How well can the potential of industrial excess heat be estimated?

Erwin Cornelis & Johan Van Bael
EnergyVille
Thor Park 8300
3600 Genk
Belgium

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Abstract
There is a huge potential of industrial waste heat that can be tapped and used to cover heat demand in other sectors. Designers of a sustainable heat and cooling policy need accurate estimates of this potential as an input for their strategies. Some methods to estimate the potential of industrial waste heat have been developed in recent years.

In this paper, three different methods to estimate industrial waste heat are applied on the 384 most energy intensive companies in Flanders, Belgium. These methods are developed in different EU Member States and respectively lead to an estimation of the theoretical and technical potential. These estimates are in addition compared to company specific assessment of the technical waste heat potential made for two subsets of 17 to 18 companies of the 384 companies studied. The aim of this paper is to compare the resulting estimations in order to derive an accuracy of the waste heat potential of industry.

Applying these methods leads to estimates that differ with a factor up to ten dependent on the sector. The first method concludes that, for the whole of the 384 examined companies, theoretically 70 % of the fuel is available after consumption as waste heat; whereas the two other methods conclude that technically 20 % of the fuel is available after consumption as waste heat, of which 8 % has a temperature above 80 °C. The validation of these estimates to the company specific assessments confirms these differences. The estimations of the first, second and third method are respectively about 10, 1.5 and 2 to 3 times higher than these company specific assessments.

Based on these results, it is recommended to use a method based on estimated or monitored waste heat assessments of individual companies to estimate the industrial waste heat potential. Still, these estimates can still deviate with a factor 2 to 3 of what in reality can be delivered. Local waste heat potential studies will be needed to validate the estimation results.

Introduction
About three quarter of the final energy consumption in industry in the EU28 consists of fuel and the lion's share of this fuel consumption is used for heating purposes[1]. Heat degrades when used in accordance with the second law of thermodynamics. Part of it can be reuse internally to cover heat demand at lower temperature or supplied to nearby companies in integrated heat networks, but still a large share is dumped into the environment. The waste heat supply potential of about 1,200 energy-intensive industrial companies is estimated at 2.9 EJ (Persson, 2015). This technical potential has been estimated to cover a significant share the EU's space heating demand[2]; the economically recoverable potential, however, requires analysis of local conditions. Realising this heat integration is one of the challenges the European Commission acknowledges in its strategy to make heating and cooling more efficient (European Commission, 2016).

1. Eurostat: final energy consumption industry (2014): total: 11.5 EJ – fuels: 7.9 EJ – electricity: 3.6 EJ

2. Eurostat: total petroleum products in final energy consumption of residential, fishing, agriculture/forestry and services (2014): 2.7 EJ: total fuel consumption in final energy consumption of these sectors (2014): 12.3 EJ

There is a growing interest in having more accurate estimates of the waste heat from industry. Art 14 of the so-called Energy Efficiency Directive (Directive 2012/27/EC) for instance obliges the EU Member States to make a comprehensive assessment of the potential for the application of high-efficiency cogeneration and efficient district heating and cooling. Supplying at least 50 % waste heat is one of the ways to comply with the definition of efficient district heating and cooling, and one of the waste heat sources to consider is the industry (SWD(2013) 449 final).

Some methods to estimate the waste heat potential from industry have been developed. An overview is presented by Brücker et al. (2014); when categorising these methods, they differentiated between, see Figure 1:

- Bottom-up data collection: collecting information from individual industrial companies via a survey or by mandatory reporting.
- Bottom-up estimations: by deriving efficiency ratios for single machines or processes and by aggregating those to loss coefficients of sectors.
- Top-down estimations: by applying efficiency factors on industrial sectors.

In addition to this categorisation, different potentials can be considered:

- A theoretical or physical potential: only considering physical constraints.
- A technical potential: also considering the technical feasibility of extracting the heat.
- An economic potential: including financial parameters.

They concluded that there are three perspectives to consider when classifying methods: the scale of the study, the way the data were acquired (survey or estimation) and the approach followed (top-down or bottom-up) to gain the result.

The aim of this paper is to assess the accuracy of estimations of industrial waste heat. To this end, the waste heat potential of 384 energy intensive companies in Flanders, Belgium is estimated using different methods. These estimates are then validated by waste heat supply assessments resulting from audits for some of these companies. The comparison of these results gives an indication of accuracy and for which sectors the estimations are more accurate than for others.

The next chapter provides more details on the methods to estimate the waste heat potential, the sample of the 384 energy-intensive companies and the methods to validate the waste heat estimations. The following chapter presents and compares the results. The last chapter discusses these and draws some conclusions on the estimation methods for industrial waste heat and their accuracy.

Methodology

METHODS TO ESTIMATE THE WASTE HEAT POTENTIAL

In this paper, three are methods are applied to estimate the waste heat potential of 384 energy intensive industrial companies in Flanders, Belgium. These methods according to the categorisation of Brücker et al. (2014):

1. Method 1: a top-down estimation resulting in a theoretical potential.
2. Method 2: a top-down application of a bottom-up survey resulting in a technical waste heat potential.
3. Method 3: a combined bottom-up/top-down estimation resulting in a technical potential.

They are now described one by one.

First method: a top-down estimation resulting in a theoretical potential

The first method was developed by the Dutch engineering company PDC (Vleeming H., van der Pol E., 2011) to assist the Dutch authorities in mapping industrial heat demand and potential heat supply. This method subdivides the heat demand into three temperature ranges: above 200 °C, below 120 °C and in between.

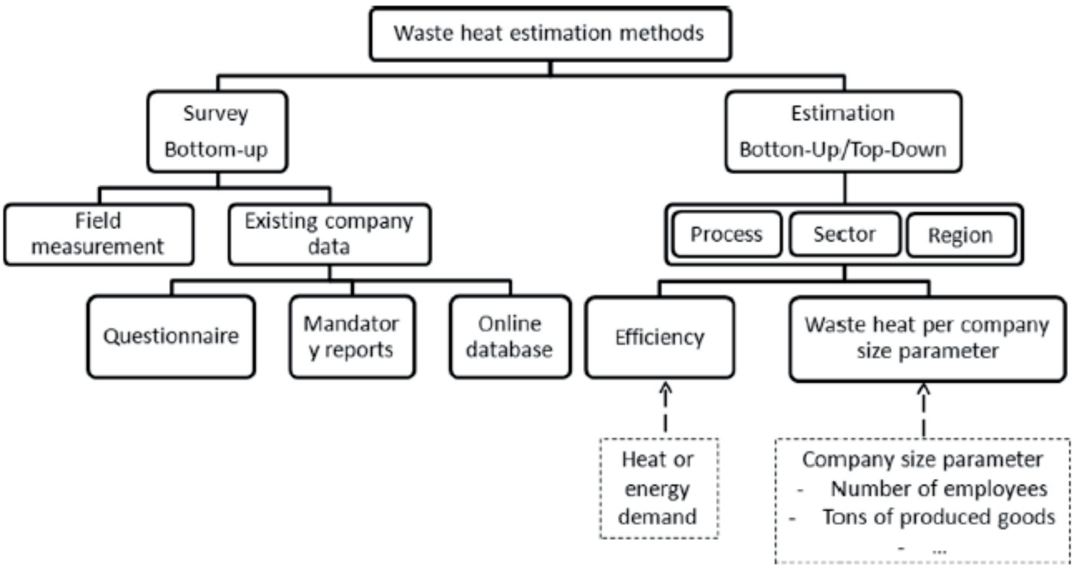

Figure 1. Categorisation of waste heat estimation methods, copied from Brücker et al. (2014).

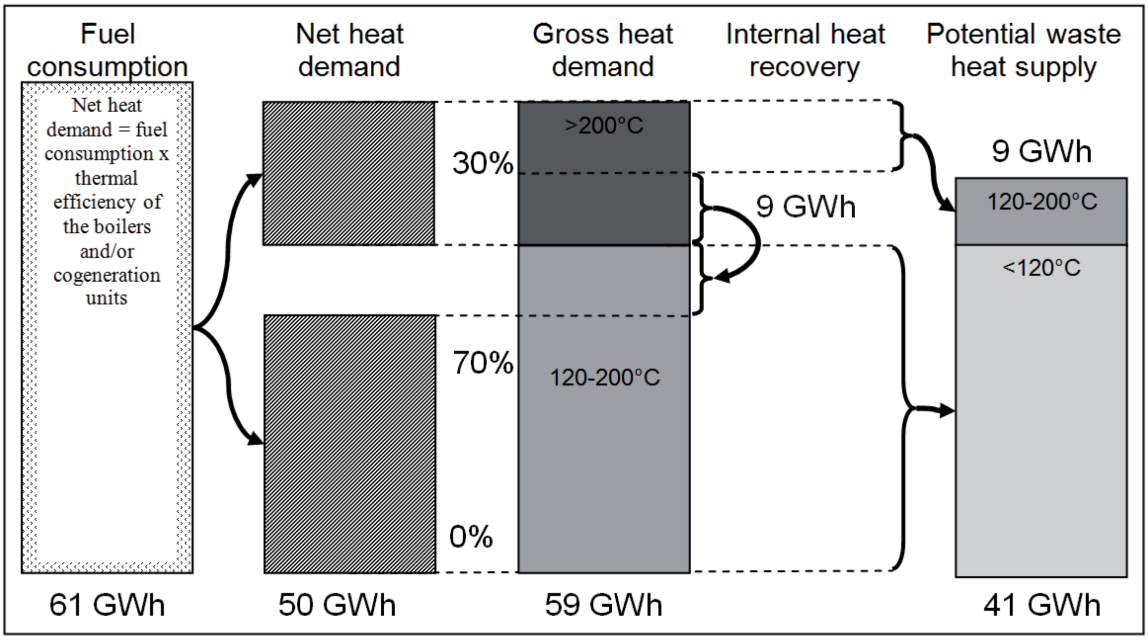

Figure 2. Illustration of the PDC method to estimate waste heat potential from industry.

The basis assumption of this method is that half of the gross heat demand in an upper temperature ranges can be recovered internally in the company to satisfy (part) of the gross heat demand in a temperature range below and that the other half is available as waste heat to external heat customers. Based on expert judgement on the process characteristics, a data set with a distribution of the gross heat demand in these three temperature ranges is compiled for 148 subsectors. This set of data allows to calculate the share of internally recovered heat. Subtracting the latter from the gross heat demand, results in the net heat demand, which in turn can be calculated by multiplying the fuel consumption with the thermal efficiencies of the boilers and/or the cogeneration units. This ultimately leads to a quantification of the potential waste heat supply. Figure 2 illustrates this method for a company with a fuel for heat consumption of 61 GWh, an overall thermal efficiency of 81 % and following split in heat consumption: 30 % above 200 °C, 70 % between 120 and 200 °C and none below 120 °C.

This method is applied to each of the 384 companies, taking the characteristic distribution of the gross heat demand of its corresponding subsector into account. This method is hence according to the classification of Brücker et al. (2014) a top-down estimation resulting in a theoretical or physical waste heat potential.

Second method: a top-down application of a bottom-up survey resulting in a technical waste heat potential

As a second method, estimates on waste heat potentials for industrial sectors in France are transposed to the set of Belgian companies. The starting point of the overview of waste heat in the industry in France by Berthou and Bory (2012) was a combination of an energy consumption database with a thermal equipment stock characterization database and expertise of industrial sectors and processes. Eight heat effluents and nine temperature ranges were considered. In view of the technical details taken into account, the resulting waste heat potential can be considered as a technical potential.

This categorisation was used to estimate the waste heat potential for 140 industrial subsectors characterised by 4-digit-NACE codes. The results are aggregated into ten sectors, however Berthou and Bory (2012) provide details only five sectors, covering 78 % of the total identified waste heat potential. Figure 3 shows the estimate for the French food production and beverages sector as an example.

These bottom-up estimations for the French industry is then applied top-down on the sample of the 384 companies in Flanders. The ratio between the total amount of waste heat and the fuel consumption of the five sectors, of which Berthou and Bory (2012) provide details, is used to calculate the total waste heat amount of the Flemish companies in the corresponding sectors. This is further distributed over the nine temperature ranges by using the distribution of the corresponding sectors.

This method is according to the classification of Brücker et al. (2014) a top-down application of a bottom-up survey resulting in a technical waste heat potential.

Third method: a combined bottom-up/top-down estimation resulting in an technical potential

This method applies a set of sector specific figures, derived by the Swedish Statistical Office, see Table 1. These data indicate the ratio between actual waste heat deliveries and the total heat consumption of these waste heat supplying companies (Cronholm et al., 2009). Only companies in the proximity of conurbations of 200 inhabitants with less than 200 m between the dwellings were considered.

This method is according to the classification of Brücker et al. (2014) a combination of bottom-up and a top-down estimation. The result is a technical potential.

THE SAMPLE OF INDUSTRIAL COMPANIES

These three methods are applied on 384 industrial companies located in Flanders, the northern part of Belgium, having the obligation to report the energy consumptions in accordance with Council Directive 96/61/EC of 24 September 1996 con-

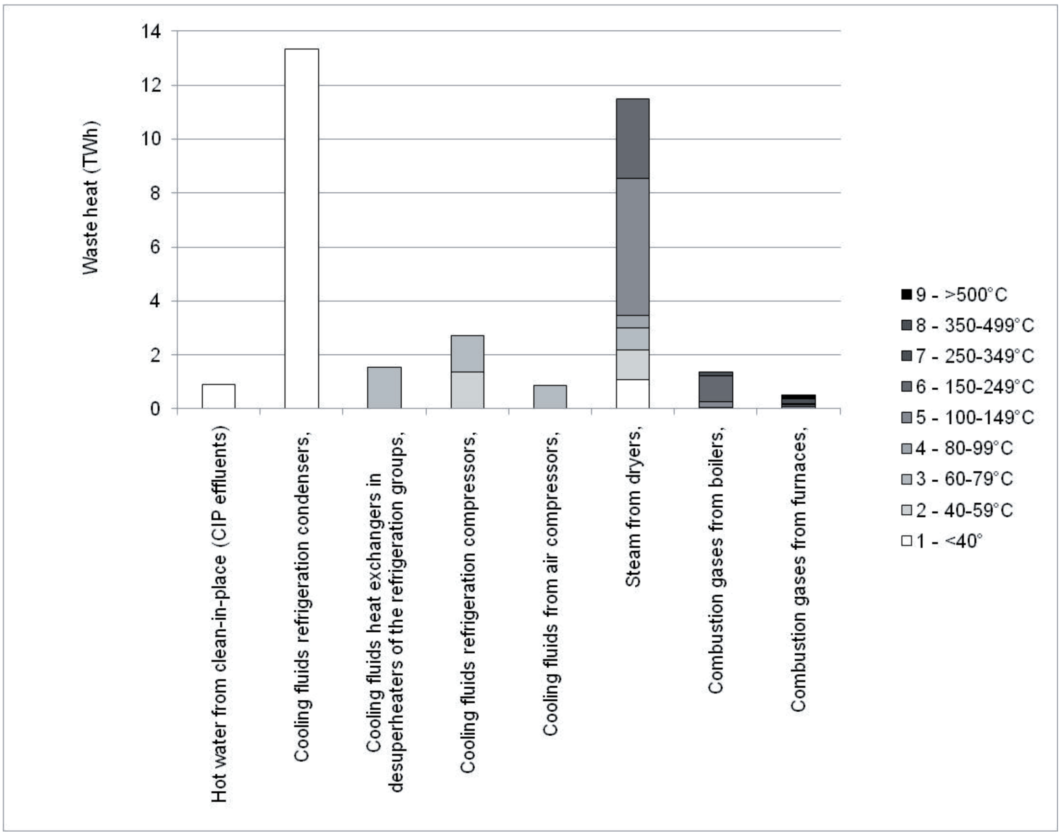

Figure 3. Estimation of the waste heat potential in the French food production and beverages sector; copied from Berthou and Bory (2012).

Table 1. Waste heat delivery per fuel used, copied from Cronholm et al. (2009).

Sector	Waste heat/fuel use	Sector	Waste heat/fuel use
Quarry and mining	3.5 %	Non-metallic mineral	1.7 %
Food and beverages	8.6 %	Non-ferrous metals	11.2 %
Textile industry	0 %	Iron and steel	2.5 %
Wood processing	18.2 %	Metal processing	8.8 %
Paper and printing	5.8 %	Machinery	2.8 %
Pulp	2.8 %	Micro-electronics	0 %
Paper production	3.2 %	Vehicle assembly	2.7 %
Oil refinery and chemicals	24.3 %	Furniture/waste treatment	30.8 %
Plastics	1.2 %		

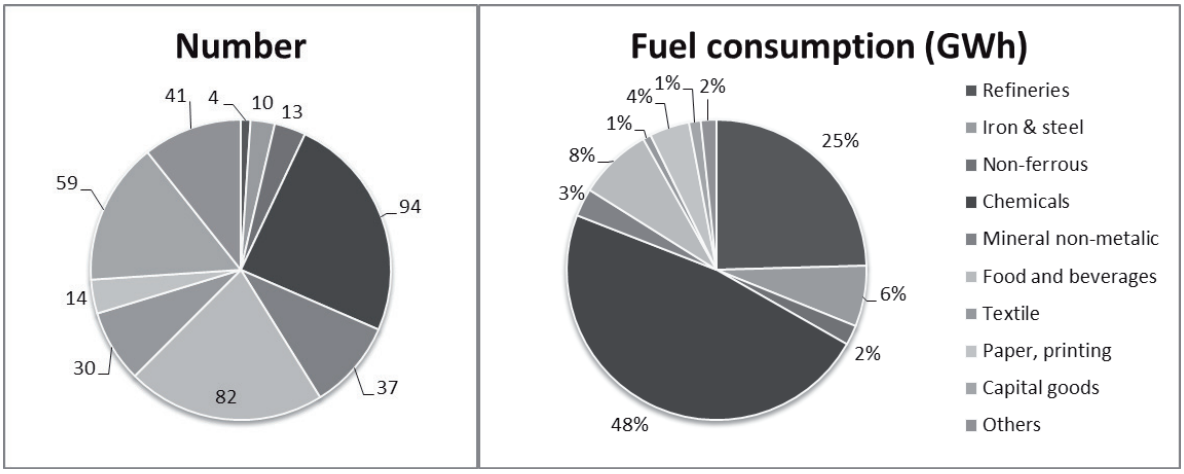

Figure 4. Sectoral breakdown of the number and fuel consumption of the study sample.

cerning integrated pollution prevention and control, or because their annual primary energy consumption exceeds the threshold of 0.1 PJ. The companies' NACE codes have been used to select the corresponding figures from each of the three methods. None of the methods specified the waste heat potential for the textile industry, so no waste heat potential for the 30 textile companies of the study sample could be made. Method 1 and 3 could be applied to all other 354 companies. Method 2 provides estimates for five sectors (chemical, mineral non-metallic, food and beverages, paper and printing, and capital goods) and could only be applied to 286 companies within the corresponding sectors.

The energy data for the year 2012 were used in this exercise. The fuel consumption of these 384 companies amounts to 244 PJ, representing 85 % of the total fuel consumption by industry in Flanders. Figure 4 shows a sectoral breakdown of the number and fuel consumption of the study sample. The individual fuel consumption ranges from 0.001 to about 50 PJ.

METHOD TO VALIDATE THE WASTE HEAT ESTIMATIONS

Two surveys are used in this study to validate the waste heat estimates.

A first survey is conducted in the Port of Antwerp (Port of Antwerp, 2012). It aimed at assessing the technical waste heat potential of this fourth biggest petrochemical cluster in the world. An inventory was made of the waste heat flows of three oil refineries and fifteen chemical companies. Their total fuel consumption amounts to 49 TWh, which is about half of the total industrial fuel consumption in Flanders. This survey focused on waste heat sources with following characteristics:

- A temperature between 80 and 120 °C.
- A minimum thermal capacity of 1 MW.
- Exclusion of waste heat flows from electricity production (cogeneration).

A thermal capacity of in total 481 MW was detected. Although the study excluded waste heat flows of above 120 °C in its survey, it was observed that similar amount of such heat was dumped as well.

A second dataset consists of energy audit results conducted by VITO aiming at estimating the technical potential of waste heat supply. This dataset covers in total 41 industrial companies, 17 of which make part of the sample of 384 industrial companies covered in this study. These 17 companies cover 8 different industrial sectors. Their annual fuel consumption ranges from 1 GWh to 12 TWh, with an average of 1.4 TWh.

Results

ESTIMATION OF THE INDUSTRIAL WASTE HEAT

Figure 5 presents the results of the estimation of the industrial waste heat per sector using the three selected methods. The results are scaled to the fuel consumption in order to protect the confidentiality of the companies' energy data.

It can be observed that in general method 1 (resulting in a physical potential) results in higher estimates than method 2, in turn higher than method 3 (both resulting in an technical potential). There are three exceptions: the food and beverages, and capital goods sectors, for which method 1 results in lower estimates than method 2; and the chemical industry for which method 2 results in lower estimates than method 3.

Table 2 compares the waste heat estimates to the fuel consumption for the lump sum of the assessed companies. Method 1 concludes that theoretically 70 % of the fuel is available after consumption as waste heat. This ratio increases to 82 % for the energy-intensive sectors (refineries, chemical, iron & steel, non-ferrous and mineral non-metallic), of which 34 % has a temperature above 120 °C and 48 % below (not indicated in Table 2). Method 2 and 3 both conclude that for the whole of the Flemish industry about one fifth of the fuel after consumption is available as waste heat. However, a significant share of the waste heat, estimated by method 2, is low temperature heat; 4.4 TWh has a temperature above 80 °C, which is 8 % of the fuel consumed by the five sectors examined.

VALIDATION OF THE ESTIMATION TO SURVEY DATA

The estimations of the waste heat by the three different methods can be compared to company specific assessments of the technical waste heat potential for some of the companies in the sample. Figure 6 makes the comparison:

- For all 18 companies in the Port of Antwerp: comparing method 1 and 3 to survey results.
- For the 15 chemical companies in the port: comparing methods 1, 2 and 3 to survey results.
- For the set of 17 companies: comparing method 1 and 3 to survey results.
- For a subset of 10 companies: comparing methods 1, 2 and 3 to survey results.

This comparison reveals that the lump sum of the waste heat estimated by method 1 exceeds the amounts identified in the surveys with a factor 7 (subset of 10 companies) to 12 (all companies in the Port of Antwerp). The deviation between the estimates using method 3 and the survey results is smaller; nonetheless, method 3 results in estimates that are 2 times (set of 17 companies) to 3 times (companies in the Port of Antwerp) higher than the amounts identified in the surveys. The best agreement is observed for method 2. This method lead to estimates that are 1.3 times (chemical companies in the Port of Antwerp) to 1.5 times (subset of 10 companies) higher than what was identified in the surveys. There is still a disagreement on the split of this waste heat in the different temperature ranges. When excluding waste heat below 80 °C, the ratio between the method 2 estimate and the survey results are 0.8 for the chemical companies in the Port of Antwerp and 2.0 for the subset of 10 companies.

Discussion and conclusion

Three different methods were used to estimate the potential of waste heat for external use of 384 energy-intensive companies in Flanders, Belgium:

- Method 1: a top-down estimation method, developed in the Netherlands, based on expert judgements on the process characteristics of 148 subsectors; leading to an estimation of the theoretical potential.

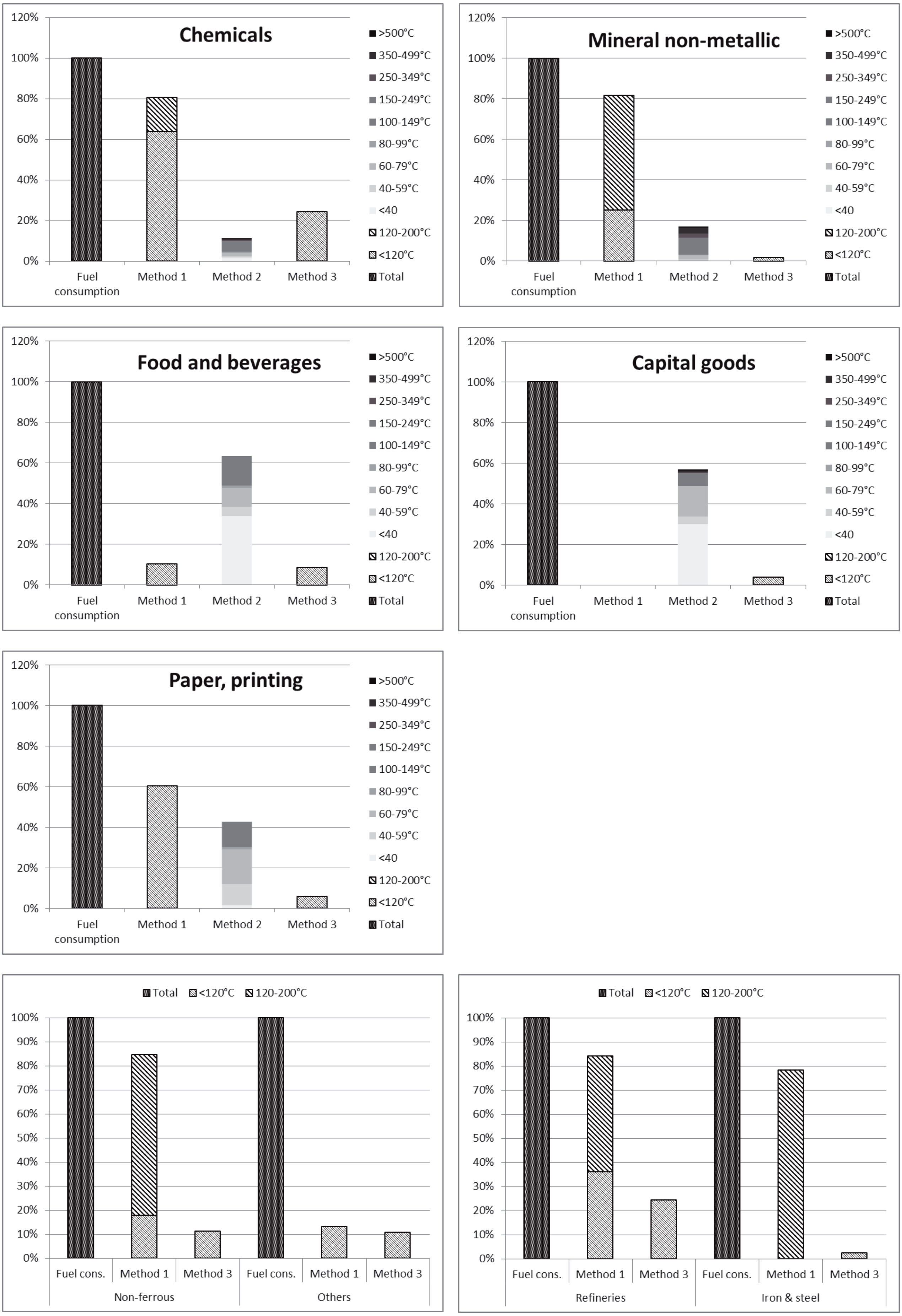

Figure 5. Estimation of waste heat per sector using three estimation methods.

Table 2. Comparison of waste heat estimations of the different methods.

	All sectors (354 companies)		Five sectors (286 companies)	
	TWh/a	Estim./fuel cons.	TWh/a	Estim./fuel cons.
Fuel consumption	83.6		53.6	
Estimation – method 1	60.3	72 %	37.1	69 %
Estimation – method 2			11.2	21 %
Estimation – method 3	16.0	19 %	10.5	20 %

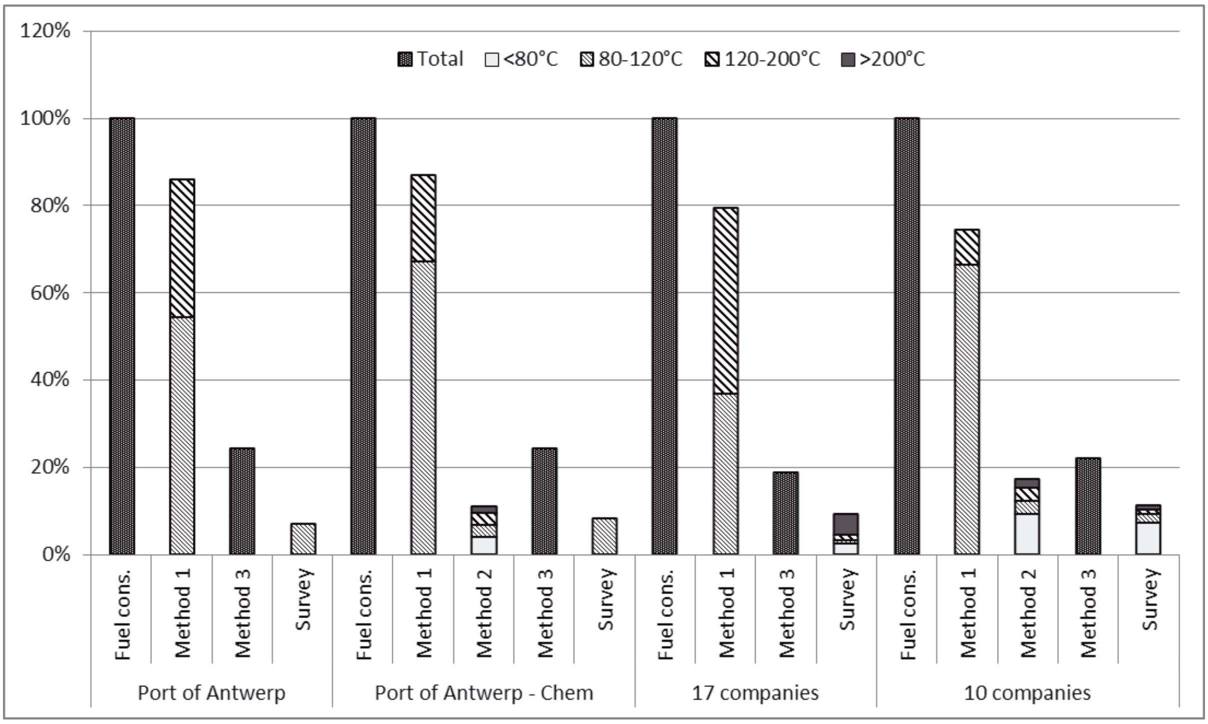

Figure 6. Comparison of waste heat estimations to survey data.

- Method 2: a top-down application of detailed bottom-up surveys on waste heat supplies carried in France, leading to an estimation of the technical potential.
- Method 3: a combined top-down/bottom-up estimation method, based on waste heat delivery and fuel use statistics compiled in Sweden, leading to an estimation of the technical potential.

Applying these methods to the 384 energy-intensive companies leads to estimates that differ considerable; the difference between the results of two methods can be as high as a factor 10.

The highest differences are observed between method 1 and the two other methods. This indicates that the theoretical potential is an overestimation of what the company could deliver as waste heat to other entities. Indeed, this method only takes a general assumption on the degradation of heat into consideration and disregards the form in which the heat is presented. The level of overestimation is outspoken in sector operating high temperature processes, such as iron and steel and the ceramic sector. According to this calculation principal, method 1 concludes that all internal heat eventually becomes available as waste heat. One can hence question whether such theoretical estimations are a good starting point to discuss potential waste heat supply by industry.

Methods 2 and 3 are, in contrast to method 1, based on real live waste heat supplies or deliveries. These methods leads to estimates that are more in accordance with waste heat potential that was observed for some of the 384 energy-intensive companies. The difference in estimates of both methods is nonetheless as high as a factor 2 to 3. Similar factors are observed when comparing these estimates to waste heat potential assessments for some of these 384 energy intensive companies.

The underlying cause of this inaccuracy is twofold. First of all, there are inaccuracies when estimating the waste heat potential of individual companies. They are a consequence of the fact that waste heat flows are usually not monitored by the industry; they need to be estimated. Some parameters, needed for this estimation, might be monitored well, such as the temperature of flue gases, but others are not, such as the flow of the flue gases. Secondly, additional inaccuracies are added when deriving more general key figures from these individual waste heat potential assessments. They are usually derived for a specific sample of companies in a particular countries. However, the fabric of companies, even in the same sector, can differ significantly from one country to another. As a result, the sample of companies in one country, for which a key figure is derived, might not be representative for a sample in another country.

These results and considerations lead to following conclusion to this study: it is recommended to use a estimation method based on estimated or monitored waste heat assessments of individual companies to estimate the waste heat potential of industry. These estimates can still deviate with a factor 2 to 3 of what in reality can be delivered as waste heat. These estimation methods are suitable to provide a first indication of the potentially available waste heat from industry, but they need to be complemented with site specific assessments. Both the industry and the academic community would benefit from a harmonised method on how to assess waste heat flows of industrial companies as correctly as possible.

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