Model-based quantification of the contribution of industrial heat pumps to the European climate change mitigation strategy

M. Sc. Stefan Wolf & PD Dr.-Ing Markus Blesl
Institute for Energy Economics and the Rational Use of Energy (IER)
University of Stuttgart
70565 Stuttgart
Germany
Stefan.Wolf@ier.uni-stuttgart.de

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Abstract
The European climate and energy strategy for 2030 establishes political targets and thus paves the way towards a decarbonisation of energy generation in order to mitigate climate change. Heat pump technology has proven in private housing sector that it can contribute to the formulated targets of abating CO_2 emissions and raising energy efficiency. Recent technical developments have enabled heat pump technology to be applied in the industrial sector. Modern industrial heat pumps meet the criteria of large heating capacities up to several MW_{th} and high deliverable temperatures of 100 °C and beyond.

Applying a detailed model using a combined top-down and bottom-up approach allows the quantification the final energy conservation as well as the CO_2 abatement potential resulting from the application of heat pumps to the EU-28 industrial sector. In an industrial branch and country specific analysis both potentials are analysed with regard to technical and economic boundaries. The purpose of this work is to evaluate of the possible contribution of industrial heat pumps to the European climate and energy targets.

Introduction
The discovery of the earth's greenhouse effect by Fourier (1827) and the discovery of a global warming trend by Callendar (1938) induced the rise of a new research field covering climate change and its cause. With increasing modelling detail and input data quality the greenhouse gas (GHG) CO_2 originating from the combustion of fossil fuels was identified as a key factor in the cause of climate change. In 2007 the Intergovernmental Panel on Climate Change (IPCC) states in its fourth assessment report that the observed climate change can be attributed to human activities with a very high degree of certainty (Intergovernmental Panel on Climate Change 2007a). Combining this knowledge with the anticipation of predominantly negative effects of climate change on human life (Intergovernmental Panel on Climate Change 2007b) leads to the necessity of political action. Following this call the European Union (EU) formulated a climate change mitigation strategy targeting at a cut of 80 % of 1990's GHG emissions (European Commission 2011). From this overall objective the EU derived the targets of the current 2030 climate & energy framework comprising a 40 % cut on GHG emissions from 1990 levels, a 27 % share of renewable energies in energy supply and a 27 % improvement in energy efficiency compared to the bau scenario (European Commission 2014). These targets apply to all sectors of the European economy.

HEAT PUMPS IN REFERENCE TO EU CLIMATE AND ENERGY POLICY
The heat pump technology nearly ideally matches both the EU climate and energy targets and the consequences implied by fulfilling these targets. Constructive overlaps between heat pump technology and the EU targets are symbolised by marked check boxes in Figure 1. The targets of reducing GHG emissions and raising the share of renewables in energy supply imply a decarbonisation of electricity generation. This, in turn, lowers the CO_2 emissions attributable to heat generation by electrically driven heat pumps. By utilising ambient heat, heat

	EU climate & energy targets	target year	HP technology
explicit target	80% reduction of GHG emissions from 1990	2050	☑
	27% share of renewables in energy supply	2030	☑
	27% improvement in energy efficiency compared with bau scenario	2030	☑
implicit target	→ decarbonization of electricity generation		☑
	→ reduction of energy consumption		☑
	→ secure grid stability		☑
	→ affordable heating and cooling		☐

Figure 1. Classification of heat pump technology regarding the EU climate & energy targets.

pumps also contribute to raising the share of renewable energy sources.

Utilizing waste heat through the application of heat pumps, however, leads to an improvement in energy efficiency that aids to the overall reduction of energy use. Furthermore electrically driven heat pumps can improve grid stability, if heat storages are available. Only the aim to reach these targets in an affordable manner partly contradicts the application of heat pumps as the economic feasibility of heat pumps is strongly related to operating conditions.

In domestic heating applications heat pumps have emerged to become a well-established heating technology. In the European Union about 800,000 heat pump units are sold per year amounting to a total of 7.5 million installed units in 2015 (Nowak 2015). A large leap in technical development now enables heat pumps to be applied the industrial sector. Modern industrial and commercial heat pumps are able to deliver high temperature heat at large heating capacities. This opens up the opportunity to upgrade the temperature of vastly available industrial waste heat streams and to recycle them back into the production process.

APPLICATION OF HEAT PUMPS IN THE INDUSTRIAL SECTOR

Although the final report of IEA HPP/iets Annex 35/13 sheds some light on the application of heat pumps in the industrial sector (Annex 35/13 2014) a comprehensive analysis of the application potential in the European industry is missing. So far few studies have analyzed the application potential of heat pumps focusing on specific countries and/or specific industrial branches.

The technical potential for the application of heat pumps in the German industry was quantified by Lambauer et al. (2008). Due to the rapid progress of heat pump technology this potential was updated by Wolf et al. (2014). A very detailed bottom-up analysis of CO_2 abatement as well as economic potential for the French food and beverages industry was presented by Hita et al. (2011). This industrial branch has also been subject to a less detailed top-down analysis conducted by Heat Pump & Thermal Storage Technology Center of Japan (2010) for China, Germany, Spain, France, Italy, Japan, Netherlands, Norway, Sweden, United Kingdom and the USA. Bonilla et al. (1997) analyzed the waste heat availability in the industrial sector of Basque Country and calculated the technical application potential for different heat recovery technologies including heat pumps. Due to differences in the basic approach, the level of detail and the focus on specific countries and regions, the potential for heat pump application in the European industry can't simply be derived from a combination and extrapolation of these studies.

State of the Art of heat pump technology

Modelling the potential of heat pump application requires the analysis of technical limits of the commercially available heat pump technology. The heat pump principle of lifting low temperature heat to a higher temperature level has been implemented in various technical ways.

Among these the electrically driven closed cycle compression heat pump is the most advanced heat pump technology (Wolf et al. 2012). They are available at heating capacities of up to 20 MW_{th}. The development of high pressure compressor technology for the refrigerants R744 and R717 and the application of new refrigerants like R245fa (Wolf and Fahl 2014) and Eco1 (Ochsner 2014) have pushed the temperature limit for commercially available heat pumps to 105 °C (Johnson Controls Inc. 2015). With the combination of a closed and an open cycle compression heat pump Kobe Steel Ltd. et al. (2011) generated steam at 165 °C with a temperature lift of 95 K. This product, however, has not yet been introduced into the European Market. The specific investment for compression heat pumps ranges between 240 and 770 EUR per kW_{th} depending on the heating capacity (Soroka 2015; Wolf et al. 2014). Compression heat pumps offer a high degree of flexibility and have been demonstrated in a wide range of industrial processes (Annex 35/13 2014).

Absorption heat pumps are available with heating capacities of 25 to 350 kW_{th} (20 MW_{th} for customized plants). Due to their large active thermal mass they can't modulate the heat output as flexible as compression heat pumps. Thus, predominantly static operating conditions are to be preferred for the application of absorption heat pumps. These heat pumps become especially interesting when they can be driven by free high temperature waste heat (>100 °C). The technical properties of the most commonly used working pairs $LiBr/H_2O$ and H_2O/NH_3 alongside other technical boundaries limit the achievable heat delivery temperature to 120 °C (Wu et al. 2014). Most commercially available absorption heat pumps, however, are limited to a temperature of 90 °C. Furthermore absorption heat pumps require larger capital investments compared to equally sized compression heat pumps. Because of these reasons only few industrial applications of absorption heat pumps have been documented so far (Zotter and Rieberer 2014; Wolf et al. 2014; Wu et al. 2014).

Newly developed hybrid heat pumps combine the cycles of absorption and compression heat pumps and thus overcome the technical limitations of absorption technology. These heat pumps can be adjusted flexibly to the operating conditions. The first commercially available hybrid heat pump can reach 115 °C at heating capacities of 250 to 2,500 kW_{th} (Goget 2012). It has been demonstrated in eight industrial applications mainly in food and chemical industry (Goget 2012). Further work on this relatively new field of research has been carried out by Jensen et al. (2015) and Kim et al. (2013).

Other new heat pump concepts like stirling cycle (Høeg 2013) and rotatory (Riepl 2014) heat pumps offer high working temperatures and high achievable temperature lifts but they are still in an early demonstration phase. More detailed information on these heat pumps has been documented by Annex 35/13 (2014).

The comparison of heat pump types reveals that electrically driven compression heat pumps are the most versatile heat pump type. This is underlined by a large number of applications in various industrial branches. Therefore the following potential analysis focuses on this heat pump type.

Modelling Methodology

The chosen modelling methodology applies a combined top-down and bottom-up approach. At first the available statistical data of industrial final energy consumption is broken down to country and branch specific heat demand and waste heat availability by applying a top-down data model. This disaggregated energy data is then fed into the bottom-up potential analysis model that solves the efficient allocation of waste heat to heat demand via the use of compression heat pumps. The result of this analysis is the quantification of both final energy conservation and CO_2 abatement potential achievable through the application of heat pumps in the industry. These potentials are differentiated into a technical and an economic potential. Figure 2 gives an overview on the structure of the conducted potential analysis. Information flows appear as arrows.

DATA MODEL

A comprehensive overview on the structure of the data model is given in Figure 3. The model is fed with individual data on the final energy demand of the industrial sectors of all 28 EU member states. For each country the branch specific energy demand is then aggregated to ten industrial branches. The aggregation is performed for the production of metal and the manufacturing of non-metallic mineral products, since previous studies have shown only little potential in these branches (Lambauer et al. 2008; Wolf et al. 2014).

The final energy demand is then broken down by energy application. The model differentiates energy used for heat generation and other uses. This is done assuming that fuels are solely converted into heat. The share of electricity used for heat generation is calculated based on data of a detailed breakdown of energy use in the German industry (Arbeitsgemeinschaft Energiebilanzen e. V. 2013). This is calculation is performed with individual data for each industrial branch.

The heat demand is then broken down by temperature level using the branch specific temperature split parameters given in Table 1. These parameters are derived from the analysis of different studies on the German industry (Blesl 2014; Nast et al. 2013; Lauterbach et al. 2012; Wagner et al. 2002; Wünsch et al. 2012), on the English industry (Hammond and Norman 2012) and on the French food industry (Hita et al. 2011).

As the share of space heating differs from country to country due to climatic conditions this fraction of heat demand is scaled as a linear function of the country specific heating degree days (HDD_C) that is formulated in equations 1 and 2. The temperature split parameters ($h_{i,j}$) needed for these equations are taken from Table 1.

$$h_{C,i,1} = h_{i,1} \cdot \frac{\mathrm{HDD}_C}{3{,}239} \tag{1}$$

$$h_{C,i,j} = h_{i,j} \cdot \frac{1 - h_{C,i,1}}{1 - h_{i,1}} \quad \forall\, j \in \{2; 3; 4; \dots; 7\} \tag{2}$$

The calculation of the branch specific temperature split of the heat demand ($H_{C,i,j}$) is performed by multiplying the country specific heat demand of the respective branch (H_C) with the temperature split parameters as shown in equation 3.

$$H_{C,i,j} = h_{C,i,j} \cdot H_C \tag{3}$$

Since the feasibility of a heat pump application strongly relates to the operating conditions data on the available heat sources is needed to calculate a conclusive potential. Therefore the final energy consumption is broken down to available waste heat streams. As knowledge about waste heat availability in the industry is rather limited in scientific literature, a series of international studies had to be analysed to derive the data needed for modelling the waste heat potential. A qualitatively profound set of data has been collected by Sollesnes and Helgerud (2009). They conducted an empirical study on 72 companies that cover 69 % of the total final energy consumption of the Norwegian industry. McKenna and Norman (2010) and Hammond and Norman (2012) used EU ETS data of 425 sites in the UK to perform a branch specific analysis of industrial heat demand and waste heat availability. By comparing actual data of 260

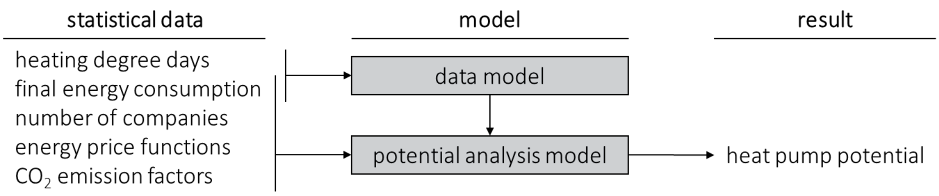

Figure 2. Structure and information flows of the conducted potential analysis.

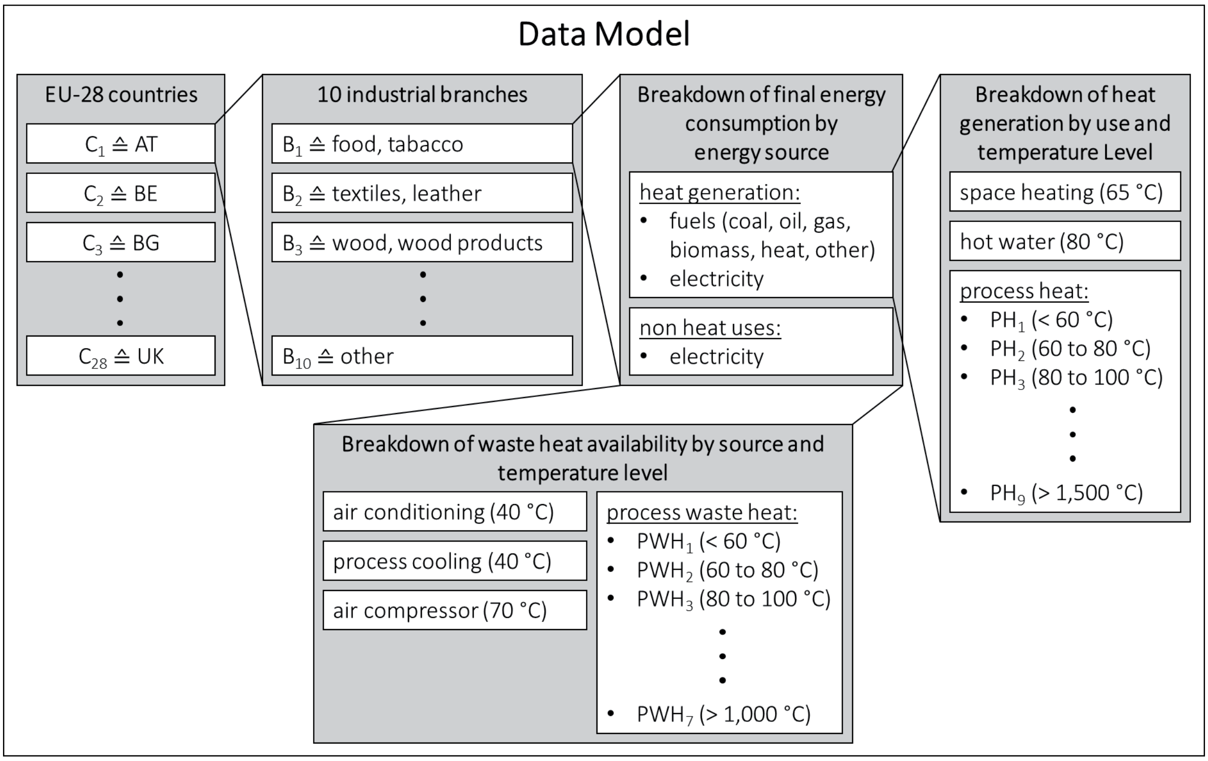

Figure 3. Structure and disaggregation level of the data model.

Table 1. Calculation parameters for the branch specific temperature split of the heat demand.

industrial branch (B_i)	heat demand ($h_{i,j}$)						
	$h_{i,1}$	$h_{i,2}$	$h_{i,3}$	$h_{i,4}$	$h_{i,5}$	$h_{i,6}$	$h_{i,7}$
	SH	HW	PH_1	PH_2	PH_3	PH_4	PH_5 to PH_9
NACE Rev. 2	65 °C	80 °C	< 60 °C	60 to 80 °C	80 to 100 °C	100 to 150 °C	> 150 °C
C 10, 11, 12	50 %	6 %	4 %	9 %	2 %	7 %	10 %
C 13, 14, 15	48 %	6 %	3 %	10 %	3 %	6 %	0 %
C 16	41 %	3 %	13 %	3 %	5 %	9 %	10 %
C 17, 18	50 %	6 %	4 %	9 %	2 %	7 %	56 %
C 19, 20	48 %	6 %	3 %	10 %	3 %	6 %	76 %
C 23	41 %	3 %	13 %	3 %	5 %	9 %	87 %
C 24	50 %	6 %	4 %	9 %	2 %	7 %	93 %
C 28	48 %	6 %	3 %	10 %	3 %	6 %	22 %
C 29, 30	41 %	3 %	13 %	3 %	5 %	9 %	24 %
other	50 %	6 %	4 %	9 %	2 %	7 %	26 %

legend: space heating (SH); hot water (HW); process heat (PH)

Sources: (Blesl 2014), (Nast et al. 2013), (Lauterbach et al. 2012), (Wagner et al. 2002), (Wünsch et al. 2012), (Hammond and Norman 2012), (Hita et al. 2011).

industrial companies with the ideal energy flows based on unit operations Bonilla et al. (1997) quantified the waste heat potential for the Basque Country. Lindqvist Land et al. (2002) and Cronholm et al. (2009) performed a process based analysis of the waste heat potential in 994 Swedish companies and extrapolated the results for the whole Swedish industry. Applying a theoretical process based approach Pellegrino et al. (2004) quantified the industrial waste heat potential in the USA at a high level of detail. In the course of a study on the heat demand structure of the German state of Baden-Württemberg Blesl et al. (2011) calculated the waste heat potential of the industrial sector differentiating three temperature levels.

The studies discussed above point out that only a share of the total available waste heat can technically be recovered. Therefore it is assumed in this work that the share of waste heat that can be utilized by heat pumps is 50 % for air conditioning (AC) and active process cooling (PC) and 20 % for compressed air production (CA). Regarding waste heat generated by industrial processes it is assumed that only guided waste heat streams can technically be utilized. This leads to branch specific shares of utilizable waste heat, since production processes differ between industrial branches. The resulting relative utilizable waste heat potential shown in Table 2 refers to the total final energy consumption of the respective industrial branch.

Combining the results of the evaluated studies the utilizable waste heat potential is broken down to temperature levels. In this way the branch and heat source specific waste heat utilization factors ($w_{i,j}$) given in Table 2 were derived. The utilizable waste heat ($W_{C,i,j}$) differentiates between the two source categories of electrical devices and general process waste heat. For the calculation of waste heat generated by AC, PC and CA equation 4 is applied on the respective waste heat utilization factors taken from Table 2. These factors are multiplied with the country specific electrical energy consumption ($E_{el,C,i}$) of the respective branch and the branch and source specific conversion ratio ($\varepsilon_{i,j}$). The conversion ratios are set to 0.7 for air compressors, to 4.7 for air conditioning and to 2.8 to 4.2 for process cooling depending on the branch.

$$W_{C,i,j} = w_{i,j} \cdot E_{el,C,i} \cdot \varepsilon_{i,j} \quad \forall\, j \in \{1;2;3\} \tag{4}$$

The amount of utilizable general process waste heat is calculated by applying equation 5 on the respective waste heat utilization factors given in Table 2. These factors are multiplied with the country and branch specific final energy consumption excluding the consumption of AC, PC and CA.

$$W_{C,i,j} = w_{i,j} \cdot \left(E_{f,C,i} - \sum_{k=1}^{3} E_{el,C,i} \cdot w_{C,i,k} \right)$$

$$\forall\, j \in \{4;5;6;7\} \tag{5}$$

POTENTIAL ANALYSIS MODEL

An overview on the core functionality of the potential analysis model is given in Figure 4. The model calculates the branch specific technical and economic potential for energy conservation and CO_2 abatement through the application of heat pumps. Since technical and economic feasibility of a heat pump application are strongly dependant on the operating conditions and thus the coupling of heat sources and heat sinks this coupling has been modelled with great detail.

The potential analysis model calculates a specific seasonal performance factor (β) for each possible coupling applying equation 6 to the data generated by the data model. In equation 6 T_c resembles the heat source temperature, T_h the sink temperature, ΔT the temperature difference at the heat exchangers (HEX) and g the Carnot efficiency ratio. The parameters T_c and T_h are part of the heat data set, ΔT is set to 5 K and g to 0.5 (Hita et al. 2011). The technical limit for the application of heat pumps is set to a maximum sink temperature of 100 °C, since analysed year is 2013 and heat pumps exceeding this limit even today are still in demonstration phase.

$$\beta = \left(\frac{T_c - \Delta T}{T_h - T_c + 2 \cdot \Delta T} \cdot g + 1 \right) \tag{6}$$

The amount of heat that can be generated by a coupling of heat source and sink is limited by a simultaneity factor derived from typical load profiles. This factor ranges from 0.1 for the coupling of air conditioning and space heating to 0.9 for heat generation utilizing ambient air as heat source.

The calculation of energy conservation and CO_2 abatement potential requires the comparison of the heat pump system to the reference heating system. This heating system is implemented corresponding to the consumed energy carriers as a fossil fuel, secondary fuel or biomass fired boiler, a district heating station or an electrical heater. The reference system generates heat at the temperature specific conversion efficiency η_W. This efficiency ranges from 1 for electrical heaters to 0.86 for the heat generation by secondary fuel fired boilers at 90 °C. For both the energy conservation and the CO_2 abatement potential a technical and an economic analysis have been done.

The technical potential for the application of heat pumps is defined as the maximum energy conservation or CO_2 abatement that can be achieved through the application of heat pumps and the substitution of heat generated by the reference systems. As observed in various real world heat pump applications the reference heating system is kept in place covering

Table 2. Calculation parameters for the branch specific temperature split of the utilizable waste heat.

industrial branch (B_i) NACE Rev. 2	utilizable waste heat potential	waste heat utilization factor ($w_{i,j}$) $w_{i,1}$ AC 40 °C	$w_{i,2}$ PC 40 °C	$w_{i,3}$ CA 70 °C	$w_{i,4}$ PWH_1 < 60 °C	$w_{i,5}$ PWH_2 60 to 80 °C	$w_{i,6}$ PWH_3 80 to 100 °C	$w_{i,7}$ PWH_4 to PWH_7 > 100 °C
C 10, 11, 12	14 %	4 %	16 %	7 %	1 %	2 %	1 %	0 %
C 13, 14, 15	24 %	3 %	0 %	14 %	12 %	4 %	4 %	0 %
C 16	26 %	0 %	0 %	15 %	9 %	6 %	3 %	6 %
C 17, 18	7 %	1 %	0 %	8 %	2 %	1 %	1 %	0 %
C 19, 20	16 %	1 %	4 %	2 %	8 %	1 %	1 %	2 %
C 23	11 %	1 %	0 %	17 %	5 %	5 %	4 %	3 %
C 24	21 %	0 %	0 %	3 %	8 %	0 %	0 %	22 %
C 28	31 %	4 %	0 %	14 %	7 %	2 %	2 %	0 %
C 29, 30	22 %	2 %	0 %	12 %	9 %	3 %	3 %	0 %
other	20 %	3 %	0 %	14 %	3 %	1 %	1 %	1 %

legend: air conditioning (AC), process cooling (PC), compressed air (CA), process waste heat (PWH)

Sources: (Sollesnes and Helgerud 2009), (McKenna and Norman 2010), (Hammond and Norman 2012), (Bonilla et al. 1997), (Lindqvist Land et al. 2002), (Cronholm et al. 2009), (Pellegrino et al. 2004), (Blesl et al. 2011).

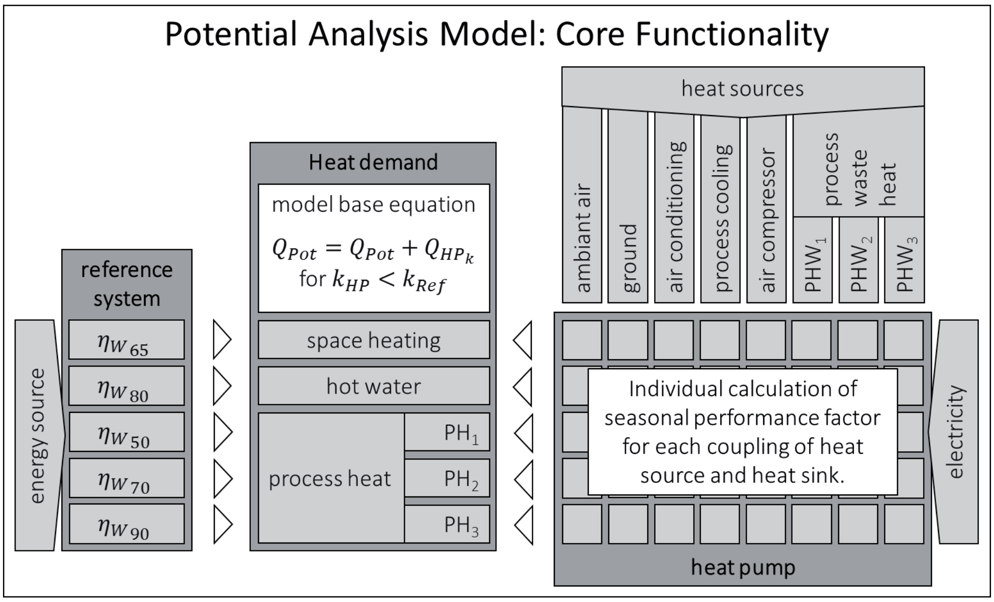

Figure 4. Structure and core functionality of the potential analysis model.

peak loads and generating heat when the heat source of the heat pump system is not available (Annex 35/13 2014).

Thus, in the calculation of the economic potential capital and operating costs of the reference system are neglected. Consequently the heat generation costs of the reference system are equal to the consumption costs, whereas for the heat pump system all three cost categories have to be considered. The consumption costs are calculated from the division of energy price through the conversion efficiency (β or η_W). The energy prices of the energy sources are specifically calculated for each branch by applying the average amount of energy consumed per company onto country specific cost curves. To calculate capital costs of the heat pump system a specific investment of EUR 420/kW_{th} (Wolf et al. 2014), an interest rate of 15 % (Brunke and Blesl 2014) and a useful life of 18 years (Verein Deutscher Ingenieure e.V. 2012) are assumed. The operation costs are assumed to be 4 % p.a. of the total investment into the heat pump system. As shown in Figure 4 the heat generated by the heat pump system is added to the economic potential, if its generation cost is lower than the heat generation cost of the reference system.

Data

The data demand of the developed model is briefly visualized in Figure 2. More detailed information on the used data is given in the following.

ENERGY CONSUMPTION

The European industrial sector accounts for 25 % of the European final energy consumption. As shown in Figure 5 this final energy consumption is distributed rather inhomogeneous among the 28 European member states (eurostat 2015a). The German industry alone accounts for 22 % of the total industrial final energy demand followed by France, Italy and the United Kingdom. The remaining 14 member states combined account for less than 50 % of the total industrial final energy consumption. This demand for energy is largely covered by the combustion of fossil fuels as shown in Figure 5. With a share of 7 %, CO_2 neutral renewable energies play a merely marginal role.

HEAT DEMAND AND WASTE HEAT AVAILABILITY

Heat demand and waste heat availability are calculated from (eurostat 2015a) and (eurostat 2015c) using the data model. The results are shown in Figure 6. The upper bar chart represents the utilizable waste heat available at temperatures below 100 °C while the lower bar represents the heat demand. Of particular note is the large heat demand classified as "other branches". This results from the fact that especially the UK, Spain, France and Poland assign a relatively large share of their industrial final energy consumption to this category.

ENERGY RELATED CO_2 EMISSIONS

The industrial CO_2 emissions resulting from energy consumption amount to 508 Mt CO_2 based on own calculations applying the emission factors given in Table 3. The factors represent the weighted average of the subsumed energy sources calculated using (eurostat 2015a) and (Intergovernmental Panel on Climate Change 2006). The chosen approach draws the system boundaries around the energy consumer, attributing all CO_2 emissions to the energy consumption of the industrial sector. This is relevant for the electricity related emissions which would otherwise be attributed to the power sector. The country specific CO_2 emissions used in the model average to 117.6 t CO_2/TJ for the EU-28. Renewables, however, are the only exception from this accounting scheme. By assuming a specific CO_2 emission factor of 0 t CO_2/TJ the system boundary also includes the production of renewable energies.

ENERGY PRICES

The energy prices are calculated using data on the number of companies taken from the European business demography data set (eurostat 2016c). This data is combined with European statistics on the final energy demand (eurostat 2016a) and then applied onto country specific cost curves derived from the analysis of eurostat (2016b), eurostat (2015b), Bun-

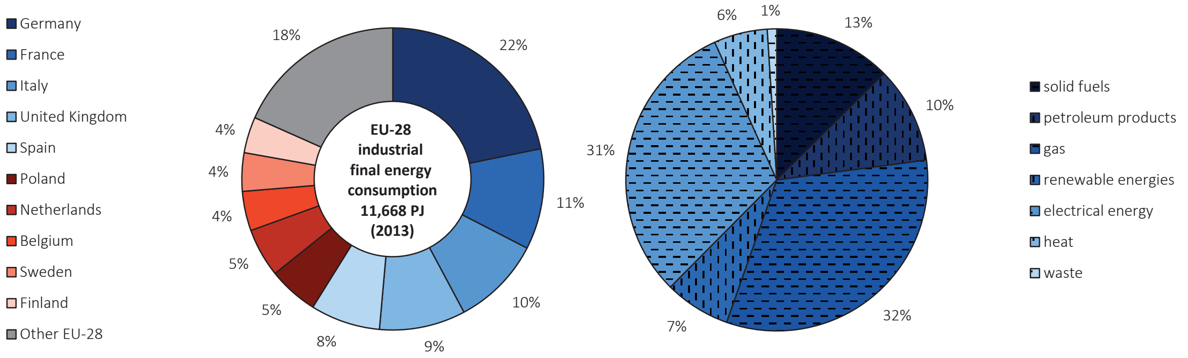

Figure 5. Structure of the final energy demand in the European industrial Sector.

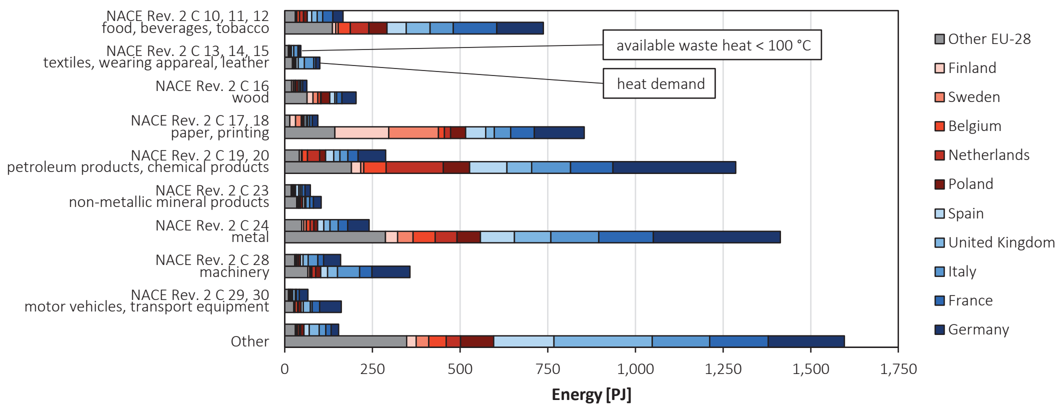

Figure 6. Industrial heat demand and utilizable waste heat.

Table 3. Specific CO_2 emissions factors applied in the calculation of energy related CO_2 emissions.

energy source	CO_2 emission factor [t CO_2/TJ]
solid fuels	98.6
petroleum products	75.7
gas	55.3
renewable energies	0
electrical energy	117.6
heat	82.6
waste	81.3

desministerium für Wirtschaft und Energie (2015), Centrales Agrar-Rohstoff Marketing- und Energie-Netzwerk e.V. (2015), Bonnet and Viertel (2006), Lechtenböhmer et al. (2006) and Reichmuth et al. (2014). Results of this approach are the country and branch specific energy prices shown in Figure 7.

Results

The results of the potential calculation are visualized in form of potential cost curves. This form of presentation allows the compact graphical representation of the individual technical and economic potential of each EU-28 country. Beside these advantages Wächter (2013) also points out the shortcomings of this visualization method, being the neglect of technology diffusion rates, the radical change of appearance of the curve when altering input parameters and false implications by ranking measures by their specific abatement costs.

These weaknesses can partly be compensated by a clarification of the informative value of the potential cost curves shown in Figure 8 and Figure 9. Therefore the following statements have to be made.

- The curves are only valid for the given set of parameters.
- To point out the influence of these parameters on the calculated potentials the sensitivity analysis shown in Figure 10 has been carried out.

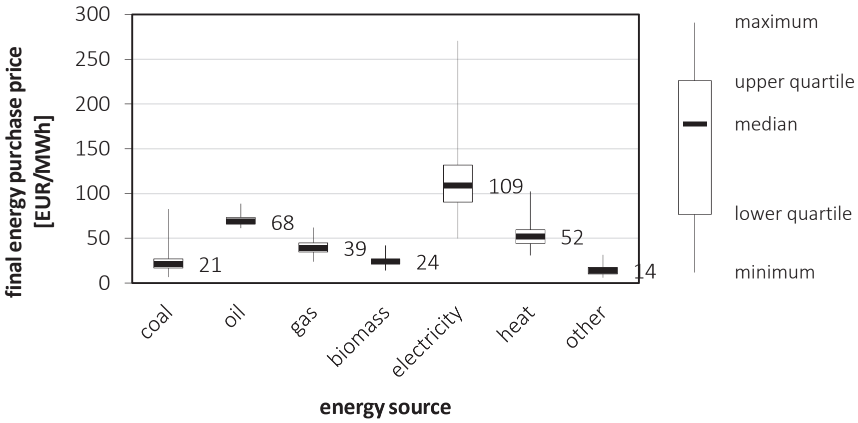

Figure 7. Country and industrial branch specific energy prices used for the potential analysis.

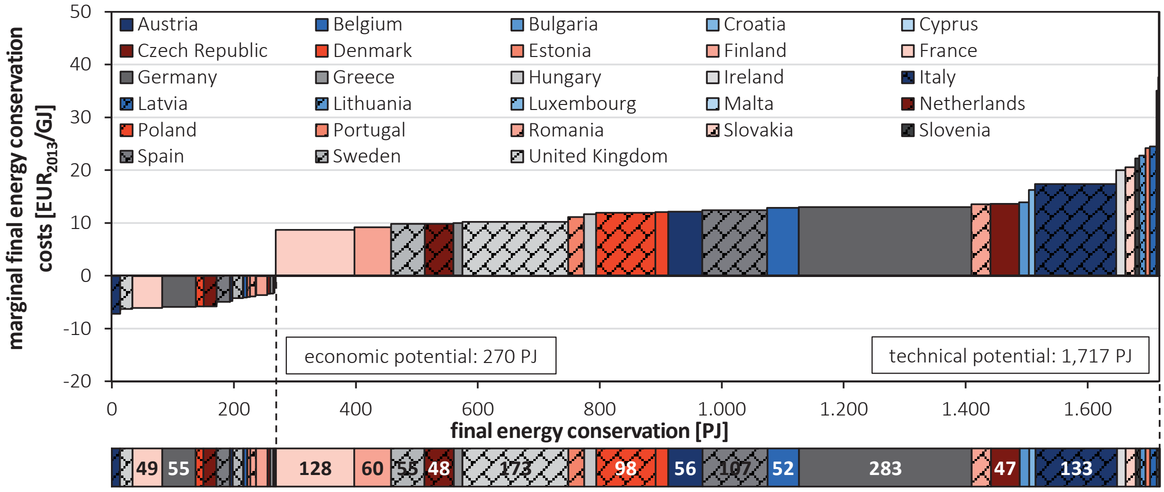

Figure 8. Final energy conservation cost curve for the application of heat pumps in the EU-28 industrial sector.

- The ranking by specific abatement costs identifies countries with low potential development costs. Since this study solely focuses on one technology the systematic error bound to the neglect of unknown transaction costs is of no effect.
- To ensure the economic potential to be found at the intersection of the potential cost curve with the abscissa, heat pump application cases with negative and positive specific abatement costs have been aggregated separately for each country.

The final energy conservation cost curve (Figure 8) shows a technical potential of 1,717 PJ which represents 15 % of the total final energy consumption of the EU-28 industrial sector. Major energy conservation potentials can be found in food, chemical and paper industry. Taking into account economic boundary conditions the final energy conservation potential decreases to 270 PJ or 2.3 % of the industrial final energy consumption. The countries with the lowest total marginal final energy conservation costs are France, Finland, Sweden and the Netherlands.

Due to country specific CO_2 emission factors of electrical energy in addition to the varying mix of fuels used for heat generation, the shown final energy conservation potential does not directly translate into the CO_2 abatement potential shown in Figure 9. The technically abatable CO_2 emissions amount to 86.2 Mt representing 17 % of the total energy related CO_2 emissions of the European industry. Considering economic boundary condition the potential decreases to 21.5 Mt CO_2 which represents 4.2 % of the total emissions. Large potentials with low marginal CO_2 abatement costs can be found in France, Finland, Sweden and Austria. The Netherlands, however, fall out of this ranking due to relatively low gas prices.

The impact of a variation of fundamental model parameters on the calculated CO_2 abatement potential has been studied in a sensitivity analysis shown in Figure 10. The parameters have been varied by ±25 % and 50 %. The technical CO_2 abatement potential varies in a range from 60 to 120 Mt. While the specific CO_2 emissions of electrical energy have the highest impact on the technical potential they are of negligible relevance for the economic CO_2 abatement potential which shows a large volatility ranging between 4 and 50 Mt. Here the most influential parameter is the fuel price followed by the heat pump investment, the assumed Carnot efficiency ratio and the electrical energy price. The result points that a faster diffusion of industrial heat pumps is bound to a reduction of the investment and an increase in fossil fuel prices.

Conclusion

This work has shown that the application of heat pump technology in the EU-28 industrial sector can contribute to the European climate and energy targets in terms of CO_2 reduction and a gain of energy efficiency. The detailed combined top-down and bottom up approach considers not only the heat demand structure but also the availability of heat sources and delivers industrial branch and country specific results on the application of heat pumps.

In total the final energy conservation potential amounts to 1,717 PJ, representing 15 % of the industrial final energy consumption. In consideration of 2013's energy prices the conservation of 270 PJ of final energy are economically feasible. The total CO_2 abatement potential amounts to 86.2 Mt, representing 17 % of the energy related CO_2 emissions of the EU-28 industrial sector. Adding economic boundaries the CO_2 abatement potential reduces to 21.5 Mt.

The results of the sensitivity analysis show that an increase of fuel prices and a reduction of the investment for an industrial heat pump system can have a significant effect on the economically feasible CO_2 abatement potential. Further research has to show in which way political instruments could be applied to stimulate the diffusion of this technology in the industrial sector. Furthermore standardized implementation schemes need to be developed to simplify the application of heat pumps and thus reduce transaction costs.

Nomenclature

ABBREVIATIONS

AC	Air conditioning
CA	Compressed Air
GHG	Greenhouse gas
HEX	Heat exchanger
HP	Heat Pump
HW	Hot water
PH	Process heat
PWH	Process waste heat
SH	Space heating

SYMBOLS

β	Seasonal Performance Factor (–)
B_i	Industrial Branch (–)
C_i	Country (–)
η_W	Heat generation efficiency of the reference system (–)

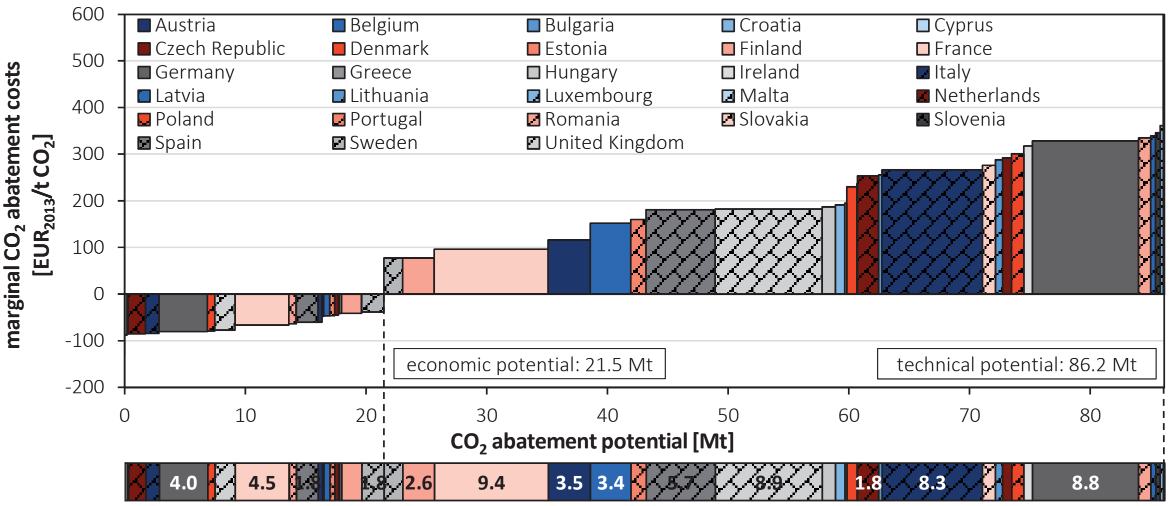

Figure 9. CO_2 abatement cost curve for the application of heat pumps in the EU-28 industrial sector.

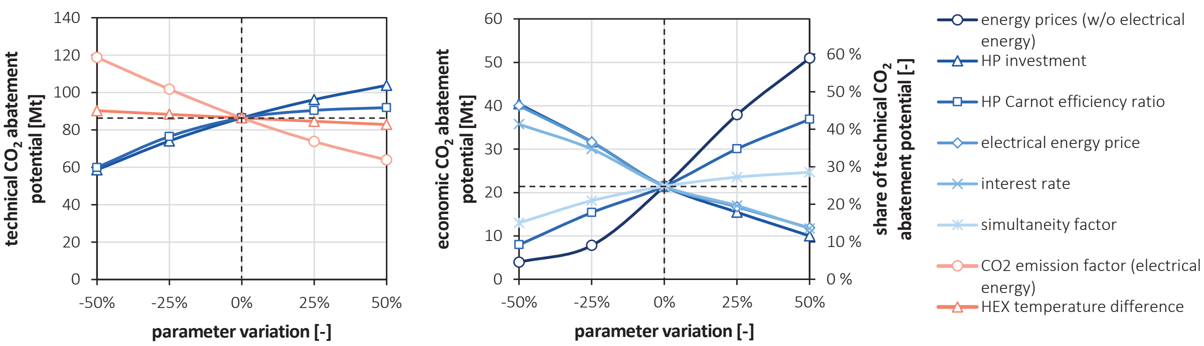

Figure 10. Sensitivity analysis for the technical and economic CO_2 abatement potential.

$E_{el,C,i}$ Country and branch specific electrical energy consumption (PJ)
$E_{f,C,i}$ Country and branch specific final energy consumption (PJ)
g Carnot efficiency ratio (–)
H_C Country specific industrial heat demand (PJ)
$H_{C,i,j}$ Country and branch specific industrial heat demand (PJ)
$h_{C,i,j}$ Country and branch specific heat split parameter (–)
$h_{i,j}$ Branch specific temperature split parameter (–)
HDD_C Country specific heating degree days (–)
T_c Heat source temperature (°C)
ΔT HEX temperature difference (K)
T_h Heat sink temperature (°C)
$W_{C,i,j}$ Country and branch specific industrial waste heat availability (PJ)
$w_{C,i,k}$ Country and branch specific consumption of electrical energy (–)
$w_{i,j}$ Branch specific waste heat split parameter (–)

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