What about heat integration? Quantifying energy saving potentials for Germany

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Kewords

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Abstract

Industry accounts for approximately 30 % of the final energy demand in Germany. 75 % of this is used to provide heat. A quite substantial fraction of this heat leaves processes and factories unused. Current bottom-up estimations indicate that the available excess heat potential in Germany equals up to 13 % of industrials fuel consumption. The most common approach to utilize excess heat is to recover it for heating up other processes, also known as heat integration. However, heat integration within a company requires the presence of heat demands with lower temperatures than the temperature of the excess heat currently unused. If this is not given, inter-company heat integration offers an alternative. Nevertheless, up to now there is no quantification of energy saving potentials for heat integration at all, or inter-company heat integration in particular. Thus, we make a start by applying a top-down cascade approach for Germany.

First, we estimate excess heat potentials differentiated by industry sectors and temperature intervals for Germany using a top-down approach. Therefore, we use energy balances for Germany differentiating heat demand by industry sector and temperature intervals.

Second, we calculate which fraction of the excess heat is usable within the industry sector it comes from. Therefore, we balance cascade like excess heat and heat demand at lower temperature levels in the same sector, which results in the energy saving by intra-company heat integration.

The previous step leads to the conclusion that some industry sectors have still excess heat after the cascade balancing and some don't. Consequently, we calculate how much of this excess heat can still be used to heat up demands at lower temperatures in other industry sectors as a third step.

Adding up energy saving potentials by intra- and inter-company heat integration, the final results indicate energy saving potentials of roughly 11 % referred to industrials final energy demand in Germany.

Introduction

Increasing energy efficiency in every sector is a major pillar of Germany's energy policy to tackle climate change and increase supply security (BMWi, 2014). Heat integration is one option to increase energy efficiency in industry. So far, the potential energy savings in industry due to heat integration have not yet been estimated for Germany. Thus, this paper presents a methodological top-down approach to systematically quantify these potentials.

In this context, this paper is structured as follows. First, the term heat integration is introduced briefly. Special emphasis it put on inter-company heat integration as this energy efficiency measure is not as common in industry as is the case for intra-company heat integration. Inter-company heat integration refers to integrating the heat supply of companies in close spatial proximity to each other. Second, the database used for applying the top-down approach in this paper is introduced. Third, the methodology of the top-down approach to quantify energy savings by heat integration is explained. Finally, results are presented and the approach is discussed with a critical perspective.

Heat integration

Heat integration has "several definitions, almost invariably referring to the thermal combinations of steady-state process streams or batch operations for achieving heat recovery via heat exchange" (cf. Klemeš and Kravanja 2013). Heat integration can therefore be understood as a technical concept for reducing the energy requirements of industrial plants and thus as an energy efficiency measure. Heat integration is part of process integration. Process integration is a holistic approach to design, retrofit and operate processes (cf. Dunn and Bush 2001, El-Halwagi, 1997).

Heat integration has its origins in the 1970s. Due to the oil crises of 1973 and 1979, the most energy-intensive companies in the chemical and petrochemical industry were looking for solutions to minimize their energy consumption (Klemeš and Kravanja 2013). Heat integration was a promising option. The fundamental development of pinch analysis by Bodo Linnhoff and subsequent expansions of the method were finally milestones for the design and optimization of heat integration (Linnhoff and Flower 1978, Linnhoff and Hindmarsh 1983, Linnhoff and Ahmad 1990, Ahmad et al 1990). The new method included a structured approach that allowed process engineers to design and optimize heat exchanger networks for old and new plants. Heat integration has therefore become widespread within the chemical industry (Natural Resources Canada 2003). Today, heat integration is a common energy efficiency measure in the chemical industry (Smith 2005).

Heat-integration can be applied within a company and across company boundaries. The application of heat-integration within a company is called intra-company heat integration in this paper. The application of heat-integration across company boundaries is called inter-company heat integration. Here, two or more companies use heat integration with the aim of reducing their overall energy demand with respect to heating and cooling.

The scientific literature addresses inter-company heat integration directly and indirectly. There are several case studies analysing large production sites or industrial estates to assess potential energy savings. The papers focus mainly on the methodologies for analysing sites and address inter-company heat integration only indirectly. For example, Hackl et al. (2011) apply total site analysis (TSA) to an industrial estate consisting of five chemical companies. They show that the current utility demand could be eliminated completely by using a heat integration.

Moreover, a few publications are explicitly dedicated to the field of 'inter-company energy integration'. For instance, Hiete et al. (2012) examine a hypothetical case study where a set of companies is located around a chemical pulp manufacturer. They assess heat integration interconnecting these sites including investments in pipes and heat exchangers. Furthermore, they model the decision process to find out under which economic boundaries how heat integration could take place between the participating companies using game theory. Please note that 'inter-company energy integration' is the umbrella term for 'inter-company heat integration' and covers two or more companies sharing utilities as well as HENs across company boundaries (Fichtner et al., 2002). Hills et al. (2014) also deal explicitly with inter-company heat integration. They analyse the suitability of different industries for inter-site heat integration. First, they model heat loads for a steel, cement, paper and fertiliser plant. Then, they demonstrate the theoretical savings which could be achieved by interconnecting these sites using heat integration.

Finally, heat integration is in general connected to the topic of excess heat. This is based in the reason that excess heat might be described as fuel for heat integration. Excess heat is generated by many industrial processes using process heat. From a technical point of view, excess heat can be described as unwanted heat generated by an industrial process (Pehnt, 2010). From a social point of view, it can be described as heat which is a by-product of industrial processes and currently not utilized, but which could be used for society and industry in the future (Viklund et al., 2014). Several measures have to be considered for the evaluation of excess heat potentials (SAENA, 2012). First, measures to eliminate excess heat should be evaluated. However, if this is not possible, it should be explored whether heat recovery measures are energetically and economically feasible. Thus, heat integration comes into place.

Database

The methodology in this paper is based on heat demand values for Germany derived from the project 'Datenbasis Energieeffizienz'. This project developed a consistent and detailed database for primary, final and useful energy consumption differentiated by sectors (households, industry, commercial and trade, transport) and fields of application for Germany (Rohde et al. 2013, Kemmler et al. 2016).

In the project 'Datenbasis Energieeffizienz', the final energy demand for heat generation within the industry sector is derived based on the energy balances prepared by the AG Energiebilanzen. In these energy balances, the final energy demand for industry sectors is given differentiated by energy carrier. The final energy demand for process heat is derived conducting the following steps for each industry sector:

- First, the final energy demand for fuels is calculated by subtracting the final electricity demand from the overall final energy demand. This calculation is based purely on the values given in the energy balances prepared by the 'AG Energiebilanzen'.
- Second, the share of the final energy demand for fuels used to generate mechanical energy is subtracted from the above result. Nowadays, this share is rather small, as it is mainly limited to applications driven by combustion engines (e.g. pumps and compressors driven by steam turbines). Furthermore, transport activities not included in the transport sector fall under this category. This share is calculated based on assumptions derived from the literature. Some uncertainties regarding sectoral distribution can be tolerated due to the minor share of this application.
- Third, the share of final energy demand for space heating and hot water is subtracted from the above result. This share is derived by combining official statistics and assumptions taken from the literature. In a first step, the office and production floor area are estimated per industry. This is done by multiplying the number of employees per industry sector

with the specific space requirements per employee. No comprehensive data are available on the specific space requirements per employee in German industry, so a specific value based on a comprehensive survey in the trade, commerce and service sector in Germany is applied to industry as well (Fraunhofer ISI et al. 2009). Finally, average values for the specific energy demand for space heating and hot water in German industry are used to calculate the overall share of final energy demand for space heating and hot water based on the areas previously calculated.

- Fourth, the final electricity demand to generate process heat is added to the result above. This is based on the fact that many process heat applications require electrical energy such as the electrolysis process in the aluminium or copper industry. The demand is basically estimated by taking into account the specific electricity consumption for the appropriate process and the production value of the assigned product per year. Thus, the fourth step yields the final energy demand for process heat per industry.
- Finally, the share of process heat per temperature interval is estimated. This is defined as the 'temperature profile' in the following. A basic source for this is Hofer (1994), who conducted an analysis of the process temperature intervals applied in different industry sectors. Hofer (1994) analysed the processes applied in the examined industries. The original goal of the analysis was to estimate potentials for combined heat and power plants.

An overview of the approach is given in Figure 1. Finally, we use the estimated final energy demand for process heat per industry sector, and per temperature interval presented in Rohde et al. (2015) to calculate a relative share for the separate temperature intervals for each industry sector. The industry sectors are then structured using the NACE classification. Please note finally that we use the temperature profiles from the project 'Datenbasis Energieeffizienz' to depict the process heat consumption for all industrial production sites contained in the E-PRTR. We are therefore assuming that the temperature profiles based on data for Germany are representative for Europe as well.

Methodology

The method for the top-down estimation of potential energy savings by intra- and inter-company heat integration basically consists of two steps.

- In the first step, the theoretical excess heat potential is estimated for each industry sector and temperature interval.
- In the second step, the previously estimated theoretical excess heat potential is used to first calculate potential energy savings through intra-company heat integration. This is then followed up by a calculation of savings for inter-company heat integration.

All steps mentioned previously are carried out based on data for whole industry sectors and are not based on data for individual industrial plants. Thus, for the theoretical consideration, it is assumed that the distribution of the heat demand over the temperature intervals in plants equals the structure in the underlying database. Consequently, this approach represents a

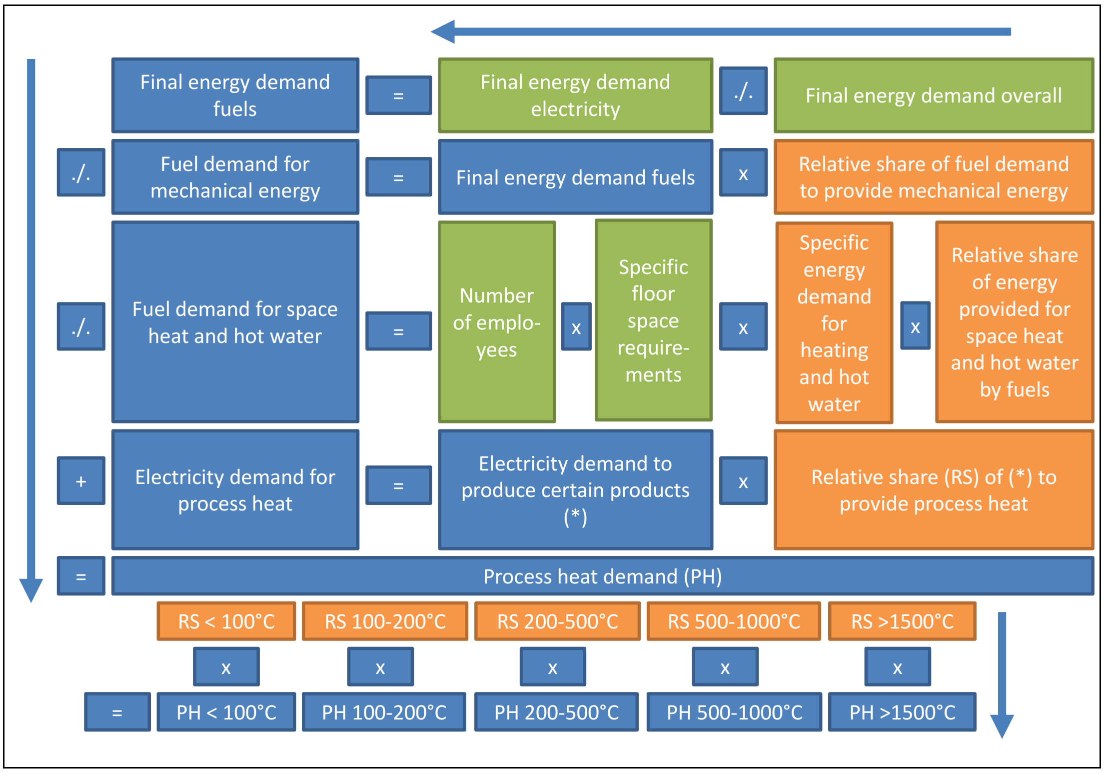

Figure 1. Concept to estimate the process heat demand in line with the study 'Datenbasis Energieeffizienz'; 'x' indicates a multiplication; './.'indicates a subtraction. Green: derived from statistics; Orange: derived from literature; Blue: calculated/modelled.

simplified abstraction, neglecting that within the industry sectors more or less heterogeneous industrial plants in terms of heat demand and supply structure are composed.

TOP-DOWN ESTIMATION OF THEORETICAL EXCESS HEAT

The theoretical excess heat potential is estimated with a top-down approach using two steps. First, a relative excess heat quantity (*RE*) is set for each industry for two temperature intervals (>500 °C, 100–500 °C) from the database. In that context, *RE* represents the ratio between estimated theoretical excess heat potential and final energy demand of the respective industry sector in the corresponding temperature interval (cf. the following exemplary equation).

$$RE_{Industry\ i,\ \ temperture\ interval\ A} = \frac{Excess\ heat_{from\ industry\ i,temperature\ interval\ A}}{Process\ heat\ demand_{from\ industry\ i,temperatue\ interval\ A}} \quad (1)$$

In the second step, the theoretical excess heat potential per industry sector and temperature interval is calculated. Therefore, the process heat demand for each temperature interval from each industry is taken from the database and multiplied with the corresponding *RE* set.

The idea behind this approach is that the final energy demand for specific temperature intervals might be traced back to specific processes for some industry sectors. For example, the final energy demand above 500 °C in the industry sector "glass production" is mainly due to the actual melting process in the glass melting tank. For glass melting tanks in turn Sankey diagrams give information on the proportion of excess heat related to the energy demand. However, not all sectors covered in the database are suitable for such technical considerations, as production routes contained in the sectors are more diverse. In that cases indications from Pehnt et al. (2010) had been used to define assumptions. In Pehnt et al. (2010) the industrial excess heat potential for Germany is estimated by deriving parameters based on a Norwegian study (Sollesnes and Helgerud 2009). This study is again based on a survey of companies. Furthermore, for the sector basic chemicals assumptions based on Neelis et al. (2007) had been used. Neelis et al. (2007) produced energy and CO_2 balances for 68 petrochemical processes for the Netherlands, Western Europe, and worldwide. To do this, they create an energy and mass flow model, which in turn is validated against public statistics.

Furthermore, it is assumed that the heat demand in the temperature range between 100 °C and 500 °C is mainly due to steam systems. For industrial steam boilers in Germany, based on an Ecodesign preparatory study for the European Commission, an efficiency of about 90 % is assumed (Paolo Gentili et al. (2015), Aydemir et al., 2015). Therefore, the relative excess heat factor for the temperature interval between 100 °C and 500 °C is assumed to be 10 %. The assumptions for RE for each temperature interval and industry used are presented in Table 1.

CASCADE BALANCING

The cascading balancing is first used to calculate, which fraction of the estimated excess heat might be used within the industry sector it comes from. This is done by balancing cascade like excess heat and heat demand at lower temperature levels in the same sector. Therefore, the energy amounts balanced

Table 1. Assumptions for *RE.*

Industry sector		$RE_{100\text{-}500°C}$	$RE_{>500°C}$	Reason/source for setting $RE_{>500°C}$.
Quarrying, other mining	08	Not considered.		
Food and tobacco	10,11,12	10 %	–*	
Paper	17		22	Based on Pehnt
Basic chemicals	20.1		9	Based on Neelis
Other chemical industry	20 and 21 without 20.1		–*	–
Rubber and plastic products	22			
Glass and ceramics	23.1, 23.2, 23.31, and 23.4		30	Own assumption based on the technical consideration that furnaces dominate >500 °C.
Mineral processing	23 without 23.1, 23,2, 23.31, and 23.4			
Manufacture of basic metals	24.1			
Non-ferrous metals, foundries (ferrous and non-ferrous metals)	24.4, and 24.5			
Metal processing	24.2, 24.3 and 25			
Manufacture of machinery	28 without 28.23			
Manufacture of transport equipment.	29,30			
Other segments	all other classifications, except 05.1,05.2, 06, 09, 19.1, and 19.2		20	Based on Pehnt for the category "other sectors"
*Nearly or completely no demand Nearly no demand in database for process heat demand >500 °C.				

1	$EX_{>500} = RE_{>500} \cdot PH_{>500}$			
2	$red\_PH_{100-500} = PH_{100-500} - EX_{>500}$			
3	If			
4	$red\_PH_{100-500} > 0$:		$red\_PH_{100-500} \leq 0$:	
5	$EX_{100-500} = RE_{100-500} \cdot red\_PH_{100-500}$		$red\_PH_{<100} = PH_{<100} + red\_PH_{100-500}$	
6	$red\_PH_{<100} = PH_{<100} - EX_{100-500}$		$red\_PH_{100-500} = 0$ *	
7	If		If	
8	$red\_PH_{<100} > 0$:	$red\_PH_{<100} \leq 0$:	$red\_PH_{<100} > 0$:	$red\_PH_{<100} \leq 0$:
9	$red\_PH_{<100}$ fixed	$red\_PH_{<100} = 0$ *	$red\_PH_{<100}$ fixed	$res\_EX_{>500} = \lvert red\_PH_{<100} \rvert$
10	$res\_EX_{>500} = 0$	$res\_EX_{>500} = 0$	$res\_EX_{>500} = 0$	$red\_PH_{<100} = 0$ *

Legend

- PH indicates the process heat demand as in the database, indices indicate the corresponding temperature interval.
- RE indicates the excess heat quantity, indices indicate the corresponding temperature range RE is applied for.
- EX indicates excess heat, indices indicate the corresponding temperature range of the corresponding process heat demand where the excess heat comes from.
- $red\_$ refers to the PH and means reduces process heat demand after balancing with excess heat.
- $res\_$ refers to residual excess heat after balancing. If this value is >0 after balancing, then excess heat from the sector remains for inter-company heat integration.
- ‚*' means that a specific value is set for consistency reasons (i.e. to avoid negative demands).

Figure 2. Concept for cascade balancing.

within one industry sector represent energy savings by intra-company heat integration in this paper. This way of calculation shall reflect an optimized process management within each corresponding industry. The calculation method is presented in Figure 2. Please note that the calculation method does not include any technical or economic criteria and thus all energy-saving potentials derived with this method can be only treated as theoretical potentials.

If, after the cascade balancing within an industry sector still excess heat is available, this is considered as excess heat which could be delivered to other industry sectors by applying inter-company heat integration. Thus, this amount represents the theoretical energy saving potentials by inter-company heat integration. Please note, that for inter-company heat integration only residual excess heat calculated based on the demand from the temperature interval above 500 °C is considered. A visual representation of the method is given in Figure 3 for the industry sector 'basic chemicals' and in Figure 4 for the industry sector 'manufacture of basic metals'.

To sum it up, the calculation method allows to calculate theoretical energy-saving potentials by heat integration for an industry sector as follows.

- The amount of excess heat balanced cascade like within an industry sectors represents the theoretical energy-saving potential through intra-company heat integration.
- The theoretical energy-saving potential through inter-site heat integration is determined by the sum of the resulting amounts of excess heat that can be shifted across industry sectors.

Case variation

The calculation method presented rather results in 'maximum values' for the estimation of the energy saving potential for intra-company heat integration. This is because the method of calculation assumes that the distribution of heat demand in the companies is as is the underlying database. By tendency, this leads to the fact that for most of the sectors the excess heat can be balanced fully within the industry. Thus, only few sectors remain with excess heat for the supply to other industry sectors, which leads to energy savings by inter-company heat integration. Thus, for some sectors it seems to be plausible to vary the calculation method in the way that the excess heat is not balanced fully within a sector. This is for example for industry sectors the case, in which on the one hand manufacturer for raw products with high melting temperatures are contained (i.e., foundries) and on the other hand manufacturer post processing these raw products, which might be not integrated in the plants producing the raw goods. Thus, for this paper two cases varying the boundaries for the calculation methods had been used to show how such aspects affect the theoretical potential of savings for inter-company heat integration.

- 'Standard Cascade': The calculation method is applied as in Figure 2 for all industry sectors.
- 'Limited Cascade': The calculation method is only applied for some sectors as in Figure 2. For some other sectors, a balancing within the sector does not takes place fully. An overview for this case is given in Table 2.

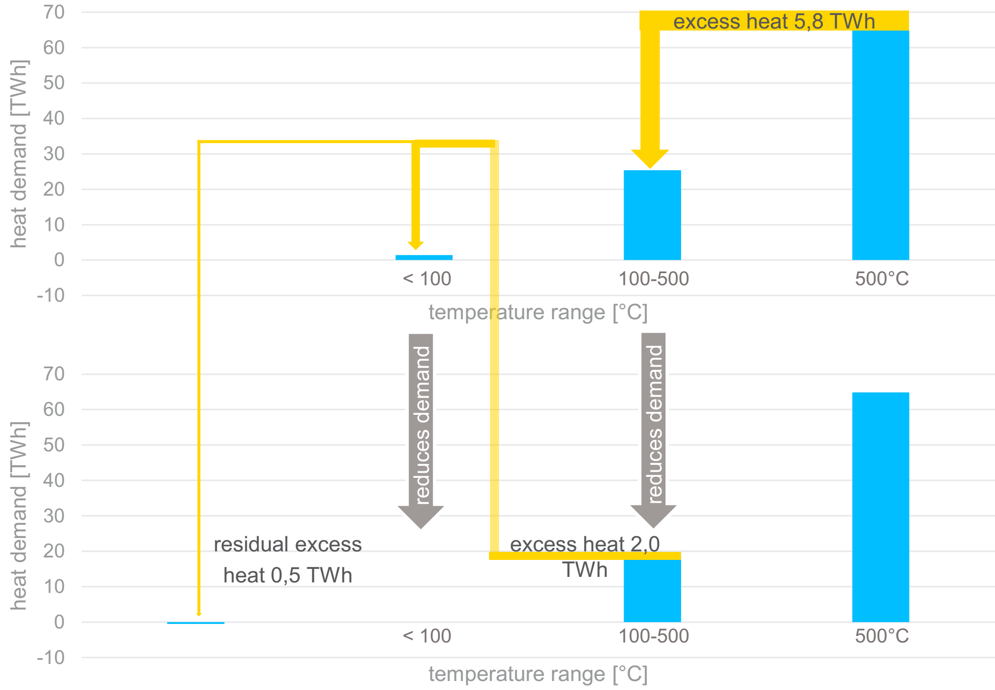

Figure 3. Cascade balancing for the industry sector 'basic chemicals'.

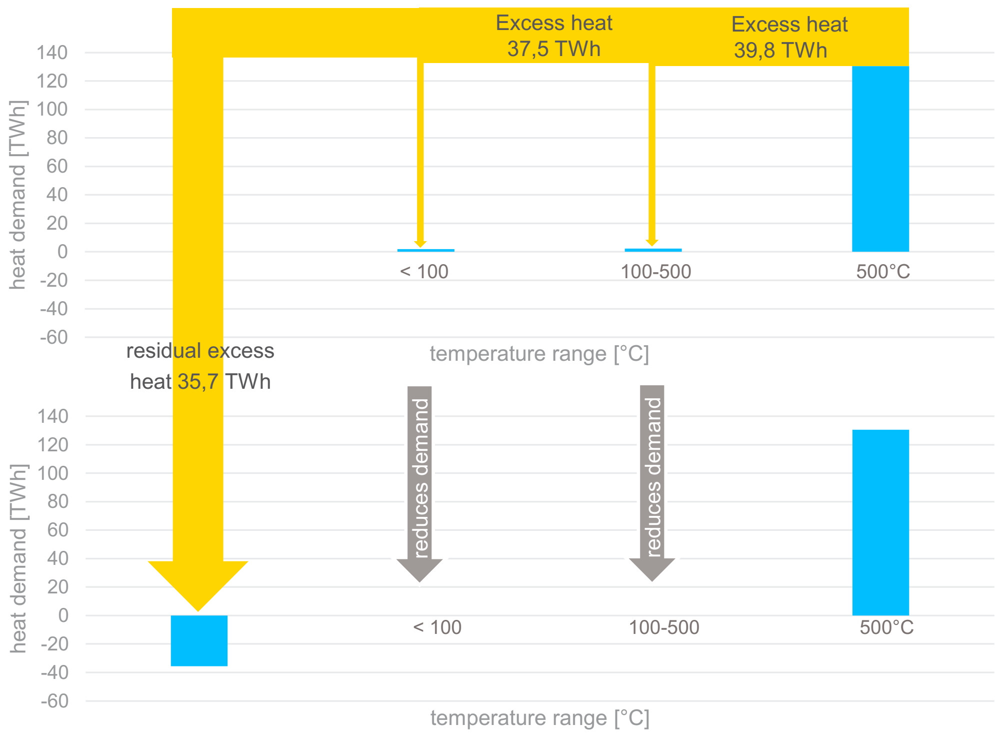

Figure 4. Cascade balancing for the industry sector 'manufacture of basic metals'.

Table 2. Assumptions for the case "Limited Cascade".

Industry sector	Full cascade balancing [Yes/No]	Comment
Quarrying, other mining	Not considered.	
Food and tobacco	Yes	It is assumed that the production processes are rather 'deep', i.e. have long value chains within the companies. Thus, excess heat sources may often be used internal for heat sinks. Thus, for this industry sectors also in the case 'Limited Cascade' the balancing takes place fully as in Figure 2.
Paper		
Basic chemicals		
Other chemical industry		
Rubber and plastic products		
Metal processing		
Manufacture of machinery		
Manufacture of transport equipment.		
Other segments		
Glass and ceramics	No	It is assumed that these sectors include manufacturers of raw materials and partly also processing companies, which are not integrated. Thus, heat sources would often face no heat sinks. This is reflected in the way that only the excess heat streams from the temperature interval 100–500 °C are balanced within one sector and the streams from the ranges >500 °C are not used for cascade balancing within a sector.
Mineral processing		
Manufacture of basic metals		
Non-ferrous metals, foundries (ferrous and non-ferrous metals)		

Results

The total estimated theoretical excess heat potential for the German industry is an intermediate result of the cascade balancing and is therefore presented first and compared with the most recent value from the literature for Germany. Building on this, results for the estimated energy-saving potentials by intra- and inter-company heat integration are presented.

EXCESS HEAT ESTIMATION

With the top-down approach, a total of approximately 77.3 TWh of excess heat potential is estimated for the case 'Standard Cascade'. For the case 'Limited Cascade' the estimate is slightly higher (78.6 TWh), which is due to the reason explained in the following. For the case 'Standard Cascade', the excess heat from the temperature interval> 500 °C is balanced within a sector for all sectors. As a result, the heat demand in the temperature interval 100–500 °C disappears for some sectors (glass and ceramics, mineral processing, manufacture of basic metals, non-ferrous metals, foundries). This again results in the fact, that no excess heat coming from the temperature interval from 100–500 °C is calculated for these sectors.

For Germany, the most up to date estimation on industries excess heat had been conducted by Brückner et al. (2017). For the estimation, a bottom-up approach is used. The data are based on emission reports compiled by the environmental offices of the respective federal states. For the estimation of the excess heat, a method for the anonymous evaluation of data on exhaust gas flows, which are present in the emission reports, has been developed. This method was used to evaluate about 81,000 exhaust gas flows in German industry. The evaluated companies cause about 58 % of industrial fuel consumption in Germany. For the evaluated companies, this results in an excess heat potential of 35 TWh per year, which corresponds to about 13 % of the fuel consumption of the companies. In addition, a top-down estimate for Germany is made on this basis. This results in a potential of about 62 TWh per year. The value is therefore about 20 % below the values that have been estimated in this paper using the top-down approach. However, the estimate in Brückner et al. (2017) is based only on emissions data from installations in Germany, where the companies from the production sector are required to report their exhaust gas emissions to a state ministry every four years (in context of a legal ordinance related to emission control called 'Bundesimmissionsschutzverordnung – BimSchV'). Within that context not all installations have to report their exhaust gas emissions.

ENERGY SAVINGS BY INTRA-COMPANY AND INTER-COMPANY HEAT INTEGRATION

Figure 5 shows the amount of balanced excess heat within each sector and furthermore the residual excess heat which might be provided for other sectors for the two considered cases ('Standard Cascade', 'Limited Cascade'). Both values are referred relatively to the heat demand of each corresponding sector. For the two cases, it can be observed the following.

- 'Standard Cascade': It can be seen that after cascade balancing only five sectors remain which could provide heat for other sectors. For this group, potential savings by intra-company heat integration range between 3 and 22 %. Among this group, the sector 'manufacture of base metals' is outstanding as here only 3 % is balanced within the sector and 26 % might be provided to other sectors. For the other group, where no excess heat for the other sectors remain, the potential savings by intra-company heat integration ranges between 4 % and 10 %.
- 'Limited Cascade': For the group where no excess heat remains to be transported for other sectors consequently also the potential savings by intra-company heat integration remain as in the case 'Standard Cascade'. However, for the

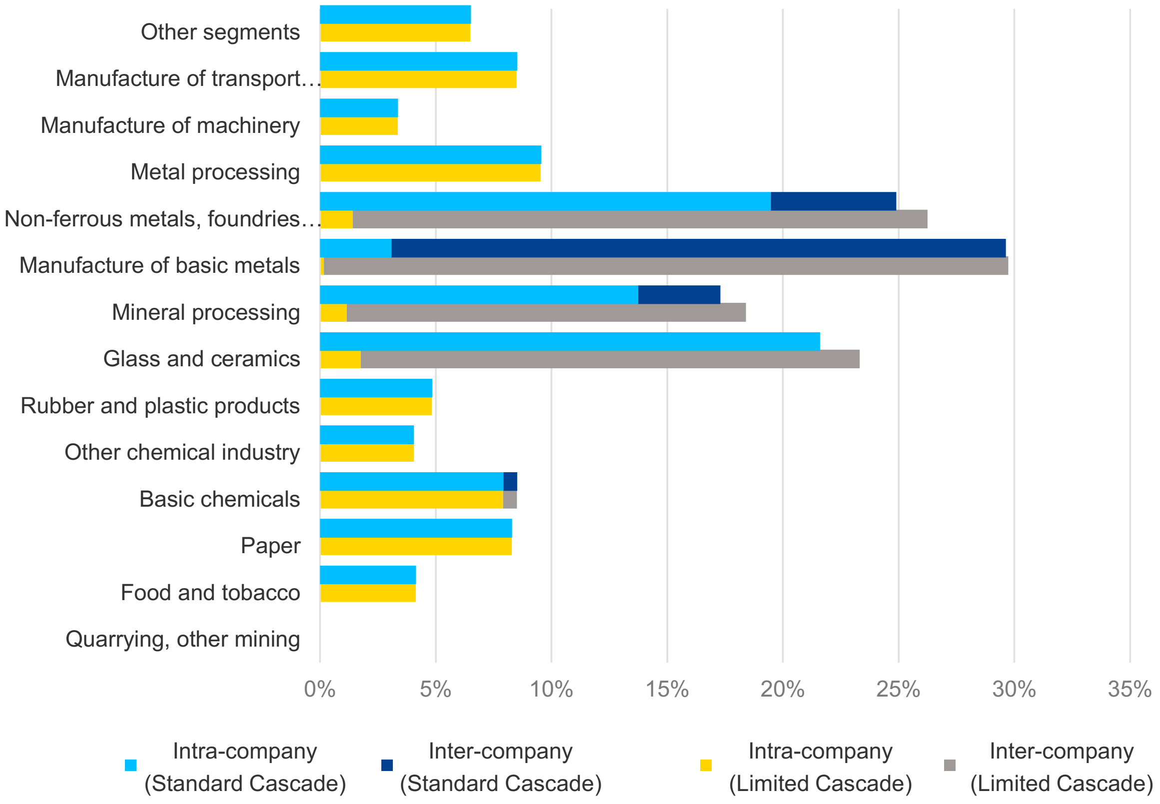

Figure 5. Results: Energy saving potentials by intra- and inter-company heat integration for each industry related to the process heat demand of each industry.

other group potential savings by intra-company heat reduction are reduced nearly to zero. This is explained by the assumptions set in Table 2. Consequently, this results overall in higher potentials for intra-company heat integration.

With regard to absolute figures, the values for the cases are as follows. For the case 'Standard Cascade' the potential energy saving by intra-company heat integration is approximately 56 TWh and 21 TWh for inter-company heat integration for German industry. For the case 'Limited Cascade' potential savings are approximately 40 TWh for intra company heat integration and 38 TWh for inter-company heat integration. If the savings potentials for the intra- and inter-company heat integration are added up for both cases, a corridor results for energy savings by heat integration at all for Germany. Based on the final energy demand of the industry, this corridor lies between 5.4 % and 5.6 % if the industry sector 'manufacture of base metals' is excluded. Including the sector 'manufacture of base metals' results in a corridor between 10.9 % and 11.1 %.

Discussion

The methodology applied in this paper is purely based on a top-down approached. Thus, depending on the case ('Standard Cascade', 'Limited Cascade') the estimated potentials for intra-company or inter-company heat integration might be treated rather as maximal values based in the reasons explained in the following. In the case 'Standard Cascade' it may be argued that the estimated value for intra-company heat integration represents rather a maximal value, as for most sectors heat sinks for excess heat are available within the sector. This is due to the reason that the used distribution of temperature intervals from the database only give an abstract view on the distribution of temperature intervals in real plants. Consequently, in the case 'Limited Cascade' for some sectors balancing of excess heat within industry sectors has been limited massively. However, this again may result in overestimating the potentials for inter-company heat integration. Nevertheless, deriving the corridor for energy savings by heat integration at all when considering both cases together, heat integration seems still to be a promising option for reducing industrials energy demand in Germany. Although this option has a rather long history, going back to the 1980s.

As there are plenty of studies concerning methodological aspects of heat integration, further works might deal more intensive with the topic to find out what boundary criteria result in the adaption of heat integration by companies and which instruments might increase the adaption of heat integration. Within that context especially the uncertainty of calculating the economic efficiency of 'more complex' energy efficiency measures might play a central role. Applying heat integration within a plant is complex as it effects several infrastructure systems within the plan (heat generation, piping, heat usage, etc.). Thus, especially research assessing projected and realised energy savings of applied heat integration to benchmark the uncertainty could be very valuable. As heat integration affects many technical components (pumps, heat exchangers, etc.) also research on planned investments versus realised investments for heat integration projects applied in reality might have great value as they could give energy managers orientation on the uncertainty planning heat integration measures.

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