Chapter 9
Renewable Energy for Industry Supply

Sven Teske, Thomas Pregger, Sonja Simon, and Carina Harpprecht

Abstract This section focuses on technologies that provide heat, and especially process heat, with renewable energy and electrical systems. All the technologies described, except those that use high-temperature geothermal or concentrated solar heat (CSH) for process heat, are used for the OECM 1.5 °C pathways described in Chaps. 5, 6, 7, and 8. The authors have included geothermal and solar technologies to highlight the further technical options available and to underscore that more research is required in the area of renewable process heat.

Keywords Industry process heat by sector · Renewable process heat · Electric process heat · Solar · Bio energy · Geothermal · Heat pumps · Arc furnace · Hydrogen · Synthetic fuels · Power-to-X)

9.1 Introduction

Heat generation relies currently, to a large extent, on combustion processes. In 2019, 77% of global heating for buildings and industrial process heat came from fossil fuels, whereas only 3.2% was provided by electric heating systems, and 23% was supplied by renewable heating almost entirely from biomass. Only 0.9% derived from solar and geothermal heating systems. To decarbonize the global heat supply is more challenging than to decarbonize the electricity sector, because geographic

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

T. Pregger · S. Simon
Department of Energy Systems Analysis, Institute for Engineering Thermodynamics (TT), German Aerospace Center (DLR), Stuttgart, Germany
e-mail: thomas.pregger@dlr.de; sonja.simon@dlr.de

C. Harpprecht
Institute of Networked Energy Systems, German Aerospace Center (DLR), Stuttgart, Germany

S. Teske (ed.), *Achieving the Paris Climate Agreement Goals*,
https://doi.org/10.1007/978-3-030-99177-7_9

limitations make it difficult to provide high-temperature heat with direct solar or geothermal energy due to their dependency on locally available resources. However, the use of renewable electricity for heating is key to a successful 1.5 °C pathway. This section provides a short overview of the suitable technologies available and the temperature levels that these technologies can generate.

Industry involves a large variety of processes that demand heat. These requirements range, for example, from 40 °C to around 300 °C in the food industry to metal production with furnaces well above 800 °C and cement production with dry kilns at around 1500 °C. Figure 9.1 shows that the metal, chemical, and mineral industries require particularly large amounts of high-temperature process heat.

Decarbonizing process heat for energy-intensive industries, such as the steel, aluminium, cement, and chemical industries, is a major prerequisite to remaining within a 1.5 °C increase in the global temperature. Three main groups of technologies can provide renewable process heat at different temperatures:

1. *Direct heat systems*: geothermal and concentrated solar systems
2. *Electric heat systems*: heat pumps, electromagnetic, di-electric, infrared, induction, resistance, and arc furnace heating
3. *Fuel-based heat systems*: that use bio-energy, hydrogen, and other synthetic fuels

The energy sources for these heat generation technologies are either biomass, geothermal energy, solar energy, or electricity, used either directly or as fuels produced with electricity, such as hydrogen and other synthetic fuels. Whereas the most efficient transformation to renewable energy is the direct application of renewable heat, many industrial processes require higher temperatures or fuels, which cannot be provided directly by renewables. Therefore, as the next best option in terms of efficiency, the direct electrification of processes is preferable. However, some processes

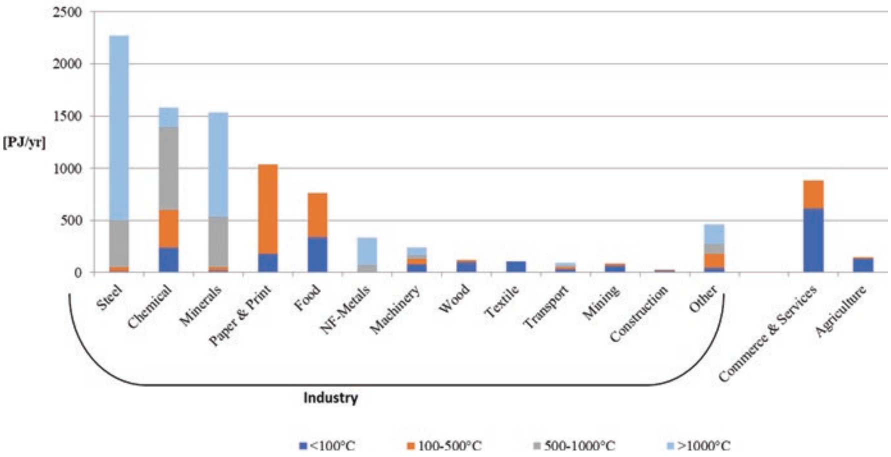

Fig. 9.1 Distribution of process heat demand across all branches of industry in Europe. (Naegler et al., 2015)

will still rely on fuel input in the future. In this case, power-based synthetic fuels will be required, with increasing efficiency losses along the chain from hydrogen to synthetic gas to synthetic liquid fuels. To comply with the 1.5 °C carbon budget, all the electricity used for heat or fuel production must be produced from renewable energy.

In Table 9.1, we compare the technology options used in the OECM for generating different levels of heat. Their descriptions are provided in the following subchapters. It can be seen that the use of fuels is most suitable for high-temperature process heat, although direct electrification is also suitable to some extent. Geothermal energy is particularly suitable for lower temperatures, whereas direct solar energy can only be used to generate high-temperature heat via central receivers. This illustration does not consider the opportunities for or barriers to renewable heat integration that may arise from technical or local structural constraints.

Table 9.2 shows the average breakdown between heat and fuels and electricity in percentages of the industry sectors analysed, which are included in the OECM. The data demonstrate the large share of high-temperature heat in the primary industries. The average energy demand for the steel industry in 2019, for example, was mainly for the generation of process heat (86%), with 14% for electricity. The value for process heat includes fuels.

Table 9.1 Technology options to generate renewable heat by temperature level

	0 °C	50 °C	100 °C	200 °C	300 °C	400 °C	500 °C	600 °C	700 °C	800 °C	900 °C	1000 °C	1100 °C	1200 °C	1300 °C	1400 °C	> 1500 °C
OneEarth Climate Model (OECM) temperature levels used in the 1.5 °C pathway	Low temperature			Medium-temperature process heat				Industrial process heat					High-level process heat				
Bioenergy																	
Fixed-bed boiler										🟩	🟩	🟩					
Fluidized-bed boiler									🟩	🟩							
Gasification									🟩	🟩	🟩						
Gasification for syngas production						🟩	🟩	🟩	🟩	🟩	🟩		🟩	🟩	🟩	🟩	🟩
Anaerobic digestion							🟩	🟩	🟩	🟩							
Fermentation—ethanol					🟩	🟩											
Fermentation—methanol					🟩	🟩											
Geothermal																	
Dry steam plants	🟨	🟨	🟨														
Flash plants	🟨	🟨	🟨														
Binary cycle		🟨	🟨	🟨													
Combined cycle		🟨	🟨	🟨													
Solar thermal																	
Flat-panel solar collectors	🟨	🟨															
Vacuum tubes		🟨	🟨														
Parabolic trough			🟨	🟨	🟨	🟨											
Linear Fresnel lens system			🟨	🟨	🟨												
Parabolic dish				🟨	🟨	🟨	🟨	🟨	🟨	🟨							
Central receiver / solar tower					🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨				
Electric heating																	
Residential heat pumps	🟦	🟦	🟦														
Industry heat pumps			🟦	🟦													
Electromagnetic heating						🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Non-thermal electromagnetic			🟦	🟦	🟦												
Electric resistance heating						🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Electric arc furnace						🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦

Table 9.2 Average electricity and heat shares by industry in 2019 (heat includes electricity for heating and fuels)

Industry sector	Electricity (non-heat related) [%]	Process heat from fuels and electricity [%]	Shares of required heat levels (Naegler et. al 2015)			
			< 100 °C	100–500 °C	500–1000 °C	> 1000 °C
Iron and steel	14%	86%	5%	2%	19%	75%
Chemicals and petrochemicals	25%	75%	18%	22%	48%	12%
Non-ferrous metals	52%	48%	10%	4%	20%	66%
Aluminium	60%	40%	8%	2%	18%	72%
Non-metallic minerals	17%	83%	5%	2%	30%	63%
Cement	19%	81%	5%	2%	30%	63%
Transport equipment	47%	53%	72%	10%	5%	13%
Machinery	34%	66%	57%	15%	9%	20%
Mining and quarrying	41%	59%	13%	2%	28%	57%
Food and tobacco	30%	70%	54%	46%	0%	0%
Paper, pulp, and print	32%	68%	20%	80%	0%	0%
Wood and wood products	29%	71%	37%	63%	0%	0%
Construction	35%	65%	48%	18%	11%	23%
Textiles and leather	42%	58%	100%	0%	0%	0%
Unspecified (industry)	40%	60%	43%	19%	12%	25%

However, whereas the share of the actual heat demand will remain stable for each sector in the OECM until the end of the scenario period in 2050, the electricity used to produce heat will increase. A more detailed bottom-up analysis broken down into primary and secondary steel and aluminium and new manufacturing processes has been undertaken. The assumptions for the process heat calculation for each industry sector are presented in Chap. 5.

In the following section, these different technologies are outlined, and their respective areas of application are explained.

9.2 Direct Renewable Process Heat

9.2.1 *Bioenergy and Biofuels*

'Biomass' is a broad term used to describe materials of recent biological origin that can be used as a source of energy. It includes wood, crops, algae, and other plants, as well as agricultural and forest residues (Teske & Pregger, 2015). Biomass is used to generate electricity, heat, and fuels. The following section focuses on heat generation.

The majority—around 90%—of bioenergy is used in direct combustion processes to generate heat and/or electricity, mostly for domestic and low-temperature applications. However, many studies and scenarios that have considered the potential of biomass have envisaged a shift in its currently limited potential to allow the generation of high-temperature industrial process heat, in the transition towards a renewable energy system (Lenz et al., 2020).

In principle, two biomass conversion routes are available for the production of heat for industry, using several biomass technologies:

(a) Thermochemical processes:

- Direct combustion
- Gasification
- Pyrolysis

(b) Biochemical conversion processes:

- Anaerobic digestion
- Fermentation

9.2.1.1 Thermochemical Processes

Direct Combustion

The direct combustion technologies relevant to the generation of process heat can be differentiated according to the state in which the biomass is fed into and burned in the process.

In fixed-bed combustion applications, the air is first passed through a fixed bed for drying, gasification, and charcoal combustion. In the second step, the combustible gases produced are burned with air, usually in a zone separated from the fuel bed. Fixed-bed combustion is adaptable to a variety of fuels such as wood, straw chips, and pellets. Therefore, the range of capacities is large, ranging from 10 kW to 60 MW.

The fluidized-bed technology involves the combustion of particulate solid fuel in an inert material bed (usually sand), which is fluidized by the flow of a gas. This type of flow allows efficient gas–solid contact, so it is widely used in covering particles, drying, granulation, blending, combustion, and gasification processes (Philippsen et al., 2015). This technology provides almost complete combustion, with very stable temperatures and low emissions. The prerequisites are fuels with particle sizes <100 mm and ash melting temperatures >1000 °C (Kaltschmitt et al., 2009). Entrained-flow combustion is suitable for fuels that are available as small particles, such as sawdust or fine shavings, which are pneumatically injected into the furnace. Fluidized-bed combustion is generally used in larger systems (> 20 MW), because it is expensive (Teske & Pregger, 2015; ARENA, 2019).

Gasification

Biomass gasification is a method for upgrading solid biomass and is especially valuable in processing biomass of low caloric value or moist biomass, e.g. many residues. The partial oxidation of the biomass fuel provides a combustible gas mixture mainly consisting of carbon monoxide (CO). Gasification provides a homogeneous fuel and controlled combustion, which can increase the efficiency along the whole biomass chain, although at the expense of additional investments in the more sophisticated technology, or the efficient use of low-quality biomass. During the first step, the volatile components of the fuel are vaporized in a complex set of reactions at temperatures <600 °C. Gasification is an intermediate step between pyrolysis and combustion. It is a two-step, endothermic process (IEA BioEnergy Agreement Task 33, 2020).

Biomass gasification is increasingly used to generate high temperature levels. The most commonly available gasifiers use wood or woody biomass, whereas especially designed gasifiers can convert non-woody biomass materials (Norfadhilah et al., 2017). Gasification is more efficient than combustion, providing better-controlled heating, higher efficiencies in power production, and the possibility for co-producing chemicals and fuels (Kirkels & Verbong, 2011). Gasification can also reduce emission levels better than power production with direct combustion and a steam cycle. Finally, gasification can also be the first step in the production of synthetic fuels (Malico et al., 2019) (see next section).

Pyrolysis

Pyrolysis is a technology that ‘upgrades’ biomass, providing products of high caloric value for combustion. It has been long used in the production of charcoal (Malico et al., 2019). Technically, thermal decomposition occurs in the absence of oxygen. It is also always the first step in combustion and gasification processes, where it is followed by the total or partial oxidation of the primary products (IEA BioEnergy Agreement Task 34, 2021). Pyrolysis produces a solid (charcoal), liquid (pyrolysis oil or bio-oil), and gas product. The relative amounts of the three products are determined by the operating temperature and the residence time used in the process. Lower temperatures produce more solid and liquid products, and higher temperatures, more biogas. All the products are then available for the production of industrial process heat.

9.2.1.2 Biochemical Conversion Processes

Anaerobic digestion and fermentation are the two main biochemical processes that provide energy from biomass with high moisture content, such as food waste or agricultural residues, including liquid manure.

Anaerobic Digestion

In a biogas plant, organic waste is broken down by bacteria in an oxygen-free (= anaerobic) environment in about two-thirds methane (CH_4) and one-third CO_2. This gas is used either directly in power, heating, or cogeneration plants, or purified gas is fed into renewable gas pipelines. For its direct injection into natural gas pipelines, the CH_4 content must be increased to approximately 95% (Wall et al., 2018). The quality of the renewable gas produced depends on the energy content of the feedstock. Possible feedstocks include food waste, livestock manure, process effluent, sewage sludge, and domestic biowaste.

Alcoholic Fermentation

The alcoholic fermentation of sugar and starch is a 'state-of-the-art' technology. Plants with high sugar and starch contents, such as sugar cane, are broken down into ethanol and methanol by microorganisms. Because the use of sugar and starch plants for this purpose is in direct competition with human nutrition, one direction of research focuses on the fermentation of lignocellulose, e.g. from straw or grass. Although lignocellulosic processes are more complex than the fermentation of carbohydrates, the first production plants have been developed in Germany (DBFZ, 2015). The products can be used as combustible fuels for power, heat, or cogeneration plants and as a vehicle fuel. However, in the future, these products will become more important as low-emission feedstocks in a circular economy, with increased competition for the limited biomass potential (Table 9.3).

9.2.1.3 Bioenergy and Reduction of Greenhouse Gas (GHG) Emissions

Bioenergy is not necessarily carbon neutral. Depending on the feedstock, which can be agricultural or forestry waste, other biogenic residues, or energy crops, bioenergy production has different upstream burdens in terms of the consumption of materials and energy, land-use changes, and emissions that have a significant impact on GHG emissions. Given the environmental effects of the production of energy crops, the global use of biomass in the 1.5 °C pathway is limited to 100 EJ per year,

Table 9.3 Bioenergy for process heat—overview

Process	Technology	Heat level	Remarks
Thermochemical	Fixed-bed boiler	800–1000 °C	
	Fluidized-bed boiler	750–850 °C	
	Gasification	750–900 °C	
	Gasification for syngas production	400–900 °C	Low H_2 content
		1200–1700 °C	High H_2 content
Biochemical systems	Anaerobic digestion	550–900 °C	High H_2 content increases temperature level
	Ethanol/methanol production via fermentation	–	Combustion temperature depends on application

Sources: IEA, ARENA, UTS/ISF, and DLR (own research) which is the estimated threshold of carbon-neutral sustainable biomass based on residuals and organic waste (Thrän et al., 2011).

9.2.2 Geothermal

Geothermal resources consist of thermal energy from the Earth's interior stored in both rocks and trapped steam or liquid water (IPCC-SRREN CH_4, 2011). Although geothermal resources are available in all countries, their utilization is concentrated in regions where geothermal heat is available close to the Earth's surface. Geothermal 'hotspots' with high temperature levels occur in the western part of the USA, west and central Eastern Europe, Turkey, Iceland, and 'the ring of fire' around the Pacific, from Japan, the Philippines, South-East Asia, and Indonesia to New Zealand.

Geothermal energy resources are classified by temperature level (Huddlestone-Holmes, 2014). Each temperature level involves different technologies and applications. The global average thermal gradient is around 25–30 °C per km depth (Beardsmore & Cull, 2001), which results in an average crustal temperature of around 150 °C at a depth of 5000 m. Higher temperatures can be achieved by drilling deeper or by focusing on areas with favourable conditions. In such areas, the following temperatures are usually possible:

- Low temperature (<90 °C)—direct heat used near the surface and from boreholes drilled to <2000 m depth
- Medium temperature (90–150 °C)—direct heat used near the surface and from boreholes usually drilled to >2000 m depth
- High temperature (<150–250 °C)—from boreholes drilled to depths up to 5000 m

To date, high-temperature geothermal systems are almost exclusively used for power generation. However, high-temperature geothermal systems, around 200 °C, can also be utilized to provide direct process heat (ARENA, 2019).

Geothermal systems predominantly provide low-temperature process heat, which can be used, for example, in the food-processing industry (see Fig. 9.1).

In high-temperature hydrothermal reservoirs, water occurs naturally underground in its liquid form under pressure. As it is extracted, the pressure drops and the water is converted to steam. The residual salty water is sent back to the reservoir through injection wells, sometimes via another system that uses the remaining heat (Teske & Pregger, 2015). The hot water produced from intermediate-temperature hydrothermal or enhanced geothermal system (EGS) reservoirs can be used in heat exchangers, to generate power in a binary cycle, or directly in heat applications. The recovered fluids are also injected back into the reservoir (Younger, 2015).

The key technologies for EGS are:

- *Exploration and drilling* involve the localization and analysis of geothermal resources, including the depth required and the dimensions for drilling. The maximum depth is currently around 5 km, using methods similar to those of the oil and gas industry. Exploration and drilling are among the most cost-intensive parts of a geothermal project and include technical risks (IRENA-Geo, 2017).
- *Reservoir engineering* focuses on determining the volume of the geothermal resource and the optimal plant size. Ideally, the sustainable use of the resources and the safety and efficiency of the operation are considered.
- *Geothermal power and heat plants* use the steam created from heating water by natural underground sources to power the turbines that produce electricity and/or process heat. Three main technologies are used:
  - Dry steam plants
  - Flash plants (single, double, or triple)
  - Binary combined-cycle plants or hybrid plants
- Dry steam plants operating at sites with intermediate- or high-temperature resources (≥150 °C), with unit sizes ranges between 20 $\mathrm{MW_{electric}}$ and 110 $\mathrm{MW_{electric}}$ (IRENA-Geo, 2017).
- Flash plants—similar to dry steam plants but the steam is obtained from a separation process, called 'flashing'; this is currently the commonest type of operational geothermal electricity plant (IRENA-Geo, 2017).
- Binary-cycle plants operate with low- and medium-temperature heat (100–170 °C) and heat exchangers that transfer the heat into a closed loop (IEA Geo, 2011). For process heat, fluid ammonia/water mixtures are used in Kalina cycles or hydrocarbons in organic Rankine cycles,[1] which have boiling and condensation points that must match the geothermal resource temperature (IRENA-Geo, 2017). The typical plant sizes are in the 10–50 MW range.
- Combined-cycle/hybrid plants use two different heat cycles—one for heat and one for power generation. This increases the overall electric efficiency. Other heat, such as that from solar thermal power plants, can feed into the heat cycle to increase the temperature and output.

9.2.3 Concentrated Solar

Concentrating solar technologies generate high-temperature heat that can be used for industry processes (CSH) or to produce electricity via steam turbines (concentrated solar power—CSP).

---

[1] A Rankine cycle power system is a heat engine that converts thermal energy into work. Similar to the vapor compression heat pump, it comprises four main components: a boiler (sometimes called an 'evaporator'), a turbine, a condenser, and a pump (Fig. 9.2). The working fluid, in a low-pressure slightly subcooled liquid state, is brought to high pressure by the pump. The pump consumes power (ARENA2019).

Like high-temperature geothermal plants, concentrating solar technologies are currently predominantly utilized to generate power. However, the process heat temperature required for direct use in industrial processes (to 400 °C) is technically possible (DLR-ISR, 2021).

Direct normal irradiation—sunlight not dispersed by clouds, fumes, or dust in the atmosphere—is concentrated by mirrors to a single point or line to heat a liquid, solid, or gas to a temperature between 400 °C and >> 1000 °C, depending on the technology used. Concentrating solar plants require direct sunlight, which limits the areas of application to regions with more than 2000 h of direct sunlight per year.

There are several different CSP/CSH system types, but all require four main elements: a concentrator, a receiver, some form of transfer medium or storage, and a power conversion system or a connection that directs process heat to the site of its applications. An overview of the commonest concentrating solar systems is given by Pitz-Paal (2016).

Parabolic trough plants use rows of parabolic trough collectors, each of which reflects solar radiation into an absorber tube. The troughs track the sun around one axis, which is typically oriented north–south. Synthetic oil circulates through the tubes and is heated to approximately 400 °C. The hot oil from numerous rows of troughs is passed through a heat exchanger. The direct evaporation of water in the parabolic troughs, which has been developed to operational maturity for years, will allow the realization of decentralized plants with relatively small solar fields, because heat exchangers and (possibly) toxic synthetic heat transfer fluids will no longer be required. Increasingly, CSP plants use thermal storage systems, such as molten salt, to store high-temperate heat (up to 400 °C) to allow their operation without sunlight or at night. The land requirements are around 2 km^2 for a 100 MW plant, depending on the collector technology and assuming that no storage is available.

Linear Fresnel systems use a series of long, narrow, flat Fresnel mirrors instead of a parabolic trough to concentrate solar radiation to a linear absorber positioned above the lenses. All the other parts of the system correspond to those of parabolic trough plants.

Central receivers or solar towers focus solar radiation to a single point and achieve higher temperatures than parabolic troughs or Fresnel lenses. This technology uses a circular array of mirrors (heliostats) in which each mirror tracks the sun, reflecting the light onto a fixed receiver on top of a tower. Temperatures exceeding 1000 °C can be achieved. A heat-transfer medium absorbs the highly concentrated radiation reflected by the heliostats and converts it into thermal energy to be used for the subsequent generation of super-heated steam for turbine operation or as industrial process heat. The heat transfer medium is currently either water/steam, molten salts, liquid sodium, or air and possibly also pressurized gas or air at very high temperatures. The unit sizes range from 20 to 200 MW.

Parabolic dishes use a shaped reflector to concentrate sunlight onto a receiver located at their focal points. The receiver moves with the dish. The concentrated beam radiation is absorbed into the receiver to heat a fluid or gas to approximately 750 °C. This is then used to generate electricity via Stirling engines or a micro-turbine attached to the receiver. Dishes have been used to power Stirling engines up to 900 °C and also to generate steam. The largest solar dishes have a 485 m^2 aperture and are in research facilities or demonstration plants. Individual unit sizes are in the double-digit kilowatt range and can be combined in modular systems to form utility-scale plants. The generation of process heat is possible but is not yet commercially available.

Concentrated solar heat (CSH) system applications: In addition to its use in different types of solar reflector systems, a CSH system can be used to directly feed into industrial processes, or to desalinate water. The significant cost reduction with solar photovoltaic systems has led to a focus on the application of concentrated solar for to heat generation rather than to the generation of electricity.

Thermal storage, when integrated into a system, is an additional and increasingly important asset in concentrated solar plants, providing heat outside the hours of sunshine and even during the night. Additional concentrator area can be added to produce heat for storage purposes, increasing the capacity factor. There are three categories of storage medium that can be used in CSP plants (Pitz-Paal, 2020):

- *Advanced sensible heat-storage* systems use two tanks with molten salts at different temperatures. These temperatures are high, at around 300–600 °C. Other materials, such as ceramic particles, have also been used and evaluated in research projects as sensitive heat-storage materials.
- *Latent heat-storage* systems transfer heat as a phase change, which occurs in a specific narrow temperature range in the relevant material. The phase-change materials most frequently used for this purpose are molten salt, paraffin wax, and water/ice (Jouhara et al., 2020).
- *Thermochemical energy storage* is achieved via a reversible chemical reaction, resulting in the highest energy density of all thermal storage options, but with a reaction efficiency that decreases with time. For example, different thermochemically active redox materials can be used for the thermochemical storage of CSP (Buck et al., 2021).

The storage capacity currently installed is, on average, around 8 full-load hours.

Concentrated solar power plants have been developed to generate electricity, but the technology has significant potential to provide high-temperature process heat in sunny regions, such as Australia, Chile, North Africa and the Sahara, parts of Central Asia, India, and China, as well as the Middle East. Research is targeting CSP as a source of high-temperature process heat that can directly feed reactors for endothermic chemical reactions. Currently, solar metal-oxide redox cycles and sulphur cycle processes have been developed that rely on temperatures of 1000–1500 °C (Roeb et al., 2020). The first applications of this technology, for hydrogen production, have achieved technology readiness levels of 5–6, for example, in the SUN-to-LIQUID project (Koepf et al., 2019). Newer projects go beyond hydrogen and integrate the direct air capture of CO_2 for the production of chemical feedstocks, such as methanol (Prats-Salvado et al., 2021).

9.3 Electric Process Heat

9.3.1 Heat Pump Technology

Heat pumps are largely known as electric heating (and cooling) systems that supply buildings with space heat and hot water. However, in general, heat pumps are devices that transfer heat from one medium at a lower temperature to another medium at a higher temperature. Therefore, they allow the efficient recycling of low-temperature heat, such as waste heat.

Heat pumps use a refrigeration cycle to provide heat or cold. They use renewable energy from the ground, water, or air to move heat from a relatively low-temperature reservoir (the ‘source’) to a temperature level required for a specific thermal application (the ‘output’). Heat pumps commonly use two types of refrigeration cycles:

- Compression heat pumps use mechanical energy, most commonly electric motors or combustion engines, to drive the compressor in the unit. Consequently, electricity, gas, or oil is used as auxiliary energy.
- Thermally driven heat pumps use thermal energy to drive the sorption process—either adsorption or absorption—to make ambient heat useful. Different energy sources can be used as auxiliary energy: waste energy, biomass, solar thermal energy, or conventional fuels.

Compression heat pumps are most commonly used, but thermally driven units are considered a promising future technology. The efficiency of a heat pump is described by the coefficient of performance (COP), the ratio between the annual useful heat output and the annual auxiliary energy consumption of the unit. In the residential market, heat pumps work best for relatively warm heat sources and low-temperature applications, such as space heating and sanitary hot water. They are less efficient in providing higher-temperature heat and cannot be used for heat over 90 °C. For industrial applications, different refrigerants can be used to efficiently provide heat of 80–90 °C, so they are only suitable for part of the energy requirements of industry.

Heat pumps are generally distinguished by the heat source they exploit:

- Ground-source heat pumps use the energy stored in the ground at depths from around 100 m up to the surface. They are used for deep borehole heat exchangers (300–3000 m), shallow borehole heat exchangers (50–250 m), and horizontal borehole heat exchangers (a few meters deep).
- Water-source heat pumps are coupled to a (relatively warm) water reservoir typically at around 10 °C, such as wells, ponds, rivers, and the sea.
- Aero-thermal heat pumps use the outside air as a heat source. Because the outside temperatures during the heating period are generally lower than soil or water temperatures, ground-source and water-source heat pumps are typically more efficient than aero-thermal heat pumps.

Heat pumps require additional energy apart from the environmental heat extracted from the heat source, so the environmental benefit of heat pumps depends upon both their efficiency and their emissions associated with the production of working energy. When a heat pump has a low COP and a high share of electricity from coal power plants, for example, the CO_2 emissions relative to the useful heat produced might be higher than for conventional gas condensing boilers. However, efficient heat pumps powered with renewable electricity are emission-free.

Reversible heat pumps can be operated in both heating and cooling modes. When they operate in cooling mode, heat is extracted from, for example, a building, and ‘pumped’ into either a reservoir or the open environment, without storage. When a reservoir is used, the heat can be reused. Alternatively, renewable cooling can be provided by circulating a cooling fluid through the relatively cool ground before it is distributed in a building’s heating/cooling system (‘free cooling’). However, in a GHG-emission-free system, this cooling fluid must not be based on hydrofluorocarbons (HFCs) or chlorofluorocarbons (CFCs) but on ammonia, water, or air (ARENA, 2019).

In principle, high-enthalpy geothermal heat can provide the energy required to drive an absorption chiller. However, only a very limited number of geothermal absorption chillers are in operation throughout the world. Heat pumps have become increasingly important in buildings but can also be used for industrial process heat. Industrial heat pumps offer various opportunities for all types of manufacturing processes and operations and use waste process heat as their heat source. They deliver heat at medium temperatures for use in industrial processes, heating, or preheating or for space heating and cooling in industry. Heat pumps with operating temperatures below 100 °C are state-of-the-art technologies, and high-temperature industrial heat pumps in the range of 160–200 °C are beginning to enter the market. Essential aspects of the future use of heat pumps are efficient system integration and flexibility via heat storage.

9.3.2 Electric Heating Systems

There are four main technological types of electric heating systems, which use different physical methods. Each of them has different temperature levels and applications.

1. Electromagnetic heating
    (a) Dielectric heating
    (b) Infrared heating
    (c) Induction
2. Non-thermal electromagnetic heating
    (a) Ultraviolet
    (b) Pulsed electric field

Table 9.4 Electromagnetic process heating technologies

Technology	Induction	Radio	Microwave	Infrared	Visible light	Ultraviolet
Frequency	50–500 kHz	10–100 MHz	200–3000 MHz	30–400 THz		1–30 PHz
Maximum temperature	3000 °C	2000 °C	2000 °C	2200 °C		–
Power density (kW/m^2)	50,000	100	500	300		100
Efficiency	50–90%	80%	80%	60–90%		
Application	Rapid internal heating of metals	Rapid internal heating of large volumes	Rapid internal heating of large volumes	Very rapid heating of surfaces and thin material		Non-thermal curing of paints and coating

Source: ARENA, 2019

   (c) Microwave[2].

3. Electric resistance heating
4. Electric arc furnaces

Electromagnetic heating systems are used to transfer energy to a target material or process without the need for a heat transfer medium. The main advantage of this technology is that heat can be generated and delivered to the point of need, which makes this an energy-efficient technology (ARENA, 2019).

Non-thermal electrical systems generate heat directly on the target object, and no additional medium is required to transfer the heat (Xiong, 2021). Both technology groups use different frequencies to generate heat (Table 9.4).

9.3.2.1 Electric Resistance Heating

Materials conduct electricity to different degrees. The lower the electrical conductivity of a material, the higher the heat developed within that material. This physical law—*ohmic resistan*ce—is used in electric resistance heating devices. There are two types of electrical resistance heating:

- Direct resistance: the targeted material is heated by an electricity current.
- Indirect resistance heating: a resistive heating element transfers heat to the target material by radiation and convection.

---

[2] Microwaves can generate significantly higher temperatures over time. Objects continue to heat while microwaves are emitted.

This technology is among the oldest electrical heating systems and has been used for room heat, industrial ovens, furnaces, and kilns for decades. Different configurations of indirect resistance heating are:

- Electric furnaces: use high-temperature heating elements, usually made of silicon carbide (SiC), molybdenum disilicide ($MoSi_2$), or nichrome (NiCr), that can reach temperatures in the range of 1000–2000 °C.
- Electric ovens: the ohmic heating elements mounted in the oven heat the products through convection and radiation, achieving temperatures up to 1000 °C.
- Electric boilers: unit sizes are from kilowatts to megawatts, with possible heat generation to temperatures up to 220 °C.

9.3.2.2 Electric Arc Furnaces

An electric arc occurs when an electric current jump between electrodes. As the current passes through air (or another gas), it produces a plasma discharge, generating heat and light. Lightning is a natural form of electric arc (ARENA, 2019). Electric arc furnaces are predominately used in steel recycling, to melt scrap steel. However, they are also used in other industries that require temperatures up to 1500 °C, such as the processing of copper and other metals.

9.4 Synthetic Fuels and Hydrogen

When the direct use of renewable heat sources (first choice) or electrification (second choice) is not applicable, industrial processes will still rely on the input of fuels based on renewable electricity. For efficiency reasons, hydrogen is the next best choice. However, as a last fuel option, synthetic hydrocarbons can provide the necessary energy.

9.4.1 Hydrogen: The Basics

Hydrogen can be used as a feedstock, a fuel, an energy carrier, and for energy storage and has many possible applications across the industry, transport, energy, and buildings sectors. Molecular hydrogen does not occur in nature but can be produced using any primary source of energy, such as gas, oil, or coal. It can be produced by electrolysis, which requires electricity, or by directly splitting water with a solar high-temperature process. Therefore, hydrogen is not an energy source—it is a secondary energy carrier and an energy storage medium. The combustion of hydrogen gas only generates water and no further GHG emissions are produced.

The chemical formula for this process—the scientific term is ‘oxidation’—is

$$2H_2 + O_2 ? 2H_2O.$$

Today, most of the world's hydrogen is still produced in CO_2-intensive processes: steam–methane reformation (SMR) (gas, approximately 50%), oil product reformation (30%), and coal gasification (18%). In SMR, carbon (CO_2) is separated from hydrogen by the steam reformation of natural gas. This method involves the conversion of hydrocarbons and steam into hydrogen and CO (known as 'syngas').

According to the London-based *Committee on Climate Change (CCC)*, SMR has an emissions factor of around 285 g of CO_2 per kilowatt-hour (kWh) (9.5 kg of CO_2 per kg of hydrogen), and coal gasification has an emission factor of around 675 g of CO_2 per kilowatt of hydrogen, accounting only for energy use and process emissions. Therefore, arguments for the early establishment of an energetic use of hydrogen based on fossil energies are usually combined with arguments for the implementation of carbon capture and storage (CCS) technologies. Counterarguments point to the lock-in effect of investments in high-carbon infrastructure, which comes at the expense of financial resources for the expansion of renewable energies.

If hydrogen is to contribute to climate neutrality, it must achieve a far larger scale and its production must become fully decarbonized. According to the International Energy Agency (IEA), the current production of hydrogen—mainly based on natural gas—is responsible for CO_2 emissions of around 830 million tonnes per year. By comparison, Germany's total CO_2 emissions in 2020 are estimated to have been 722 million tonnes. It is estimated that 6% of global natural gas and 2% of global coal production are used for hydrogen production, whereas only about 0.1% of global dedicated hydrogen production is produced with water electrolysis.

9.4.1.1 Status Quo: Global Demand for Hydrogen in Industry

There are various applications for hydrogen in industry, as shown in Table 9.5, but only two main areas consume most of the global hydrogen produced today: ammonia production and refining processes. About 90% of ammonia is used for the production of fertilizers and the majority of the remaining 10% for cleaning products. In 2018, 43% of the global hydrogen demand was used for ammonia production and 52% for refining processes. Refineries use hydrogen to lower the sulphur content of diesel fuel. The remaining 6% of global hydrogen production is distributed across the other applications shown in Table 9.5.

The demand for hydrogen has grown continuously over the past decades, and the market shares for ammonia production and refinery processes have remained similar. The use of hydrogen for energy storage does not yet show in the global energy statistics.

Table 9.5 Current areas of hydrogen use in industry

Industry sector	Key applications
Chemical	Ammonia, polymers, resins
Refining	Hydrocracking, hydrotreatment
Iron and steel	Annealing, blanketing gas, forming gas
General industry	Semiconductors, propellant fuel, glass production, hydrogenation of fats (liquid vegetable oils made creamy), cooling of generators

Source: Pregger et al. 2019

9.4.1.2 Possible Applications of Hydrogen in Decarbonization Pathways

Although there is a huge diversity of market projections and possible future applications for hydrogen, there is a broad consensus among all market analysts that the market for hydrogen will grow significantly in the coming decade. As well as its current application as a feedstock in chemical industries, hydrogen is expected to expand in the energy sector. Once electricity has been generated and used to produce hydrogen, this hydrogen can store energy in the form of a gas or (pressurized) liquid and replace fossil and/or biofuels in power plants (including fuel cells), cogenerating or heating plants to generate electricity, as heat, or as a transport fuel for vehicles. Figure 9.2 provides an overview of the possible future applications of hydrogen.

An important new industry sector for hydrogen is primary steel production. Based on current knowledge, the use of hydrogen for steel production is among the most promising processes to decarbonize the steel industry (Recharge 2020).

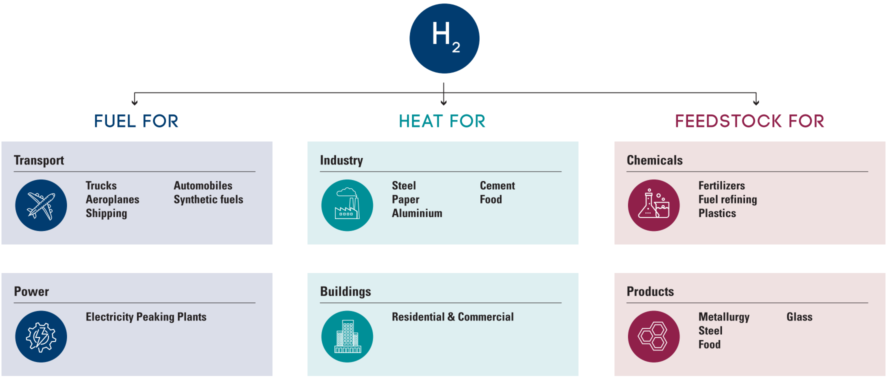

Fig. 9.2 Areas of hydrogen application. (BNEF 2020)

9.4.1.3 New Processes to Produce Hydrogen

In the public debate, colours are often used to refer to different processes for hydrogen production (IRENA 2020–1):

- 'Green' is the term applied to the production of hydrogen using water and electricity from renewable sources.
- 'Black', 'grey', and 'brown' refer to the production of hydrogen from coal, natural gas, and lignite, respectively. This process transforms the fossil fuel into hydrogen and CO_2. The life cycles of GHG emissions in the fossil-fuel-based production of hydrogen are very high.
- 'Blue' is grey hydrogen, except that during its production, CO_2 emissions are reduced by the use of CCS technology. It is also referred to as 'low-carbon hydrogen', because the full-life cycle GHG emissions are lower during its production than when hydrogen is produced with fossil fuels alone.
- 'Turquoise' (aqua, turquois) refers to hydrogen produced from methane in a thermal process (methane pyrolysis). Instead of CO_2, the process generates solid carbon (fixed carbon).

However, the only desirable production route is renewable hydrogen ('green')—only in this case is it a zero-emissions technology. In all other-coloured methods, hydrogen production still demands fossil fuels, which are the greatest cause of climate change. Consequently, our report focuses on renewable ('green') hydrogen as a key element of climate neutrality.

9.4.1.4 Hydrogen and 'Power-to-X'

When hydrogen is used as a fuel, 'power-to-X' (PtX) is often used as a term for the conversion processes and technologies involved. Power or 'P' is the electricity or input on the production side. 'X' can stand for any resulting fuel, chemical, power, or heat. PtX has received increasing public attention, because these technologies allow the indirect electrification of sectors that are (as yet) dependent on fossil fuels. PtX includes:

- Power-to-heat (PtH): transforming electricity to heat
- Power-to-gas (PtG): generation of hydrogen from electricity and (optionally) its use with a carbon source to synthesize methane (via methanation) or produce ammonium.
- Power-to-liquid (PtL): generation of hydrogen from electricity and its use with a carbon source to synthesize liquid hydrocarbons as a fuel or energy carrier (e.g. Fischer–Tropsch or methanol route)

9.4.2 Synthetic Fuels

Some (chemical) processes require either a liquid fuel or a carbon source, and will also do so in the future. Therefore, synthetic fuels are a prerequisite for carbon-neutral industry. On the one hand, these synthetic fuels are based on renewable power. On the other hand, the production of synthetic liquid and gaseous hydrocarbons and methanol requires carbon sources. In a fossil-fuel-free circular carbon economy, only a few carbon sources will be available: carbon from biomass and CO_2 emissions—from either waste incineration or flue gases, such as the process-related emissions from cement production. Therefore, possible CO_2 sources are not only industrial plants but also biogas plants or the direct air capture of CO_2. Depending upon the carbon source and the output, the different PtX processes for the generation of synthetic fuels are defined as:

- PtG: power-to-gas
- PtL: power-to-liquid
- BtL: biomass-to-liquid.
- PBtL: power-and-biomass-to-liquid.

Hydrogen, methane, and liquid hydrocarbons are studied in numerous research projects for their possible use in long-term electricity storage, a balancing option for variable wind and photovoltaic power, and fuels for transportation (see, e.g. Pregger et al., 2019). Liebich et al. (2021) give an overview of the main production routes for synfuels from a variety of energy sources, locations, and transport options, as well as their ecological and economic advantages, disadvantages, and future prospects. A variety of technical concepts and test facilities are also available, ranging from PBtL based on biomass and hydropower in Sweden to PtL based on CO_2 from cement production in Germany and PV power imports from Saudi Arabia. Because the costs are currently relatively high, the potential generation of synfuels and their use in the short term are not economically feasible, but they are primarily considered from the perspective of political expediency for the extensive decarbonization of the entire energy system.

The sustainable production of biofuels, even BtL, is limited by the availability of biomass feedstocks, e.g. residues and solid biomass. Research into and the development of the most-efficient generation routes for synthetic fuels are therefore very important, both for the decarbonization of the transport sector and for the security of future fossil-free fuel supply. Industry co-benefits can arise when emission reduction targets (e.g. for transport) lead to the accelerated development of synfuel production capacities. Synthetic fuel production processes can also provide the necessary feedstocks, such as methanol, for the chemical industries. The future availability of appropriate carbon sources from biomass or process-related emissions for industry is currently unclear, especially for biomass. The direct use of (solid) biomass in industry or the building sector might significantly reduce the remaining potential for biomass, and transport sectors (such as aviation and heavy-duty traffic) might also compete for BtL.

Here, the specific advantages of liquid synthetic hydrocarbons will also play a role. They require no special storage or transport containers, and losses during storage are negligible. The energy density is 100 times higher than today's batteries and 10 times higher than hydrogen at a pressure of 200 bar. Therefore, their handling, transport, and storage are much easier and safer, making the transport sector a major competitor for limited synfuel production. Significant improvements in development will be necessary along the complete process chain, which is as yet far from optimized.

References

ARENA. (2019, November). *Renewable energy options for industrial process heat*. Lovegrove, K., Alexander, D., Bader, R., Edwards, S., Lord, M., Mojiri, A., Rutovitz, J., Saddler, H., Stanley, C., Urkalan, K., Watt, M. https://arena.gov.au/assets/2019/11/renewable-energy-options-for-industrial-process-heat.pdf

Beardsmore, G. R., & Cull, J. P. (2001). *Crustal heat flow; a guide to measurement and modelling* (p. 324). Cambridge University Press.

BNEF. (2020). BNEF - Hydrogen Economy Outlook, Key messages, March 30, 2020. https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf

Buck, R., Agrafiotis, C., Tescari, S., Neumann, N., & Schmücker, M. (2021). Techno-economic analysis of candidate oxide materials for thermochemical storage in concentrating solar power systems. *Frontiers in Energy Research, 9*, 694248. https://doi.org/10.3389/fenrg.2021.694248

DBFZ. (2015). *Focus on Bioenergie-Technologien/Bioenergy-Technologies* (Fokusheft Energetische Biomassenutzung). Deutsches BiomasseForschungsZentrum.

DLR-ISR. (2021, May). *Solar thermal power plants. Heat, electricity and fuels from concentrated solar power*. German Aerospace Center (DLR) Institute of Solar Research, Pitz-Paal et al. https://www.dlr.de/content/en/downloads/publications/brochures/2021/brochure-study-solar-thermal-power-plants.pdf;jsessionid=DE4A92846D5767F2DBF2E3CB1BF69AA3.delivery-replication2?__blob=publicationFile & v=8

Huddlestone-Holmes, C. (2014, July). *Geothermal energy in Australia*. Prepared for the ARENA International Geothermal Energy Group, CSIRO. https://arena.gov.au/assets/2017/02/Geothermal-Energy-in-Australia.pdf

IEA BioEnergy Agreement Task 33. (2020). *Project website, IEA Task 33—Gasification of biomass and waste; November 2021*. http://www.task33.ieabioenergy.com/content/thermal_gasification

IEA Geo. (2011). *Technology roadmap—Geothermal heat and power*. International Energy Agency. https://iea.blob.core.windows.net/assets/f108d75f-302d-42ca-9542-458eea569f5d/Geothermal_Roadmap.pdf

IEA Task 34. (2021, November). *Technology Collaboration Programme, IEA, Task 34: Direct thermochemical liquefaction.* Website https://task34.ieabioenergy.com/pyrolysis-principles/

IPCC-SRREN CH4. (2011). Goldstein, B., Hiriart, G., Bertani, R., Bromley, C., Gutiérrez-Negrín, I., Huenges, E., Muraoka, H., Ragnarsson, A., Tester, J., Zui, V. Geothermal energy. In IPCC special report on renewable energy sources and climate change mitigation; Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., von Stechow, C. (eds). Cambridge University Press.

IRENA. (2020). *Green Hydrogen: A guide to policy making*. International Renewable Energy Agency, Abu Dhabi, ISBN: 978-92-9260-286-4, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_hydrogen_policy_2020.pdf

IRENA-Geo. (2017). *Geothermal power: Technology brief.* International Renewable Energy Agency. https://www.irena.org/publications/2017/Aug/Geothermal-power-Technology-brief

Jouhara, H., Żabnieńska-Góra, A., Khordehgah, N., Ahmad, D., & Lipinski, T. (2020). Latent thermal energy storage technologies and applications: A review. *International Journal of Thermofluids, 5–6*, 100039. ISSN 2666-2027. https://doi.org/10.1016/j.ijft.2020.100039

Kaltschmitt, M., Hartmann, H., & Hofbauer, H. (Eds.). (2009). *Energie aus Biomasse—Grundlagen, Techniken und Verfahren*. Heidelberg, Springer.

Kirkels, A. F., & Verbong, G. P.J. (2011, January). Biomass gasification: Still promising? A 30-year global overview. *Renewable and Sustainable Energy Reviews, 15*(1), 471–481. https://ideas.repec.org/a/eee/rensus/v15y2011i1p471-481.html

Koepf, E., Zoller, S., Luque, S., Thelen, M., Brendelberger, S., González-Aguilar, J., Romero, M., & Steinfeld, A. (2019). Liquid fuels from concentrated sunlight: An overview on development and integration of a 50 kW solar thermochemical reactor and high concentration solar field for the SUN-to-LIQUID project. In *AIP conference proceedings*. AIP Publishing LLC.

Lenz, V., Szarka, N., Jordan, M., & Thrän, D. (2020). Status and perspectives of biomass use for industrial process heat for industrialized countries. *Chemical Engineering & Technology, 43*(8), 1469–1484.

Liebich, A., Fröhlich, T., Münter, D., Fehrenbach, H., Giegrich, J., Köppen, S., Dünnebeil, F., Knörr, W., Biemann, K., Simon, S., Maier, S., Albrecht, F., Pregger, T., Schillings, C., Moser, M., Reissner, R., Hosseiny, S., Jungmeier, G., Beermann, M., … Bird, N. (2021). *System comparison of storable energy carriers from renewable energies*. Umweltbundesamt, ifeu—Institut für Energie- und Umweltforschung, Deutsches Zentrum für Luft- und Raumfahrt, Joanneum Research Forschungsgesellschaft mbH.

Malico, I., Nepomuceno Pereira, R., Gonçalves, A. C., & Sousa, A. M. O. (2019). Current status and future perspectives for energy production from solid biomass in the European industry. *Renewable and Sustainable Energy Reviews, 112*, 960–977.

Naegler, T., Simon, S., Klein, M., & Gils, H. C. (2015). Quantification of the European industrial heat demand by branch and temperature level. *International Journal of Energy Research, 39*(39), 2019–2030.

Norfadhilah, H., Tokimatsu, K., & Yoshikawa, K. (2017). Prospective for power generation of solid fuel from hydrothermal treatment of biomass and waste in Malaysia. *Energy Procedia, 142*, 369–373. ISSN 1876-6102. https://doi.org/10.1016/j.egypro.2017.12.058

Philippsen, C. G., Vilela, A. C. F., & Zen, L. D. (2015). Fluidized bed modeling applied to the analysis of processes: Review and state of the art. *Journal of Materials Research and Technology, 4*(2), 208–216. ISSN 2238-7854. https://doi.org/10.1016/j.jmrt.2014.10.018

Pitz-Paal, R. (2020). Chapter 19: Concentrating solar power. In T. M. Letcher (Ed.), *Future energy* (3rd ed., pp. 413–430). Elsevier.

Prats-Salvado, E., Monnerie, N., & Sattler, C. (2021). Synergies between direct air capture technologies and solar thermochemical cycles in the production of methanol. *Energies, 14*(16), 4818.

Pregger, T., Schiller, G, Cebulla, F., Dietrich, R.-U., Maier, S., Thess, A., Lischke, A., Monnerie, N., Sattler, C., Le Clercq, P., Rauch, B., Köhler, M., Severin, M., Kutne, P., Voigt, C., Schlager, H., Ehrenberger, S., Feinauer, M., Werling, L., Zhukov, V. P., Kirchberger, C., Ciezki, H. K, Linke, F., Methling, T., Riedel, U., Aigner, M. (2019) Future fuels—Analyses of the future prospects of renewable synthetic fuels. Energies, 13(1), 138.

Recharge. (2020). *'World first' as hydrogen used to power commercial steel production*, 28 April 2020, Leigh Collins. https://www.rechargenews.com/transition/-worldfirst-as-hydrogen-used-to-power-commercial-steel-production/2-1-799308

Roeb, M., Brendelberger, S., Rosenstiel, A., Agrafiotis, C., Monnerie, N., Budama, V., & Jacobs, N. (2020). *Wasserstoff als ein Fundament der Energiewende Teil 1: Technologien und Perspektiven für eine nachhaltige und ökonomische Wasserstoffversorgung*. Deutsches Zentrum für Luft- und Raumfahrt. https://elib.dlr.de/137796/1/DLR_Wasserstoffstudie_Teil_1_final.pdf

Teske, S., & Pregger, T. (2015, September). *Energy[R]evolution—A sustainable world energy outlook*. DLR, Instituteof Engineering Thermodynamics, Systems Analysis and Technology Assessment, Thomas Pregger, Sonja Simon, Tobias Naegler; Sven Teske, Greenpeace International.

Thrän, D., Bunzel, K., Seyfert, U., Zeller, V., Buchhorn, M., Müller, K., Matzdorf, B., Gaasch, N., Klöckner, K., Möller, I., Starick, A., Brandes, J., Günther, K., Thum, M., Zeddies, J., Schönleber, N., Gamer, W., Schweinle, J., Weimar, H. (2011). *Global and regional spatial distribution of biomass potentials—status Quo and options for specification*. DBFZ Report No. 7. Deutsches BiomasseForschungsZentrum (DBFZ).

Wall, D., Dumont, M., & Murphy, J. D. (2018). *Green gas: Facilitating a future green gas grid through the production of renewable gas*. International Energy Agency (IEA) Bioenergy Task 37: 2 2018. http://task37.ieabioenergy.com/files/daten-redaktion/download/Technical%20Brochures/green_gas_web_end.pdf

Xiong, G., Jia, J., Zhao, L., Liu, X., Zhang, X., Liu, H., Zhou, W. (2021). Nonthermal radiation heating synthesis of nanomaterials. *Science Bulletin, 66*(4), 386–406. ISSN 2095–9273, https://doi.org/10.1016/j.scib.2020.08.037

Younger, P. L. (2015). Geothermal energy: Delivering on the global potential. *Energies, 8*(10), 11737–11754. https://doi.org/10.3390/en81011737