Flexibility potential of industrial thermal networks through hybridization

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Abstract

For a cost efficient energy supply based on intermittent renewable electricity and heating sources, different flexibility options have to be applied. Because thermal energy demand in industrial applications accounts for about 22 % of the overall German energy demand, the potential of demand flexibilisation in this sector is an important area of research. One point of interest is the system-adapted application of sector-coupling technologies, such as Power-to-Heat devices. Hereby, a simultaneous inclusion of fuel and electricity-based technologies in the energy supply, called hybridization, allows an energy system adapted operation.

In industrial sites, heating and cooling are often supplied via thermal networks. Here, the potential for hybridization and flexibilisation of these networks is investigated. While the theoretical potential for network-based thermal energy supply (temperatures below 240 °C) lies at 547 PJ, only 202 PJ remain after subtracting heat that is currently provided by electricity, renewable energies, district heating, waste/waste heat and decentral supply units (still 12 % of overall industrial heat demand). Considering a design of heat generations unit for 4,000 full load hours, these networks can provide a negative load of 4.7 GW (base scenario) or 14.5 GW (maximum flexibility scenario) to the electricity supply system,.

For further research and an increase in accuracy of the results, especially the databases on industrial thermal energy supply should be broadened. Mixing of different information sources shows that the data between different sources is not consistent, which leads to wide-ranging insecurities.

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1 Introduction

In a future energy supply based on fluctuating renewable energies, the provision of flexibility to decouple energy demand and supply is essential [1], [2]. Hereby, an interconnection of different energy demand sectors increases the available flexibility and is more cost efficient than a system in which flexibility is only provide within the electricity sector [3]. For example, through an interconnection between electricity and industrial heat supply system can be realized via the implementation of Power-to-Heat systems such as heat pumps, heating rods, etc. [4]. Individual Power-to-Heat units are rather limited in flexibility, due to the smaller scale of the heat generation units themselves and the connected storage tank. In contrast to this, units connected to a thermal network have larger dimensions as they provide heat to several customers. Moreover, theses can make use of the flexibility of connected storage units as well as the grid itself.

Several studies indicated that, for the future energy supply based on renewable heat sources, the significance of thermal networks for heat supply will increase [5], [6]. In [7] it is assumed, that in 2050 about 38% of overall thermal energy supply will be provided by thermal networks, two thirds being based on renewable energies and one third on fossil fuelled CHP plants.

The aim of this study is to estimate the current technical flexibility potential, which industrial thermal networks can provide to the electricity supply system through an on-site connection of fuel-based technologies with electricity-based ones (hybridisation). This allows that, at times of lacking electricity in the supply system, the fuel-based technologies can be used, while at times of high electricity generation the electricity-based technologies are used. In the long run the fuel based technologies can use green fuels, making overall energy supply renewable.

Currently, most studies focus on the transition of network-based heat supply for households and the tertiary sector e.g. [8], [9]. Considering industrial thermal networks, the focus in research lies on mapping of waste heat potentials of industrial plants to use these in district heating networks e.g. [10], [11]. Also for the utilization of internal waste heat within industrial sites evaluations exist [12].

Regarding industrial flexibility, investigations focus on the flexibility of processes themselves (see meta-study [13]). Also possibilities for electrification of industrial heat demand have been discussed. Here one electricity-based technology is assumed to replace a fossil fuel based technology, hence series connection of several units is neglected. [14]

The status quo of usage of industrial thermal networks and the potential for flexibility in the sector is not yet investigated. In order to evaluate these, a stepwise approach is applied. Firstly, the technical boundary conditions regarding thermal network operation are given. In order to include real life limitations on the hybridization potential, data on thermal energy supply in 52 companies is compared and the main findings are stated. Then, a top-down analysis of the German industrial thermal energy demand is presented and relevant data for network-based heat supply is extracted. The hybridization potential is determined via a combination of the top-down and bottom-up analysis. Lastly, limitations of the study are discussed and an outlook on further needed research is given.

2 Network based thermal supply systems

In contrast to thermal energy supply in households, where only about 14% of households are connected to network-based thermal energy supply [15], this applies to the majority of industrial sites. Network-based heat supply allows the provision of heat in areas with low free space on-site as it is the case in industrial production sites. Here, heat is generated in a heating central and then distributed via thermal networks. While this leads to distribution losses and costs for suitable infrastructure, these are overcompensated by the decrease in specific costs of large-scale heat generation units and their higher efficiency. Another economic and practical advantage is that thermal plants need investment-intensive waste-gas treatment facilities. Hence, the usage of large-scale central plants is favoured to several small-scale individual units. Furthermore, for industrial sites, the provision of supply security is essential, making backup units essential and a centralized system more cost-efficient. Lastly, operation and maintenance of central heat supply units is easier and more cost-efficient.

However, whether thermal networks are applied highly depends on the structure of energy demand of each individual site and the growing process it has undergone.

After a description of the relevant components of industrial thermal networks (chapter 2.1), the main operation criteria are shortly described (chapter 2.2). Then the focus is on thermal energy generation technologies (chapter 2.3), operation modes of connected heat generation units (chapter 2.4) and relevant storage units (chapter 2.5). While the focus of this paper is the supply of heat, network based cooling supply underlies the same thermodynamic boundary conditional and dependencies.

2.1 Components and structure of heating networks

The network based thermal energy supply always consists of thermal energy generation units, piping system (separated for flow and return), circulating pumps, pressure tanks, several spread valves, one or more consumers and often storages.

In large industrial sites, thermal networks with different flow and return temperatures exist. Here the return of one cluster of machines can be the flow for other technologies.

In general, networks are either designed in a radial/tree structure, as a network ring or meshed (further information see [16]). Due to lower costs and less complicated operation most industrial networks show a tree structure layout. Still, this decreases the security of supply and makes adequate maintenance as well as monitoring essential.

In some networks heat exchangers connect the consuming units to the networks. Different connection methods in thermal networks, their advantages and disadvantages are stated in Table 1, which in reality are mixed. Often in one network arm several consumers are directly connected and others are separated from the network by heat exchangers.

One main challenge regarding the optimization and determination of flexibility potentials is that industrial thermal networks usually grow “organically”. Thereby, companies often do not have a current network plan including the consumers connected and their individual requirements.

Table 1: Thermal network connection methods and characteristics

Connection method	**Description**	**Advantages**	**Disadvantage**	**Application**
Direct heat supply	No separation between the primary heat network, in which the generation unit feeds, and the customers exist	Low costs for network components	No control over temperature level per consumer. Leakages in consumers/ individual branches lead to problems in overall heat supply	Rather for small-scale networks supplying similar customers
Decentral indirect heat supply	Each heat consumer is connected to the central network via an individual heat exchanger	Individual temperatures per consumer achievable (always below network temperature) Leakages in consumers has no effect on network stability	Relatively high costs Heat exchangers have to be controlled adequately	In medium scale networks supplying highly different customers
Central indirect heat supply	An heat exchanger separates the network in which the generation units feeds (primary network), from the network in which the customers are (secondary network)	Individual temperatures per secondary network achievable (always below primary network temperature) Leakages in secondary network has no effect on network stability Lower cost than individual heat exchangers	Heat exchangers have to be controlled adequately	In large scale sites often a central steam network exists. Each factory building has its individual branch

2.2 Key criteria for network operation

In thermal networks the connected consuming units determine the criteria, which have to be met. The most important criteria, status-quo values and effects on the hybridization potential are described here.

2.2.1 Temperature level

In most thermal networks the temperature level of the flow is adapted to the connected consumer with the highest requirements. While the aim always is to decrease the return temperature as far as possible, this is limited by the temperature demand of the consumers and, if applicable, the dimensions of the heat exchangers between thermal energy streams.

The temperature level of the thermal network is important in two ways. Firstly, the temperature of the thermal network is decisive for the thermal stress applied to the infrastructure and the thermal losses. As thermal losses increase with the temperature difference between supply system and surrounding, in general heat demand is not provided by a network at temperatures above 240 °C. In networks with large distances between the costumers and a low specific heat demand, lower temperature levels or decentral heating is preferable.

In Table 2 a classification of the different network types and their characteristics are given.

Table 2: Types of industrial heating networks typical temperatures and application

Network	**Flow temperature**	**Return temperature**	**Exemplary Application**
High pressure steam	> 220 °C, max. 240 °C	~ 160 – 100 °C	Process heat for chemical reactions, drying applications
Medium pressure steam	> 160 °C	~ 100 C	Provision of hygienic steam for food industry, process heat for chemical processes, paint shop
Steam	> 120 °C	~ 80 – 100 °C	Primary heat network temperature (temperature downgrade towards secondary network), drying
High temperature	~ 90 °C	~ 70 °C	Metal washing, surface heating, domestic hot water
Medium temperature	~ 50 °C	~ 30 °C	Surface heating, metal washing
Low temperature	~ 15 °C – 30 °C	~ 20 – 40 °C	Uptake of waste heat, hot side of compression cooling
Conditioning	~ 6 °C – 18 °C	~ 12 °C – 25 °C	Air conditioning
Cooling	~ 1 °C	~ 6 °C	Cooling of food products in food industry and supermarkets, chemicals
Freezing	~- 20 °C	~- 10 °C	Freezing of food products in the food industry or chemicals

In between industrial branches the presence of the different types of thermal networks vastly varies. For example, high pressure steam networks are only present in the chemical industry and freezing networks are limited to the chemical and food industry. Hereby, a broad range of network temperatures exists in reality, as this always is determined by the individual processes and connection logics of consumers.

The second effect of the network temperature is that the required flow temperature is a limiting factor for the applicability of heat supply technologies. For all heat generation units, limitations of the reachable flow temperature exist, in many cases also for the inlet temperature.

2.2.2 Volume flow

The required volume flow in the thermal network ($\dot{V}$) is calculated from the energy demand ($\dot{Q}_{\text{demand}}$), its specific heat capacity (c_p) and density (ρ_{water}) as well as the difference between its temperature at the flow (T_{flow}) and return (T_{return}) temperature, see formula (1).

$$\dot{V} = \frac{\dot{Q}_{demand}}{c_p \cdot \rho_{water} \cdot (T_{flow} - T_{return})} \tag{1}$$

The formulae indicates that the difference in flow and return temperature is crucial for the determination of the required volume flow. With the aim of reducing thermal losses, a decrease in flow temperature can be compensated by an increase in volume flow. While this is technically possible, it has to be taken into consideration that friction losses and therefore the required electric load of pumps (P) increases with the volume flow in comparison to a reference case according to formulae (2).

$$\frac{P_1}{P_2} = (\frac{\dot{V}_1}{\dot{V}_2})^3 \tag{2}$$

Therefore, for an energetically and economically efficient network based heat supply, an optimum layout including temperatures and volume flow has to be found.

2.2.3 Pressure

In order to overcome differences in altitude, a network structure-dependent pressure level has to be maintained in the network. To decrease frictional und pressure losses within the heat network, and by this required pumping energy, the layout of pipes should be with least pipe bends.

In steam networks usually a pressure of 4 to 11 bars is applied, in high pressure steam network even up to 30 bars. This is not caused by the frictional losses in the system, but mandatory to compress the steam and by this decrease the required network diameters. Again a compromise between high pressure (resulting in high pumping energy demand) and larger piping diameters has to be found.

2.3 Technologies for thermal energy supply

Thermal energy generation units can be divided into units for heating, cooling or simultaneous generation of heating and cooling. Here the focus is on heating technologies, which couple the sectors thermal energy supply and electricity, see Table 3.

Generally, all heating units need electricity as an auxiliary energy input, but this is negligible compared to the fuel demand (e.g. pumps and ventilation for fuel-based mono block burner max. 1 % in [17]). Hence, here only technologies with a relevant share of electricity input are stated. Information on high temperature technologies can be found in [18].

Table 3: Relevant heat generation units and their main characteristics [a][19], [b][20]; [c][21], [d] according to vapour pressure table, [e][22]

Technology	Target temperature	Pressure	Load	Used input energy	Efficiency
Electrode boilers[a]	Depending on system, up to 240 °C	30 bar	1 – 90 MW_{th} [b]	Electricity	97 %
Heat pump	Currently approx. 120 °C, future up to 165 °C expected[c]	120 °C ~ 2 bar[d] 165 °C ~ 7 bar[d]	2 kW_{th} – 20 MW_{th}[b]	Environmental energy, electricity	Decreases with target temperature
Combined heat and power (CHP)	Depending on exact technology, up to 240 °C definitely possible[e]	240 °C ~ 34 bar[d]	variable	Fossil or renewable fuels	Changes with capacity, e.g.[e] • el. load 5 kW: 26 $\%_{elect.}$, 63 $\%_{therm}$ • el. load 2433 kW: 43 $\%_{elect.}$, 43 $\%_{therm}$

Currently, mainly fossil fuel fired steam boilers, boilers or condensing boilers are used for network based thermal energy supply. In industries with constant heat and electricity demand also fossil-fired, or in some cases wood-fired, combined heat and power (CHP) plants are used. The wood-fired plants are mainly used in industries, where waste wood is generated (e.g. paper industry). In industries with high temperature demand at temperatures about 100 – 120 °C and high waste heat, the interest in the application of heat pumps is increasing, but still these are only seldom used.

Potential other heat sources for the future heat supply are geothermal and solar energy as well as an increase in usage of waste energy. As these sources mainly provide heat at low temperatures and are not as reliable as conventional heat generation units, which makes usage of backup systems even more essential, their integration into the thermal supply of industrial processes will be mainly focussed via heating networks.

2.4 Operation of connected thermal supply units

Case studies already indicated, that in order to reach an efficient thermal energy supply, an interconnection of several heat sources in multivalent (operating simultaneously) and multienergetic (based on several energy sources) compounds is suitable [23]. After a description of interconnection possibilities, relevant interconnection scenarios for the different temperature levels relevant for industrial thermal networks are determined.

2.4.1 Basic concept of heat generation unit interconnection

Generally, when several heat generation units are combined for thermal energy supply, these can be connected in parallel or in series to supply the required energy. The thermal demand ($\dot{Q}_{demand}$) is composed of the volume flow ($\dot{V}$), its density (ρ) and its specific heat capacity (c_p) as well as the difference in flow (T_{flow}) and return temperature (T_{return}), see formula (3).

$$\dot{Q}_{supply} = \dot{V} \cdot \rho \cdot c_p \cdot (T_{flow} - T_{return}) \quad (3)$$

In parallel connection the heat supply units provide the same temperature spread from return to flow temperature, but different loads. In this case the volume flow is divided between the supply units.

Contrary to this, in series connection the temperature spread is divided between the thermal energy supply units. This interconnection is already widely investigated and applied for the heat supply from heat pumps [24], but not for other heat supply technologies. For the provision of cooling indirect series interconnection of cooling units is already state-of-the-art. Often compression coolers provide air conditioning at a flow temperature of about 6 °C. The thermal energy uptaken at the cold side of the compression cooler is transferred via the compression cooling cycle to another energy stream passing the hot side of the cooler. Often here the temperature level of an environmental energy stream is slightly increased (e.g. ground/river water) or at cold outside temperatures the heat is emitted via free-cooling.

In Figure 1 the division in thermal load supply, either in parallel or series connection is illustrated. The overall coloured area of the graphs is the load, so in both images the overall heat load is the same, but the division of volume flow and temperature lift between the generation units varies.

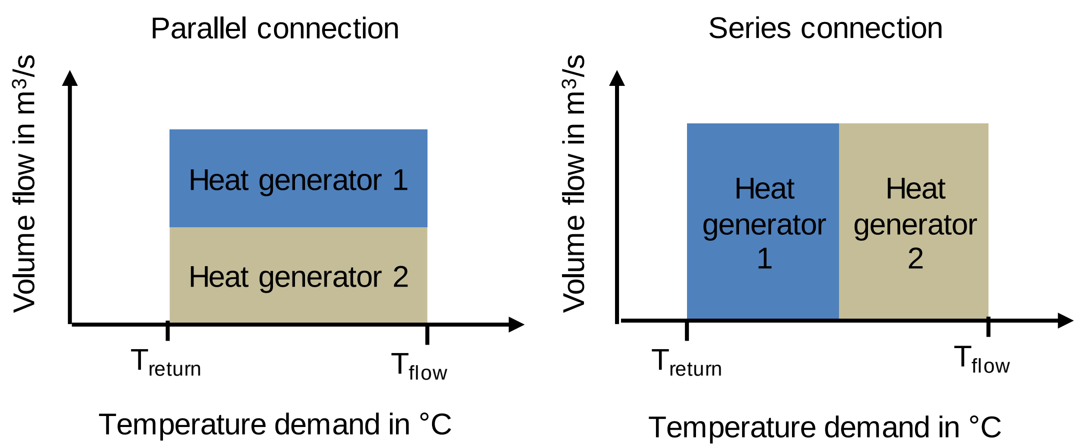

Figure 1: Illustration of heat generation unit connection in parallel (left) and series (right)

For parallel and series connection the different generation units do not necessarily have to be placed in physical proximity. Similar to already applied systems in district heating, thermal network connected temperature boosters can be situated close to the consumers with a higher requirements. In a series connection the heating network provides thermal energy at a moderate temperature and decentralised units further increase the temperature level of this (e.g. gas boilers, heat pumps). Here a decentralized utilization of fuel-based technologies would require further waste gas treatment facilities, this is not the case for the implementation of electricity based technologies.

2.4.2 Suitable connections for network based hybridized heat supply

The basic idea of the interconnections stated here is that also at times of electricity surplus in the supply system, electricity should be used as efficiently as possible. Whilst electric and electrode boilers are highly flexible and investment costs are low, due to low efficiencies and hence heat generation costs compared to heat pumps, these will also in the future not be used as base load technologies. Therefore, it is possible that for a decrease in fossil fuel demand, heat pumps become an industry wide spread technology. Here it must be considered that the efficiency of applied heat pumps is extremely dependent on presence of heat sources for the heat pump. In industries with large amounts of low-temperature waste heat, e.g. manufacturing, higher efficiencies can be obtained than in industries with low potentials, e.g. quarrying industry (information on waste heat potentials see [25]).

However, in all industrial branches heat pumps will foreseeably not be able to provide energy at temperatures needed for the medium and high pressure networks described in chapter 2.2.1 . In these systems, a temperature-wise interconnection of the low temperature heat source heat pump with high temperature heat sources, such as electrode boilers, fuel-based boilers or CHP units, is probable. An overview on suitable hybrid technology combinations depending on the flow and return temperature is stated in Table 4. The interconnection only of a heat pump and a CHP unit is unlikely, due to the need for a highly flexible low-investment peak load unit such as a conventional steam boiler. Therefore, here only the interconnection of all three units is seen as plausible technology combination.

As electrode boiler and electric resistance heating are similar, here the electrode boiler is seen as representative for both technologies.

Table 4: Overview on suitable technology interconnection by target temperature level

Target temperature	Suitable hybrid systems
Flow < 120 °C	Heat pump, fuel-based boiler CHP, fuel-based boiler
Flow > 120 °C	heat pump, electrode boiler, steam boiler heat pump, CHP, electric boiler and/or steam boiler CHP, electric boiler and/or steam boiler
Flow > 120 °C and Return > 120 °C	CHP, steam boiler and or electrode boiler steam boiler, electrode boiler

In these basic considerations the most cost efficient operation of the different heat generation units depends on the ratio of heat generation costs from electricity to the heat generation costs from fuels. Furthermore, it has to be differentiated between times of need for flexible electricity demand, which can be negative (increase in electricity demand) or positive (decrease in electricity demand). The smartest combination of the present technologies is here described depending on the ratio of electricity-to-fuel based heat supply cost and the required load (basic prioritization see Figure ***2***).

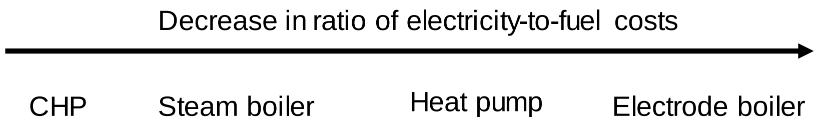

Figure 2: Technology prioritization depending on ratio of electricity-to-fuel cost

A detailed discussion on the most efficient integration of low-temperature heat generation units, depending on thermal load for an exemplary customer can be found in [23].

Heat pump and fuel-based boiler

At temperatures requirements below 120 °C it is assumed that the usage only of a boiler and a heat pump is sufficient, as both can reach the target temperature. Due to the relatively high specific costs for heat pumps, these will not be designed for covering peak loads. Figure 3 gives an overview on the interconnection of the different heat supply units depending on the boundary conditions. Here firstly the extreme scenarios are described and then the more complex medium scenario.

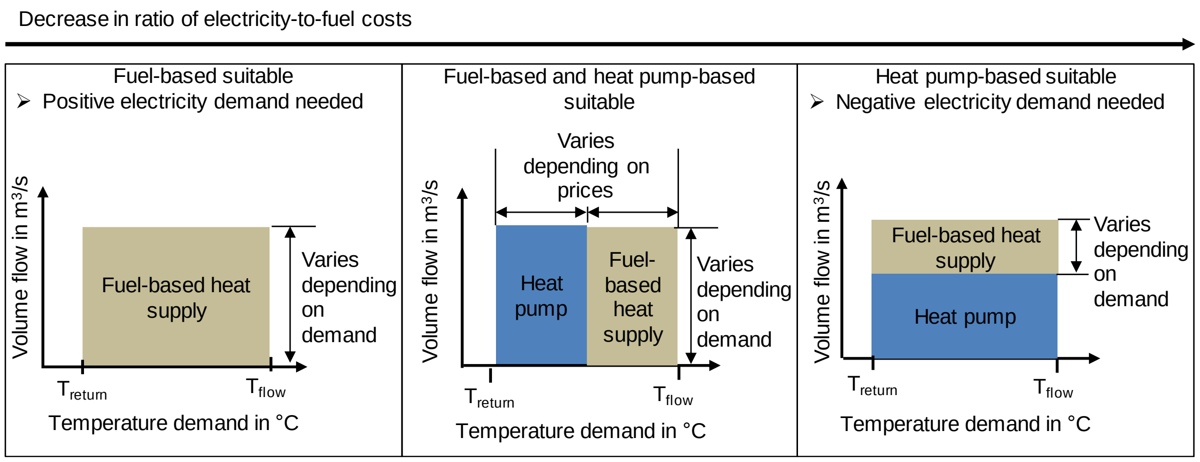

Figure 3: Interconnection of Heat pump and fuel-based boiler, depending on boundary conditions

At times of high costs for heat pump-based heat, only the fuel boiler takes over heat generation by heating the required volume flow from the return to the flow temperature (left image in Figure 3). While the temperature difference is relatively constant, the load of the heat generation unit is altered by a change in volume flow.

In contrast to this at times of negative electricity prices, the heat pump runs with its maximum load and for the entire temperature spread. By applying the maximum temperature spread its efficiency decreases, hence electricity uptake and thermal energy output maximise. If the heat load provided is higher than the demand, it has to be stored or the volume flow heated up by the heat pump is decreased. If the heat demand is at its peak and cannot be provided by the heat pump only, the fuel-based technology has to support the heat pump.

In situations, where heat supply costs based on fuels and electricity are competitive, the operation mode of the overall system varies depending on the ratio of costs. For heat pumps the efficiency decreases with the target temperature and therefore the heat generation cost increases with it. Conclusively, the suitable target temperature of the heat pump depends on the ratio of the electricity-to-fuel prices. With a decrease in the ratio, the target temperature of the heat pump is increased. Accordingly, in this scenario the heat pump may run in very low load (low temperature spread, high efficiency) to full load (high temperature spread, low efficiency).

Moreover, the suitable target temperature depends on whether the heat pump can provide the overall demand. If the demand is higher than the minimum load of the heat pump, a decrease in target temperature is more suitable than a division in volume flow between the units.

In this description it is neglected that the efficiency of the fuel-based supply unit decreases with a decrease in temperature lift provided by it. This must be included in determining the fuel- and electricity-based heat generation costs and hence the intermediate temperature.

Heat pump, fuel-based boiler and electrode boiler

The advantage of this technology combination for high temperature heat supply is that fuel-based and electrode boilers are low-investment technologies. Thereby, an oversizing of these is not as critical as for high-investment technologies such as heat pumps or CHP units. Additionally, both technologies are highly flexible and therefore can make up for the relatively slower heat pump. For this interconnection overall four scenarios exist. As for the system consisting of heat pump and fuel-based boiler only, in the scenario with high electricity prices only the fuel-based system operates, the other three scenarios are visualized in Figure 4.

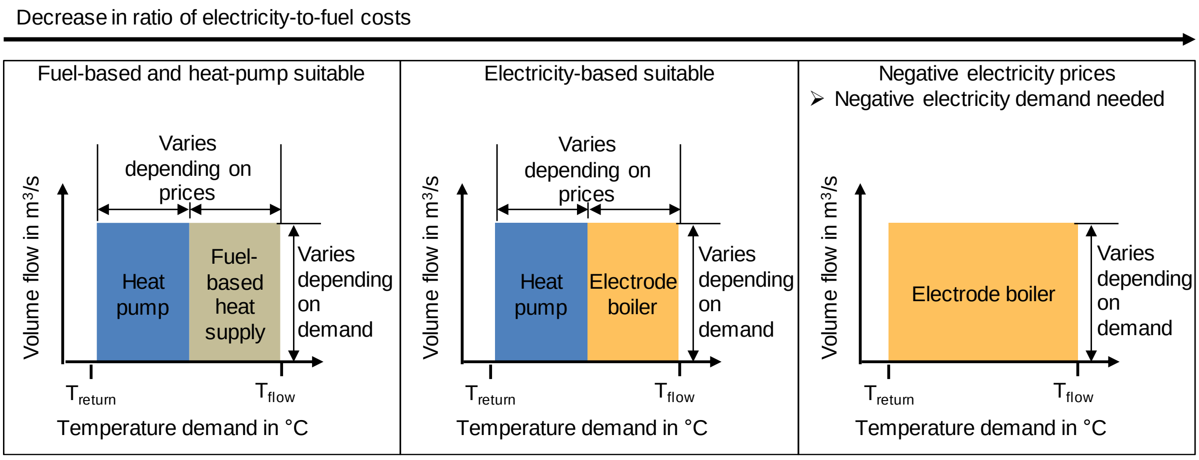

Figure 4: *Interconnection of heat pump, fuel-based boiler and electrode boiler, depending on boundary conditions*

Again with a decrease in the ratio of electricity to fuel prices, the heat pump takes up operation from low to high target temperature. At times where heat generation from the electrode boiler is cheaper than heat from the fuel-based boiler, the heat pump runs at maximum load (full volume and accordingly allowed temperature lift) and the electrode boiler provides the possibly further required temperature lift. According to information from an electrode boiler manufacturer, the electrode boiler inlet medium must be liquid, but no further limitations apply. As currently maximum outlet temperatures of heat pumps are at about 120 °C and the pressure needed for liquefaction can be provided this is not crucial for the interconnection.

The fourth scenario implies that electricity prices are negative, so for the most economical mode of operating the system the maximum load of the electrode boiler is used to provide heat. From an overall systemic point of view however, it might still be preferable, that the combination of heat pump and electrode boiler is used for heat supply. This combination allows the generation of more thermal energy than the electrode boiler only, therefore the cheap electricity can be used in several heat supply systems and hence decreases the future need for fuels/electricity.

Heat pump, CHP, fuel based steam boiler and electrode boiler

The connection of all four units is depicted in Figure 5. The operation logic of all other interconnections, stated in Table 4 are a simplification of this. As this is the first interconnection including CHP and electricity consuming units, their interconnection is shortly described. If the electricity from the CHP unit is sold at the electricity market, in this interconnection the ratio of electricity to fuel prices has an even stronger effect. In this case the operation of the CHP does not only prevent electricity consumption of the electricity based unit, but furthermore generates income.

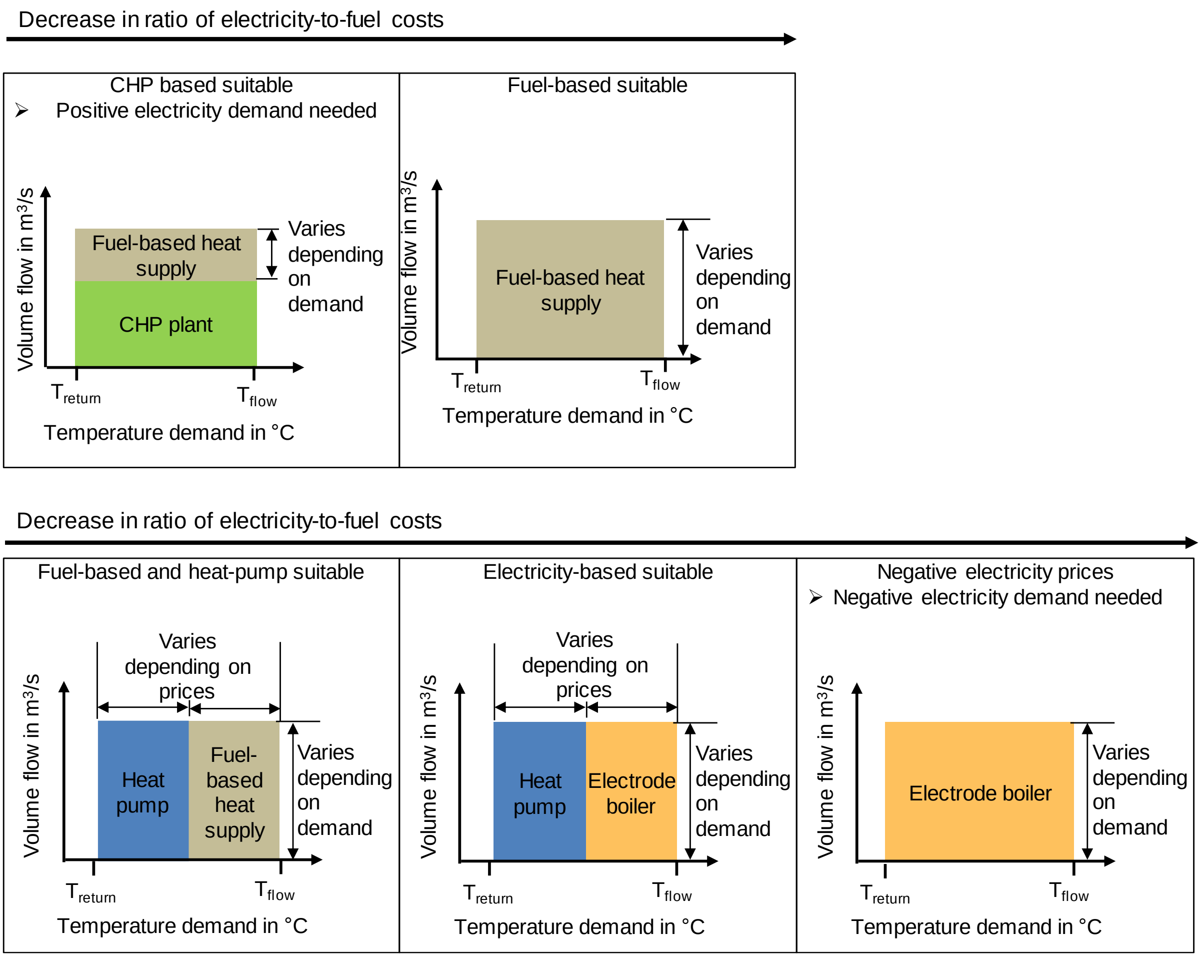

Figure 5: Interconnection of heat pump, CHP, fuel-based boiler and electrode boiler, depending on boundary conditions

However, in most industrial sites, the on-site generated electricity is also consumed on-site. Also it can be economically favourable to use the electricity from the CHP in the heat pump to generate heat instead of selling it on the market [23]. Regarding grid relief, the CHP plant is a negative electricity consuming unit, hence at times of electricity oversupply it is turned-off and turned-on at times of electricity demand.

Fuel-based steam boiler and electrode boiler

In an interconnection of fuel-based heat supply and an electrode boiler, only the two situations “fuel-based heat supply” and “electrode boiler-based heat supply” exist. Hence, as soon as heat generation from electricity is cost competitive, heat generation is completely switched from fuel-to electricity-based.

CHP, steam boiler and/or electrode boiler

In this combination CHP and steam boiler, no electricity consuming unit is present. Here the fuel-based unit still covers heat supply at negative electricity prices. Also in the combination CHP and electrode boiler, the CHP runs at high and the electrode boiler at low prices. In both combinations if necessary a parallel interconnection is preferred to a series connection due to higher overall efficiency.

2.5 Relevant thermal storage concepts

A storage concept consists of the storage technology, a supply and consumption unit combined with the storage control [26].

Storage technologies

Storage technologies themselves are differentiated into sensible, latent and chemical storage, where sensible storages have the lowest specific heat capacity but are also less capital intensive. Currently, in all areas of heating and cooling supply water-based sensible storage systems dominate, still an increasing number of research projects with latent or chemical storage units exist [27].

Control of central storages

In many cases the storage is used to increase the security of supply for the system, therefore it is constantly operated at the required flow temperature. Another vastly applied operation is the optimization of heat generation unit efficiency. The efficiency of thermal generation units depends on their operating point, e. g. full load or 60 % part load can be the most efficient operation mode. An interconnection of heat generation units with a thermal storage tank, allows that these can run in the optimal operation point and do not have to be constantly adapted to the thermal energy demand of the consumers.

In large industrial sites, where electricity prices are highly determined by the fluctuation prices on the market, storages connected to CHP plants or Power-to-Heat devices can also be used to allow a market optimal operation of these units. As most sites prefer electricity own-consumption over trade at the market, this operation is currently not frequent.

Control of decentral storages

In most industries due to lower specific costs, central storages are preferred over decentral storages. However, if these are situated in network arms with a highly fluctuating demand, here the application of decentral storages allows a smoothing of demand and by this a decrease in required piping diameters.

With the aim of reducing waste heat emissions, decentral storages take up the waste heat from one process step to serve as input energy to another process step (e. g. thermal buffer silo). In heating networks decentral storages can also be used, to allow intra-day fluctuations in heat supply to individual branches or to increase the security of supply.

3 Analysis of thermal heat supply in real factories

Through the execution of energy audits and the management of several energy efficiency networks, the FfE obtained vast data on energy supply characteristics in industrial sites. After as short description of the dataset, characteristic values for central to decentral heat supply and installed loads depending on overall demand are derived.

3.1 Description of data set

The dataset analysed for this study consisted of 52 companies from 8 industrial branches (see Figure 6). For each company it includes details on consumed final energy, installed energy generation and consumption units as well as the supply system for heating and cooling.

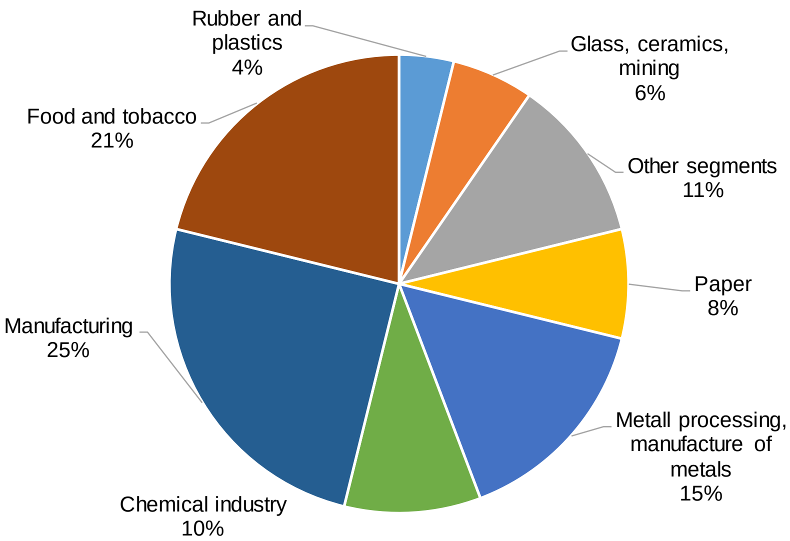

Figure 6: Composition of the analysed dataset

3.2 Status quo of network utilization in data set

Theoretically, the overall heat demand of temperatures up to 240 °C could be provided by thermal networks. Data analysis shows that the share of heat provided by thermal networks depends on the heat demand structure as well as historical developments in individual branches and therefore the industry. An overview on the relevance of network-based heat supply in the companies being part of the dataset is given in Table 5.

For example, in the manufacturing industry decentral heating units are widely applied for washing purposes. Because in manufacturing relatively wide spread factories with high waste heat from electricity-based technologies and hence relatively low specific heat demand dominate, here dark emitters are preferred over central heating units. Also in special processes or laboratories electric decentral heating is preferred due to higher accuracy in temperature management. For areas with higher specific heat demand, individual gas boilers are applied.

Table 5: Overview on share of central based heat supply at adequate temperatures in the analysed dataset

Industry	**Number of companies**	**Companies with heat demand < 240 °C**	**Share of central based process heat demand**	**Share of central based surface heating demand**
Rubber and plastics	3	3	65 %	90 %
Glass, ceramics, mining	3	2	90 %	0%
Paper	4	4	69 %	100 %
Metal processing, manufacture of metals	8	5	38 %	83 %
Chemical industry	5	5	98 %	98 %
Manufacturing	13	8	62 %	95 %
Food and tobacco	11	11	99 %	96 %

In contrast to this in the food and tobacco and chemical industry nearly all heat demand is covered by a heating central. Thereby, especially in the chemical industry heat is often extracted on several temperature levels from a central heating unit and technologies supplying simultaneously heating and cooling are applied.

4 Network-based industrial thermal energy demand

From an analysis of the thermal energy demand in different industrial branches, the relevant thermal energy demands per industrial branch and temperature level are derived.

4.1 Industrial thermal energy demand and relevant energy sources

In 2017, the German industry consumed 2.700 PJ of final energy out of which 2.040 PJ was used to provide thermal energy and therefore 22% of the overall German energy demand [28]. Overall, the thermal energy demand can be divided into process heat (89%), space heating (7%), domestic hot water (1%), air conditioning (1%) and process cooling (2%) [29]. The thermal energy demand by type and industry is depicted in Figure 7 and the cross-industrial share by final energy source for the different energy demands in Figure 8.

In several industries, especially in manufacture of metals, the high process heat demand dominated the overall thermal energy demand and is mainly based on gas or coal.

While for heating purposes the most used final energy is natural gas, conditioning and process cooling are currently exclusively provided by electricity. Overall, the composition of heat supplied by source is similar for space heating and domestic hot water, which is caused by the fact that these are usually provided from the same central heating unit. The difference is mainly the larger share of electricity in domestic hot water supply, which is caused by the frequent application of electricity based decentral instantaneous water heaters.

Overall, electricity currently provides 7% of process heat, 1% of space heating and 12% of domestic hot water.

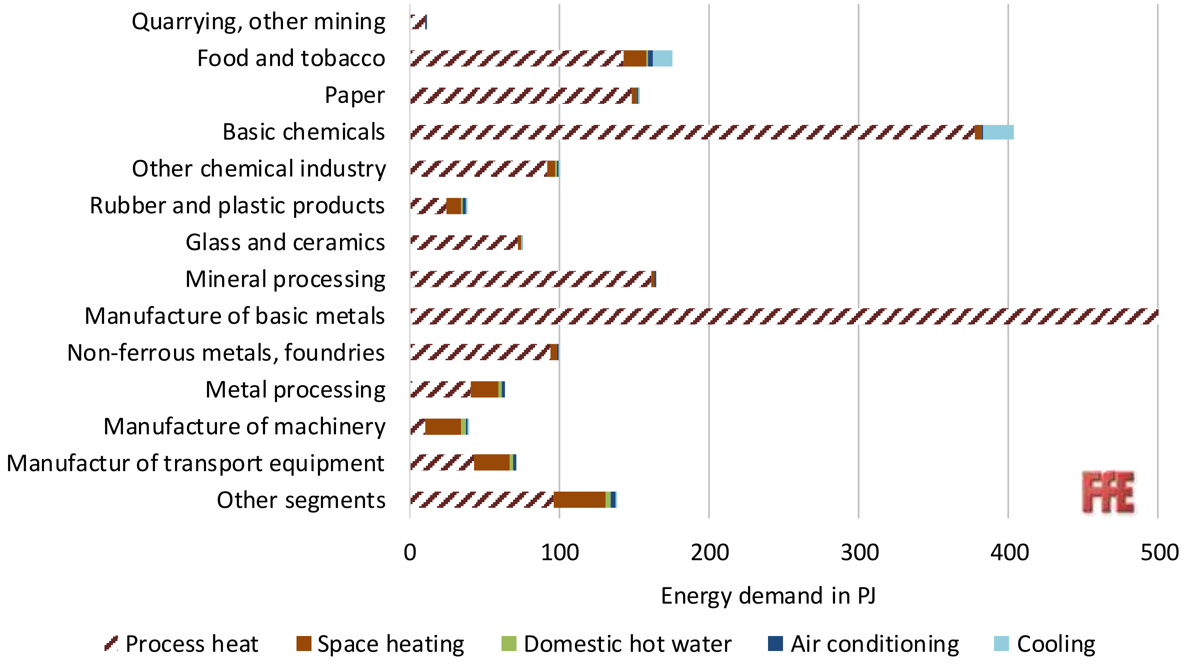

Figure 7: Thermal energy demand by industry and demand type in Germany in 2017, from [29]

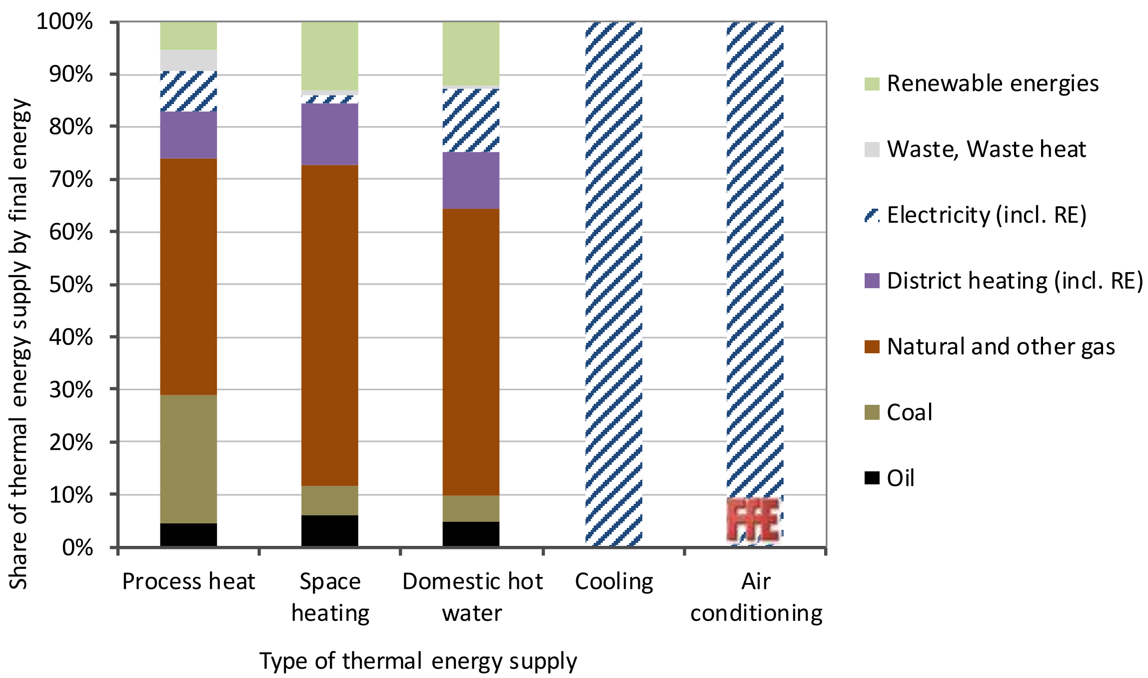

Figure 8: Provision of thermal energy supply by heat demand type and final energy in Germany in 2015, from [29]

Regarding the potential for hybridization, a more detailed investigation of process heat provision by branch is necessary (see Figure 9)

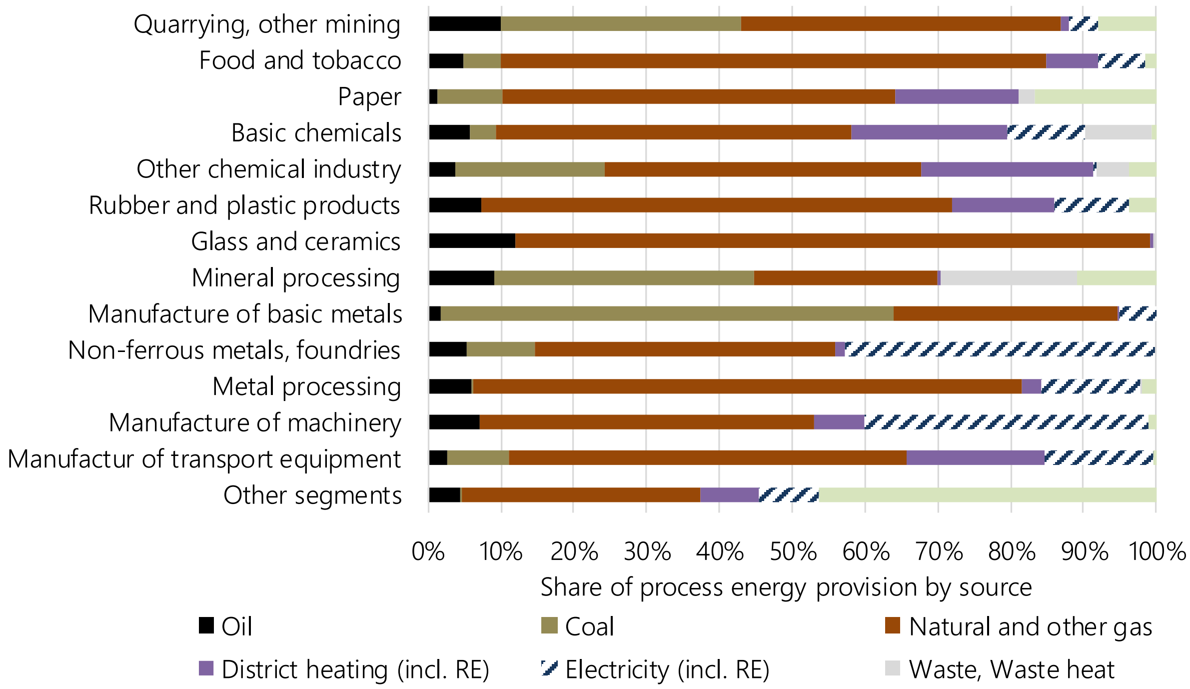

Figure 9: Provision of process heat by industry and energy source in Germany in 2015, from [29]

Unfortunately, the available data does not allow statements on the share of heat supply which is provided by industrial thermal networks. Valid assumptions are that the domestic hot water provided by electricity is mainly provided by decentral units and that all the surface heating as well as domestic hot water provided by coal is based on heat from a large-scale plant via a thermal energy network. Also all heat provided by district heating will be distributed via an industrial thermal network on-site.

While the data stated above was based on the final energy demand, an analysis of the potential of network-based thermal energy supply must be based on the actual heat demand. The final energy demand per final energy type ,in combination with representative energy conversion efficiency factors per final energy[2], indicates that the industrial heat demand lay at 1.780 PJ.

4.2 Demand by temperature levels

In [30] the process heat demand by temperature level for different industrial branches is stated. For the analysis in this paper, from the data given, the share of process energy demand by temperature level and branch is calculated. Although the basic data is from 2008, according to the assumption that the share of energy demand by temperature level is quite constant per branch, it is multiplied with the process energy demand per industrial branch of the year 2017 from [29] (results see Figure 10). In order to combine the datasets, the categories from [29] are aggregated as follows:

[2] Renewable energies, fuels, waste and waste heat 88 %; district heating 98 %, electricity 99 %

- *Mining and Mineral processing*: Quarrying, other mining; Mineral processing
- *Chemical industry*: Basic chemicals; other chemical industry
- *Metal production*: Manufacture of basic metals; Non-ferrous metals, foundries
- *Manufacturing:* Manufacturing of transport equipment + Manufacture of machinery

The process energy demand for the category “other segments” in [29] is combined with a weighted average of the heat demand by temperature level from the [30] categories wood, printing and textile.

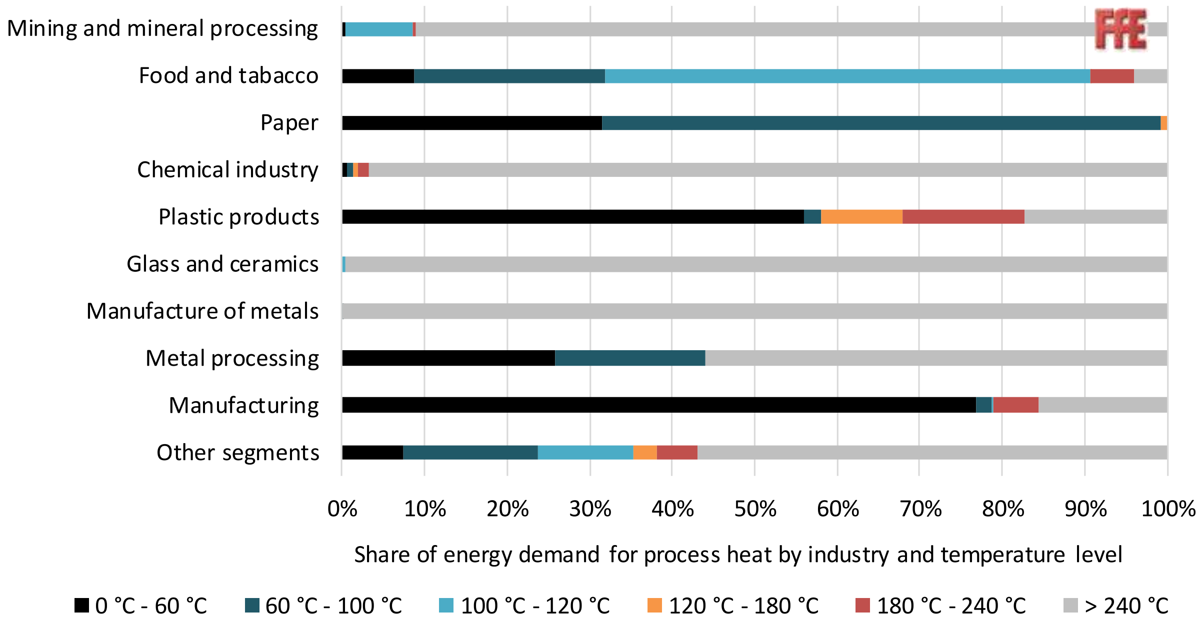

Figure 10: Thermal energy demand by industrial branch and temperature level for Germany 2017, based on data from [29] and [30]

As stated in chapter 2.2.1 thermal energy demand at temperatures of over 240 °C is not relevant for network based thermal energy supply. Hence, about 24% or 396 PJ from the overall process heat supply are the theoretical potential for grid based thermal energy supply.

This potential can be significantly increased including the demand for surface heating (136 PJ) and domestic hot water (15 PJ), reaching an overall potential of 547 PJ or 31% of overall thermal energy demand in the industry.

Due to hygienic reasons domestic hot water always has to be provided at temperatures over 60 °C, therefore it is included in the temperature range 60 – 100 °C. From an expert estimation a distribution of the surface heating demand to 30 % at the temperature range 0 °C to 60 °C and 70 % at temperatures of 60 °C to 100 °C is included in Figure 11. While in branches with high process heat demand the distribution of heat demand clusters does not change significantly, this is the case for other branches (e.g. metal processing).

Theoretically, this overall demand at temperatures below 240 °C can be supplied by industrial thermal networks and provide flexibility to the electricity supply system. The realistically available flexibility potential is calculated in the following chapter.

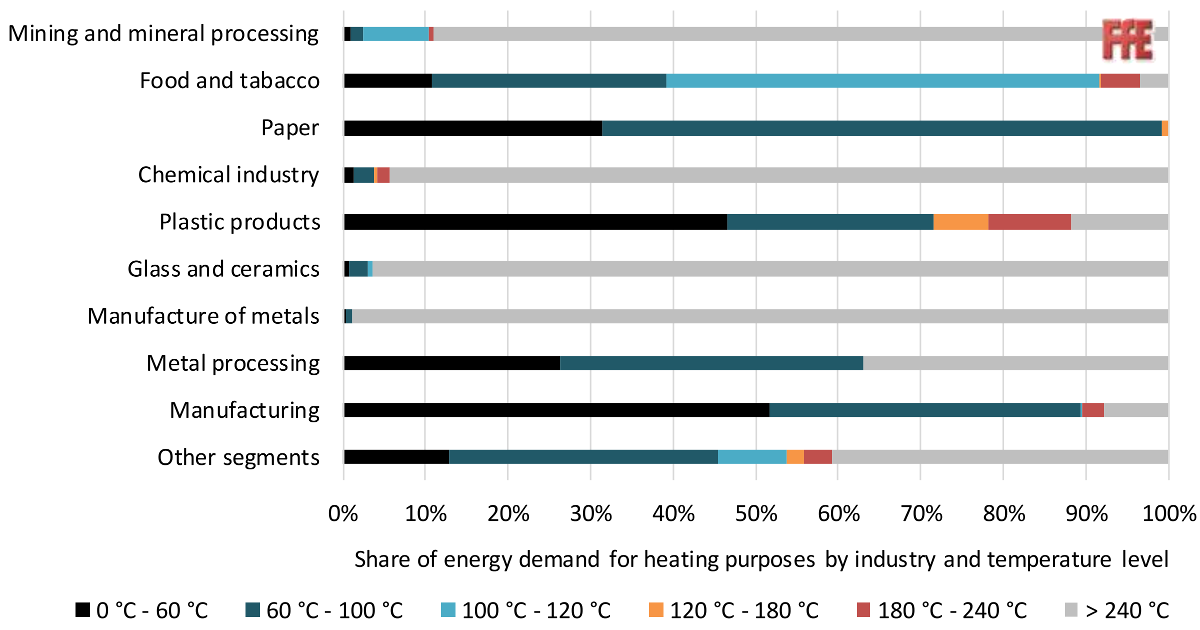

Figure 11: Energy demand for heating purposes by industrial branch and temperature level, based on data from [29] and [30]

5 Hybridization and flexibility potential of industrial thermal networks

In this chapter the basic knowledge on industrial thermal networks from (chapter 2), the data from real sites presented in chapter 3 and the top-down data discussed in chapter 4 are connected in order to calculate the probable for network-based heating

5.1 Viewpoint on flexibility

In [13] the definitions and crucial criteria for determining industrial flexibility is discussed.

- **Type of potential**: Technical potential
- **Collected parameters**: Thermal energy demand by industry and temperature level, share of network-suitable heat provided by decentral units, full load hours of network connected heat generation units
- **Direction of load flexibility**: Focus on maximum increase in negative demand (additional load); maximum positive demand is similar, as this is achieved by turning off of the electricity-based technologies
- **Time frame**: Currently installed units
- **Data collection method and calculation method:** Potential by industrial branch calculated from top-down data and data from dataset of 52 individual companies
- **Depicted potential**: Potential for each industrial branch is given in diagram and data by temperature is explicitly given in tables
- **Differentiation in technoeconomic, timely and spatial resolution:** no differentiation evaluated, overall technical maximum potential for Germany determined

5.2 Potential for network-based hybridization

The hybridization potential is based on the following idea: To all currently installed fuel-based heating units connected to an industrial thermal network an electricity-based system is connected. The electric load of these units is the theoretical potential for load flexibility. Cooling is already mainly electricity based or operated with environmental energy, e.g. well water or cooling towers. Therefore, there is no further hybridization potential.

5.2.1 Fossil-based heat supply by temperature level

In the evaluation only fossil-based heat supply is supposed to be electrified. For this, from the temperature-wise suitable potential determined in chapter 4.2, the heat demand already supplied by electricity or by renewable heat generation units must be subtracted. Furthermore, the heat supplied by district heating networks is subtracted, as these are not maintained and operated by the industrial companies themselves, but by utilities.

The electrified domestic hot water provision by branch is subtracted from the heat supply at 60 °C to 100 °C, the same is valid for the domestic hot water provision based on renewable energies and district heating. Also the heat for surface heating demand provided by electricity, district heating, renewable energies and additionally from waste and waste heat is subtracted from the heat supply before it is divided between the categories by temperature level.

In Figure 12 the process heat demand by temperature level up to a network suitable temperature of 240 °C for all branches and the current energy provision from renewables, electricity and district heating is depicted. The upper bar per branch is the heat demand by temperature level and the lower bar the heat provided by the four energy sources, which have to be subtracted.

The graph shows that in the branches mining and mineral processing, chemical industry, glass ceramics, manufacture of metals and other segments the energy provision from the four not displaceable-energy sources is higher than the actual heat demand at hybrid-heating network suitable temperature levels. Therefore, these branches are excluded from the potential.

For the remaining branches no persistent assumptions regarding the connection of heat supply sources and heat demand by temperature level can be made. While it can be assumed that renewable energies and district heating cover an energy demand at temperature below 240 °C, the heat supply by electrical energy and waste must be subtracted from all temperature levels.

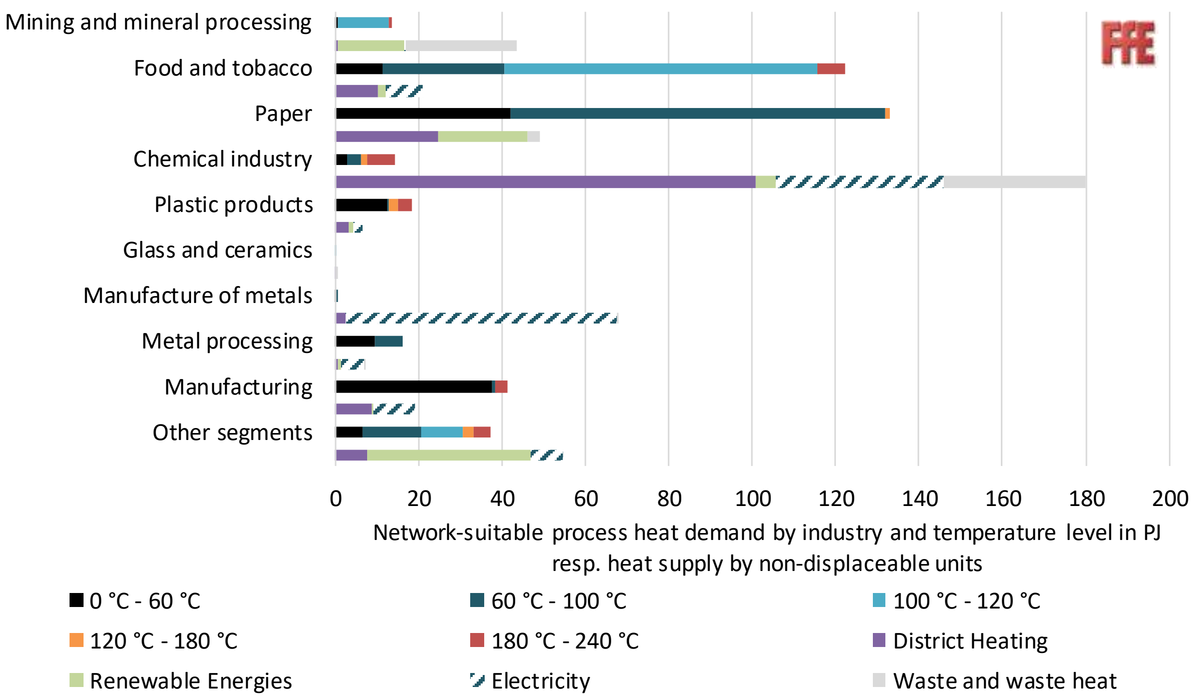

Figure 12: *Energy demand for process heat by industrial branch regarding temperature level and energy provision from renewable energies, electricity and district heating*

Here, the heat supply which has to be subtracted by branch and temperature level energy source ($\dot{Q}_{provided,\ branch,\ T\ level,\ source}$) is calculated from overall heat provided to the branch by the source ($\dot{Q}_{provided,\,branch,\,source}$) multiplied with the ratio of the heat demand by the branch for a certain temperature level divided by overall energy demand below 240 °C in the branch, see formulae (4).

$$\dot{Q}_{provided,\ branch,\ T\ level,\ source} = \dot{Q}_{provided,\,branch,\,source} \cdot \frac{\dot{Q}_{demand,\,branch,\ T\ Level}}{\dot{Q}_{demand,\,branch,\ T<240\,°C}} \quad (4)$$

The remaining potential for industrial thermal heat supply, expanded by the heat demand for surface heating and domestic hot water lies at 282 PJ and therefore at 16% of overall thermal energy demand in the industry. This can be differentiated between the temperature levels as stated in Table 6 and by temperature level and branch as shown in Figure 13.

Table 6: Potential for network based hybridized thermal energy supply

Temperature level	**Theoretical potential for network based hybridized thermal energy supply in PJ**
0 °C – 60 °C	79
60 °C – 100 °C	137
100 °C – 120 °C	57
120 °C – 180 °C	2
180 °C – 240 °C	8

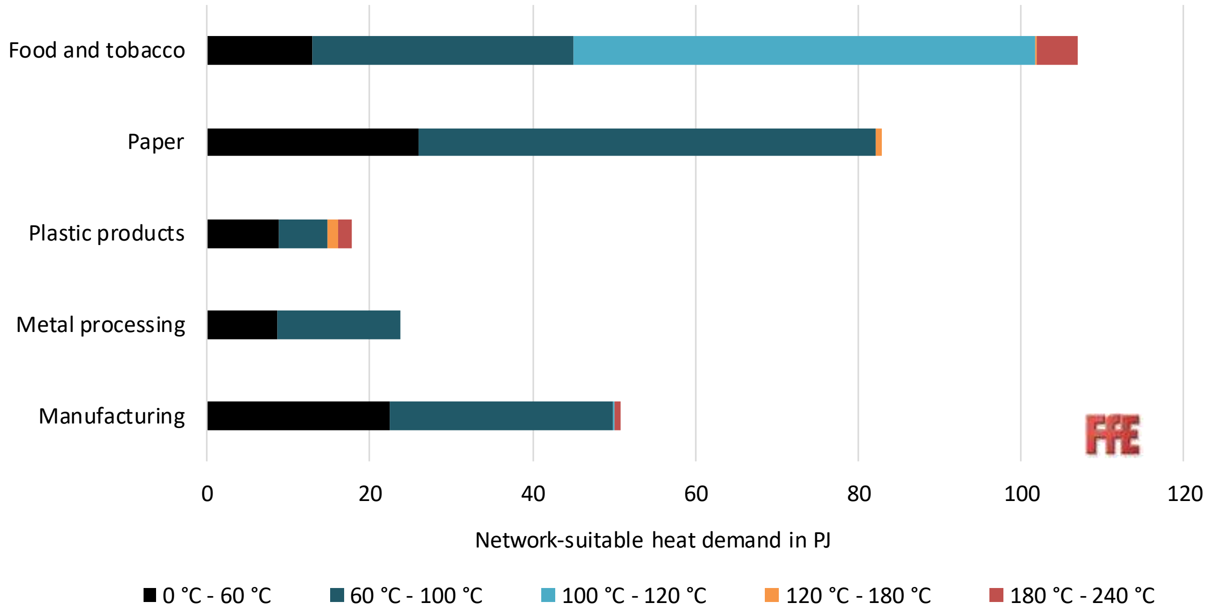

Figure 13: Energy demand for heating purposes provided by fossil fuels, potentially to be provided by hybridized industrial thermal networks

5.2.2 Subtraction of decentral heat supply

As described for the companies included in the dataset described in chapter 3, decentral heat generation units still cover an unneglectable share of process and surface heating heat supply. These units are usually electricity or gas-based. As in the prior step heat supply by electricity was already subtracted from overall thermal energy demand, the gas-based decentral heat supply still has to be excluded (results in Figure 14 and Table 7).

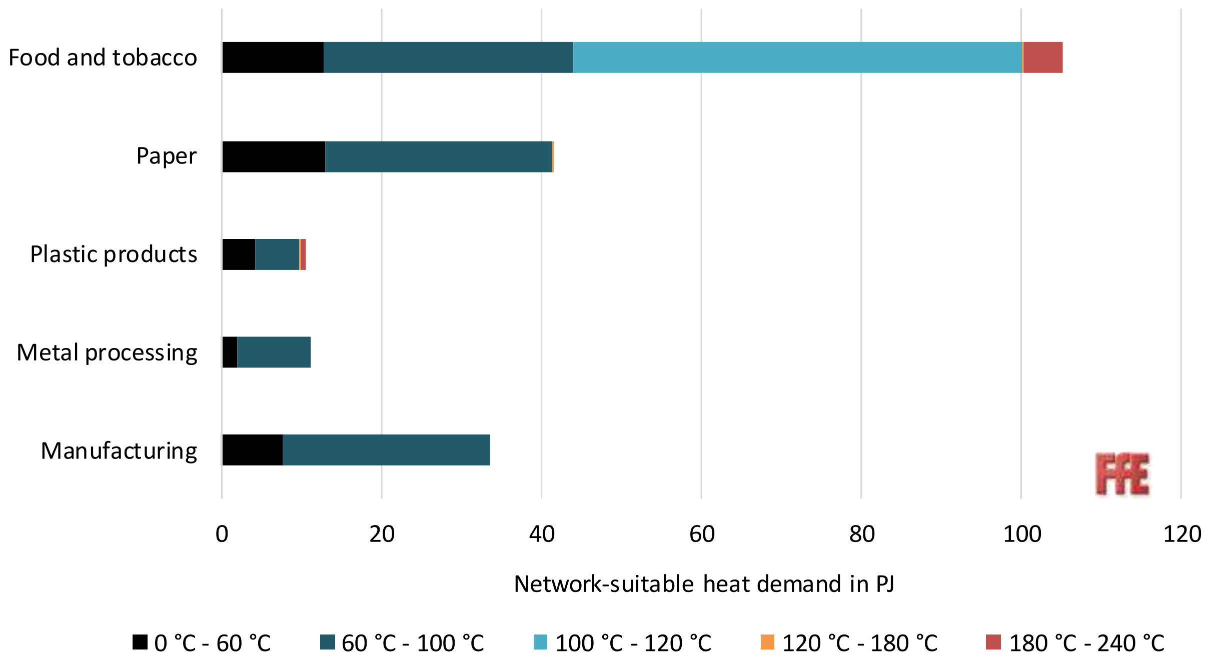

Figure 14 Energy demand for heating purposes centrally provided by fossil fuels, potentially to be provided by hybridized industrial thermal networks

Table 7: Potential for network based hybridized thermal energy supply excluding decentral heating units

Temperature level	Potential for hybridized network based heat supply in PJ
0 °C – 60 °C	40
60 °C – 100 °C	100
100 °C – 120 °C	56
120 °C – 180 °C	1
180 °C – 240 °C	5

These potentials sum up to 202 PJ or a share of 11 % of overall industrial thermal energy supply.

5.2.3 Installed network connected heat load:

In Table 8 the potentials calculated are combined with the relevant heating network and the suitable electrification unit depending on the scenario. Here the potential from Table 7 is always added at the maximum temperature level of the range defined. In the maximum flexibility scenario, a maximization of installed electricity consumption is assumed. In the base scenario, heat pumps are applied for a temperature lift up to 120 °C, hence in the medium pressure network the overall temperature lift from return to flow (100 – 180 °C) and accordingly the load in spread is between the heat generation units heat pump and electrode boiler.

Table 8: Overview on relevant temperature levels for grid based thermal energy supply, adequate technologies and flexibility potential

Grid level description	Temperature level	Theoretical potential for network based thermal energy supply in PJ	Applied technologies -> Base scenario	Applied technologies -> Maximum flexibility scenario
High pressure steam	240 °C	7	Electrode boiler	electrode boiler
Medium pressure steam	180 °C	1	Heat pump (COP = 3) + electrode boiler	electrode boiler
Steam	120 °C	180	Heat pump (COP = 3)	electrode boiler
Hot water	60 °C	48	Heat pump (COP = 4)	electrode boiler

In order to determine the technical potential regarding load provision, limitations regarding the maximum allowed thermal feed-in into the thermal network apply.

From the data available the overall installed load per thermal network can be derived. However, a significant amount of the installed heat generations units only serves as back-up units. Therefore, the maximum thermal load uptake at normal operation conditions is lower than the load of the installed heat generation units. Still, as discussed in chapter 2.2.2, the thermal energy uptake by the thermal network can be increased by an increase in volume flow or in flow temperature.

Because from the available data, no realistic assumption regarding the full load hours of thermal networks and the connected heat generation units can be drawn, the flexible load for both scenarios is presented in Table 9 and for several possible full load hours.

Table 9: Flexible load of network connected units depending on scenario and assumed full load hours

Assumed full load hours for network dimensioning	Flexible load in GW -> Base scenario	Flexible load in GW -> Maximum flexibility scenario
2,000	9.5	28.9
3,000	6.3	19.3
4,000	4.7	14.5
5,000	3.8	11.6
6,000	3.2	9.6
7,000	2.7	8.3

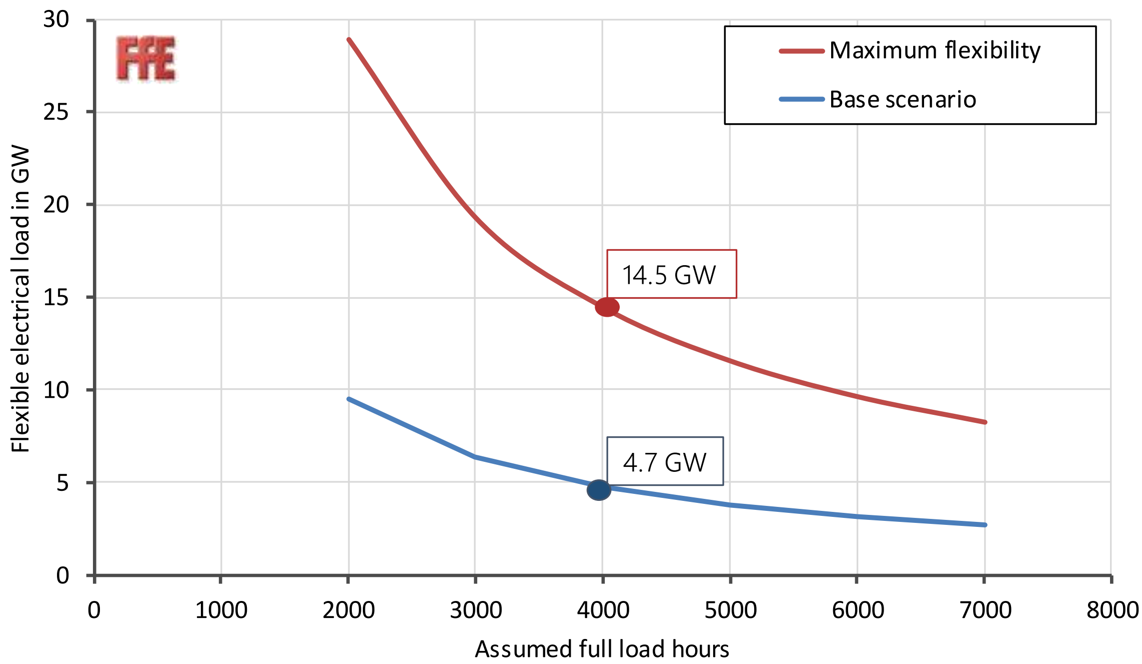

Figure 15: Visualization of flexible, electrical possibly provided from hybridized of industrial thermal networks

At 4,000 full-load hours, in the base scenario a flexible capacity of 4.7 GW is reached and 14.5 GW in the scenario with maximum flexibility. Compared to an average electricity demand in Germany of 59 GW, this makes up approx. 8 % (baseline scenario) or even 25 % (maximum flexibility scenario).

5.3 Flexibility potential via grid overheating

For economic reasons, it makes sense to first use flexibility options in the existing infrastructure, before integrating further infrastructure components such as storage. For example Power-to-Heat systems can be connected to a thermal storage tank in order to provide flexibility to the electricity supply sector. Another possibility is to make use of the thermal flexibility of the working fluid in the thermal supply system. For example, by increasing the target temperature of the flow temperature in the heating network, this can take up more energy than in the normal operation mode. This idea applies to Power-to-Heat devices as well as CHP plants. In most cases overall efficiency decreases with an increase in target temperature, but in case of electricity oversupply and connected low electricity prices, this decrease in efficiency is not crucial.

Currently, the technical applicability of thermal network flexibilisation is part of simulative [31] and practical [32] investigation.

This overheating of the working fluid in the network has several effects and its applicability is limited by several factors. Firstly, an increase in target temperature leads to higher thermal losses. Secondly, with higher temperature the thermal loading of the network pipes increases. Since the pipe material expands with an increase in temperature, stresses arise in the material. This expansion of the networks can be compensated by curved pipe shapes or compensators. Especially in industrial thermal networks high pressures are already applied at normal operation temperatures. To allow further increases in pressure, the thermal network must be constructed for this.

Thirdly, for the applicability of network overheating, heat exchangers between the thermal network and the consuming units are essential. This indirect connection of consumers to the grid allows that the temperature of the network is varied, while the specified temperatures for the consumers can be maintained at normal levels. Otherwise, the overheating of the thermal energy supply network may strain on the material of the consuming units, which may negatively affect their operation and lifetime. Hence, in order to determine the flexibility potential through overheating, only networks in which typically heat exchangers are put in place at every consuming station are relevant.

No data on the application on heat exchangers in industrial thermal networks exists. From FfE experiences regarding energy audits, it can be assumed that thermal industrial networks in which all connected consuming units are separated from the network by a heat exchanger are extremely scarce.

In large industrial parks a primary and secondary heat network exists, therefore here an overheating of the primary network can be put into practice without a negative effect on the system operation in the secondary network. No data for a profound evaluation of the potential of overheating of these primary networks exists.

Moreover, here still the fourth limitation applies. The thermal energy emitted from the thermal network to the customer is determined by the difference in flow and return temperature as well as the volume flow (see formula (1)). This means that at a constant heat demand with an increase in the flow temperature, either the return temperature increases or the volume flow decreases. As soon as the volume flow in the network is decreased, the load of the heat generation unit must be decreased. An increase in return temperature has the same effect. Therefore, the time span in which the heat generation unit can run at higher load, due to thermal network overheating, is limited to the time span until the network return reaches the thermal generation unit with higher temperatures.

From the available data it is not possible to assume an appropriate time frame, also this will highly differ by size of the supplied area.

In summary, overheating is a potential measure for increasing the flexibility of network-based thermal energy supply. However, the database for a realistic assessment of its potential is lacking.

6 Discussion and Outlook

After the most relevant limitations of the conducted research are given, an outlook on possible further research topics is given.

6.1 Limitations of methodology

The main limitations of this research include the data itself and its handling.

Data collection
The data used for the evaluation is based on theoretical work from two independent institutes and compared with own datasets. As the procedure of data generation for the information presented in [29] and [30] is not completely transparent, the respective included restrictions and inadequacies cannot be evaluated.

The own data used for the investigation is based on collected data from energy consulting in several different industrial branches. These companies are mainly medium scale companies, which are based in Bavaria. Moreover, a majority takes part in energy efficiency networks supervised by the FfE. Companies taking part in these networks generally are more aware of the importance of an efficient energy supply, which has an effect on their energy supply. Hence, the dataset is not representative for all German companies. However, the databases itself is wide and informative regarding the status quo of thermal energy supply in the industry.

The data was collected in different years, but as in all branches heat demand is mostly not significantly determined by surface heating demand and therefore not influenced by temperatures, this is neglected here.

Data Blending
For the evaluation of the hybridization potential datasets from different sources were blended with a developed logic. This logic potentially includes false assumptions, which leads to a distortion of the results. The data presented in Figure 12 compares heat demand by temperature level to the heat supply from renewables, district heating and electricity. The fact that in the case of the chemical industry the heat supply from district heating exceeds the heat

demand at temperatures below 240 °C indicates that the data does not exactly fit. The heat demand of up to 480 °C must be included in the consideration so that the provision from renewables and district heating does not exceed the heat demand. This indicates that either heating networks with temperatures up to 480 °C in the industry exist, the definition of district heating is not concise or the data is not correct.

For example cross-checking the blended data, as visualized in Figure 12, with own data clearly states inaccuracies. From the bottom-up real supply data, it becomes clear that in the chemical industry natural gas based industrial heat supply is highly relevant for hybridization. However, from the top-down data this potential was neglected.

Nevertheless, each step is presented here and with the basic data and alternative calculation logic can be applied.

6.2 Further Investigations

In this research, from available data the current and relatively easy to implement hybridization potential is investigated. Further ideas on connected research include:

Enlargement of network-based heat supply
The potential stated here could be enlarged by connecting heating units to the thermal network, which are not yet connected. This includes heat consumers at the temperature level of the thermal network, but also below (enabled by heat exchangers) and above (enable by decentral heat boosters). For example, dark emitters can be replaced by ceiling mounted panels and connected to the industrial thermal heat network. Still, as dark emitters are highly efficient as they only heat up specific areas of a factory by heat radiation, hence a replacement might not be energetically suitable.

However, the connection of additional units to the thermal network, might lead to a need for an increase in heating network dimensions, therefore it is neglected here.

Future development of the potential
Here, the flexibility potential was only calculated for the status quo, which it is assumed that all fossil fuel based technologies are replaced by electricity based technologies, hence a maximum evaluation is done. Thermal demand in the industry will decrease in the future at the time where an actual replacement of fossil technologies towards electricity based technologies takes place.

Alternative replacement technologies
In this approach only fuel-based heat supply technologies were connected with electricity-based systems, as cooling is already mainly provided by electricity. Potentially, on sites where heating and cooling is required at the same time (e.g. food industry, machining industry) these units could be displaced by trigeneration units, which would lead to a generation of electricity heating and cooling

Dependency on hybridization potential on data basis
Several data sources serve as basis for these evaluations. In order to account for their effect on the hybridization potential, a sensitivity analysis of the results on critical input data, such as energy demand by industry and temperature level, could be suitable.

Technological boundary conditions for interconnection

The technology interconnections described in chapter 2.4.2 are here discussed from a theoretical point of view. Especially for the series interconnection between high temperature heat pumps with boilers, steam boilers and CHP units an in-detail technical evaluation is needed.

Overall flexibility potential

Other studies already estimated the overall flexibility potential of industrial sites focussing on cross-sectional technologies or specific processes. In contrast to this, this study assumes that the processes are steady and only the load of the thermal energy generation units connected to the thermal network varies. However, the overall flexibility is not the sum of both potentials as these are interdependent for network-connected consuming units. E.g., a variation in process operation changes the heat consumption from the thermal supply network. Therefore, the energy content of the thermal network reduces less, than it is supposed to. This reduces the free heat capacity.

The interdependency of the cross-sectoral flexibility potential of industrial thermal networks and individual processes is another interesting research question.

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