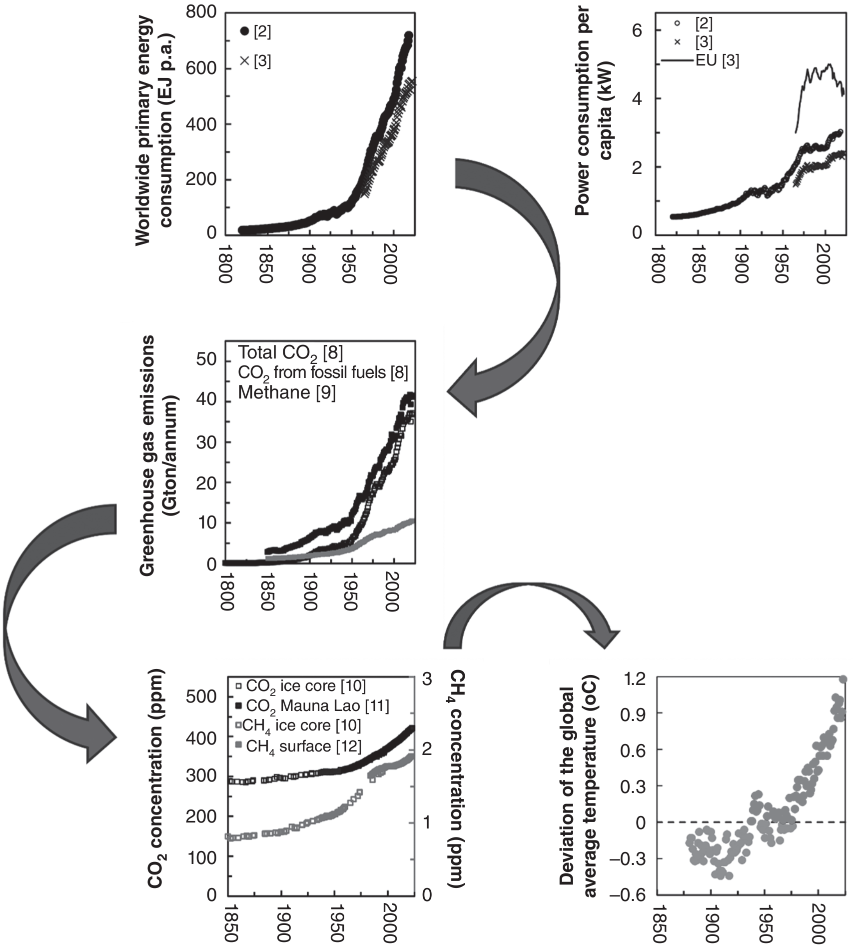

Figure 1.2 Historical trend of the primary energy consumption [2, 3], the power consumption per capita [2, 3], the emission of the greenhouse gases CO_2 (data from Global Carbon Project [4]) and CH_4 [5], the average concentration of CO_2 and CH_4 in the atmosphere on a dry air basis (from ice core data [6] and CO_2-concentrations measured at Mauna Lao [7] and the globally averaged methane concentration at marine level [8]) and the average temperature deviation from the average value in the period 1880–2018 (data from Lindsey and Dahlman [9]).

partly associated with anthropogenic activities, such as the recovery of coal and oil, and from agricultural sources and landfill sites [12] with the latter being associated with the size and living standards of the world population. Whilst greenhouse gases have natural sinks (such as growth of biomass consuming CO_2), larger emissions of these greenhouse gases will lead to an increase in their concentration in the atmosphere. As a result, the rate of uptake will need to be adjusted to account for the increased rate of release and, owing to the increased concentration, will also need to be done at a higher atmospheric CO_2 concentration than before.

The increase in the concentration of a greenhouse gas in the atmosphere will result in greater light absorption, which leads to the heating up of the atmosphere (it was already noted in 1938 that the average temperature would increase by 0.003 °C per annum due to CO_2 emissions at that time [13]). Solar light enters the earth atmosphere and is partially reflected by the clouds (ca. 30%) with the remainder travelling freely through the atmosphere (except the ultraviolet [UV]-part of the spectrum which is absorbed in the ozone layer protecting us from this type of radiation) and heats up the earth. Warm objects, and thus also the earth surface, give off radiation in the form of infrared (IR) radiation, which can be absorbed by greenhouse gases in the atmosphere (as well as water vapour). An increase in the concentration of these greenhouse gases will thus increase the absorption of light in the infrared range. The absorbed energy is released by emitting IR radiation in all directions (also back to earth) or is transformed directly into kinetic energy (via internal relaxation processes and quenching of the excited states in a collision with other molecules); the increased average kinetic energy of the molecules in the gas phase corresponds to a higher average temperature of the atmosphere.

The impact of the various greenhouse gases on the global average temperature is compound-specific and is often summarised in the Global Warming Potential (GWP), which represents the radiative forcing (difference between energy entering the atmosphere and energy leaving the atmosphere) integrated over a time frame relative to the radiative forcing induced by CO_2 over the same time frame [14]. The GWP is thus time-dependent (often an arbitrary timescale of 100 years is invoked) due to the decomposition of the compound in the atmosphere. For instance, the average lifetime of methane in the atmosphere is ca. 12 years [14]. Hence, the GWP of methane over a period of 20 years is 84 times higher than the potential of CO_2 and is over a period of 100 years 28 times higher. The total radiative forcing of methane is ca. 25% that of CO_2 as the high GWP is off set by the low concentration of methane (ca. 1.9 ppm). Ammonia has a relatively short average lifetime in the atmosphere (due to reaction and uptake by particles) [15], and hence its direct impact is small (although ammonia oxidation contributes significantly to the presence of nitrous oxide in the atmosphere [16]). Water vapour is, in principle, also a greenhouse gas, but its concentration in the atmosphere is controlled by the temperature due to its relatively low vapour pressure. However, the increasing water concentration in the atmosphere due to a higher average global temperature will amplify global warming (Table 1.1).

Table 1.1 Global Warming Potential (GWP) over 20 and 100 years for different gases (data from Myhre et al. [14]).

Compound	Chemical formula	$GWP_{20\ years}$	$GWP_{100\ years}$
Carbon dioxide	CO_2	1	1
Methane	CH_4	84	28
Nitrous oxide	N_2O	264	265

The increase in the average temperature of the atmosphere poses a problem as it may affect long-term weather patterns and thus climate both locally and globally (linking short-term changes in the weather to changes in the atmosphere is much more difficult thus giving rise to different scenarios [17–19]). The changing weather patterns may affect food supply and physical safety. This will affect various regions on the planet differently and thus the overall societal stability. The linkage between greenhouse gas emissions and the global average temperature requires a drastic reduction in the rate of emission of these gases, posing thus the significant challenge of reducing the emission of greenhouse gases in a society where the use of primary energy may increase. This requires a critical look at not only new processes but also at the replacement/modification of current processes.

1.2 Energy Carriers

The term ‘energy’ is often used loosely, but it represents the ability to perform work in a conversion process or for heating purposes (such as chemical energy powering a car or electricity powering a heater). The term ‘energy’ is thus often used as an indication of the ability to degrade an energy carrier, so that the energy given off in the degradation process can be used for driving another process via heating or delivering work.

There are many different energy carriers. In cells of the human body, the energy carrier is adenosine triphosphate (ATP), which is converted into adenosine diphosphate (ADP) upon the release of energy (which was formally stored in the phosphate bond). ADP can be transformed back into ATP using another energy carrier (e.g. carbohydrates, which are added to the body in the form of food). Other energy carriers are, for example, petrol or diesel, which releases energy upon combustion; batteries, which release electrochemical energy; or radioactive elements, which release energy through nuclear processes; or even simple water, which can release gravitational energy by bringing it down from a storage at a height.

1.2.1 Solar Energy

The sun produces an approximately constant amount of power from the hydrogen fusion taking place in its core (estimated power generated: 385 yottawatts = 385×10^{24} W [20]). The power generated in the sun radiates outwards into space, reducing the amount of power per unit area further away from the sun. At the earth, we receive ca. 173 000 TW of the power generated by the sun (i.e. only a tiny fraction of the total amount of energy released by the sun). This corresponds to an annual received amount of energy from the sun on the earth of 5.47 YJ or 5.47 million EJ. This would be sufficient to power the needs of humanity now and in the future, as the current consumption of primary energy carriers worldwide is ca. 555 EJ per annum [3] or 719 EJ per annum [2] (this corresponds to 19.1 or 22.8 TW, respectively, which represents only 0.011–0.013% of all incoming solar

Figure 1.3 Solar irradiance over the world in kWh/day/m^2 (Global Solar Atlas [21]; map from Global Solar Atlas 2.0, Global Solar Atlas).

energy). Even the anticipated doubling of the energy demand will not alter this picture significantly.

The amount of solar irradiation reaching the top of the atmosphere can be estimated from the total energy released by the sun relative to the area of the earth shading the sunlight and amounts to 1360 W/m^2 (this corresponds to an average irradiance on the surface of the earth of ca. 340 W/m^2 – the decrease by a factor of 4 originating from the sphericity of the earth). The solar irradiance is often expressed as a daily average of 8.2 kWh/m^2 or an annual average of 2981 kWh/m^2. Some of the light scatters back into space before reaching sea level, reducing the amount of light at sea level depending on cloud cover and the local climate.

Solar energy received at sea level is, by its nature, intermittent due to the rotation of the earth with the intensity changing with time as a consequence of the changing elevation of the sun (i.e. the angle between the sun and horizon). Furthermore, the intensity of solar radiation reaching the surface is impacted by the local weather conditions, the latitude and seasonal changes due to the tilt of the earth (thus changing the area being covered by sunlight). Hence, the amount of the incoming irradiance strongly depends on the location (see Figure 1.3), with Chile, Northern Africa, South Africa/Namibia, the Middle East, the Himalayas and Australia having regions where more than two-thirds of the incoming irradiance at the top of the atmosphere reaches sea level.

1.2.2 Wind Energy

Wind energy is the energy associated with the movement of air originating from pressure differences in the atmosphere, which are induced by variations in temperature. Hence, wind energy can be regarded as the first derivative of solar energy, which is transformed into kinetic energy in the atmosphere.

The amount and speed (and direction) of the wind vary over the earth with the average wind speed being the highest over the seas and in coastal regions. High aver-

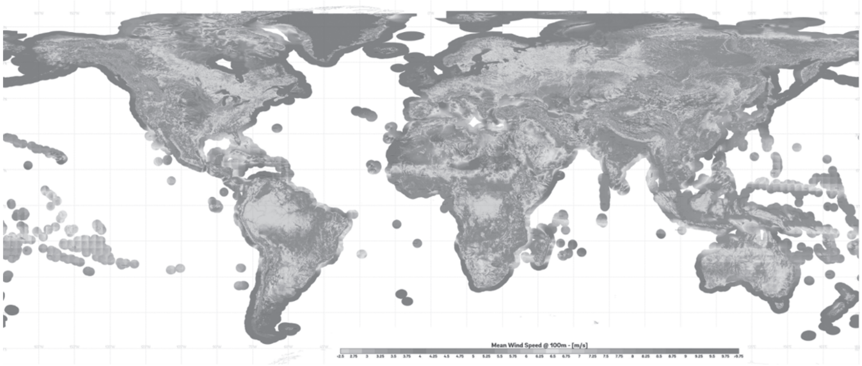

Figure 1.4 Average wind speed at a height of 100 m worldwide (Davis et al. [22]; Map obtained from the Global Wind Atlas version 3.3, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU). The Global Wind Atlas version 3.3 is released in partnership with the World Bank Group, utilising data provided by Vortex, using funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalwindatlas.info).

age wind speeds in the (near) land region have been recorded in the coastal regions of Patagonia, Alaska, Eastern Canada, Greenland, North-West Europe, Mauritania, Western Sahara, Horn of Africa, Japan, Australia and New Zealand (see Figure 1.4).

The nature of wind results in a strong variability of wind both in direction and in wind speed. Even in windy areas, the wind speed may drop to close to zero during certain times. Wind energy has an effect on large bodies of water, such as the ocean, where wind is one of the primary causes for the formation of waves, and thus wave energy.

1.2.3 Hydropower

The evaporation and condensation of water are natural processes initiated by the presence of solar irradiation. The collection of condensed water at elevated positions allows the recovery of a (very small) part of the energy, as the gravitational energy of liquid water at a height of 1000 m above sea level is less than 0.5% of the energy required to evaporate the water at sea level.

The recovery of energy in the form of hydropower requires the release of stored water over a height difference. For instance, the stored energy in the Hoover Dam in the Colorado River (USA) with a capacity of 19.55 km^3 and a hydraulic height of 180 m corresponds to 3.5 PJ (or 0.0035 EJ). Hydropower is a useful and reliable energy carrier, which should be used, if possible, but it requires a large area in order to store water at a sufficient elevation, attached to a suitable catchment area. However, it can be affected by drought or lack of rain if the dam volume or stored water volume is not sufficiently replenished in order to maintain the flow required to generate the power.

Hydropower is thus a form of solar energy, where the energy is stored as gravitational energy. Another form of gravitational energy that can be captured is tidal energy. The tides are caused by the gravitational pull of the moon and the sun, and the energy released by the movement of the tides can be captured directly in places with the appropriate geography.

1.2.4 Chemical Energy Carriers

Chemicals have been used by humankind for a long time as energy carriers. This started with the use of wood, followed by coal, oil and natural gas as energy carriers; even biofuels are chemical energy carriers (and even the food we eat is a chemical energy carrier). The energy in these substances is transformed into heat/work by converting them mostly in the presence of oxygen or air into CO_2 and water. Energy carriers, such as coal, oil and natural gas (in large reservoirs) are non-renewable as they can only be replenished on a timescale covering many millions of years. Biofuels, on the other hand, are renewable chemical energy carriers as the carbon cycle can be closed; the combustion of biofuels will release CO_2 into the atmosphere, but the same amount of CO_2 will be taken up when re-growing plants, which will be converted into biofuels.

Figure 1.5 shows the distribution of fossil fuel reserves over the world for national reserves larger than 100 EJ (this corresponds 95.2% of all proven coal reserves, 93.2% of all proven oil reserves and 82.9% of all natural gas reserves). Large coal reserves are found in the United States, China, Russia, India and Australia with significant reserves in Ukraine, Poland, Germany and South Africa. Oil reserves are

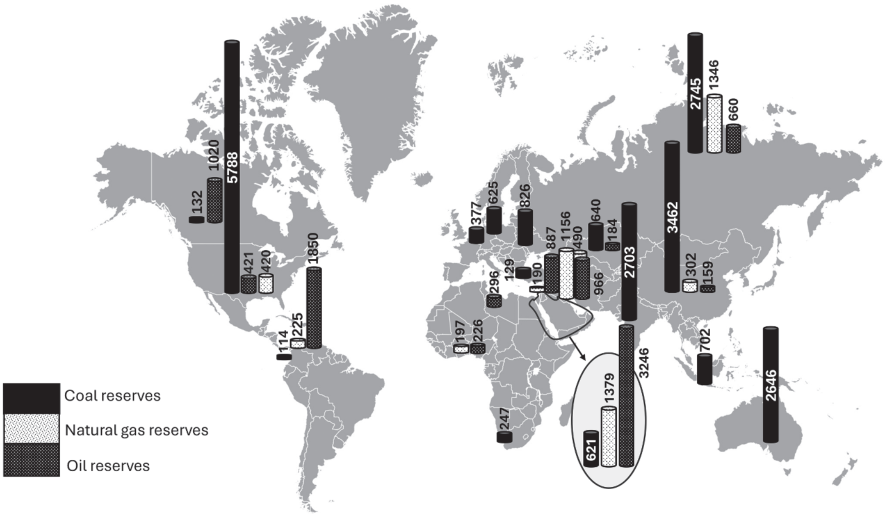

Figure 1.5 Proven reserves of natural gas, oil and coal with a reserve of over 100 EJ (value indicates proven reserves [3] in EJ calculated using a heating value for natural gas of 36 EJ/10^9 m^3; oil of 6.119 EJ/1000 Mio barrel; coal of 0.025 EJ/Mio tonne for hard coal and 0.0105 EJ/Mio tonne for lignite and sub-bituminous coal).

mainly located in the Middle East, which including Iran and Iraq accounts for 48% of all proven oil reserves worldwide. Other regions with large oil reserves include Venezuela, Canada, the United States and Russia. Natural gas reserves can be found in the oil-rich Middle East, Russia, Turkmenistan and the United States with many smaller reserves found all over the world.

These fossil fuels have a large effect on the changing composition of the atmosphere owing to their large international usage and high CO_2 output from combustion; this is the driving force to change towards the implementation of renewable or green energy carriers worldwide. Chemicals will be used as an energy carrier going forward, as they are a convenient way to store (and thus transport) energy and the energy content can be released on demand in a controlled manner. The amount of energy carried by a chemical is its heat of combustion, if the energy is released in a combustion reaction, or by the electrochemical potential, if the energy is released in an electrochemical cell. For instance, the lower heating value of hydrogen is 241.8 kJ/mol, implying that 241.8 kJ/mol or 120.9 MJ/kg will be released upon reacting hydrogen with oxygen forming water in the gas phase. However, the electrochemical potential for the electrochemical conversion of hydrogen to water is 1.23 V, which corresponds to an energy content of 237.1 kJ/mol or 118.6 MJ/kg.

The energy content of chemicals can be defined in terms of the specific energy (the energy released per unit mass of the chemical – for combustion reactions, the lower heating value is used) or in terms of the energy density (the energy per unit volume of the chemical). The energy is normalised to obtain a direct relationship between the amount of energy required in a process and the required amount of the energy carrier for this process. A high specific energy is desirable as it means that more energy can be obtained from a smaller quantity (in terms of mass or the number of molecules) of the substance. For instance, the required mass of wood (with a specific energy of ca. 15 MJ/kg) is eight times larger than the required mass of hydrogen (with a specific energy of 120.9 MJ/kg) for the same process (see Table 1.2).

However, chemicals are energy carriers that need to be transported to the required process, and the volume of the chemical to be transported becomes important (this is of particular importance in the transportation industry, where the energy carrier must be carried whilst being consumed). Diesel and petrol are well-known energy carriers, which have a reasonable specific energy of 45–47 MJ/kg and, due to their relatively high density, have a high energy density of 35.8 and 31.7 MJ/l (see Figure 1.6), respectively. Hydrogen is much less dense, and its energy density is much lower than that of diesel and petrol, despite its high specific energy of 120.9 MJ/kg. Compressing hydrogen to 700 bar or even liquefying hydrogen brings up the energy density to 4.9 and 8.5 MJ/l, respectively. Methane, which has a similar specific energy to diesel and petrol, also needs to be compressed or even liquefied to obtain energy densities approaching those of diesel and petrol. The specific energy and the energy density of other alternative energy carriers such as ammonia, ethanol and methanol are also lower than those of diesel and petrol as shown in Figure 1.6.

Chemical energy is not only released upon combustion but can also be stored in electrochemical devices. The maximum specific energy which can be stored in

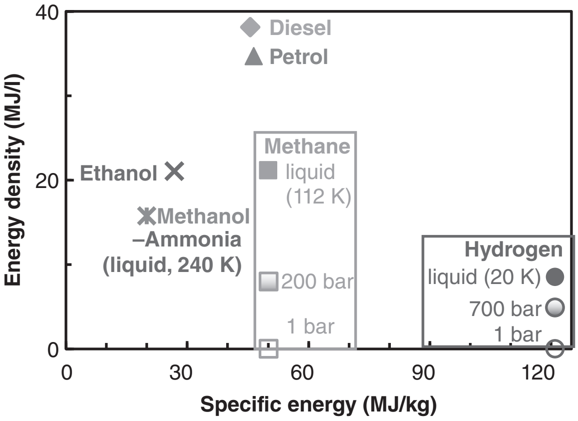

Figure 1.6 Specific energy and energy density for different gaseous and liquid energy carriers.

a certain type of battery can be estimated from the equilibrium cell potential, E_0 (which relates to the Gibbs free energy of the reaction – $\Delta_{\mathrm{rxn}}\underline{G} = -n \cdot \mathcal{F} \cdot E_0$), and the mass of the electrolytes involved in the electrochemical conversion. Batteries have a relatively low specific energy in comparison to other chemical energy carriers (see Table 1.2). It should be noted that the actual specific energy of batteries is lower than the quoted value for the specific energy as the weight of the electrodes and other internals will also contribute to the weight of the battery. Batteries do have the advantage that the reaction can be more readily reverted by changing the potential.

Table 1.2 Specific energy of some energy carriers.

Compound	Specific energy (MJ/kg)	
Hydrogen	120.9	$\Delta\underline{H}^{\mathrm{comb}} = -241.8$ kJ/mol
	117.6	In an electrochemical cell at 298.15 K
Methane	50.0	$\Delta\underline{H}^{\mathrm{comb}} = -802.6$ kJ/mol
Petrol	46.4	Approximate value [23]
Diesel	45.6	Approximate value [23]
Ethanol	26.8	$\Delta\underline{H}^{\mathrm{comb}} = -1235$ kJ/mol
Wood	15.0	Dry oak wood [24]
Anthracite	32.6	Approximate value [23]
Lignite	14.0	Approximate value [23]
Li-Co battery	2.1	$E_0 = 3.6\ \mathrm{V}$; $\mathrm{LiC_6 + CoO_2 \rightleftharpoons LiCoO_2 + 6\ C}$
Lead-acid battery	0.8	$E_0 = 2.0\ \mathrm{V}^{a)}$; $\mathrm{Pb + PbO_2 + 4H^+ \rightleftharpoons 2PbSO_4 + 2\ H_2O}^{b)}$
V-flow battery	0.3	$E_0 = 1.26\ \mathrm{V}^{a)}$; $\mathrm{VO_2^+ + V^{2+} + 2H^+ \rightleftharpoons VO^{2+} + V^{3+} + H_2O}^{b)}$

a) At standard conditions (298.15 K, 1 M ideal solution).
b) Cations balanced by sulphate ions.

1.2.5 Nuclear Energy

The nuclei of atoms contain protons and neutrons which are kept together by the strong nuclear force, which is opposed by the Coulombic repulsion between the protons. The nucleus of elements with the atomic numbers of around 26–28 is most stable, and energy can thus be obtained by either the fusion of atoms with a low atomic number or the fission of atoms with a high atomic number. The obvious advantage of nuclear energy is that the conversion and utilisation of this energy carrier is without the emission of greenhouse gases.

Radioactive decay of heavy elements has been known since the beginning of the 1900s. In the fission of ^{235}U, ca. 94% of all energy (202.79 MeV) is in the form of kinetic energy of the fragments, which can be recovered as heat. Hence, the specific energy of ^{235}U is 78.2×10^6 MJ/kg, i.e. more than a million times larger than the chemical energy carriers. Natural uranium consists of ca. 0.72% fissile uranium (^{235}U) and hence the specific energy of natural uranium is 56.3×10^4 MJ/kg.

The total uranium reserves around the world are estimated at ca. 6 million tonnes of uranium with more than 50% of the reserves located in Australia, Kazakhstan and Canada (see Table 1.3). Hence, the total known reserves of uranium represent a total energy of ca. 3400 EJ or ca. 6–7 years of the total annual primary energy demand in the world.

The use of nuclear fission as the primary energy carrier generates radioactive waste, which must be placed in a controlled environment to avoid radiation damage to the environment. This is often denoted as storage of nuclear waste, but the natural decay of the different radioactive nuclides will continue to take place gradually reducing the irradiation intensity. The high thermal output of spent nuclear fuel requires the initial storage of this material in pools of water to facilitate cooling for a period of up to 5–10 years [26], following which the material is typically stored in dry caskets. Subsequently, the material is supposed to enter long-term (over 1000 years) storage in a suitable geological location, but currently not sufficient facilities have been designated for this. This is aggravated by the great uncertainty regarding the reactions taking place during the storage at the geological location and (possible) changes of the geological site (and in particular water/brine penetration) [26].

Even when not used directly as an energy source by humans, all energy sources are ultimately derivatives of nuclear energy. One derivative found occurring naturally on earth is geothermal energy, and subterranean heat is partially generated by radioactive decay, which heats up water. The generated, pressurised hot water or steam can be used as an energy carrier if the resource can be accessed in a reasonable manner.

On the other end of the spectrum of nuclear energy is nuclear fusion using small atoms. The sun irradiates energy because of the $\mathrm{H} + \mathrm{H}$ fusion reaction yielding ^{4}He (and 26.73 MeV). Hence, the specific energy of hydrogen in the fusion reaction corresponds to 630×10^6 MJ/kg. The controlled fusion reaction would be a game-changer in the energy field, and some significant advances have been made in this field recently [27], but there is still a long road to make this technology reality.

Table 1.3 Uranium reserves across the world in tonnes (in brackets the relative amount to the total world reserves) (data from World Nuclear Association [25]).

Country	Reserve	
Australia	1 684 100	(28%)
Kazakhstan	815 200	(13%)
Canada	588 500	(10%)
Russia	480 900	(8%)
Namibia	470 100	(8%)
South Africa	320 900	(5%)
Niger	311 100	(5%)
Brazil	276 800	(5%)
China	223 900	(4%)
Mongolia	144 600	(2%)
Uzbekistan	131 300	(2%)
Ukraine	107 200	(2%)
Botswana	87 200	(1%)
USA	59 400	(1%)
Tanzania	58 200	(1%)
Jordan	52 500	(1%)
Rest of the world	266 600	(5%)
Total	6 078 500	

1.3 Current Usage of Energy Carriers

Figure 1.7 shows the global annual energy consumption as well as the contributions of the various energy carriers to the total consumption in the period 1965–2022.

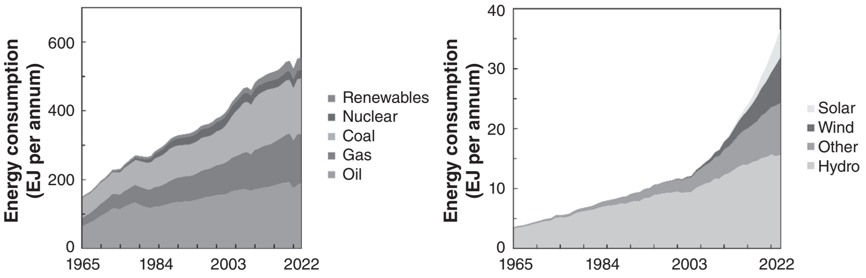

Figure 1.7 Use of the different energy carriers worldwide in the period 1965–2022 (other refers to biofuels/biomass and geothermal energy) (data from The Energy Institute [3]).

Oil dominated the energy scene in the 1960s and 1970s, and in 1973 it contributed 51.2% to the total primary energy use. Its relative contribution to the overall energy mix and even the total oil consumption dropped rapidly between 1979 and 1985, as the global economic recession in the early 1980s resulted in a drop in the overall energy demand, which together with the high price of oil enforced the use of other energy carriers. From 1985 onwards, the oil consumption increased, although its relative contribution to the total energy mix kept falling, and it stood at 34.4% in 2022.

Natural gas is seen as a better alternative to coal when it comes to CO_2 emissions for power generation (power generation with an efficiency of 40% from methane with a specific energy of 50 MJ/kg will generate 0.138 kg CO_2/MJ; a similar calculation using anthracite with a specific energy of 32.6 MJ/kg will generate 0.281 kg CO_2/MJ – these estimates are in line with the CO_2 emissions for coal and natural gas as indicated by [28]). The availability of methane through pipelines and the replacement of coal power stations with natural gas power stations may have led to an increase in the use of natural gas as the primary energy carrier [29]. In 2022, natural gas made up 25.6% of the total primary energy palette (down from a high of 26.6% in 2020, which may have been caused by the reduced delivery of Russian gas to the European market in 2021 [30] aggravated by the Russia–Ukraine war).

The use of coal as the primary energy carrier shows an interesting trend, with an almost linear increase from 58.1 EJ per annum in 1965 to 93.1 EJ per annum in 1988, after which the coal consumption remained almost constant for a decade (with coal consumption equivalent to 95.3 EJ per annum in 1999). A decade later, the coal consumption had increased by more than 50% to 158.1 EJ per annum in 2011, which is attributed to the rapid economic expansion in Asia during that time [31]. The coal consumption virtually did not change the following decade, and it remained at 158.3 ± 2.5 EJ per annum (excluding the COVID-19 year in which the coal consumption was 4% lower). This was because of the move away from coal by some countries (especially the United States) and the balance taken up by new consumers (e.g. India). The contribution of coal to the overall primary energy mix has been remarkably stable from 1973 to 2022 ($28.8\% \pm 1.7\%$).

The contribution of nuclear energy increased significantly up to 2001, where it reached 27.2 EJ per annum, representing 7.0% of the total primary energy demand in that year. The development of new nuclear energy power plants stagnated at that point as the public perception of this technology changed due to accidents such as the partial nuclear meltdown in the plant on Three Mile Island (1979) and the explosion at the Chernobyl nuclear power plant (1986). Following the nuclear accident at the Fukushima power plant, when a tsunami hit the nuclear power plant in 2011, Germany shut down all its nuclear plants by 2020. Worldwide, there has been a net decrease in nuclear energy as a primary energy carrier, and in 2022, nuclear energy contributed only 24.1 EJ to the overall primary energy mix (4.1% of the total demand mainly due to the increased total primary energy demand).

Renewable energy (hydropower, geothermal energy, biomass, wind energy and solar energy) has slowly become an important contributor to the overall primary energy mix with a total contribution in 2022 of 36.6 EJ or 6.6% of the total primary energy consumption. The contribution of renewable energy, and in particular hydro-electric energy, wind energy and solar energy, is even more remarkable as the energy contribution of these renewable energy carriers contributes directly to the available power. The efficiency of power generation using fossil fuels is typically at ca. 40% implying a much larger impact of the introduction of these renewable energy carriers to the primary energy mix.

Hydropower has a long history and is still the dominant renewable energy carrier. Hydropower is expected to be overtaken by the other renewable energy carriers (specifically wind and solar energy), despite its steady increase over the period from 1965 to 2022.

Geothermal energy is rather small, and the total installed capacity for geothermal energy is ca. 16 GW (which corresponds to a maximum annual energy consumption of 0.5 EJ) [32]. The plants are typically located in volcanically active regions of the earth with easy access to the thermal source (viz. relatively close to Earth's surface). The plants built so far are typically small with sizes that are typically less than 1 MW.

Biomass has been used for a long time as an energy carrier, and the use of biomass as an energy carrier in the formal primary energy market has increased to ca. 8 EJ per annum in 2022. Biomass is a term encompassing all kinds of biological materials (including animal waste), which can be converted into a more refined energy carrier, biofuel, for example ethanol or biodiesel. Growing biomass for the purpose of creating a renewable energy carrier competes with food supply for natural resources, such as land and water. Even in regions where water supply is not a primary issue, clearing land to grow crops to generate energy carriers not only has a detrimental effect on the environment, but will also have a sociological impact, as was seen with the cultivation of palm oil for biodiesel production in Indonesia [33]. This type of analysis is convoluted as the product can have a dual purpose, i.e. food or biofuel [34]. The use of biowaste is less controversial, but multiple processing steps are required to convert this into biofuels [35].

Wind energy contributed 7.6 EJ to the overall primary energy consumption in 2022 and its contribution has been growing substantially. At the end of the 1990s, the amount of energy recovered from wind energy grew by more than 30% annually. The growth rate has since then slowed down, and in the period 2014–2022, the growth rate of the energy captured from wind energy has grown by 13.7% ± 2.9% per annum.

Solar energy has seen a similar growth to wind energy, even though it only began contributing more than 0.1 EJ to the primary energy demand in 2010, more than a decade later than wind energy. The growth rate of solar energy in the period 2014–2022 is 28.0% ± 6.6% per annum. This period includes 2020, the year of COVID-19, which caused a significant slowdown of all economic activity and the year-on-year growth of solar energy in 2020 was 'only' 20.7%.

1.3.1 Interconversion of Energy Carriers

Although energy carriers are treated as interchangeable, the different energy carriers are used for different purposes. Figure 1.8 shows a Sankey diagram of the energy carriers worldwide to visualise the flow of various primary energy carriers to the

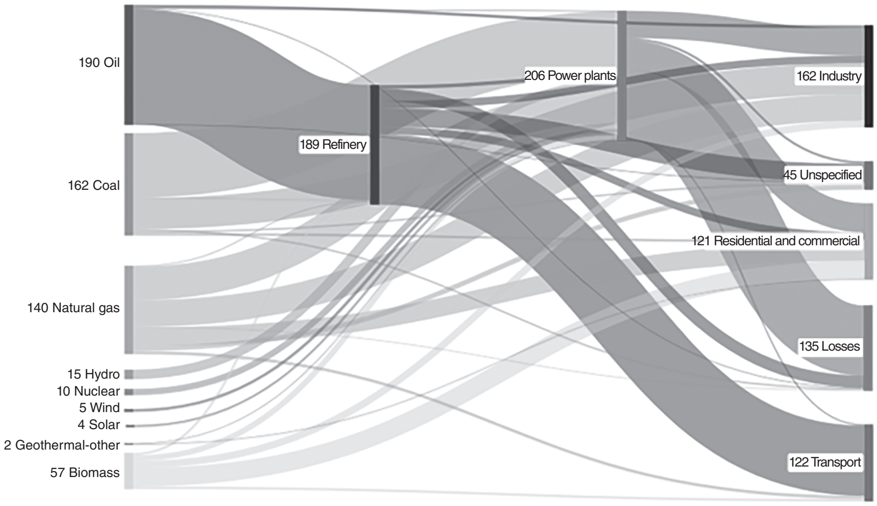

Figure 1.8 Sankey diagram of the primary energy consumption in 2019 (redrawn from Pathak et al. [36], using 'Sankeymatic', 25 February 2024).

different end users in 2019 [36]. Some of the energy carriers are transformed (e.g. in power plants) and the difference in the primary energy supply and the energy consumption indicates an overall efficiency of energy conversion of 76.6%, but not all processes are equally efficient.

Oil produced is mainly being refined (95%) with the balance being used for power generation, in industry, or in other non-specified sectors. Most of the coal (63%) is used for power generation, with industry taking ca. 30%. The use of natural gas is split between power generation (38%), industry (30%) and the residential and commercial sector (21%), where it is used for heating. A small part of natural gas is used in the transportation sector and for non-energy use (for instance, as a chemical feedstock). Hydropower, nuclear energy, wind energy and solar energy feed only into the power systems. Geothermal energy is again used in the residential and commercial sector (heating) and to some extent for power generation. Biomass shows a more varied palette of applications, viz. the residential and commercial sector (51%), industry (19%), power generation (16%) and even transport (7%).

In oil refineries, primary energy carriers (primarily oil, 96% with small contributions of biomass, natural gas and coal) are converted into refined products. The overall efficiency is high (89.9%), mostly due to the fact that the energetic efficiency of the refining of oil is high compared to the conversion of biomass, natural gas [37] or coal [38] into refined products. The refined products are subsequently mainly used for transportation (59%), with 15% going into the non-energy usage (as a feedstock for the chemical industry). The industry and the residential and commercial sectors each use ca. 6% of all refined products, with only 3% being used for power generation.

It should be noted that overall, 23.5% of the primary energy supply is lost by the time it gets to its final usage, which is caused by inefficiencies in power plants in the conversion of heat into power as well as losses in the refineries. Though it should be noted here that the energetic losses in these two sectors, which are currently the biggest, will become smaller when renewable energy sources are used to a greater extent.

Electric power is currently being generated from a variety of different primary energy carriers with coal making up ca. 50% of the total energy mix in 2019 and natural gas 26%. The remainder comes from hydropower (7%), nuclear energy (5%), biomass (4%), oil and refined products (3%), wind energy (2%) and solar energy (2%). The power generation has an overall efficiency of 46.1%, affected primarily by the relatively low efficiency of turning heat into power as expected for the conversion of coal, gas, nuclear energy, biomass and oil and its refined products into power. An energy transition with more power being generated from renewable sources such as hydropower, wind energy and solar energy should improve this efficiency. Power is being used mainly in the commercial and residential sector (48%) and industry (45%). In industry, the power is used mainly to drive machinery and appliances (ca. 87%) with only a small amount used for heating purposes (13%). In 2019, only a small fraction of electric power was used in the transportation sector.

Energy is being used throughout society with the industry using 36% of the final, total consumed energy. The energy consumed in the industry comes in the form of coal (30%), electric power (27%) and natural gas 26% (with the balance coming from oil and oil products and biomass).

Transportation and the residential and commercial sectors are the next largest users of the energy with each using ca. 27% of all consumed energy. Energy usage in the transportation sector was in 2019 still dominated by oil products (92%) with a much smaller contribution from natural gas, biomass and electric power. The residential and commercial sector (in 2019) used a variety of different energy carriers, i.e. electric power (38%), natural gas (24%) and biomass (24%).

Figure 1.9 shows the historical trend of the primary energy used for power generation as extracted from the Energy Institute data [3] (note that the relative contribution of power generation appears to be low from this set of data, possibly as a consequence of differences in scaling [10]). Electricity generation (and thus the associated consumption of primary energy) has been increasing over the period 1985–2022. The increase in electric power generation is stronger than the increase

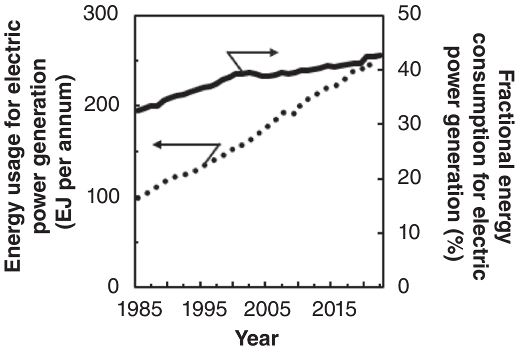

Figure 1.9 Primary energy consumption in EJ per annum for the generation of electricity and the amount used for electricity generation relative to the total amount of energy consumed in the period 1985–2022 (data from The Energy Institute [3]).

in primary energy demand, and thus the fraction of primary energy used to generate electric power has been increasing steadily with time as well. The ongoing fourth industrial revolution will push the demand for electric power up further, which may push towards a further increase in the energy demand going forward, as well as increase the utilisation of electric power.

1.4 Outlook

The world population has increased fivefold over the last century, and there is a general demand for a more equitable world in terms of economic opportunities. This would require a strong economic growth in the world overall and specifically in the developing world. Whilst there is a link between economic growth and increased energy consumption, the relationship is highly complex [39]. In open economies, energy consumption is also related to factors such as industrialisation, the presence of natural resources, energy intensity and urbanisation [40], as well as the export of energy-intensive materials [41]. Achieving this with the current energy mix will increase the concentration of greenhouse gases in the atmosphere, thus increasing the global average temperature.

Hence, the world has set itself on a path to reduce the anthropogenic emission of greenhouse gases to attempt to limit global warming. In the Paris Agreement (COP21) in 2015, the participants set as a target 'to limit global temperature increase to well below 2 °C, while pursuing efforts to limit the increase to 1.5 °C by reducing the anthropogenic emission of greenhouse gases, but also preserving natural sinks for these compounds' [42]. This legally binding agreement is supported by nationally determined contributions (NDCs), which are being monitored to track the progress biannually from 2024 onwards. The ultimate goal is to get to a net-zero society, where anthropogenic emissions are balanced by anthropogenic sinks (e.g. carbon capture and sequestration); the rate at which this is achieved will determine the expected increase in the global average temperature and the impact on global climate. Different scenarios have been developed to determine the course of the global average temperature upon reducing the net anthropogenic emission of greenhouse gases [43]. By limiting the increase of the global average temperature relative to pre-industrial levels to 1.5 °C with limited overshoot, the net anthropogenic greenhouse gas emissions should decrease by ca. 45% from the 2010 level by 2030 [36]. Higher levels of emission of greenhouse gases in 2030 will push back the time at which the net-zero state will be achieved [36, 43] and increase the likelihood of a temperature overshoot.

The net-zero scenario requires a strong and rapid reduction of the dependency of the world on fossil fuels. Electric power, which is mainly produced from fossil fuels (78% in 2019), could be replaced cost effectively [36] with renewable energy carriers such as wind and solar energy, provided sufficient storage and excess capacity is built-in [44], reducing CO_2 emissions by 40% relative to 2019 emissions and 36% relative to 2010 emissions (based on data from the Energy Institute [3]). Transportation consumes ca. 27% of all energy, and decarbonisation of this sector is necessary to achieve a net-zero situation, although some of its sub-sectors, such as aviation, may be difficult to decarbonise [45].

Industry is the largest sectorial converter of energy and will have to transform if a net-zero society is to be achieved. It should be noted that most of the greenhouse gas emissions per unit income are associated with the basic industries, whereas the derivative industries have much lower greenhouse emission per unit income [46]. For instance, the equivalent CO_2 emission per unit income in the chemical industry is 4 times higher than the emissions from the derivative group of fast-moving consumer groups; similar comparisons can be made for steel production versus automobile manufacturing (4.5 times higher), cement industry versus construction industry (46 times higher) and agriculture versus food industry (3.9 times higher). This is a consequence of the energy intensity associated with the base industries, indicating a dilution of the monetary carbon footprint down the product value chain. However, it also implies that decarbonisation efforts in industry should have a strong focus on the base industries.

Industry can classify its emissions into emissions directly emanating from its own operation (so-called Scope 1 emissions), emissions associated with its electricity usage (Scope 2 emissions), as well as the more difficult to quantify Scope 3 emissions, which are associated with all activities surrounding the production process (from the transport and production of the raw materials to getting the product to the client). Table 1.4 shows the contribution of the various sources to the Scope 1 and Scope 2 emissions of greenhouse gases by the industry in 2019 [47]. The direct emission of greenhouse gases by the industry in 2019 amounted to ca. 14.1 Gton, of which 49.4% arose from heating by fuel combustion, 22.2% was emitted as a product of the chemical processes and 16.5% was emitted as a waste greenhouse gas. The indirect emission of greenhouse gases from using electricity and imported heating sources (Scope 2 emissions) amounted to ca. 5.9 Gton in 2019 (with electricity contributing 71.9% to the indirect emissions).

A part of the transformation of the industry will be relatively invisible as greening of electric power upon the introduction of renewable energy to the power grid will reduce the Scope 2 emissions associated with the production process and thus indirectly reduce the carbon footprint of the industry. However, electric power makes up only 21% of the total energy utilisation in industry, and further measures will need to be implemented to move towards a net-zero society, such as further improvement in process efficiency, electrification of processes or even changing the materials used in the various processes.

The implementation of novel technologies to use renewable energy can be driven by an economic value proposition, as well as social factors. The economics of a process is determined by its operating and capital costs, which are a determining factor when considering the replacement of processes in industry. Policy-driving carbon pricing forms a part of these considerations as they contribute to the operating costs.

Carbon pricing can take the form of a carbon tax or emission trading systems (carbon credits) to be paid at the point of emission [48] and has been introduced in several countries as a measure to incentivise industry to reduce their emissions. Carbon pricing can be considered as a sin tax (much like taxation on tobacco and

Table 1.4 Industrial greenhouse gas emissions in 2019 (data from Bashmakov et al. [47]).

Source		**2019 emissions MiO tonne CO_2-eq.**	
Direct CO_2 emissions (fuel combustion)	Iron and steel	2481	(12.4%)
	Non-metallic minerals	1148	(5.7%)
	Chemical and petrochemical	977	(4.9%)
	Non-ferrous metals	163	(0.8%)
	Paper, pulp and printing	150	(0.7%)
	Food and tobacco	265	(1.3%)
	Other	1797	(9.0%)
CO_2 emission (chemical process)	Non-metallic minerals	2008	(10.0%)
	Chemical and petrochemical	720	(3.6%)
	Metallurgy	391	(2.0%)
	Other	25	(0.1%)
Industrial product use GHG		204	(1.0%)
Other non-CO_2 GHG		1470	(7.3%)
Waste GHG		2327	(11.6%)
Indirect emissions	Electricity	4236	(21.2%)
	Heating	1663	(8.3%)
Total		**20 025**	

gambling), which adds to the cost of manufacture and will thus increase the cost of living. Although it can be argued that the income from carbon pricing should contribute to the mitigation of the impact of greenhouse gas emissions or shelter the most affected by the increase in the cost of living, the effects of the greenhouse gas emissions and the associated effect of the global temperature are not bound by the borders of nations.

Carbon tax is often based on the amount of carbon in the fuel purchased for a process, whereas companies have to purchase carbon credits for their emissions, when going beyond their allocated carbon credits. Governments will have a better handle on emissions nationwide through the restrictive release of these credits. The carbon credits can be traded with the marketplace setting the price. This may result in fluctuations in the price of carbon credits (e.g. EU carbon credits were traded in 2022–2023 between €54.2 and €104.8 per tonne $CO_{2,eq}$ [49]). Carbon tax, on the other hand, is more predictive in nature and gives the industry more control over its production costs. It has been argued [48] that carbon tax and emission credit systems should come to the same carbon pricing, although carbon tax is determined in the political arena and carbon credits in the open market.

Carbon pricing schemes have been implemented in the EU, in various nations and even in some sub-nation regions such as California. However, in some countries, less than 30% of all greenhouse gas emissions are subject to carbon pricing, whilst the remainder is exempt [48]. Furthermore, the actual carbon price varies across the nations which have implemented carbon tax and/or an emission trading system between US$3 and 100/tonne $CO_{2,eq}$.

The variability in the carbon pricing worldwide skews the economic costs of operation and may result in the movement of industries with a large carbon footprint to regions with lower or no carbon pricing (termed carbon leakage). To counter this behaviour, carbon tariffs will be put in place by countries with a high carbon pricing [50], in principle safeguarding their own industry from competition operating in a different cost environment. In the world-trade scenario, it implies that products produced by industries operating outside the boundaries of the carbon tariff zone will have an added cost factor. A clear distinction between carbon tax and carbon tariffs is the receiver of these funds, with carbon tax being paid at the point of emission and carbon tariffs being paid at the border. The introduction of carbon tariffs by large markets should also provide an incentive for industry targeting these markets to reduce their emissions whilst not being part of that system and thus minimising the impact of the carbon tariffs on the cost of the product at the marketplace. Direct emissions, so-called Scope 1 emissions, can be addressed readily by the affected industry, but it will have less influence on so-called Scope 2 emissions, which depend on the local power grid. The effect of carbon tariffs on the world market and especially on the division between the developed and the developing world will have to be considered [51].

Industries are not operating in isolation, but form part of a society. Hence, the acceptance of their operation by society has become an important aspect in decision-making in industry, which has been termed a ‘social license to operate’ (SLO) [52]. The concept of SLO finds its origin in the resource extraction industry, where the acceptance of their operations by the local communities has slowly become an integral part of the decision-making process. The concept can be extended to all industries, as their products are offered to a global marketplace with competitors and willing and informed consumers who may prefer products with a lower environmental impact and greenhouse gas emissions.

There are sufficient driving forces to implement renewable energy in the process industry and reduce their associated greenhouse gas emissions, but there are also challenges in the implementation. These challenges will need to be addressed by the industry, but the involvement of other role players, such as power suppliers for grid connectivity, local government for local infrastructure, national government for supporting policies and financing sector, is also required. Here, we will look mainly at the technical and techno-economic aspects of changing the energy carrier in the process industry.

References

1 Quote Investigator (2018). The stone age did not end because the world ran out of stones, and the oil age will not end because we run out of oil, *Quote Investigator*, 7 January 2018 [Online]. Available: https://quoteinvestigator.com/2018/01/07/stone-age/#note-17685-1 (accessed 14 April 2021).

2 Malanima, P. (2020). World energy consumption – a database 1820–2018 (revision 2020) [Online]. Available: https://histecon.fas.harvard.edu/energyhistory/DATABASE%20World%20Energy%20Consumption.pdf (accessed 7 February 2024).

3 The Energy Institute (2023). Statistical review of world energy [Online]. Available: https://www.energyinst.org/statistical-review/about (accessed 7 February 2024).

4 Friedlingstein, P., O'Sullivan, M., Jones, M. et al. (2023). Global carbon budget 2023. *Earth System Science Data* 15 (2023): 5301–5369.

5 Jones, M.W., Peters, G.P., Gasser, T. et al. (2023). National contributions to climate change due to historical emissions of carbon dioxide, methane, and nitrous oxide since 1850. *Science Data* 10: 155.

6 MacFarling Meure, C., Etheridge, D., Trudinger, C. et al. (2006). Law dome CO_2, CH_4 and N_2O ice core records extended to 2000 years BP. *Geophysical Research Letters* 33 (14): L14810.

7 Lan, X. and Keeling, R. (2024). Trends in CO_2, CH_4, N_2O, SF_6 [Online]. Available: https://gml.noaa.gov/ccgg/trends/data.html (accessed February 2024).

8 Lan, X., Thoning, K.W., and Dlugokencky, E.J. (2024). Trends in globally-averaged CH_4, N_2O, and SF_6 determined from NOAA Global Monitoring Laboratory measurements. Version 2024–02 [Online]. Available: https://doi.org/10.15138/P8XG-AA10 (accessed 7 February 2024).

9 Lindsey, R. and Dahlman, L. (2024). Climate change: Global temperature [Online]. Available: https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature (accessed 7 February 2024).

10 Lightfoot, H. (2007). Understand the three different scales for measuring primary energy and avoid errors. *Energy* 32: 1478–1483.

11 de Vries, A. (2023). The growing energy footprint of artificial intelligence. *Joule* 7 (10): 2191–2194.

12 Lau, B. (2022). What are the major sources of methane in the atmosphere? [Online]. Available: https://earth.org/sources-of-methane-in-the-atmosphere (accessed 8 February 2024).

13 Callendar, G.S. (1938). The artificial production of carbon dioxide and its influence on temperature. *Quarterly Journal of the Meteorological Society* 64 (275): 223–240.

14 Myhre, G., Shindell, D., Bréon, F.-M. et al. (2013). Anthropogenic and natural radiative forcing. In: *Climate Change 2013: The Physical Science Basis.*

Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (ed. T.F. Stocker, D. Qin, G. Plattner, et al.), 659–740. Cambridge, UK: Cambridge University Press.

15 Nair, A.A. and Yu, F. (2020). Quantification of atmospheric ammonia concentrations: a review of its measurement and modeling. *Atmosphere* 11: 1092.

16 Pai, S.J., Heald, C.L., and Murphy, J.G. (2021). Exploring the global importance of atmospheric ammonia oxidation. *ACS Earth and Space Chemistry* 5 (7): 1674–1685.

17 Carvalho, D., Rafael, S., Monteiro, A. et al. (2022). How well have CMIP3, CMIP5 and CMIP6 future climate projections portrayed the recently observed warming. *Scientific Reports* 12: 11983.

18 Hausfather, Z., Marvel, K., Schmidt, G.A. et al. (2022). Climate simulations: recognize the 'hot model' problem. *Nature* 605: 26–29.

19 Randall, D.A., Wood, R.A., Bony, S. et al. (2007). Climate models and their evaluation. In: *Climate Change 2007: The Physical Science Basis. The Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. S. Solomon, D. Qin, M. Manning, et al.), 589–662. Cambridge, UK: Cambridge University Press.

20 Larson, R.B. and Bromm, V. (2004). The first stars in the universe. *Scientific America* 14 (4): 4–11.

21 Global Solar Atlas (2025). Global Solar Atlas 2.0 [Online]. Available: https://globalsolaratlas.info (accessed 28 August 2025).

22 Davis, N.N., Badger, J., Hahmann, A.N. et al. (2023). The global wind atlas: a high-resolution dataset of climatologies and associated web-based application. *Bulletin of the American Meteorological Society* 104 (8): E1507–E1525.

23 Engineering Toolbox (2003). Higher and lower calorific calues [online]. Available: https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html (accessed 16 February 2024).

24 Engineering Toolbox (2003). Wood - combustion heat values [Online]. Available: https://www.engineeringtoolbox.com/wood-combustion-heat-d_372.html (accessed 16 February 2024).

25 World Nuclear Association (2023). What is uranium? How does it work? [Online]. Available: https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/introduction/what-is-uranium-how-does-it-work.aspx#Who%20Uses%20Nuclear%20Power? (accessed 20 February 2024).

26 Ewing, R. (2015). Long-term storage of spent nuclear fuel. *Nature Materials* 14: 252–257.

27 Tollefson, J. and Gibney, E. (2022). Nuclear-fusion lab achieves 'ignition': what does it mean? *Nature* 612: 597–598.

28 Schlömer, S., Bruckner, T., Fulton, L. et al. (2014). Annex III: Technology-specific cost and performance parameters. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. O. Edenhofer, R. Pichs-Madruga, Y. Sokona, et al.), 1329–1356. Cambridge, UK: Cambridge University Press.

29 Ritchie, H. (2021). How have the world's energy sources changed over the last two centuries? http://OurWorldInData.org, 1 December 2021 [Online]. Available: https://ourworldindata.org/global-energy-200-years (accessed 19 February 2024).

30 IEA (2022). Russian supplies to global energy markets, IEA, Paris, Licence: CC BY 4.0 [Online]. Available: https://www.iea.org/reports/russian-supplies-to-global-energy-markets (accessed 19 February 2024).

31 Alvarez, C. and Arnold, F. (2020). What the past decade can tell us about the future of coal, IEA, 02 December 2020 [Online]. Available: https://www.iea.org/commentaries/what-the-past-decade-can-tell-us-about-the-future-of-coal (accessed 19 February 2024).

32 Lu, M. (2023). Energy transition: Explainer: this is how geothermal energy works, World Economic Forum, 04 January 2023 [Online]. Available: https://www.weforum.org/agenda/2023/01/geothermal-energy-infographics-data-renewable (accessed 20 February 2024).

33 Obidzinski, K., Andriani, R., Komarudin, H., and Andrianto, A. (2021). Environmental and social impacts of oil palm plantations and their implications for biofuel production in Indonesia. *Ecology and Society* 17: 25.

34 Meijaard, E., Brooks, T., Carlson, K. et al. (2020). The environmental impacts of palm oil in context. *Nature Plants* 6: 1418–1426.

35 Osman, A., Mehta, N., Elgarahy, A. et al. (2021). Conversion of biomass to biofuels and life cycle assessment: a review. *Environmental Chemistry Letters* 19: 4075–4118.

36 Pathak, M., Slade, R., Shukla, P. et al. (2022). Technical summary. In: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. P. Shukla, J. Skea, R. Slade, et al.), 51–147. Cambridge, UK: Cambridge University Press.

37 Ermolaev, I., Ermolaev, V., and Mordkovich, V. (2014). Efficiency of gas-to-liquids technology with different synthesis gas production methods. *Industrial & Engineering Chemistry Research* 53 (7): 2758–2763.

38 Li, Y.-M., Khurshid, A., and Khan, K. (2023). Optimization of coal-to-liquid processes; a way forward towards carbon neutrality, high economic returns and effective resource utilization. Evidences from China. *Fuel* 344: 128082.

39 Ozturk, I., Aslan, A., and Kalyoncu, H. (2010). Energy consumption and economic growth relationship: evidence from panel data for low and middle income countries. *Energy Policy* 38: 4422–4428.

40 Azam, M., Gohar, A., and Bekun, F. (2022). Estimating the energy consumption function: evidence from across the globe. *Environmental Science and Pollution Research* 29: 59060–59075.

41 Wu, X., Guo, J., Meng, J., and Chen, G. (2019). Energy use by globalized economy: total-consumption-based perspective via multi-region input-output accounting. *Science of the Total Environment* 662: 65–76.

42 UN Climate Change. Key aspects of the Paris agreement [Online]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement (accessed 22 February 2024).

43 Rogelj, J., Popp, A., Calvin, K. et al. (2018). Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change* 8: 325–332.

44 Tong, D., Farnham, D., Duan, L. et al. (2021). Geophysical constraints on the reliability of solar and wind power worldwide. *Nature Communications* 12: 6146.

45 Jaramillo, P., Ribeiro, S.K., Newman, P. et al. (2022). Transportation. In: *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. P. Shukla, J. Skea, R. Slade, et al.), 1049–1160. Cambridge, UK: Cambridge University Press.

46 Gomez, F., Kolomanska-van Iperen, J., Sandström, J. et al. (2021). Implementing low-carbon emitting technologies in the chemical industry: a way forward. World Economic Forum, 2021 [Online]. Available: https://www3.weforum.org/docs/WEF_Implementing_Low_Carbon_Emitting_Technologies_in_the_Chemical_Industry_A_Way_Forward_2021.pdf (accessed 21 May 2024).

47 Bashmakov, I., Nilsson, L., Acquaye, A. et al. (2022). Industry. In: *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. P. Shukla, J. Skea, R. Slade, et al.), 1161–1243. Cambridge, UK: Cambridge University Press.

48 Parry, I., Black, S., and Zhunussova, K. (2022). Carbon taxes or emissions trading systems? Instrument choice and design. International Monetary Fund, July 2022 [Online]. Available: https://www.imf.org/en/Publications/staff-climate-notes/Issues/2022/07/14/Carbon-Taxes-or-Emissions-Trading-Systems-Instrument-Choice-and-Design-519101 (accessed 21 May 2024).

49 Trading Economics (2024). Carbon credits [Online]. Available: https://tradingeconomics.com/commodity/carbon#:~:text=EU%20carbon%20permit%20prices%20have%20stabilized%20at%20around,demand%20offset%20the%20recovery%20in%20natural%20gas%20prices (accessed 21 May 2024).

50 Keen, M., Parry, I., and Roaf, J. (2021). Border carbon adjustments: rationale, design and impact. International Monetary Fund, September 2021 [Online]. Available: https://www.imf.org/en/Publications/WP/Issues/2021/09/24/Border-Carbon-Adjustments-Rationale-Design-and-Impact-466176 (accessed 21 May 2024).

51 Böhringer, C., Fischer, C., Rosendahl, K., and Rutherford, T. (2022). Potential impacts and challenges of border carbon adjustments. *Nature Climate Change* 12: 22–29.

52 Moffat, K., Lacey, J., Zhang, A., and Leipold, S. (2016). The social licence to operate: a critical review. *Forestry* 89: 477–488.