A review of power to heat technologies according to the process temperature to be reached in the range from 40 °C to more 1500 °C incl. reachable technology efficiencies

Torsten Buddenberg, Sven Bosser and Emmanouil Kakaras

Introduction

In the energy transition electrification of processes will gain importance to avoid indirect and direct greenhouse gas emissions of fossil combustion. As higher the process temperature is as more difficult the electrification is. As for room heating the heat pump is an established technology it is not easily to be used for temperatures more than 200 °C. For higher temperatures the technologies get divers and can be electric boilers (up to 300 °C) or direct ohmic heaters (up to 1100 °C). Current work in research and development is moving already towards heat pumps with temperatures up to 500 °C. To replace direct gas burners in furnaces or similar processes (melting of metals, in temperature ranges up to 1500 °C or even 2200 °C) ohmic heaters must be replaced by other technologies as microwave plasma heaters, induction gas heaters or else. All main technology routes will be mapped incl. their reachable coefficients of performance, their reachable temperatures. This will be compared to the use of fuel replacement by hydrogen or biogas and will be projected to the heat use in Germany. Also, power to heat to power will be discussed [1].

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Power to Heat Technologies for Electrification

As mentioned in the introduction the understanding of the possibilities of the power to heat processes is necessary. It must be understood how these can be seen in relation to the standard technologies as natural/biogenic gas use or the option to use electric generated green hydrogen as replacement fuel. To review this, we must understand that there are wide options for electrification and related electrification technologies [2]. Today´s electric heat generating technologies in use are already heat pumps up to 200 °C incl. mechanical vapour recompression, electric steam generators up to 300 °C, infrared heaters up to 1000 °C, microwave heaters for temperature >1000 °C, induction furnaces for temperature >1000 °C, resistance furnaces for temperature >1000 °C, electric arc furnaces for temperature >1000 °C and plasma technologies for temperature >1000 °C. With some engineering also gas heating can be performed by resistance, induction, or microwave plasma technology. So, in general there is an open toolbox to replace any fuel used for process heat by direct electricity use. Of course, this does not count for process heat, where the fuel is additionally used for chemical reactions as reduction of iron oxides to iron in steel industry. In those cases, green hydrogen is the reduction agent of choice [3]. The comparison of the electric solution with direct fuel fired solutions has also to consider that usually the fired solution has a significant energy loss by the exhaust gas of the system, which becomes higher as higher the needed process temperature is [4]. This disadvantage can be avoided for electric heated processes, because here an exhaust gas recirculation can avoid this loss and minimise the process loss to system radiation and used process energy for heating, evaporation, or else process related consumption.

The current article is too short to discuss all the mentioned technologies and the authors decided to focus on some, which will be the most important to show the possibilities of electrification of heat. These technologies are heat pumps, ohmic heaters, which include electric steam generators, and induction gas heating devices, which are mainly competing to microwave plasma gas heating for hot gas generation. The microwave plasma gas heating is here only mentioned but excluded from the detailed discussion. This is for the main reason that for larger outputs in the megawatt range the needed magnetrons are getting in the range of magnetrons for military use, which makes it beside the high cost difficult that there will be in future a significant usage in the industry.

Heat Pumps

Heat pumps today are for room heating a standard technology and gaining more and more importance already also in large scale for district heating and are developed to commercial scale up to process heat temperatures of 200 °C as process steam [5,6]. The coefficient of performance for heating ($COP_{Heating}$) of heat pumps, which is used as

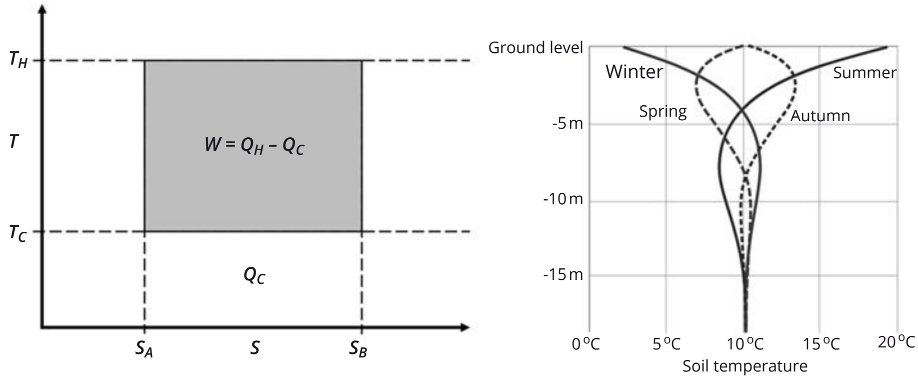

Fig. 1. Carnot Cycle in T, s – Diagram and the 15 m Depth geothermal Temperature for TC [A].

the main performance factor for heat pumps can be defined from the Carnot cycle efficiency as the theoretical optimum. This is multiplied with the reached system efficiency with is the quotient between the electrical energy necessary according to the Carnot cycle and the real system consumption. As lower temperature in the Carnot cycle (T_C) 10 °C (283 K) is used in the basic calculation of this publication because this is the geothermal constant temperature, which can be found at any location independent from the geographical location [A]. This can be seen as a worst-case scenario and usually the reachable COP is higher, because for the heat source higher temperatures are available.

Please find here Figure 1 and formulas 1-3 showing the principle of the Carnot cycle and how to use it for brief process calculations.

(1) $$\eta_{Carnot} = \frac{T_H - T_C}{T_H}$$

(2) $$\eta_{System} = \frac{W_{Carnot}}{W_{System}}$$

(3) $$COP_{Heating} = \frac{\eta_{System}}{\eta_{Carnot}}$$

To make more detailed calculations in this, review the mentioned literature and previous publications on this topic [7,8,9]. System efficiencies are here reported with 55-65 % for the best available technology of heat pumps. It is obvious that the design of heat pumps is depending on many parameters individual for the use case, where the main selection must be taken on the refrigerant, the heat pump process, and the chosen compressor technology. For higher temperatures a heat pump can be a cascade of heat pumps to reach the full temperature lift.

An example here is steam generating heat pump with one heat pump for the atmospheric water evaporation and a second heat pump for steam compression to the target steam pressure [10]. This heat pump is operating with R600a (Iso-Butane) as refrigerant on the lower cycle and R718 (Water) on the upper cycle – the steam compression. In the mentioned literature the full equations for the system calculation are given. Figure 2 is showing the brief process flow and an arrangement plan.

Independent from the chosen process and the reachable COP the limiting factor for the heat pump is the allowed compressor exit temperature. Commonly here are mentioned 280 °C for compressor standard materials, but this is not the real limit. Compressors working in gas turbines already today reach much higher temperatures of approx. 500 °C, but are not limited to this [11,12]. The literature mentions here about 670 °C as today max. material temperature. Figure 3 shows an example for a very high temperature heat pump process with Argon as refrigerant and the environment as heat source [13]. Such heat pumps with temperatures much above 200 °C are today not state or the art, but there is no real research necessary to build such machines. The design of such a heat pump type is engineering because all processes are known and the materials used are proven in industry. Therefore, the technical readiness level acc. to EU standard is TRL 7-8.

Electrical Ohmic Heaters

Ohmic heating elements are used in electrical radiation furnaces and are used in inert

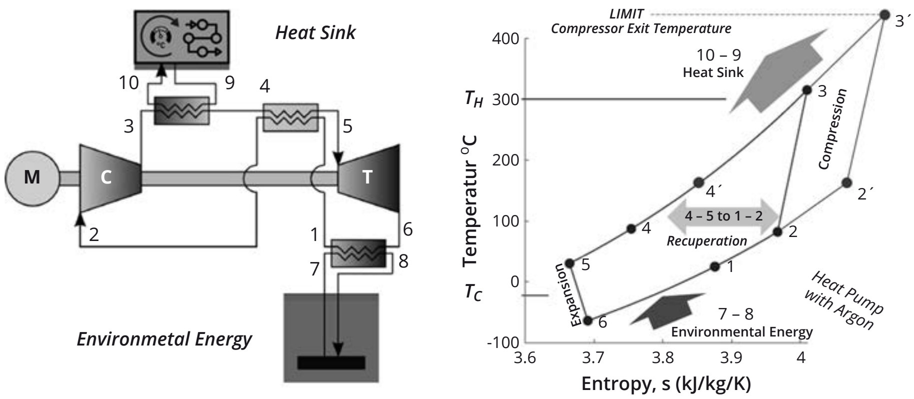

Fig. 3. VHT Heat Pump based on cold/hot Gas Process with av. Temperature lift > 300 °C.

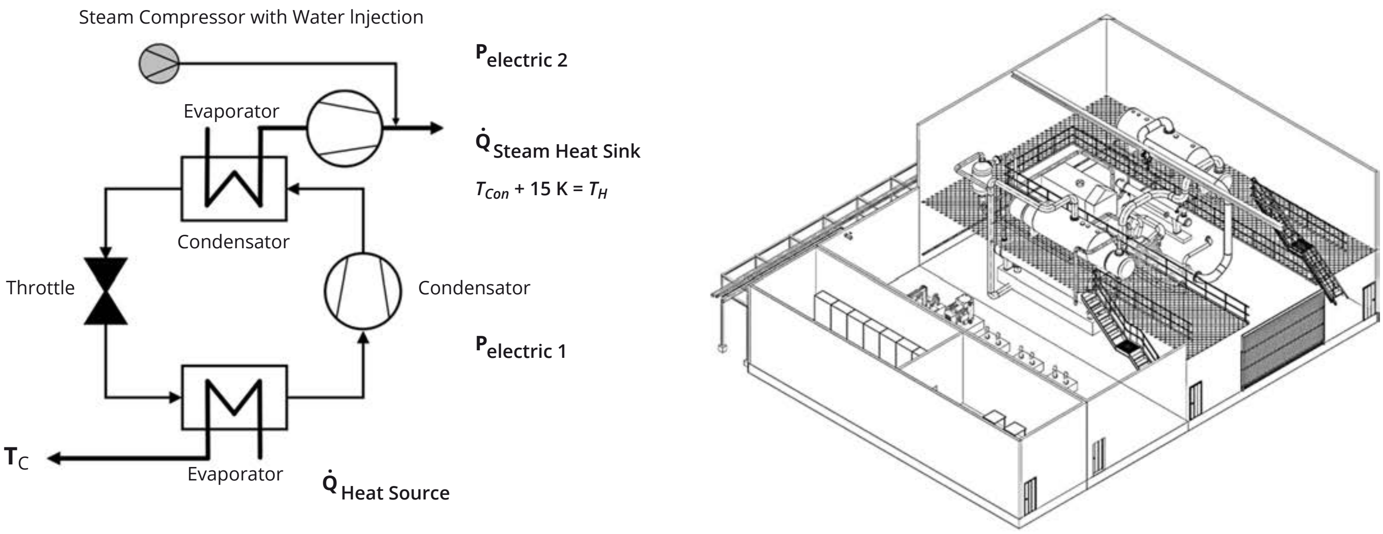

Fig. 2. Process Flow Diagram and Arrangement Plan of Steam generating Heat Pump [11].

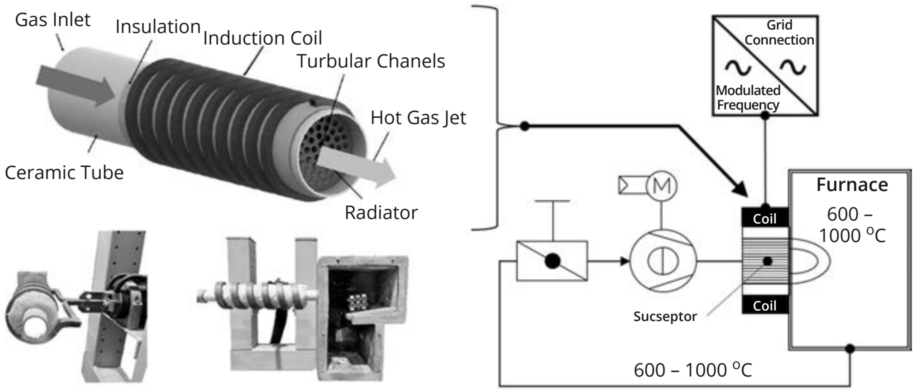

Fig. 4. Ultra-High-Temperature (UHT)-Thermo-Jet Test Facility for Aluminium Smelting Tests [15].

atmospheres up to temperature above 2000 °C, but this is a special use for special applications. Otherwise ohmic heaters are mainly known as electric boiler and are also known as electrode boilers, which have been in use since the late 1930[th] [14]. These can produce steam with pressures up to any pressure but are usually around 85 bar(a) and 300 °C. Also, electrical steam superheating is a standard application. Other ohmic heaters for gas heating are known as duct heaters in e.g. ventilation systems and are today for low pressure or atmospheric hot gas (air) generation up to 600 °C a standard solution [15]. In this low temperature range the losses for the heat generation are very low and efficiencies of >95 % are reachable. Even higher temperatures can be reached with ohmic heating but for temperatures above 650 °C the losses are getting higher for construction reasons in the arrangement of the heating elements in the heating device and the also the necessary construction volume is increasing significantly. On commercial basis heaters up to 1100 °C in the kW-range are known to the authors, but also bigger with higher temperatures are in the development and are currently at a technical readiness level (TRL) of 4-5.

Heating gases containing oxygen and/or water vapour to high temperature above 650 °C the heating elements must be very corrosion resistant and this is the main difficulty in the design of such devices. This topic of corrosion resistant materials for the design of ohmic heating elements is not further discussed here, because it is an own field of research and it would lead to far for this article to discuss this point further. We only note there are design materials for ultra-high temperatures (UHT) above 1500 °C, which are either ceramic coated metal or electric conduction ultra-high temperature ceramics [16,17]. Here is also the cross point with the next section the induction gas heating, because here the same corrosion problems are observed.

In both cases the material shall be an electrical conductor, but with high ohmic resistance (ρ) or low electric conductivity ($\kappa = \rho^{-1}$) to have high energy density and high efficiency in power to heat. The system efficiencies for ohmic heating can be expected to be at 95-99 % for temperatures up to 300 °C, at approx. 85-90 % for high temperatures up to 1000 °C and are dropping to 70-80 % for ultra-high temperatures above 1000 °C.

$$(4)\quad Q_{\text{Ohmic Heat}}(I, T_{high}) = \frac{I^2\,[A] \times L_{Element}\,[m]}{\kappa(T_{high})\left[\frac{1}{\Omega m}\right] \times A[m^2]} \times \eta_{\text{System}}$$

(with κ = elctrical Conductivity)

In the formula 4 can be observed why the conductivity is preferred to be low, because it is in the denominator of the formula. The system efficiency here is dropping with the final exit temperature, because the unused parts of the heating elements, which are covered by the duct insulation is getting larger with the temperature supplied.

Electrical Induction Gas Heaters

Electrical Induction Gas Heaters today are under development for the replacement of natural gas burners in various industries as aluminium industry, steel industry or ceramic/cement industry [18]. There the technology shall deliver ultra-high process heat without direct greenhouse gas emissions.

Figure 4 is showing the basic principle of such devices and is showing that a susceptor material is inductive heated by an electric coil and from this the gas stream reheated is taking the energy by convective heat transfer. Here the main losses are caused by the electrical losses of the inverter system and the efficiency of the induction. This is shown in its basic principle in the formulas 5 and 6. These also give the evidence that also for induction heated systems the material conductivity shall be low, because it is also here located in the denominator.

$$(5)\quad Q_{\text{Induction Heat}}(I, T_{low}) = \frac{I^2\,[A] \times L_{Coil}\,[m]}{\kappa(T_{low})\left[\frac{1}{\Omega m}\right] \times A[m^2]} \times \eta_{\text{Induction}}$$

(with κ = elctrical Conductivity)

$$(6)\quad \eta_{\text{Induction}} = \frac{\sqrt{\kappa(T_{low})_{\text{Induction-Coil}}}}{\sqrt{\kappa(T_{low})_{\text{Induction-Coil}}} + \sqrt{\kappa(T_{high})_{\text{Susceptor}}}}$$

$$\times\ \eta_{System} \geq 80\,\%$$

The real losses of such systems are still under investigation in research and development, but our newest work shows that for such systems the efficiencies in the ultra-high temperature range are expected to be higher compared to the ohmic heating systems. These findings are used in the following.

One advantage of electric heating as replacement of natural gas versus the replacement by hydrogen. Contrary to hydrogen the electric heating is not changing the atmosphere used today. This advantage is significant, because changing hot gas composition has influence e.g. on corrosion processes, material qualification processes and a lot of other process parameters. This can not be discussed here in detail but is of high value in process variation.

Power to Heat Technology Mapping

Figure 5 is showing the mapping of all such devices with conservative performance assumptions and a heat source temperature of 10 °C for the heat pumps, while these are compared to the reachable efficiencies of natural/biogenic gas process heating and process heating based on green hydrogen or its derivates as ammonia or methanol. For the hydrogen generation good performance electrolysers are assumed with an efficiency of 68 % of output of lower heating value of hydrogen versus the power feed from the grid. In this comparison, the hydrogen is also seen as a power to heat device.

For other modeling from the data also an approximate solution for average coefficient of performances (COPs) can be derived and are converged in the formulas 7-9. These formulas do not reflect the full truth but are very helpful to judge in basic models the behaviour of technology decisions.

$$(7)\quad COP_{\text{Electrification}} = \left[0.6 \times \frac{T+273}{T} + 0.7 \times \frac{T}{2200}\right] \qquad \pm 7\%$$

$$(8)\quad COP_{\text{Biogas}} = \left[-\frac{80}{1000} \times \ln(T) + \frac{1271}{1000}\right] \qquad \pm 3\%$$

$$(9)\quad COP_{\text{Hydrogen}} = \left[-\frac{56}{1000} \times \ln(T) + \frac{884}{1000}\right] \qquad \pm 5\%$$

For an example of the usage of the formula set in Table 1 is shown how much energy as electric power is used by the electrification device in comparison to either natural/biogas as lower heating value or electric power used for the electrolysis of hydrogen. This is calculated for relevant process temperatures and it can be shown that the energy use is always lower and mostly even significant lower in the comparison.

This makes to the opinion of the authors the usage of electrification of process heat very attractive in comparison to the use of hydrogen as fuel for process heat generation.

Discussion of a possible Electrification Impact in the Example of Germany

In the year 2021 the usage of primary energy in Germany was as shown in Figure 6 [19,20]. Electricity is not the main energy consumption. Compared to the electric

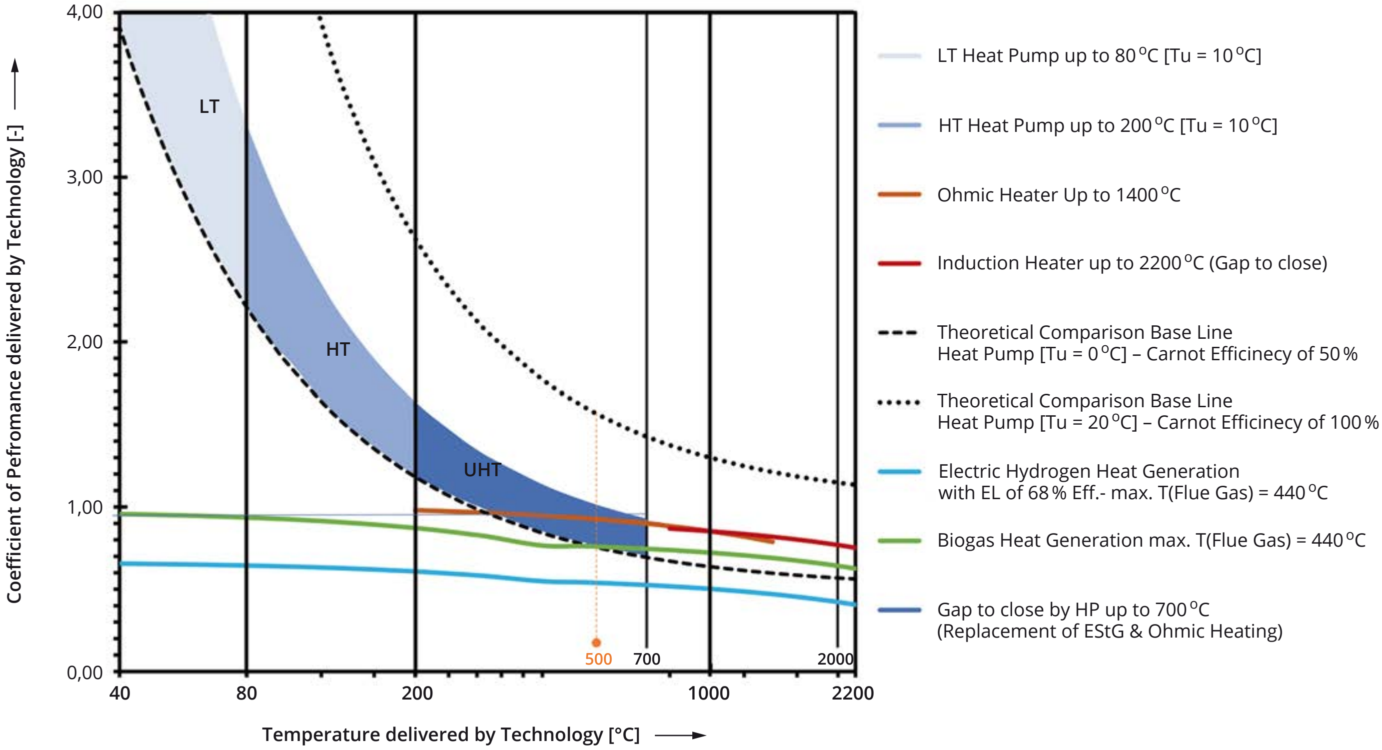

Fig. 5. Power to heat technologies versus fired heat generation – A mapping showing its options.

Tab. 1. Comparison table for energy demand of electrification vs. gas firing or green hydrogen firing.

Needed Process/Room Temperature in °C	70	100	200	400	800	1000	> 1000
Electrical Power for P2H instead of Biogas LHV	32 %	40 %	59 %	77 %	89 %	90 %	91 %
Electrical Power for P2H instead of Electrolyser Power	22 %	28 %	41 %	53 %	61 %	62 %	63 %

consumption (≈ 480 TWh) the usage of heat (≈ 1240 TWh) is going with a factor 2.6, while at the same time the system losses (≈ 740 TWh) are mainly caused by the efficiency losses of fossil power generation. The most heat is used at a temperature below 100 °C and for this reason has the option be stored in hot water or other low temperature heat storages. Only 25 % (≈ 310 TWh) of the total used heat is consumed above 100 °C.
Now this data is used for a thought experiment. It is assumed that these heats are produces by electrification, while at the same time 80 % of the direct consumptions of the mobility are replaced by electric mobility under the assumption of double energy efficiency of battery electric drives in comparison to internal combustion engines [21,22]. All electricity shall be produced be renewable energy sources (RES) as wind and solar. For the System losses is assumed that beside the transmission losses of 7 % it needs to be added that also a significant amount of renewable electricity must be used for power to gas to power devices as our Mitsubishi Hydaptive™ power plants [23]. These

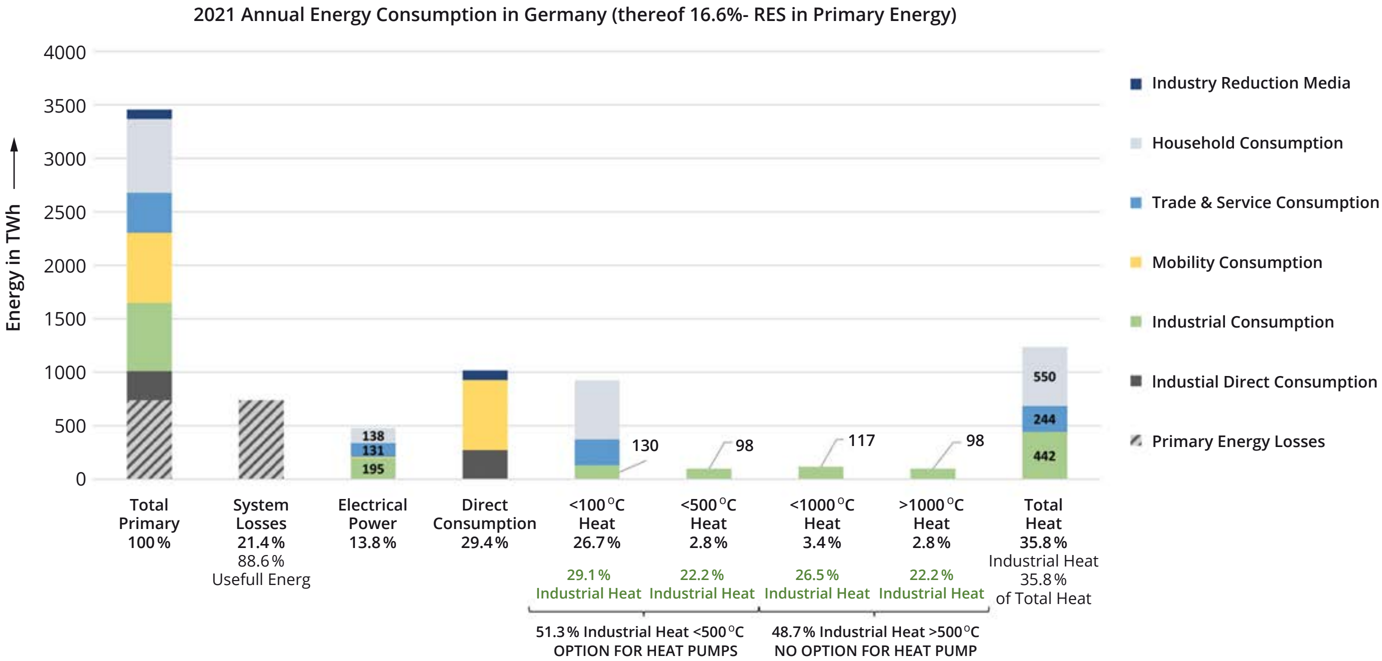

Fig. 6. Primary energy demand in Germany 2021 – Data from [17,18] incl. own calculation.

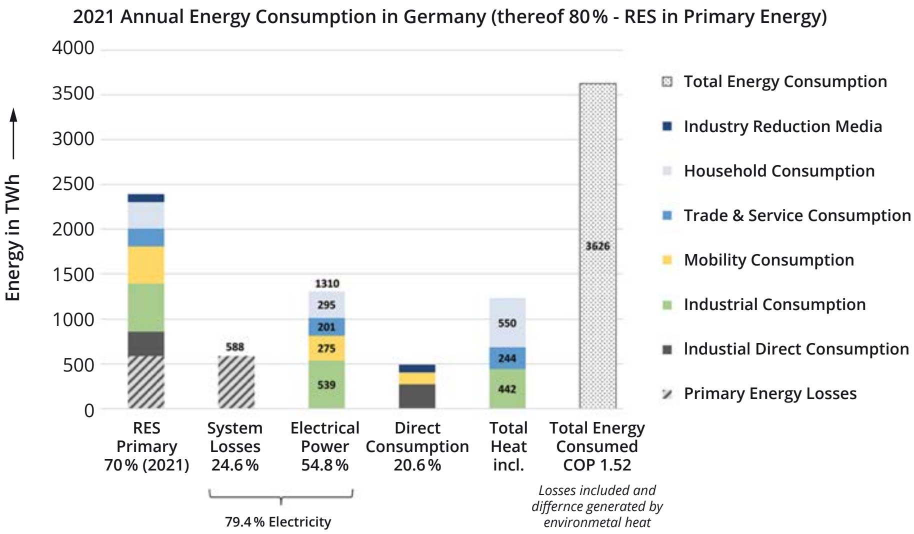

Fig. 7. Primary energy demand in Germany 2021 – Based on 100 % electrification.

Hydaptive™ power plant type consists of an 300-500 MW hydrogen electrolysis plant, a hydrogen cavern storage with 16000 t of hydrogen (8 caverns with 300000 m³) and a combined cycle hydrogen power plant and can produce about 650 MW electrical power with 330 GWh (3 weeks operation) in a single device. Round-trip efficiencies are about 40 % with investments about 2500 €/kW. The first plant like this is currently under construction in the USA [D]. With the current gas storage capacities in Germany of ca. 24 bnNm³ 100 % revamped to hydrogen this can serve 75 GW for three weeks in base load [24]. The usage of this assumptions leads to the values in Figure 7. Furthermore, it can be set as a low assumption that about 20 % (≈ 100 TWh) of the direct consumptions can be supplied by biogas produced in Germany [25].

The main analysis of these two cases a) as today (Figure 6) and b) as 2050 (Figure 7) is that an electrified country is using much less primary energy, minus thirty percent, compared to today at almost identical consumptions. For this it was not considered that future industries, households, or services in an electrified environment are operated with higher efficiencies compared to today [26]. Such an expectable efficiency gain would be about 20 % as best engineers guess.

The total RES generated are in the not optimised case ≈ 1900 TWh. This is about 7 times more than produced in 2023 in Germany. With a considered efficiency gain this can be reduced to about a factor of 5.5 times the 2023 RES generation. This for sure would need some outstanding efforts in investments in the future but are not in a not reachable range. In 2023 the RES installations are approx. 165 GW installed power [B]. With an average assumption for these installations it would need an addition of approx. 1 TW installed capacity of RES, which can be covered by reachable German RES potentials if policies are not too restrictive [27]. With an assumption of 2500 €/kW incl. the investments for the electrification it calculates to a necessary investment of 2500 bnEUR, which is about 3.4 times the total private investments of Germany in in all sectors in 2022 according to the Federal Statistical Office of Germany. This is for sure a very high figure but needs to be understood to be spend over the next decades. This makes the figure less frightening. Assuming 20 years it would be about 16 % of the annual investment of the country.

If one assumes that these efforts will be done by simply switching the fossil fuels used today to green derived hydrogen or its derivates it is obvious that more than double of RES installations or more will be necessary. This explains the international statistics of the International Energy Agency (IEA) [C]. Here are the investments is electrification about 8.5 times higher than in low carbon fuels and have the highest relative growth in the last 8 years compared to all other energy sectors (Table 2 for more details). It is simply more effective compared to a fuel switch. This is at the same time going along with a high growth in RES, while investments in fossil fuels are significantly reduced.

Electrification is already a trend in the investments and has the potential to become a mega-trend. The chance for this is higher as compared to the promised mega-trend towards hydrogen. For sure the technical implementation of the electrification is in wide parts easier and with less technical risks compared the switch to a hydrogen society. Both technology routes will be part of the future, but to the opinion of the authors hydrogen will not be dominating the development as sometimes currently is reported.

Finally, there is also a short view of the usage of power to heat for the use in power to heat to power (P2H2P) on the comparison with power to gas to power (P2G2P) technology for the generation of balancing power.

Initial a look on the reachable round-trip efficiency of P2H2P. Figure 8 gives here reachable values for this efficiency over the heat storage temperature.

It is shown that the reachable round-trip efficiency of P2H2P is not in a comparable range versus P2G2P. Another disadvantage for this technology is in the storage energy density and so the storage duration will be significantly lower compared to P2G2P, but still will be higher compared to battery or pumped hydro storage power plants. The advantage is that heat storage will be independent from

Tab. 2. Development of Investments in Energy between 2015 and 2022 [B – IEA-Data].

Technology Area	2015	2022	Change		Comment on Investment Size
	bn$	bn$	bn$	[-]	
Renewable Power	362	660	298	82 %	Highest absolute Gain
Energy Efficiency	271	391	120	44 %	Comes with Electrification
Electric Grids	326	352	26	8 %	Constant Needs for Grids
Electrification	36	147	111	308 %	Highest relative Growth
Low Emission Fuels	8	17	9	113 %	Still emerging Market
Hard Coal & Lignite	209	179	-30	-14 %	Large Loss & Loss Ratefor fossil Fuels
Hard Coal & Lignite	1112	822	-290	-26 %	

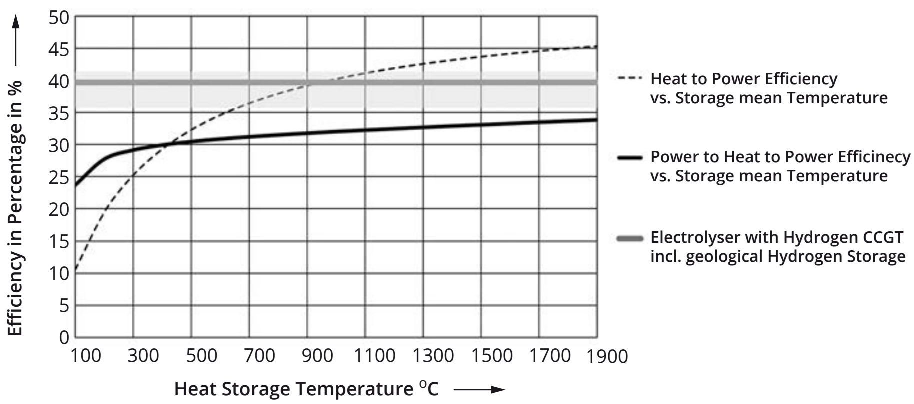

Fig. Bild 8. Power to Heat to Power Efficiency based on the above Power to Heat efficiency curve.

the geological sub-surface. For these reasons it is not expected that P2H2P becomes an option for power storage in Germany. It is expected that for a nice market the usage of power to heat for power storage will make sense, but this will be for sure not the reason to develop this technology field.

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Abstract

Eine Übersicht zu Kraft-Wärme-Kopplungs-Technologien in Abhängigkeit von der zu erreichenden Prozesstemperatur im Bereich von 40 °C bis über 1500 °C inkl. erreichbarer Technologie-wirkungsgrade

Im Rahmen der Energiewende wird die Elektrifizierung von Prozessen an Bedeutung gewinnen, um indirekte und direkte Treibhausgasemissionen der fossilen Brennstoffeg zu vermeiden. Je höher die Prozesstemperatur ist, desto schwieriger ist diese Elektrifizierung. Während für die Raumheizung die Wärmepumpe eine etablierte Technologie ist, ist sie für Temperaturen über 200 °C nicht ohne weiteres einsetzbar. Für höhere Temperaturen werden die Technologien vielfältiger und können auch Elektrodampferzeuger (bis zu 300 °C) oder direkte ohmsche Heizungen (bis zu 1100 °C) sein. Die derzeitige Forschung und Entwicklung geht auch in Richtung von Wärmepumpen mit Temperaturen bis zu 500 °C. Für den Ersatz von Gasbrennern in Öfen oder ähnlichen Prozessen (z.B. dem Schmelzen von Metallen, in Temperaturbereichen bis 1500 °C oder sogar 2200 °C) müssen ohmsche Heizungen durch andere Technologien wie Mikrowellen-Plasmaheizungen, Induktionsgasheizungen oder andere ersetzt werden. Ein Querschnitt der Technologien wird mit ihren erreichbaren Leistungszahlen und ihren erreichbaren Temperaturen diskutiert und eingeordnet. Dies wird mit dem Einsatz von Brennstoffersatz durch Wasserstoff oder Biogas verglichen und auf den Wärmeverbrauch in Deutschland hochgerechnet. Ebenso wird Power-to-Heat-to-Power diskutiert.

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21 and 22 May 2024
Salzburg, Austria

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Konferenzen | Fachtagungen

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Workshop
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Frankfurt a.M., Germany

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Chemie im Wasser-Dampf-Kreislauf
vgbe | Seminar
13. und 14. November 2024

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Offshore Windenergieanlagen – Arbeitsmedizin 2024
Fortbildungsveranstaltung
6. und 7. September 2024
Emden, Deutschland

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Immissionsschutz- und Störfallbeauftragte 2024
Fortbildungsveranstaltung
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https://t1p.de/tud-kwt (Kurzlink)