Electrification of industrial process heat: long-term applications, potentials and impacts

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Abstract

Converting electricity into heat offers the opportunity to make of use large scales of renewable (surplus) energy in the long run in order to reduce shut-downs of renewable power plants and to substitute fossil fuels. Electrification seems to be also very promising for industrial heat applications, as it enables high process temperatures to be achieved in a tailor-made and efficient way and enables the utilisation of other energy sources like waste heat, geothermal or ambient heat (via heat pumps).

This article analyses theoretical and technical electrification potentials of *Steam Generation* and *Other Process Heat Generation* in the following energy-intensive branches: iron & steel, non-ferrous metal, iron foundries, refineries, base chemicals, glass, cement clinker and paper industry in Germany. Literature research, expert interviews as well as own modelling were conducted to determine potentials and their implementation barriers. Based on these methods, market potential to electrify industrial steam generation was estimated. On the basis of two climate protection scenarios, the effects of both a monovalent and a hybrid industrial power-to-heat strategy were quantified with regard to greenhouse gas reduction and energy efficiency (primary energy saving).

The pathway towards electrification will be reflected by criteria such as path dependency, dependency of infrastructure and system compatibility. Recommendations for research and development as well as policies are derived from the overall analysis.

The article shows that electrification can be an important option to achieving high CO_2-savings in the industrial heating sector in a long-term perspective. However, the scenario calculations show that electrification does not in itself guarantee reduction of greenhouse gases or savings of primary energy. To reach these goals, it is essential to further develop industrial heat pumps and to map electrification and further development of renewable energy (including infrastructure such as power networks and storage facilities) in a concerted strategy.

Introduction

Power-to-Heat (PtH) is the term used to describe energy conversion technologies, in which electrical power is specifically transformed into heat and thus represents a coupling between the electricity and heat sectors. These can be purely electrical processes that convert electricity directly or indirectly into heat as the main energy source, or processes in which electricity serves as auxiliary energy to raise existing (low-temperature) heat (e. g. waste heat or environmental heat) to a higher and thus technically usable temperature level. The classic example for the latter application is the electrically operated heat pump (HP). But also an electric vapour compressor can be used to convert no longer usable low-pressure steam to a higher pressure and temperature level (Wolf et al. 2012 p. 2, 2014 p. 3), which is needed in a lot of applications in the energy intensive industries.

Despite tax reliefs and lower charges for distribution the electricity retail price for energy intensive industries is higher than that of natural gas. The aluminium industry – as the most electricity-price sensitive industry – has to pay a net price of

Table 1. Technologies for electrical heat generation in various sectors.

Households and TCS	Industry and process heat
Resistance heating systems – Heater rod – Flow heaters – Surface heating systems – Infrared radiator	Processes and procedures – Conductive resistance heating – Inductive heating – High-frequency heating – Magnetic direct current heating – Electrical infrared heating
Electrode boilers (commercial)	
Electric heat pump	Electrode boiler (where appropriate with CHP)
Bivalent (hybrid) heating systems	Electric heat pumps

Source: (Kleimaier 2016 fol. 13).

5 Eurocent per kilowatt-hour (Ct/kWh) for electricity and paper industry's electricity price was assessed to be 6.50 Ct/kWh (Grave et al. 2015), whereas the wholesale price for natural gas and industrial customers was only 3.80 Ct/kWh (Statistisches Bundesamt 2017). Nevertheless, also in today's industry electricity is already used to generate heat, if simpler design of the process with less investment, better energy efficiency and better process control can overcompensate the lower price for natural gas or other fossil fuels.

A basic distinction can be made between direct and indirect electrical heating processes. With the *direct processes* (inductive/conductive/dielectric) the transformation into heat is carried out in the work piece itself without the need for a heat transfer medium. In *indirect processes* (resistance/arc/infrared heating) the conversion into heat takes place outside the work piece. The heat is transferred via the surface of the material, with the aid of a heat transfer medium (air, steam, liquid baths …), via heat conduction and convection or via heat radiation (infrared). (Bechem et al. 2015; Pfeifer 2013.)

The decarbonisation strategy of PtH discussed in this paper opens up the heating sector for renewable electricity. In Germany this market segment represented an annual final energy demand of around 1,315 TWh in 2015, which represents 53 % of total final energy demand (AGEB 2016a). Electricity has a 9 % share in final energy demand for heating (122 TWh), which is 23 % of the total electricity demand in Germany (520 TWh). An overview of diverse potential PtH applications in the sectors of households, trade, commerce and services (TCS) and industry is shown in Table 1.

This article deals with the (long-term) electrification potential in the energy-intensive industry and examines possible development paths in this respect. According to the authors' literature analysis, only few more or less systematic analysis of PtH potentials across various industrial sectors and technologies are yet available in the literature (Guminski 2015; Guminski and von Roon 2017; Quaschning 2016 p. 19; von Roon and Dufta 2016 p. 6), some of them cover also the use of industrial high-temperature heat pumps e.g. (Bechem et al. 2015 p. 120; Gruber et al. 2015 p. 14 f.; Wolf et al. 2012, 2014). In particular, hardly any long-term electrification potentials of industrial process heat have been investigated so far, of which development is essential for (almost complete) decarbonisation of the industrial sector from today's point of view. Often, investigations are limited to short to medium-term potential for flexibility with a more economically oriented focus, e. g. for using cost-effective surplus electricity or for participating in the balancing energy market (Krzikalla et al. 2013 p. 36). For example, the start-up and control characteristics of an electrode boiler enable participation in the control energy market[1]. However, this potential represents only a fraction of the total technical electrification potential.

The aim of the analysis was to identify specific technical PtH potentials in the energy intensive industry motivated by decarbonisation and to assess how it could be developed over time. Therefore, own bottom-up modelling work was carried out based on an industry stock database and literature analysis.

Scope and methodology

This article discusses power-to-heat technologies as an overall strategy to decarbonise industry's heat supply in the long term. However, since actual applications in industrial processes are very diverse only a sample of 105 process types representing the most energy-intensive industrial production stock was taken into the in-depth analysis about technical options and potentials of applications[2]. Respective sub-technologies were analysed individually and examples of relevant technologies (e. g. inductive heating) or sectors (e. g. steel industry) or cross-sectional applications (e.g. steam generation) will be given. Due to the large application potential, the energy-intensive industries of paper & board, refineries, basic chemicals, glass & ceramics, cement & lime & bricks, iron & steel, non-ferrous metals & iron foundries as well as food & beverages were selected for the analyses for the electrification of process heat. However, the food and beverages sector was not investigated in depth due to its diversity and often smaller scale of production[3]. A synoptical overview of the various underlying PtH technologies for industrial applications with their respective physical principles, industrial branches and – if available – with information on performance, efficiency and temperature level is compiled in

1. According to the company, approximately 70 MW of control power is provided by a manufacturer's high-voltage electric boiler on the German balancing energy market (VAPEC AG 2018).

2. One sample of energy intensive processes has been analysed by (Fraunhofer ISI et al. 2011). This sample was amended by an in-depth literature analysis of processes in steel industry, non-ferrous-metal industry, the chemical industry and the refineries.

3. The analysis is based on a database containing energy intensive production stock with its respective annual nameplate production capacities and attributed to production sites to account for heat (i.e. steam) exchange between processes. Smaller scale stock like dairy plants, breweries etc. are not recorded in the database.

(Schneider and Schüwer 2017 p. 59 ff.) and (Görner and Lindenberger 2018), based on (Pfeifer 2013) and other literature.

In the discussion of operational concepts, a distinction was made between *hybrid* (electric *and* fuel-based) and *monovalent* (purely electrical) versions or *flexible* and *inflexible* (basic load) modes of operation. Potentials were derived taking these different options into account.

METHODOLOGY AND MODEL DESCRIPTION

Literature evaluations, expert interviews as well as our own modelling and potential assessments were carried out to determine the PtH potential and the obstacles to its realisation.

Modelling of electrification potentials

In order to obtain a consistent overview on the electrification potential for the most relevant energy-intensive industrial processes, assessments of potential were made on the basis of modelling and literature research, which was validated during the interviews with stakeholders. To this end, the capacities and production quantities (status: 2015) as well as the specific energy demands of energy-intensive processes in Germany for electricity, steam and fuels were at first determined individually. The calculation is based on our own database with 105 different production processes and 970 individual plants at 457 sites in Germany, which is the basis of "WISEE INDUSTRY" – the industry module of Wuppertal Institute's "WISEE" energy system model. So, the model is of a bottom-up type, process specific and can thus be used at any spatial level. It has been applied on a cluster scale (Rotterdam, see (Samadi et al. 2018)), a regional scale (e.g. North-Rhine Westphalia, see (Görner and Lindenberger 2018)) and – in the context of the study described in the paper at hand – also at the level of a state (i.e. Germany). The process specific energy intensity indicators recorded have been used and validated before in various projects analysing production, energy and GHG statistics and discussed with stakeholders and experts. (Schneider et al. 2014) Within the study at hand stakeholders gave feedback to proper system boundaries when analysing PtH and on probabilities of reaching PtH potentials.

According to the national energy statistic total industrial energy consumption (incl. refineries and coking plants) amounted to 235 TWh for electricity and 560 TWh for fuels and steam (aggregated) in the year 2014 (AGEB 2016b). Energy intensive industries are only part of this greater aggregate that includes also less energy intensive branches. The following selection of eight energy-intensive industries was modelled bottom-up:

- Paper & cardboard
- 59 processes of basic chemical industry
- Cement
- Non-ferrous metals
- Refineries
- Glass (incl. glass fibres and rock wool)
- Iron & Steel
- Iron foundries

The modelling covers 84 TWh of today's electricity demand (36 % of the total statistically recorded electricity demand of the manufacturing sector) as well as 239 TWh of fuel and 91 TWh of steam (60 % of total energy use in industry, see Table 4. The calculation includes reduction agent demand (especially coke use in steel industry), but not the fuel consumption of industrial CHP power plants (IPP). On the other hand, steam supply of IPP has been taken into account and steam was balanced at the level of individual sites, i.e. an assessment of steam demands and potential steam feed-in of processes with excess-steam was carried out.

As steam supply via PtH is a very relevant cross-sectional application, model validation in this respect is shortly discussed. In German energy balances only a part of the steam demand is recorded separately[4], namely that which is supplied by an external energy company (no self-production). However, the majority of industrial steam demand is covered by industrial plants (CHP and steam boiler) and is therefore not directly covered by statistical accounting. Instead, the fuel requirement for generating the steam is recorded and aggregated together with the remaining fuel requirement. As in Germany there are no statistics on industrial steam use available, it had to be modelled in a bottom-up way, without the option of direct validation.

Although the model only covers nearly 60 % of aggregated fuel and steam use of total industry, the coverage on the branch level is much higher (see Table 5). In order to determine the technical electrification potential, those processes that are not suitable for electrification (or would require a complete process change), i.e. where energy sources are used as reducing agents, were excluded. The most prominent example of using coke as a reducing agent is the blast furnace in iron making. Actually, iron making could also be directly electrified by an electrolysis, but we did not regard this as power-to-heat.

Furthermore, for such fuel-intensive processes, where (in a typical configuration) process-related excess fuel gas arise as by-products (steam crackers, refineries, integrated steel mills) a balance was made, i.e. the potential heat supply amount by excess fuels was subtracted from the technical electrification potential (see Figure 1).

Modelling of the savings potential of greenhouse gases and primary energy sources

The German government targets a greenhouse gas emission reduction of 80 % to 95 % until 2050 compared to 1990 (Bundesregierung 2010). For the transformation of all sectors of the energy system towards a low-carbon economy the government developed the *Climate Action Plan 2050* that postulates an emission reduction of 49–51 % for the industrial sector by 2030 (BMUB 2016 p. 8). On that score for the derivation of the greenhouse gas and primary energy saving potentials, two climate protection scenarios for Germany (Repenning et al. 2015) with 80 % (GER_80 %) and 95 % (GER_95 %) greenhouse gas reduction by the year 2050 (compared to 1990) are calculated as a bandwidth. The specific GHG emission factors for the electricity mix of the two scenarios (Table 2) are derived from the ratios of absolute emissions and net electricity generation.

4. Actually, not "steam supply" is recorded in statistics but "district heat". In the case of supplies to industry steam is the most common kind of supply.

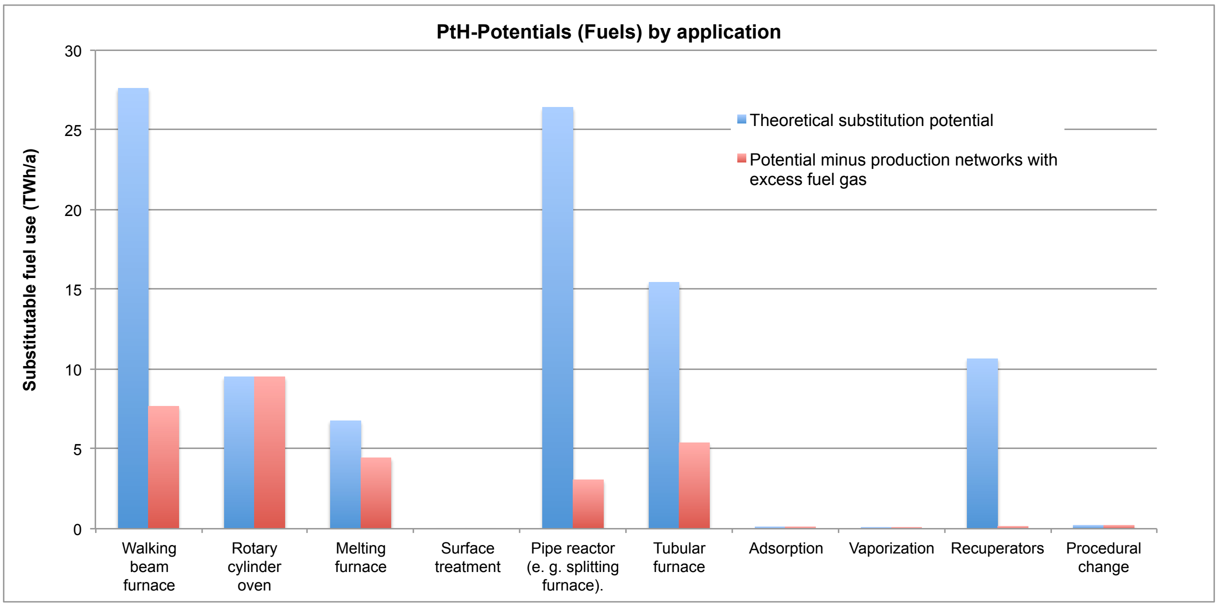

Figure 1. Reduction of the PtH potential by excluding production networks with excess fuel gas. (Note: In the case of the potentials shown in this diagram, no sharp balancing of sources and sinks has been carried out, so that these are not directly comparable with the overall potentials in Table 5).

Table 2. Specific GHG emission factors (CO_2eq) and primary energy factors (PEF) for the electricity mix and for natural gas in the climate protection scenarios.

	Electricity mix					Natural gas	
	CO_2eq		PEF			CO_2eq	PEF
	GER_80 %	GER_95 %	GER_80 %	GER_95 %	100 %-EE	All scenarios	
	g/kWh	g/kWh	kWh/kWh	kWh/kWh	kWh/kWh	g/kWh	kWh/kWh
2020	464	428	2.35	2.34	1.0	201	1.1
2030	361	240	1.88	1.82	1.0	201	1.1
2040	221	130	1.55	1.38	1.0	201	1.1
2050	79	17	1.40	1.24	1.0	201	1.1

Source: Own calculations with emission data from (Repenning et al. 2015); PEF: (Repenning et al. 2015 p. 131).

Table 2 also shows the corresponding primary energy factors (PEF) for both scenarios.

Interviews

Seven interviews were conducted between January and July 2017 with in total 19 experts from the five energy-intensive sectors of aluminium (1), steel (9), chemicals (2), cement (3) and glass (4). Interviewees were chosen according to different criteria to gain specific knowledge of plant manufacturers and the energy-intensive industry operating potential PtH. Technical experts of R&D, industrial management and strategic departments were involved. The interviews aimed in particular at deepening the technical understanding of the industry-specific processes, verifying identified technical PtH potentials, discussing potential schemes of PtH operation as well as drivers and barriers. Due to the explorative nature of the study, we did not seek for a broad coverage of involved companies but on peers, who are used to discuss innovative ideas and technologies. To give space for discussion of ideas and concerns we did not use a standardized questionnaire but used the method of the problem-centred interview according to Mayring (2002). The problem-centred interview is an open, half-structured interview type. “Open” implies that the interviewee can answer freely without having to choose from different options. “Half-structured” means that the interviewer has a prepared question catalogue but can deviate from it.

Results

In this chapter, the technologies states of the art, the results of the potential analysis and modelling as well as the observed obstacles and risks to the development of power-to-heat paths are presented.

STATE OF THE ART

Many of the industrial PtH technologies are already commercially available, even if they still have considerable potential for optimization. Development stage, risks and potential of process engineering PtH applications depend on the processes in the individual industries. Table 3 provides a rough assessment of the stage of development for a selection of representative, energy-intensive industries. A distinction is made between electrical steam generation, which can be used across the industries, and PtH applications, which replace fuel-heated systems (burners or furnaces) in the respective industries. The estimates are based on bibliographical references and the expert interviews. A more detailed description of the development stages of PtH technologies for the industries listed in Table 3 is documented in (Schneider and Schüwer 2017 p. 65 ff.).

DEFINITION OF POSSIBLE FUTURE OPERATION SCHEMES

Although R&D needs still exist in promising technologies such as inductive, dielectric, arc, plasma and electron beam heating, these technologies are in themselves commercially available. However, their use is often limited to niche applications where other heating technologies, for example, do not offer sufficient product quality or processing speed. If the focus is on electrification as such – in the sense of long-term decarbonisation – there is still great potential for application. The real challenge lies in the integration of electrical heating technologies into the various production and processing processes. Methodologically, a distinction between *monovalent* (purely electrical) and - in particular for existing plants and for a transitional period – *hybrid* or parallel (electric and fuel-based) process control appeared to be useful:

1. Monovalent electrically operated process:
   - Discontinuous batch process with capacity increase and product storage
   - Continuous (partial load capable) process
2. Hybrid production process (with two heating systems):
   - Bypass: Second (electrically operated) heat supply system (e. g. additional supply line with resistance heating)
   - Second heating system in the same unit (e. g. additional resistance heating in the fuel fired oven)
3. Parallel production processes (two different production lines):
   - Capacity increase by (additional) fully electrically operated production process (e. g. fuel fired oven + additional microwave oven)

ESTIMATION OF THE POWER-TO-HEAT POTENTIAL FOR GERMANY

As described above, the technical PtH potential was derived from the theoretical potential by excluding processes that are not suitable for electrification for various reasons (process change required, energy carriers as reducing agents). In a further step, it was also investigated to what extent existing fuel gas surpluses in production networks represent a potential limitation. Transport of such gases, that do not comply with defined standards (like natural gas), is usually rather expensive because of lacking infrastructure and commercialisation thus difficult. These kinds of fuels are therefore a very cheap energy source (i.e. low cost opportunity) for heat or electricity generation at the site. Figure 1 above shows the relevance of this differentiation: Fuel-intensive processes in which process-related excess fuel gas is present in a typical configuration of different production processes include steam crackers, refineries and the integrated steel mills of the blast furnace route.

Table 3. Development stages for PtH applications for electrically generated steam (cross-sectional technology) and as a fuel substitute for six exemplary industries.

Branch	Relevant technologies	TRL[1]	Developmental stage
Cross-sectional	Electric steam generation	7	Demonstration: Prototype test in operating environment
Paper and cardboard	Microwave (drying)	8	Demonstration: Qualified system with verification of functional capability in operating environment
Basic chemistry	Miscellaneous	4	Technology development: Basic functional verification of technology/application in the laboratory
Glass, pottery	a) Inductive/indirect resistive b) Conductive	5 9	a) Demonstration: Functional verification in application-relevant environment b) Commercialisation: Successful commercial use of the system (small scale speciality glass troughs)
Cement, lime, bricks	Resistive	3	Technology development: Basic functional verification of individual elements of an application/technology
Iron & Steel	Conductive/inductive	9	Commercialization: (Full scale) successful commercial use of the system (secondary steel making)
Non-ferrous metals	a) Inductive/Immersion Heater[2] b) Plasma heating/ Microwaves	9 6	a) Commercialisation: For small holding furnaces already achieved today (induction furnaces and immersion heaters) b) Demonstration: Coupling of thermal treatment and melting process (e. g. for paint stripping and melting of aluminium scrap), Plasma heating (demonstration project of Hydro in Norway)

[1] TRL= Technology Readiness Level

[2] Immersion Heater = Ceramic tube or heating element with integrated resistance heating elements.

Application of this methodology resulted in a technical (static) electrification potential for

1. **Fuels** of **59 TWh** (= 25 % of modelled demand) with typical focal points in the sectors of metal production and processing, individual processes in basic chemicals, cement industry and float glass plants and for
2. **91 TWh** (= 100 % of modelled demand) **steam** with typical focal points in chemical industry, refineries and the pulp and paper industry.

The branch specific potentials for the individual modelled industries can be found in Table 5. They are up to 41.6 TWh (paper and cardboard) for steam and up to 21.5 TWh (cement, lime and brick) for fuels.

ASSESSMENT OF MARKET POTENTIAL FOR GERMANY

From a technical point of view, replacing fuels for steam generation is the easiest way to phase-in PtH (total potential 91 TWh final energy). Due to the high degree of uncertainty and the required depth of investigation in detail for a reliable assessment of possible developments of the remaining fuel substitution potentials (59 TWh), the following investigations of market potential are therefore limited to the electrification of steam generation. Assuming that PtH market shares of 10 % to 60 % in total investment (in a national 80 % climate protection scenario) or 20 % to 100 % (in a national 95 % climate protection scenario) can be achieved in the coming decades, the PtH potential to be developed amounts to 5 to 27 TWh (GER_80 %) or 9 to 45 TWh (GER_95 %) per decade from 2020 onwards (Table 6). In this calculation, a lifetime of the steam generators was assumed to be 20 years. Based on the total potential of 91 TWh, this represents an average annual reinvestment in conventional and electrical systems with a steam generation capacity of 4.54 TWh/a.

Based on a stock of 91 TWh of fossil steam generators (electrification rate of 0 %) in 2020, the stocks of electric steam generators for the respective scenario years were calculated using the market development values of Table 6. According to the assumptions about the reinvestment cycle 45 % (41 TWh) of the technical steam potentials could be realized in the GER_80 % scenario and 85 % (77 TWh) in the GER_95 % scenario in the target year 2050 (Table 7).

Table 4. Overview of the actual and the (partly) modelled industrial energy demand in TWh/a for electricity, fuels and steam and the derived technical electrification potentials.

Energy carriers	Total consumption industry sector 2014 (according to AGEB)	WISEE modelling (selected processes)	**Technical electrification potential**
Electricity	235	84	**–**
Fuels	560 (aggregated)	239	**59**
Steam		91	**91**
Sum	795	414	**150**

Source: Own calculations, consumption data according to (AGEB 2016b).

Table 5. Overview of technical electrification potentials according to industries (source: own calculations, consumption values according to (AGEB 2016b)).

Boundaries AGEB	Boundaries WISEE	Final energy input 2014 according to AGEB*	WISEE-Modell Steam	WISEE-Modell Fuel	**Technical electrification potentials Steam**		**Fuel**		**Sum**
		TWh_{Hi}	TWh	TWh_{Hi}	**TWh**		**TWh**		**TWh**
Paper and cardboard	Paper and cardboard	43.3	41.6	0.0	**41.6**	100 %	**0.0**	0 %	**41.6**
Refineries	Refineries	67.1	10.8	46.3	**10.8**	100 %	**1.6**	4 %	**12.4**
Basic chemistry	59 Processes of basic chemistry	103.5	34.5	24.2	**34.5**	100 %	**6.9**	28 %	**41.4**
Glass, pottery	Glass (incl. glass fibres and rock wool)	18.7	0.0	14.7	**0.0**	0 %	**11.2**	76 %	**11.2**
Cement, lime, bricks	Cement	45.7	0.0	21.5	**0.0**	0 %	**21.5**	100 %	**21.5**
Iron and Steel	Iron and Steel	137.8	3.9	123.5	**3.9**	100 %	**8.4**	7 %	**12.3**
Non-ferrous metals	Non-ferrous metals	13.7	0.0	3.9	**0.0**	100 %	**3.9**	100 %	**3.9**
& iron foundries	& iron foundries		0.0	5.3	**0.0**	0 %	**5.3**	100 %	**5.3**
Sum		**429.7**	**90.8**	**239.4**	**90.8**		**58.8**		**149.6**

** Including use of fuel to generate steam in steam boilers and cogeneration plants.*

Table 6. Analysis of the national market potential for the power-to-heat technology field using the example of electric steam generators (TWh final energy steam).

Year	Scenario storyline GER_80 %		Scenario storyline GER_95 %	
	Assumed share of PtH in total new installations or re-investments (capacity based)	Total PtH investment per decade	Assumed share of PtH in total new installations or re-investments (capacity based)	Total PtH investment per decade
	%	TWh	%	TWh
2014–2020	0 %	0	0 %	0
2021–2030	10 %	5	20 %	9
2031–2040	30 %	14	70 %	32
2041–2050	60 %	27	100 %	45

Table 7. Bandwidth of national technology use for the PtH technology field using the example of electric steam generators (absolute values of steam generation of all installed plants in respective reporting years).

Year	Scenario storyline GER_80 %		Scenario storyline GER_95 %	
	Total PtH stock installed (TWh)	Degree of PtH realisation (% of total technical potential)	Total PtH stock installed (TWh)	Degree of PtH realisation (% of total technical potential)
2020	0	0 %	0	0 %
2030	5	5 %	9	10 %
2040	18	20 %	41	45 %
2050	41	45 %	77	85 %

Table 8. Annual avoided greenhouse gas emissions due to power-to-heat (electric steam generator) in Germany compared to the reference case (natural gas boiler).

Mt CO_2eq/a	Scenario storyline GER_80 %			Scenario storyline GER_95 %		
	vs. power mix (monovalent)		vs. RE-Mix* (hybrid)	vs. power mix (monovalent)		vs. RE-Mix* (hybrid)
	Electrode	HT-HP	Electrode	Electrode	HT-HP	Electrode
2020	0.0	0.0	0.0	0.0	0.0	0.0
2030	- 0.6	0.4	1.0	- 0.2	1.2	2.0
2040	0.0	2.5	4.1	3.8	7.0	9.1
2050	5.9	7.9	9.1	15.9	16.7	17.3

** Theoretical savings based on the assumption that sufficient renewable energy (RE) surpluses are available!*
Steam generation by electrode boiler (Electrode) or high-temperature heat pump (HT-HP) with COP = 2.5. Fields with grey background: negative values (additional emissions).

CONTRIBUTION TO CLIMATE PROTECTION

Based on the range of national PtH use in steam supply displayed in Table 7, the resulting annual mitigated greenhouse gas emissions (GHG) are shown in Table 8 using the specific GHG emission factors for the electricity mix of the two national climate protection scenarios (see Table 2). A natural gas boiler with 90 % efficiency (EU 2016 p. 58) and a specific emission factor for the combustion of natural gas of 55.944 kg/TJ (201.4 g/kWh) were assumed as the reference technology (UBA 2016 p. 22). An efficiency of 99 % is assumed for steam generation in an electrode boiler (Guminski 2015 p. 69).

With the development of new refrigerants (R245fa) heat pumps for temperatures above 140 °C also appear to be feasible (Bechem et al. 2015 p. 65). To estimate the upper limit of the GHG reduction potential the theoretical case of a complete PtH supply by industrial high-temperature heat pumps (if necessary supported by vapour compressor) was also calculated.

As the source of industrial waste heat is in general continuously available and heat pumps have high investment costs, the use of heat pumps seems to be worthwhile for the monovalent operation mode – a monovalent but flexible operation in combination with high-temperature heat storages should be regarded however in future analyses. The coefficient of performance (COP) for steam generation depends on the pressure level and varies between 2.0 (@20 bar) and 4.0 (@1 bar) (Buddenberg 2016 p. 4). The value was conservatively set to 2.5 on average, corresponding to a typical pressure level of 6 bar at about 170 °C. If it is assumed that high-temperature heat pumps are increasingly being used for steam generation, the specific GHG emission factor for the production of one kilowatt-hour of steam will improve accordingly by a factor of approximately 2 to 4 compared to electrode boilers. If the complete PtH potential would be realised by heat pumps, maximally additional 2.5 Mt/a (GER_80 %) and 3.2 Mt/a (GER_95 %) of CO_2eq could be saved by 2040 compared to the steam generation by electrode boilers.

The negative values for the year 2030 mean that, at least until this point in time, the *monovalent electrification* of steam generation by electrode boilers will result in additional emissions of

Table 9. Annual avoided primary energy consumption due to power-to-heat (electric steam generator) in Germany compared to the reference case (natural gas boiler).

PJ/a	Scenario storyline GER_80 %			Scenario storyline GER_95 %		
	vs. power mix (monovalent)		vs. RE-Mix* (hybrid)	vs. power mix (monovalent)		vs. RE-Mix* (hybrid)
	Electrode	HT-HP	Electrode	Electrode	HT-HP	Electrode
2020	0	0.0	0.0	0	0.0	0.0
2030	-11.1	7.7	3.5	-20.2	16.2	6.9
2040	-22.5	39.4	13.9	-25.3	98.6	31.2
2050	-28.2	97.5	31.2	-8.4	201.9	59.0

** Theoretical savings based on the assumption that sufficient renewable energy (RE) surpluses are available!*
Steam generation by electrode boiler (Electrode) or high-temperature heat pump (HT-HP) with COP = 2.5. Fields with grey background: negative values (additional consumption).

0.2 to 0.6 million tonnes per year compared with the reference application. This is due to the higher specific GHG emissions of power generation compared to natural gas, which cannot be compensated by higher electric boiler efficiencies. In the year 2040, there is parity between electricity and natural gas steam generation in the 80 % GHG scenario, while in the 95 % scenario an emission reduction of 3.8 Mt/a CO_2 equivalents can already be achieved (due to higher renewable shares in electricity generation). Assuming a developed PtH potential of 77 TWh/a, a maximum of 15.9 Mt/a can be achieved in 2050. The supply of steam by (the more energy-efficient) *heat pumps* would result in emission reductions during the entire period (including 2030) and contribute to maximum savings of 16.7 Mt/a by 2050.

If the entire technical potential for industrial process steam of 91 TWh/a was realized by 2050, this would result in savings of 18.7 Mt/a (electrode boilers) or 19.7 Mt/a (heat pumps). In addition, if the process-related fuel substitution potential of 59 TWh/a (see Table 4) was fully realized, a further maximum reduction of 10.8 Mt/a CO_2eq would be feasible in monovalent operation. However, stock exchange in high-temperature applications like ovens in most cases lasts 30 to 40 years, and today's TRL are partly significantly lower than the electric supply of steam. So the full realisation of PtH in the supply of high-temperature heat will probably take more time than the remaining 30 years until 2050.

In the case of *hybrid electrification*, where PtH is operated in a flexible manner and fed from renewable electricity surpluses alone, the emission values for the renewable energy mix are set to (approximately) zero. This results in GHG savings of 1 to 2 Mt/a in 2030 and maximum savings of 17.3 Mt/a (3rd and 5th column in Table 8) in 2050. It should be noted, however, that these are theoretical values, as these estimates have not been able to ascertain whether there is sufficient excess renewable electricity available in the respective years, which would otherwise have to be regulated. Therefore, this value has to be regarded as the upper limit that – if ever –probably only can be achieved by means of sufficient thermal and/or electric storages.

CONTRIBUTION TO PRIMARY ENERGY SAVINGS

In order to calculate the energy savings from electrification of steam generation, the primary energy factors for the electricity mix or for natural gas (Table 2) are multiplied by the respective electricity values and natural gas (reference) values. Since the efficiency losses in the upstream electricity production chain are significantly higher than those in the upstream gas supply chain, *monovalent electrification* by electrode boilers results in an increase in primary energy consumption of up to 28.2 PJ (80 % scenario in 2050) in all scenario years and in both scenarios compared to the reference case. Only in the 95 % scenario there is a decline in excess consumption from 25.3 PJ in 2040 to 8.4 PJ in 2050 overcompensating additional PtH capacities. This decline is due to the high shares of renewable energy in the more ambitious climate protection scenario[5].

In the case of *hybrid electrification* by electrode boilers, primary energy savings of 31.2 to 59.0 PJ/a can be achieved in 2050, assuming 100 % electricity from renewable sources.

The realisation of the PtH potential completely by industrial high-temperature *heat pumps* would reduce the primary energy need during the entire period and culminate theoretically at 202 PJ (56.1 TWh) in the GER_95 % scenario by 2050. For cost reasons, this would also only be useful in the monovalent case.

Discussion

POWER-TO-HEAT POTENTIALS

Within the scope of this work, processes relevant for the electrification of process heat from the energy-intensive industries paper & cardboard, refineries, basic chemicals, glass & ceramics, cement & lime & bricks, iron & steel as well as non-ferrous metals & iron foundries were investigated. Based on the modelled final energy of 414 TWh in 2014, a long-term technical electrification potential of around 150 TWh/a was identified, which is made-up of 91 TWh/a steam and 59 TWh/a fuel substitution. By comparison the total potential corresponds to 71 % of today's total renewable electricity generation in Germany (211 TWh in the year 2017 including hydropower and biomass) or to 105 % of fluctuating renewable generation (142 TWh wind and solar energy).

A comparison with potential estimates from literature shows that our own calculations are close to the figure of 153 TWh reported by *Guminski* (2015 p. 41 ff.) (based on a total industrial final energy demand of 723 TWh in 2013). The electrification potential of approx. 180 TWh derived in *Gruber et al.* (2015

5. For almost complete electricity generation from renewable energies, the primary energy factor converges towards 1.

p. 14 f.) in the "heat pump & electrothermal processes" scenario is 20 % higher. *Bechem et al.* (2015 p. 120) derive an electrification potential for the year 2050 for various industrial sectors of 201 TWh for high-temperature process heat (and a further 70.6 TWh for the use of heat pumps up to 140 °C). The differences in the potential calculations and estimates are mainly due to the focus on certain industries or (e. g. energy-intensive) processes[6]. Other reasons for deviations are the varying levels of detail and different base and end years.

MARKET POTENTIALS

Under the assumptions made here, for the target year of 2050 a market potential of 45 % (41 TWh) could be realized in the GER_80 % scenario and of 85 % (77 TWh) in the GER_95 % scenario, each related to the total technical steam electrification potential of 91 TWh. The market potential assessment was limited to steam applications, as the expenditure for PtH process integration in fuel applications differs greatly from industry and product-specific, and no sufficiently robust predictions can be made on the time required to get from lower TRL levels to commercialization. Whereas, for example, electric melting processes are already being used commercially in the steel industry, it is not expected that electrically operated rotary kilns will be available on an industrial scale in the cement industry in the coming years. The reason for this assessment is, on the one hand, that a completely new plant design has to be developed in terms of thermodynamics and process technology, that only new plants would be considered and that – in competition with the very cheap substitute fuels used today – large quantities of cheap electricity would have to be available.

CONTRIBUTION TO GHG MITIGATION AND PRIMARY ENERGY SAVINGS

In the medium term (until 2030), GHG emissions will increase by up to 0.6 Mt of CO_2eq/a (Table 8) with *monovalent electrification* (balancing versus electricity mix). This underlines the important fact that high renewable expansion targets in the electricity sector are a central prerequisite for an early electrification strategy aiming at decarbonisation. A 100 % realization of the electrification potential for industrial process steam (90.8 TWh/a) would correspond to savings of 18.7 Mt/a and a maximum of 10.8 Mt/a for fuel substitution potential (58.8 TWh/a). The latter calculation is very simplified and based on the conservative assumption that the same efficiencies as for the fossil-based reference processes apply to the electrical replacement processes. However, electrical processes are often more efficient – especially in partial load operation – because, for example, exhaust gas losses are eliminated and the heat can be inserted more precisely. The extent to which the technical fuel substitution potential can actually be implemented would have to be analysed in depth for the individual sectors and processes.

If it is assumed that high-temperature heat pumps (possibly supplemented by vapour compressors) are increasingly being used for steam generation the specific GHG emission factor for the production of one kilowatt-hour of steam will improve by a factor of approximately 2 to 4. This underlines the need to further develop industrial high-temperature heat pumps and to use them in a wide range of applications for the utilisation of industrial low-temperature waste heat (<100 °C). The monovalent use of PtH by electrode boilers results in an increase in primary energy consumption of up to 28.2 PJ/a, while savings of up to 59.0 PJ/a are recorded for hybrid applications (Table 9). Here, the same statements apply with regard to the urgency of the simultaneous expansion of renewables and the temporal and spatial availability of renewables as in the discussion of the GHG results. The use of industrial waste heat using highly efficient high-temperature heat pumps reduces also primary energy consumption by a factor of 2 to 4 compared with a simple electric steam generator. Then substantial primary energy savings of 126 PJ/a (GER_80 %) and 210 PJ/a (GER_95 %) could be reached by 2050 compared to simple electrode boilers. Though potential assessments from literature indicate that sufficient industrial waste heat potential is theoretically available (Wolf et al. 2012 p. 548), it should be noted that in practice heat sources and sinks and / or temperature levels spatially not necessarily match. Hence the application potential for heat pumps is likely to be smaller and must be identified individually.

Conclusion

In the case of industrial process heat supply by PtH it is reasonable to differentiate between the cross-sectional technology of electrical steam generation and high-temperature heat supply as a substitute for high-temperature fuel-related processes (especially ovens).

Electric steam generation is largely independent of the industrial branch and thus in technical respect comparatively easily to implement. Demonstrators have already been developed. The development of standardized hybrid processes for different power levels and steam parameters should be promoted in order to establish the use of cost-effective and flexible PtH processes as a marketable cross-sectional technology. In the long term (until 2050) GHG savings of up to 15.9 Mt of CO_2eq/a are feasible. This equals to 13 % of today's total energy related CO_2 emissions of the manufacturing industry in Germany (UNFCCC 2017) and is therefore a single strategy with great overall mitigation potential.

The *electrification of industrial ovens* requires greater differentiation both on the side of technologies and on the side of industries and processes (e. g. in the chemical industry). Although the fundamental principles of direct and indirect heat supply can be regarded as proven (and often commercially available for niche applications) there is still considerable need for further development in order to design efficient and inexpensive electrification processes adapted to certain industries and their processes.

The challenge to be solved is the integration of electrical heating technologies into the various production processes. There is strong need for research into how process applications can be made technically and organizationally more flexible and to what extent flexibility leads to a loss of efficiency (see e.g. Ecofys 2016). There is still a need for research in this area, particularly as regards the investigation of the technical, economic as well as the implementation and market potential

6. A simple – and therefore uncertain – extrapolation of the potential determined by the WISEE model to all industrial processes would result in a total potential of 150 / (239 + 91) × 560 TWh = 254 TWh.

for individual industries and processes. A promising approach appears to systematically examine both the PtH-flexibilisation potential as well as the product and process-specific co-benefits of electrification for individual industries. In addition to improving efficiency and reducing emissions, targeted research funding for the optimization of the above-mentioned processes can indirectly (via co-benefits) increase the incentives for electrification. Thermal storages can play an important role in the flexibilisation and sector coupling of industrial processes. Particularly for the high-temperature range relevant to industrial processes, there is still a need for R&D in this area, see also (FVEE 2017 p. 25).

The (monovalent) electrification of base load heat supply will not be economically feasible in many cases, given the current spread between gas and electricity prices, which can be expected to be robust in the medium term. For this reason, possible applications in the short and medium term are limited to (hybrid) flexibilisation and processes that promise additional advantages, e.g. in terms of product quality or product output (process speed).

Electrification is an important option for achieving high (long-term) CO_2 savings in the heating sector. However, as the scenario calculations for industrial applications show, electrification itself is neither a guarantee for the reduction of greenhouse gases (Table 8) nor for the saving of primary energy (Table 9). The picture changes, however, if more energy efficient heat pumps are taken into account wherever the temperature level and the process specifications allow to do so. Research and development of industrial high-temperature heat pumps is therefore of high relevance – especially in combination with the use of (low temperature) waste heat sources. Finally, it is important to stress that electrification and the extension of renewable electricity capacities (including other infrastructures such as networks and storage facilities) should be considered in a common strategy.

Within the study literature research and stakeholders feedback from expert interviews assure proper system boundaries when analysing PtH and estimating the probabilities of reaching PtH potentials. However, further system analysis and detailed bottom-up modelling should be carried out to establish roadmaps for PtH development and to monitor it. So far there are only a few papers dealing with the potentials of a complete electrification of industrial process heat systematically and considering possible dynamics in the future. The bottom-up approach presented here for Germany can be applied at any spatial level within the EU, be it on a regional, national or EU scale. The potential GHG reductions calculated should be rated as a first approximation giving however reason to integrate such strategies into integrated energy system models to test them against other mitigation options, including other electrification strategies like power-to-fuels or power-to-chemicals.

The bottom-up approach discussed does not cover total steam and fuel demand in industry. By focusing on the most energy intensive processes, however, it reveals specific spatial power-to-heat potentials (with e.g. net steam balances on a site level), allowing for a deeper analysis of source-sink matching of industrial waste for the application of heat pumps or for electricity grid flow calculations in the future, which are necessary for an integrated assessment of such an electrification strategy.

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