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Decarbonizing the German industrial thermal energy use with solar, hydrogen, and other options–Recommendations for the world

Robert Pitz-Paal[a,*], Joachim Krüger[b], Juliane Hinsch[c], Ahmet Lokurlu[d], Martin Scheuerer[e], Martin Schlecht[f], Mark Schmitz[g], Gustl Schreiber[h]

[a] *DLR, Institute of Solar Research, Cologne, Germany*
[b] *Solarlite GmbH, Bentwisch, Germany*
[c] *DCSP, Berlin, Germany*
[d] *Soliterm Group, Aachen, Germany*
[e] *Protarget AG, Cologne, Germany*
[f] *Dornier group, Berlin, Germany*
[g] *TSK Flagsol GmbH, Berlin, Germany*
[h] *Siemens Energy, Munich, Germany*

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ABSTRACT

This paper is based on a position paper of the German Industry Association Concentrated Solar Power e.V. to the German government and discusses options on how to decarbonize the heat demand of the domestic industry. Among other option, concentration solar collectors are a suitable option in Germany, which has not been expected by many experts. The paper derives requirements that are needed to ensure a quick and sustainable way to decarbonize industrial heat demand. They are considered to also be relevant for many other countries that follow the same ambition to become climate neutral in the next decades.

They major statements are:

- A mix of different renewable energy technologies in conjunction with efficiency measures is needed to ensure a secure, climate-friendly and cost-efficient heat supply for the industry
- The different technology options for the provision of heat from renewable sources, through electrification and through hydrogen can and must be combined and integrated with each other.
- In this context, concentrating solar thermal represents an important part of the hybrid supply portfolio of a decarbonized industry

This requires:

- The definition of an expansion target for process heat and the flanking measures
- Ensuring the equivalence of renewable heat, renewable electricity and green hydrogen - also as hybrid solutions
- The promotion of concentrating solar thermal reference projects as an impetus for market ramp-up in Germany
- The launch of an information campaign for heat consumers and the establishment of a pool of consultants.

1. Introduction - The heat demand in the industry in Germany

The heat supply in the German industry is still very dependent on fossil fuels, but accounts for about 20 % of the total energy demand. With an energy demand of 440 TWh in Germany alone, the decarbonization of this sector will be a mammoth task. In 2020, only 6 % or 26 TWh were attributable to renewable energies. The various industrial sectors have extremely heterogeneous and multi-layered framework conditions and require individual supply: Steam, different pressure levels, direct heat from electricity, as well as constant demand or demand that varies over time. A mix of different renewable energy technologies in combination with efficiency measures is needed to cover the heat demand cost-effectively and reliably thus driving forward the decarbonization of the German industry. Renewable energies should be used in the truest sense of the words "steaming up".

The aim of this position paper is to place various low-carbon technologies in the context of the heat transition. In doing so, we shed light on which of the options may be implemented rapidly and how integra-

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[*] Corresponding author.
E-mail address: robert.pitz-paal@dlr.de (R. Pitz-Paal).

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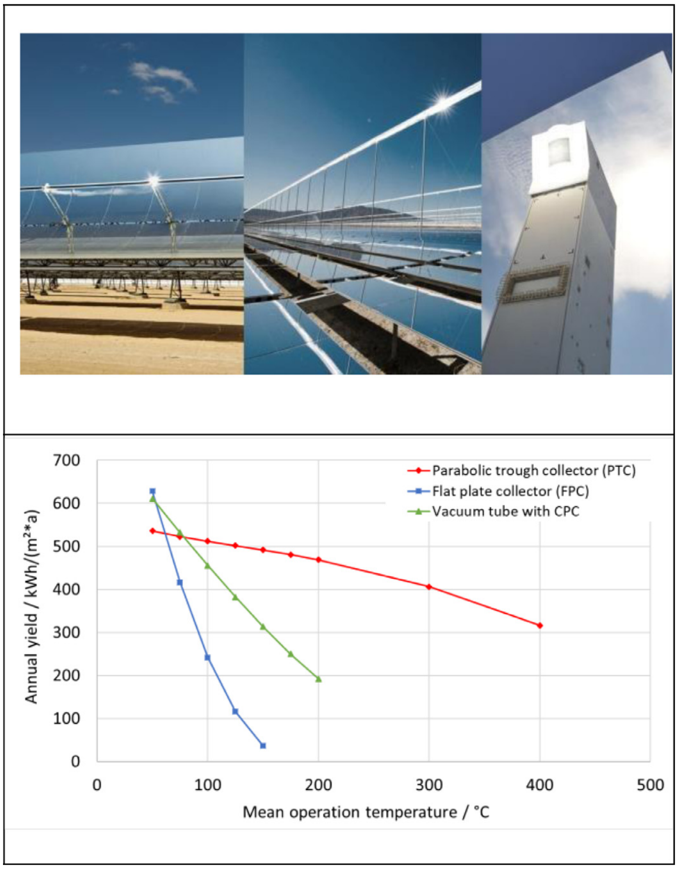


tion and interaction of the various technologies can contribute to a rapid replacement of fossil fuels for heat supply in industry. As the German industry association for Concentrated Solar Power (DCSP), we would also like to draw attention in this context to the potential of concentrating collectors for heat supply in Germany and Europe, a potential that has been underestimated in the past.

Concentrating solar thermal

Concentrating solar thermal energy is a technology that is established worldwide but little known in the German heating market. Parabolic troughs supply controllable heat between 50 and 430 °C in Central Europe and can therefore also be used in Germany in an economically viable way. This means that they can be used in a number of industrial sectors, e.g., in the food, textile, chemical and automotive industries. Thanks to the integration of heat storage systems, a high degree of solar coverage of up to 75 % can be achieved. The hybridization of a solar thermal plant with other renewable sources enables the year-round provision of renewable process heat.

The diagram on the left side [1] depicts the annual yield of different solar thermal collectors at a site in Germany (TMY Potsdam) as a function of the collector temperature. For a temperature above 80 °C Parabolic trough collectors provide a higher yield compared to flat plate or evacuated tube collectors. For larger collector areas (> 10,000 m^2), installation cost of 400 €/m^2 are estimated. At the currently high gas prices (140 €/MWh) in Germany and a 50 % investment federal subsidy a pay-back time of less than 3 years can be achieved.

2. Technical options for low-carbon heat supply to industry, availability and costs

An overview of the technologies considered here for decarbonizing the industrial heating sector is given in Table 1. The selected low-carbon technologies have been tested internationally, but are still hardly used in the German industry. A combination of these technologies offers the opportunity to meet the individual requirements of different industries with regard to their heating needs and to drive decarbonization forward.

Table 1
Overview of low-carbon technologies.

○ (Concentrating) solar thermal
○ Heat accumulator
○ Electric direct heating
○ Heat pump
○ Storage power plant (CHP)
○ Deep Geothermal
○ Bioenergy for industrial heat
○ Green hydrogen

Table 2
Criteria for the presentation and comparison of low-carbon technologies.

❖ Operating principle
❖ Temperature level
❖ Energy efficiency
❖ Technical availability
❖ Time availability - storage capacity
❖ Profitability (today)
❖ Land requirement (incl. power generation)
❖ Integration
❖ Potential Germany and Europe

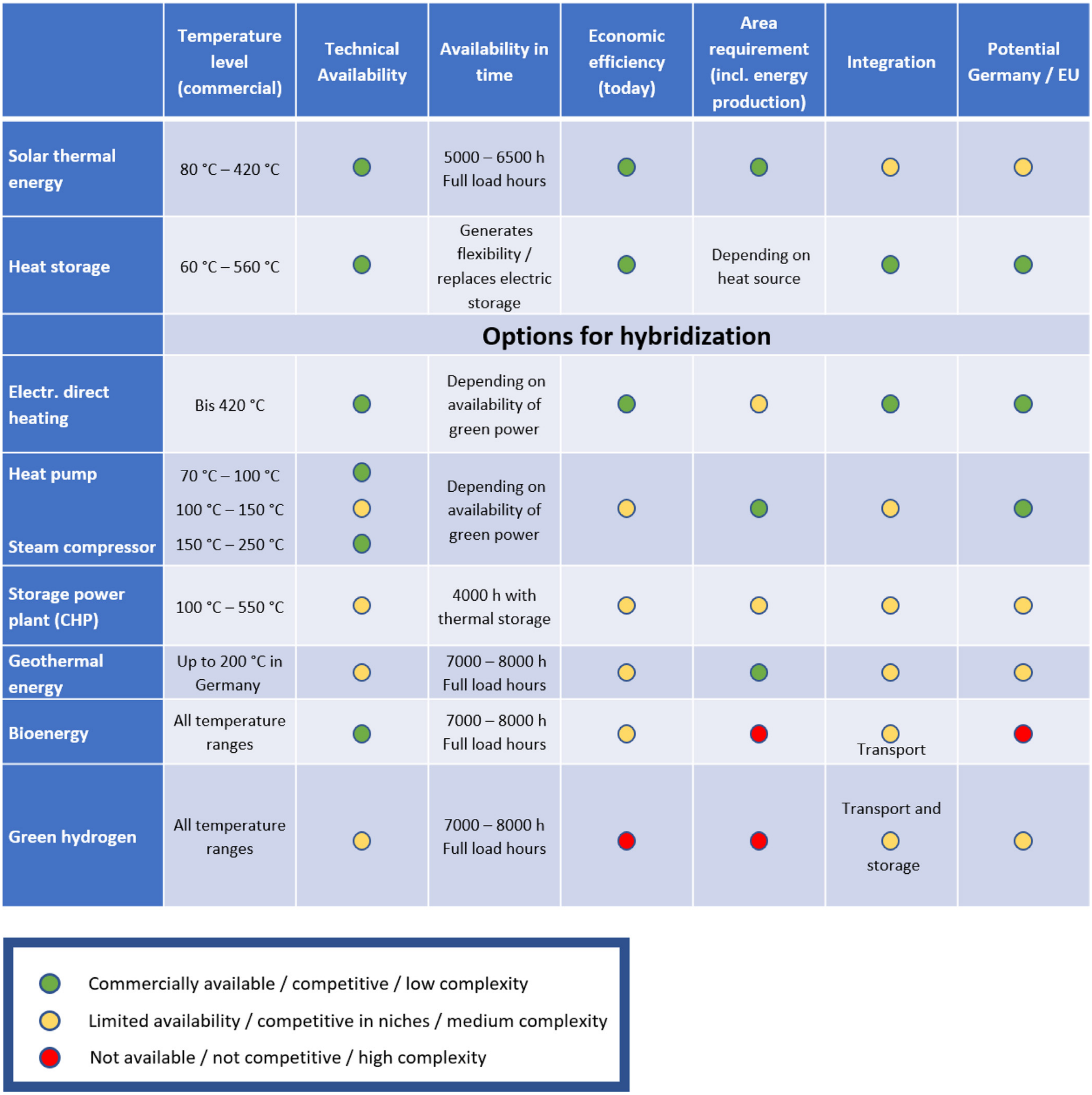
The technologies considered are described in terms of their functional principle and compared in terms of their technical maturity and application temperature. Important assessment criteria, such as area requirements, environmental properties, and the use of the technology, are also discussed, environmental properties, socio-economic aspects and cost-effectiveness in context (see Table 2). The respective assessments refer to the commercially available state of the art today. The in depths review on the low-carbon technologies is depicted in Appendix A. The estimates of the DCSP are further summarized in color-coded form in the following Table 3, which provides guidance for the selection of suitable technologies for selected industries.

3. Discussion

The evaluation matrix (Table 3) was drawn up on the basis of the explanations of the individual technologies in the appendix and shows a clear trend. In principle, all the technologies considered are already commercially available and in operation on a small scale (often up to 10 MW). However, only solar thermal, heat storage and direct electric heating in combination with renewable electricity are economically viable in the short term. These technologies can make a significant contribution to decarbonizing industrial heat demand, but must be supplemented with other options for full decarbonization.

The technologies currently under development for the use of industrial high-temperature heat pumps and the use of co-generation plants, which are about to be launched on the market, expand the possibilities of replacing larger shares of fossil energy sources at competitive costs. Geothermal energy can also make an additional contribution in the temperature range up to 200 °C, especially if the risks involved in tapping geothermal sources can be further reduced. The use of bioenergy is viewed critically due to its limited potential. Here, it seems more expedient to use the biomass potential for material use and for the production of synthetic fuels instead of simply burning the biomass. The use of green hydrogen currently fails not only because of its availability and the still missing infrastructures for transport and storage, but also because its costs are significantly higher compared to the other options. However, for the demand for high-temperature heat beyond 600 °C, green hydrogen may become a valid option.

Table 3
Assessment of low-carbon technologies for the industrial heat transition, status today.



	Temperature level (commercial)	Technical Availability	Availability in time	Economic efficiency (today)	Area requirement (incl. energy production)	Integration	Potential Germany / EU
Solar thermal energy	80 °C – 420 °C	🟢	5000 – 6500 h Full load hours	🟢	🟢	🟡	🟡
Heat storage	60 °C – 560 °C	🟢	Generates flexibility / replaces electric storage	🟢	Depending on heat source	🟢	🟢
	Options for hybridization						
Electr. direct heating	Bis 420 °C	🟢	Depending on availability of green power	🟢	🟡	🟢	🟢
Heat pump **Steam compressor**	70 °C – 100 °C 100 °C – 150 °C 150 °C – 250 °C	🟢 🟡 🟢	Depending on availability of green power	🟡	🟢	🟡	🟢
Storage power plant (CHP)	100 °C – 550 °C	🟡	4000 h with thermal storage	🟡	🟡	🟡	🟡
Geothermal energy	Up to 200 °C in Germany	🟡	7000 – 8000 h Full load hours	🟡	🟢	🟡	🟡
Bioenergy	All temperature ranges	🟢	7000 – 8000 h Full load hours	🟡	🔴	🟡 Transport	🔴
Green hydrogen	All temperature ranges	🟡	7000 – 8000 h Full load hours	🔴	🔴	Transport and 🟡 storage	🟡

🟢 Commercially available / competitive / low complexity
🟡 Limited availability / competitive in niches / medium complexity
🔴 Not available / not competitive / high complexity

To ensure security of supply through the technologies, diversity and versatility in the heating sector will be essential. In many cases, the problem cannot be solved cost-effectively with a single technology. To replace fossil fuels, a combination of different solutions tailored to specific requirements is needed. Storage technologies will ensure the supply of heat even beyond the fluctuations of electricity or direct heat generation and, just like direct heat producers, are part of the portfolio of low-carbon alternatives.

For every industrial company, it makes sense to plan this conversion step by step and to successively increase the share of renewable energies. In this way, technologies can be considered in the long term for which the current cost situation or infrastructure availability preclude their use.

4. Conclusion - recommendations for policy makers

The analysis of low-carbon technologies shows the fundamental feasibility of the heat transition in Germany, but also beyond national borders. Implementation can succeed in stages if accompanied in parallel by research and transfer activities. The achievable speed depends strongly on accompanying political measures.

The authors would like to make the following recommendations for action:

Development of target paths

- The rapid **phase-out of fossil heat** should be the goal of all upcoming legislative amendments. The fuel risk and the dependence on oil

and gas imports must be reduced as quickly as possible. To this end, the market ramp-up of climate-friendly heating technologies must be accelerated with vigour and at top speed;
- Anchoring of an **expansion target for renewable energies in process heat in** addition to the targets for renewable energies in the heat supply as a whole;
- Development of a catalogue of measures for the decarbonization of industry, which provides for a renewable hybrid supply portfolio based on comprehensive efficiency measures. In this portfolio, the possibilities of renewable heat sources and heat storage, technologies for electrification and green hydrogen are equally considered as solution options;
- **Technology openness** should be the central requirement. A one-sided focus on specific and individual technologies should be avoided. The ambitious expansion targets can only be achieved through the parallel use of all technologies.

Creating suitable framework conditions and incentives

- Anchoring renewable heating, cooling generation and storage technologies as an **essential pillar for decarbonizing industry**;
- Development of an **exempt heat tariff** or a **heat-guarantee price** to create investment security for the user side;
- **Adapt the promotion of** thermal, climate-friendly technologies to the current level of promotion of heat pumps or green hydrogen. A level playing field for CO_2-saving technologies that is open to all technologies is needed, flanked by appropriate **market incentive programs;**
- Adequate compensation for flexibility and grid-serving services;
- Implementation of **energy communities** for industry for low-threshold joint development of heat potentials and for greater acceptance of the use of renewable heat and waste heat;
- Faster **planning and approval processes**;
- Promotion of **digitization** in the industrial sector and in the context of approval procedures.

Promote innovation and create information offerings

- **Information campaign for the** use of thermal technologies and other technology options for decarbonizing industry for politicians, associations, engineering offices and multipliers;
- Promote **demonstration projects** to showcase solution options. With the aim of **accelerating the market ramp-up,** the focus should be on ensuring that the technology can be implemented and functions quickly on an industrial scale;
- Introduction of an **innovation bonus** for innovative technologies to reduce CO_2 emissions. The CO_2-abatement costs, for example, could be used as a criterion for this.

Consulting & concept creation

- Establishment of a **pool of consultants** for application- and system-oriented consulting. In the industrial segment, there are no one-size-fits-all solutions. This poses a considerable challenge for the industry in identifying a suitable combination of technologies;
- Promotion of **energy flow measurement** in industry, as the data situation at companies is often insufficient and thus many decarbonization and savings options remain unrecognized;
- **Promoting the development of solution concepts** for individual industrial sites and companies through free, pro-active initial consultation in the form of so-called funding/design checks.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Juliane Hinsch reports financial support was provided by DCSP. All authors reports a relationship with DSCP that includes: board membership.

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The authors thankfully acknowledge the work of the German Concentrated Solar Power (DCSP) industry association. This entity has been advocating the generation and use of electricity, heat, and fuels from concentrating solar technologies since 2013 in dialog with politics and administration, representing the strengths and interests of German market participants.

A. Appendix: Technical details

A.1. Solar thermal

Concentrating collectors such as parabolic troughs and Fresnel collectors as well as flat-plate and vacuum tube collectors use direct or diffuse solar radiation to provide heat in desired temperature ranges. This heat can be used to supply industrial processes, but also to generate electricity via downstream energy conversion.

The choice of collectors is a decisive factor for the **operating temperatures.** Concentrating collectors are available in various designs that differ in efficiency and price. They can provide heat on demand between 30 °C and approx. 420 °C for industrial processes. Flat-plate and evacuated tube collectors are well suited for operating temperatures up to approximately 120 °C. Both parabolic trough and Fresnel technologies are **mature and thus available,** but their design requires experienced engineering offices. As recent studies have shown, concentrating collectors can also provide heat cost-effectively in moderate climates such as Germany. Research is also being conducted into the provision of higher temperatures by solar tower systems in the Sun Belt.

By generating the heat themselves, the user has independent **availability**. The limited number of sunshine hours requires storage of the heat to increase availability. For this purpose, depending on the demand profile and the degree of coverage, daily, multi-day, or seasonal storage tanks are connected to the solar field.

At present, it is mainly plants from 1 MW upwards that are **economically viable.** For large plants with a collector area of 10,000 m^2 or more, parabolic trough collectors in **Germany** achieve heat production costs of 3 – 4 €Cent/kWh, which can still be significantly reduced by an approx. 50 % federal subsidy of the investment[1].

Due to the high thermal **efficiency** of approx. 70 %, parabolic trough collectors, like Fresnel collectors, require a small installation area, even taking into account the necessary distances to keep mutual shading low. Additional **land use** between the collectors, e.g., as a mowing meadow, also improves the ecological footprint.

The **integration of** heat from the solar field and storage tank is similar to that of a boiler and can be done in parallel. Typically, only one connection for flow and return has to be provided. A component of a solar system is always also a power transfer station. Temperatures are controlled according to the requirements for the feed, in the case of saturated steam feed via the pressure. For larger outputs, installation on open spaces will usually be necessary. Roof integration is possible for static collectors as well as for small parabolic trough and Fresnel collectors and for stationary collectors.

The availability of open space limits the **potential** for solar thermal energy to be used for industrial consumers. First commercial parabolic trough plants in Central Europe show a high thermal yield of more than 400 kWh/(m^{2*}a) at operating temperatures of about 250 °C in the collector field, confirming calculations in scientific studies [2].

The amount of energy provided by collectors depends on the technology used and the solar irradiation. All technologies are treated in the same test standards and certificates and are therefore easily comparable with each other. For the determination of solar yields, heat costs, and the comparison of solar thermal with e.g., fossil systems, the use of simulation software like Greenius and SAM (both freeware) is required.

A.2. Heat storage

Heat storage systems are used as power storage systems for short-term storage of surplus power or as energy storage systems for longer-term storage of heat. The storage time for seasonal storage in solar heating networks is several months. Heat storage systems allow heat to be supplied on demand, even if heat demand and generation are not present at the same time. They thus increase the flexibility of heat supply and expand the possibilities for use even with fluctuating heat sources or generators. The integration of storage systems depends on the storage medium, heat transfer medium and temperature range. It is possible with existing or new systems without any problems using widely available heat exchangers. The most important heat storage technologies available on the market are briefly described below.

Hot water storage tank – heat is stored as hot water with temperatures up to 95 °C without pressure and up to 130 °C in the pressure vessel (pressure 3 - 5 bar) and mainly used for district heating/hot water systems. The heat content depends on the lower storage temperature. Realized storage volumes (unpressurized) depend on the type of construction: tank material steel up to 200 m^3, reinforced concrete tanks up to 12,000 m^3, earth basin storage up to 200,000 m^3 (equivalent to 15 GWh_{th}). In combination with electric-rod boilers, pressure-resistant steel storage tanks below 100 m^3 are possible. The cost of water storage is largely dependent on the size: While costs of about 15 €/kWh are still to be applied for small buffer storage tanks of 1 m^3, this value is halved for 20 m^3 size. For larger underground storage tanks, this value drops to about 0.5 €/KWh [3].

The Ruth accumulator is a pressure-resistant steel steam accumulator in which water is stored in the boiling state (e.g., at 200 °C at 15 bar). It is used as a power accumulator. A typical design ranges from 15 min to 1 h in heat storage; otherwise the volumes become too large [4]. This type of storage is unsuitable for long-term storage because of the high investment costs (about 100 €/kWh).

Molten salt storage with molten nitrate salts as the liquid storage medium stores high-temperature heat from biomass combustion or concentrating collectors, which indirectly transfers the heat to the molten salt by means of intermediate heat transfer fluids or directly. Depending on the heat transfer fluid, temperatures up to 550 °C are possible. The lower temperature is determined by the melting point of the salt and must be well above this. CSP plants with thermal oil as heat transfer fluid (parabolic trough) operated an indirect 2-tank system between 280 °C and 380 °C, while CSP with molten salt as heat transfer fluid (tower, Fresnel) operated a direct 2-tank system between 280 °C and 550 °C. Modular storage systems with several GWh_{th} have been realized. The cost per stored energy content depends here on the selected temperature spread. While the indirect system with $\Delta T = 100$ K achieves about 40 €/kWh, this value drops to 15 €/kWh for the direct system with $\Delta T = 270$ K. At the time of writing, typical capital costs of large-scale molten salt storage systems range from 15 to 80 €/kWh_{th} depending on parameters such as scope of delivery, capacity and power level as well as the temperature difference between hot and cold tank [5].

High-temperature solid-state storage systems in combination with air as a heat transfer medium are used commercially as regenerators in individual applications, for example in the steel or glass industry or for exhaust air purification. Air flows through bricks, bulk material or honeycomb structures and heats them up to 800 °C [6]. A new application is power-to-heat at the electric thermal heat storage (ETES) brick store with an air system that is heated by electricity and then transfers the heat to a waste heat boiler. This generates steam, which can then either be used directly in the process or expanded via a steam turbine to generate electricity. An initial test plant (2.5 MW_{el}, 30 MWh_{el}) has been in operation in Hamburg for several years.

A.3. Electric direct heating

In an electrically heated heat transfer system, heat is introduced into the heat transfer medium by means of one or more heating flanges. Depending on the availability of electricity from renewable sources, outputs of several megawatts can be generated in a carbon-neutral manner. Furthermore, in contrast to fossil-fired heating systems, electric direct heating systems have a higher degree of control accuracy and do not require a separate boiler room, thus giving the industrial company greater flexibility in integrating them into the production processes.

Water, steam, molten salt, air, or heat transfer oils can be used as heat transfer media. When using silicone heat transfer oils, for example, a **temperature level** of up to 420 °C can be achieved. Energy losses are only present in the form of radiation heat. Depending on the system insulation, an **efficiency of** 98 % can be achieved without great effort.

The technologies used, such as heating flanges, pumps, and instrumentation, are mature and **have been available on the market** for **years.** By applying the regulations and standards that are mandatory in each country, a very high safety standard can be guaranteed with simultaneous automated operation.

Due to the small space requirement and the high power and temperature ranges, electric direct heating systems can **replace** fossil heating systems with relatively **little effort**. In addition to CO_2 neutrality, this also reduces or eliminates dependence on gas or oil for industrial operations.

The **investment costs are** slightly higher than for fossil heating systems. Although the burner for burning the fossil fuels is not required, which represents a large cost block, the electrical components, which are required due to the power interconnection, are investment-intensive. Overall, the **economic efficiency** compared to fossil energy generation is very good due to the relatively low investment costs, short project implementation phase and low maintenance costs.

The **space requirement of** an electric heater is smaller than that of a fossil heater, which means that it can be easily integrated into the production process of the industrial plant. Outdoor installation with a roof or in a container is also possible.

Example: A 2.5 MW electric heater can be accommodated in a 40-foot container [7].

In addition, the area required for power generation, for example by photovoltaics, must be taken into account. The temporal availability of the heat energy generated by the electric heater cannot be answered in a general way, but depends on the availability of renewable electricity generation.

The **integration of** the electric heater in combination with concentrating collectors and thermal storage allows a high degree of independence from the power grid while at the same time providing security of supply for the industrial processes. The **operating risk** is considered low due to the mature technology. The conversion and embedding must be well planned to minimize production downtime.

The **potential** in Germany and Europe is very high, since process heat by fossil heating is widespread. The pressure of suffering due to the ecological and geopolitical risks will therefore induce many industrial companies to switch to electrically heated plants.

A.4. Heat pumps

Heat pumps (HP) generate useful heat using electricity by transforming heat at lower temperatures (heat source) into heat at the useful temperature. There are significant differences in terms of application (building heating vs. industrial use) and temperature levels.

In general, a distinction can be made between HPs for useful temperatures up to 100 °C (established technology), high temperatures up to 150 °C (demonstration) and very high temperatures above 150 °C (isolated plants). Steam generation with temperatures up to 250 °C is feasible by combination with a steam compressor.

The ratio of useful heat to electrical energy used, a key figure for the **efficiency of** the heat pump (Coefficient of Performance, COP), decreases with increasing temperature difference (temperature deviation) between heat source and heat sink (useful temperature) and also depends strongly on the useful temperature itself and the media involved. Typical values of commercial systems for building heating are in the range of COP approx. 4 - 6 at a temperature swing of 40 - 20 K. For industrial systems, a much higher temperature swing can be found. Here, depending on the size of the system, the COP can vary between 5.8 and 1.6 for a temperature swing of 25 - 130 K. HPs for **useful temperatures** up to 100 °C use ambient or waste heat as a heat source, have a very high degree of maturity and are widely used today in the field of building heating. Large-scale HPs with high capacities have been in operation in Scandinavia (up to 85 °C) since the 1980s [8].

Industrial HPs for useful temperatures up to 150 °C are under development and the first demonstration plants are being built. Typical power classes in the range of 50 kW - 10 MW (thermal useful energy) are available, but plants up to 50 MW have also been announced. A challenge for the application is to provide or to develop suitable heat sources on a medium temperature level. HPs provide useful heat **flexibly and according to demand as** long as the applied electricity (grid) and the heat source are available. In case of a fluctuating heat source, heat recovery units can be used. As a rule, HPs are at full load within 15 min from the cold state and their output can be varied by more than 10 %/min.

The **costs of** a heat supply with HP are strongly dependent on the electricity price, the boundary conditions in operation (full or partial load operation) as well as on the power class and the associated development of the necessary heat sources. Thus, the share of the HP unit can be reduced to 1/3 of the total investment costs with increasing power class. Here, the investments in infrastructure, source development and integration come more to the fore. HPs are compact systems with manageable **space requirements**; proximity to the heat source and the consumer of the useful heat is favourable. Limited distances can be bridged with heat pipes, if necessary.

In principle, heat pumps can be **well integrated** and are usually adapted to the temperature level of the useful heat and the available source. The **operating risk** lies in the reliable provision of the suitable heat source and renewable electricity at predictable costs. The **potential for** the use of HP up to 150 °C in German industry is estimated as 6 GW_{th}, in the EU 28 GW_{th}. The use of a steam compressor up to 250 °C would double the potential. HPs can in principle be hybridized with heat from solar thermal and heat storage, for which various concepts and interconnections are possible for different temperature levels.

A.5. Storage power plants

A storage power plant uses renewable electricity to drive a conventional power plant process (steam power plant). The power plant itself is operated as a CHP plant (combined heat and power), so that heat can be extracted from the turbine at different temperature levels. The proportion between heat extraction and electricity generation can be flexibly adjusted to demand. Heat is converted into electricity by direct heating or, in perspective, by means of a heat pump. The generated heat can be buffered in a thermal storage and allows flexible operation.

Heat is supplied in the form of steam at various pressure and **temperature levels** resulting from the steam parameters of the power plant. This typically covers the range between 100 °C - 550 °C. The degree of conversion from heat to electricity (without heat utilization) is between 40 % (electric heaters) and in the future 60 - 70 % (with heat pumps). If additional heat is used, **utilization rates of** over 90 % are possible.

Storage power plants with electric heaters are based on **commercially available** components. However, no commercial reference systems exist yet. Suitable high-temperature heat pumps with an application temperature above 400 °C will only be ready for the market in about 5-10 years.

With storage power plants, electricity and heat can be provided with **very high full-load hours** through the dimensioning of the thermal energy storage, thus guaranteeing a high level of supply security.

The costs for the renewable electricity, for the electric heater (or in the future the heat pump), the power plant and the thermal storage are the main cost components. Lowest **total costs** result if an existing power plant can be converted. DLR estimated them at 10 - 14 €Cents/kWh (without heat utilization).

The **area required for** the provision of renewable electricity by wind or PV is the essential part. These plants can be installed spatially distant from the storage power plant if there is a grid connection with sufficient capacity.

Integration is particularly easy if a conventional power plant already used to supply heat and electricity to the industrial plant can be converted. The **operational risk** lies in the reliable supply of renewable electricity at predictable costs. The **potential** for retrofitting CHP plants in industry in Germany is in the medium range due to the necessary couplings.

A.6. Geothermal energy

Deep geothermal energy uses thermal water from tapped deposits at depths below 400 meters. The prerequisite for a hydrothermal system is a productive, water-bearing rock layer. In most cases, the thermal water is used with two or more boreholes. A so-called doublet consists of a production well and an injection well. The hot thermal water is pumped to the surface via the production well and the heat stored in it is extracted via a heat exchanger. The cooled thermal water is then returned to the subsurface via the injection well. In geothermal energy, the underground storage of heat plays an important role. It is the only way to store large quantities of heat in the long term. Liquid energy carriers (thermal water) are stored in natural or artificially created cavities in deep geological formations or aquifers.

The possible temperatures that can be reached are highly dependent on the location and the nature of the substrate. The upper limit is likely to be in the range around 200 °C. Industrial processes in the **lower to medium temperature range** (e.g., drying processes) can be served. If required, heat pumps can be used to raise the temperature level. The technology is **highly efficient**. In the field of deep geothermal energy, up to 30 kWh of constant heat can be provided using 1 kWh of electricity.

Across Germany, there are already 42 plants **in operation** – of which 30 are heating plants, 3 are power plants and 9 are combined heat and power plants (heat + power) with a heat output of approx. 350 MW and an installed electrical output of 47 MW. A major advantage is the **base-load capability of** the technology, which means that it is not subject to daily, seasonal or weather fluctuations. This predictability and the low operating costs, also due to the high efficiency, have a positive effect on the payback calculation.

It is characteristic for geothermal heat projects that 50 % of the total investment (drilling, surface systems, first phase of grid expansion) is incurred in the first years of the project. Positive operating results and cost-covering revenues from heat sales are achieved with a significant time lag. Geothermal heat supply - like any other infrastructure measure - requires a very long-term view and capital commitment (30 years and longer).

Since a large part of geothermal systems is installed underground, the **land requirement** per kWh is the lowest of all technologies considered. **Integration** is easy when geothermal heat generation plants are connected to existing heating networks.

The greatest financial **risks** are associated with discoverability if an economically insufficient thermal water production rate is achieved and/or an insufficient temperature is encountered during the development of a geothermal resource. The exploration risk can be significantly reduced by high-quality forecasting (subsurface knowledge). Drilling risks refer to drilling time extension or material loss, which is currently only partially insurable. Environmental risks refer to a possible impairment of the subsurface or groundwater as a result of thermal water drilling. This risk can be significantly reduced by trained personnel and professional well design.

The **potential of** deep hydrothermal geothermal energy is estimated in a recent study by the Fraunhofer-Gesellschaft and the Helmholtz Association at 300 TWh of annual energy or 70 GW of installed capacity. Suitable areas are mainly located in the North German Plain, the Upper Rhine Graben and the South German Molasse Basin.

A.7. Bioenergy

Bioenergy comprises three areas: Solid biomass (esp. wood), biomethane, and the combustion of residual and waste materials with biogenic components. For the use of bioenergy for the provision of industrial process heat, only biomass from waste, residual and damaged wood is considered, in order to avoid land use competition for food production and material use. As a rule, energy is made available from thermal processes and combustion. The **temperature ranges** from low heating temperatures to the highest combustion temperatures and differ due to the processes and areas of application.

Biomass combustion has been **in use for many years** and can be efficiently combined with other technologies. With biomass boilers in the process heat sector, steam temperatures of up to > 200°C can be provided 24/7 365 days a year if sufficient resources are available. The use of biogas or biomethane in industry is obvious, whereby the availability of bio-recyclable materials as a waste product from production is a prerequisite for in-house production. The use of residual materials as fuel for electricity and steam generation is a technology that has been tried and tested for decades. Steam can also be transported over some distances via heat networks [9].

Bioenergy plants are **economical** if they use residual and waste materials or production residues from the company's own operations. In regions with high biomass availability, bioenergy is an economical option. Current price developments are based on the availability of the biomass used.

The **land requirement** of the technology itself is low, but the land requirement for biomass supply differs greatly. The solid biomass used for medium-temperature heat consists almost exclusively of old and damaged wood as well as residual materials from the forestry industry and wood processing industry, for which no additional land is consumed [10]. Here, however, the regional availability has to be considered. In the high-temperature range, the use of biogas or biomethane is necessary, which is currently obtained in many cases from cultivated biomass, which has a comparatively high land consumption. The use of landscape management material, forest residues and thinning material does not require additional land. Areas for the location of the fuel at the plant must be taken into account [11].

The **integration capability of** all three areas can be described as technically common, but also represents a complexity.

The purchase of biogas via the gas grid is possible, but can vary greatly in terms of availability and price. For plants near residential areas, the acceptance is rather questionable, therefore the use of bioenergy is rather interesting for new plants in the countryside and in industrial areas.

The **potential of** bioenergy from waste and residual materials for decarbonization in process heat demand is limited due to the availability of biomass[8]. However, it contributes significantly to the decarbonization of industry regardless of the weather and through established processes, especially in combination with the other technologies listed here [12].

A.8. Green hydrogen

Green hydrogen can be produced by the electrolysis of water using renewable electricity. Since many existing industrial process heat plants (gas/oil-fired) can be easily converted to hydrogen operation, **almost all desired process temperatures can be provided.**

The **efficiency of** converting renewable electricity into hydrogen is between 65 and 80 %, depending on the technology and mode of operation (excluding distance-dependent transport losses). Green hydrogen production is in the **market introduction phase**. Currently, green hydrogen is not yet available on the market in relevant quantities; only 10 MW-scale plants are in operation. Plants on a 100 MW scale are currently still in the project planning phase. Today, there is hardly any infrastructure available for the transport of green hydrogen, but a retrofit of the gas grid is possible. Political support measures are expected to lead to significant cost reductions and infrastructure expansion in the future [13]

Since hydrogen is a chemical energy storage medium, it allows the same **flexibility of use as** natural gas, for example. However, transport and storage are associated with higher costs. The **total costs for** green hydrogen therefore depend on the price of renewable electricity, the investment costs of the electrolyzer and the achievable full load hours. These result from the choice of technology (PV, wind, CSP), the storage technology used and the location. Today, they are above 6 €/kg and thus at least twice as expensive as fossil alternatives [14].

The **land required** for green hydrogen production is about twice that of renewable electricity because of the associated conversion losses during production and transport. Domestic land is only expected to be sufficient to meet a maximum of 50 % of the demand to produce green hydrogen. It is expected that large parts of green hydrogen will have to be imported. Its **availability** and cost may therefore develop volatilely [15].

Transport and storage of hydrogen are the **main challenges** in the integration of hydrogen. If the hydrogen is located in the industrial plant, it is relatively easy to use it by converting existing plants. Technically, a large part of the industrial heat demand could be generated by green hydrogen. However, this is likely to be a very expensive approach compared to other technologies, with the risk that corresponding **production sites** will be **relocated.**

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