PEER-REVIEWED PAPER

Assessment of the economic viability of the integration of industrial waste heat into existing district heating grids

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Abstract

In many industrial enterprises in the European Union a large amount of waste heat from various processes still remains unused. A recent study in Austria detected a technically feasible industrial waste heat potential of around 15 TWh yearly. This is more than 25 % of the final thermal energy demand of the Austrian industry and about 74 % of the final energy demanded in district heating networks. Reusing industrial waste heat is essential in order to increase the energy efficiency of the European energy system and to reach the 20-20-20 targets of the European Union. However, up to now economic and non-economic barriers are hindering the uptake of this potential.

This research aims at analysing the economic viability of the integration of industrial waste heat into existing district heating grids. We investigate different system components, sources of waste heat, return temperatures of the district heating grid as well as the distance between plants and grids, including sensitivity analyses. A techno-economic modelling tool was developed that simulates the integration of industrial waste heat into district heating grids following the concept of Levelized Costs of Heat (LCOH).

We find the following highly influencing factors on the economic viability of such projects: the distance between the waste heat sources and the district heating grid, the return temperature of the district heating grid, the available waste heat power, the full load hours of the system as well as the economic assessment period. This underlines the importance of low-temperature heating grids allowing a larger number of waste heat sources to be reused. For many combinations of the stated parameters we calculated LCOH remarkably below 1 ct.EUR/kWh. This is considerably lower than the current prices for district heat.

Introduction

The European Union agrees to decrease the use of fossil resources and increase the efficiency of its energy systems by 2020 and beyond. Heating and cooling accounts for a large part of the overall energy need and is demanded in various economic activities at different temperature levels. Many industrial processes provide significant amounts of waste heat at temperature levels that can be used in other processes, for hot water preparation, for space heating and for cooling purposes. A significant waste heat potential in industry has been identified in many studies across the European Union. For Austria (Niedermair et al., 2012) detected a technically feasible industrial waste heat potential of around 15 TWh yearly using a bottom-up approach. This is more than 25 % of the final thermal energy demand of the Austrian industry and about 74 % of the final energy demanded in district heating networks. (Groß and Tänzer, 2010) analysed the potential for the use of industrial waste heat in Germany using a top-down estimation. They calculated a theoretically usable waste heat potential between 50 and 60 % of the final energy currently demanded for space heating in residential buildings.

Industrial waste heat can be reused either at the industrial plant, in neighbouring companies and buildings or be fed in existing or new district heating grids. In this context the question arises, for which cases it is meaningful to integrate industrial waste heat into district heating grids? The main research question of this study is: "What is the economic feasibility of the integration of industrial waste heat into existing district heating grids under different conditions?" The aim is to identify the parameters that have the highest influence on the economic efficiency of such systems, and to estimate expectable supply costs for industrial waste-heat-to-grid systems.

In order to carry out this analysis the following steps are taken: (1) a techno-economic modelling tool is developed that simulates industrial waste-heat-to-grid systems on an hourly basis. It is able to carry out sensitivity analyses automatically. (2) Data research is conducted on costs of industrial waste heat recovery and feed in district heating grid systems, representative process and heating grid specifications and prices for district heating and (3) a reference scenario is defined and a sensitivity analysis is carried out in order to identify the parameters with the highest influence on the economic feasibility.

In order to calculate first results of expectable heat generation costs for industrial waste-heat-to-grid the following assumptions have been made. It is assumed that the district heating grid can absorb the heat provided by the waste heat integration system at any time of the year for which waste heat is available. Furthermore the developed model didn't include a heat storage unit for the calculation of these results, therefore the assumption was made that all process load profiles are identical. This is likely not to be expected in existing plants. These assumptions are discussed in the final chapter of this paper. However, further analysis on the influence of differing process load profiles and limited access to district heating grids on the economic feasibility has to be carried out.

Methodology

DESCRIPTION OF THE TECHNICAL SIMULATION AND THE MAIN TECHNICAL INPUT PARAMETERS

Investigated Waste Heat Integration System

The design of systems to reuse industrial waste heat in district heating grids depends on a variety of different aspects. The main factors are the process and plant characteristics as well as the type and organisation of the district heating grid or other users. The existence and technical usability of waste heat streams determines whether a theoretical waste heat source can be operated or not. The load profiles of the processes and the type and power of the grid determine if a storage tank is needed to balance supply and demand. The waste heat integration system chosen for this survey has the following characteristics (see Figure 1): the system consist of two circuits, which connect the waste heat sources on the one side with the district heating grid on the other. The absorption circuit collects usable waste heat from the different demand locations (process water, compressor and flue gas) in the plant and transports it to the transfer station. The transfer station thereby is understood as part of the absorption circuit in this paper. The distribution circuit then connects the transfer station with the existing district heating grid. While the pipes of the absorption circuit are located above ground in the industrial site, the pipes of the distribution circuit are laid underground outside of the plant area. Therefore the heat losses appearing in the absorption circuit are denominated as internal losses, the heat losses in the distribution system as external losses. Furthermore pumps are needed to maintain the flow in the pipes, one pump in each of the described circuits.

The integration of industrial waste heat into district heating grids can be realised in three different ways. The heat can directly be fed into the flow pipe, it can directly be fed into the return pipe, or the return pipe can be connected to the flow pipe. In the first case only a small part of the waste heat can be used due to the high temperature level of the flow. In the second case the temperature of the return to the district heating plant(s) is increased, which results in lower technical efficiencies of these plant(s). It furthermore leads to higher heat losses in the return pipes of the district heating grids. Due to these reasons we chose to simulate a direct connection between return and flow to integrate the industrial waste heat into the district heating grid. Part of the return medium is extracted into the distribution circuit of the modelled system. It is increased to flow temperature of the district heating grid and is brought back into the flow pipe.

The configuration of waste heat integration systems depends on different aspects, which can be classified into technical and economic considerations. In the following sub-sections the considerations undertaken in the analysis are explained for the different parts of the technical system.

Heat Absorption Circuit

The absorption system connects the waste heat sources with the transfer station. Three sources of industrial waste heat are investigated in this analysis: process water, a cooling compressor and flue gas. In order to increase the distribution medium (water) from the return temperature to the flow temperature of the district heating grid a serial arrangement of the three waste heat sources is used. The heat source with the lowest temperature level is used for the first temperature increase, the heat source with the highest temperature level for the last temperature increase. In the modelled system counterflow heat exchangers are used. The outlet of the heat absorbing medium thereby is in contact with the inlet of the heat transferring medium. With increasing heat exchange surface the temperature difference between these the two mediums can be decreased, while at the same time the costs of the heat exchanger rise. It is assumed that due to economic considerations the heat exchangers are designed having a temperature difference of 5 K at the input and the output. The following Table 1 shows the assumptions for the temperatures of the available waste heat sources as well as the temperature increase of the distribution medium in the heat absorption circuit.

The return temperature of the district heating grid determines whether a source of waste heat can be used for the integration into the grid or not. In the analysis we calculate three different scenarios of the return temperature: 40 °C, 50 °C and 60 °C. Due to the economic limitation of the heat exchange surface as described above, only in case of the lowest return temperature of 40 °C the waste heat of the process water can be used.

To collect the waste heat of the industrial processes three different types of heat exchangers are used (see Table 1). The dimensions of the apparatus used in the system are reflected by the heat exchange surface in case of the plate as well as the tube bundle heat exchangers, and by the nominal power of the

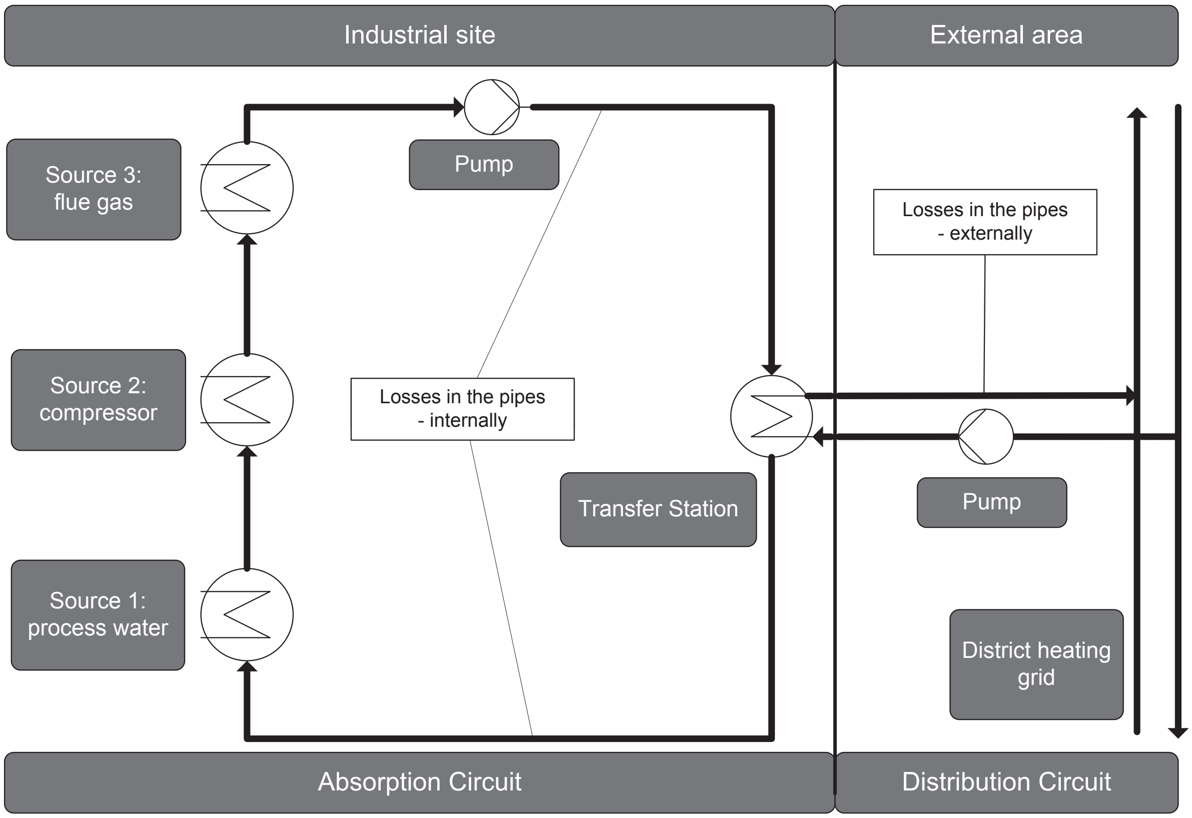

Figure 1. Waste Heat Integration System Concept used for the study.

Table 1. Defined temperatures at the heat exchanger in- and outputs for the analysis of the lowest return temperature of the district heating grid (40 °C).

Heat Exchanger (HEx)	Connection between	Temperature waste heat stream		Temperature absorbtion stream		Temperature distribution stream	
		HEx in	HEx out	HEx in	HEx out	HEx in	HEx out
		[°C]	[°C]	[°C]	[°C]	[°C]	[°C]
plate heat exchanger	process water - absorbtion circuit	60	50	45	55		
compressor heat exchanger	compressor - absorbtion circuit	80	60	55	75		
tube bundle heat exchanger	flue gas - absorbtion circuit	250	120	75	95		
transfer station	absorption circuit - distribution circuit			95	45	40	90

compressor in case of the compressor heat exchanger. For every heat exchanger the maximum load to be transferred $P_{HEx,max}$ is the main determinant of the size of the device. In the analysis these values are estimated on the basis of the maximum total available waste heat power and the defined temperature differences in the heat exchangers. The heat exchange surface of the plate and the tube bundle heat exchangers A_{HEx} then is given as a function of the maximum transfer power $P_{HEx,max}$, the logarithmic medium temperature difference (*LMTD*) and the heat transfer coefficient *k*, according to the following formulas:

$$A_{HEx} = \frac{P_{HEx_{max}}}{k\ LMTD}$$

$$LMTD = \frac{\Delta T_{HEx_{max}} - \Delta T_{HEx_{min}}}{ln(\frac{\Delta T_{HEx_{max}}}{\Delta T_{HEx_{min}}})}$$

The *LMTD* of a heat exchanger depends on the temperature differences ΔT_{HEX_min} and ΔT_{HEX_max} between the heat dissipating medium and the heat absorbing medium at both sides of the device.

The heat transfer coefficient *k* depends on the construction type of the heat exchanger and on the absorbing and transferring media and their aggregate state. For this analysis the heat transfer coefficients were calculated based on the technical specifications of the heat exchangers for which cost data was accessible. We calculated a *k*-value of 0.0528 kW/m²K for the tube bundle heat exchanger, and a *k*-value of 4.8872 kW/m²K for the plate heat exchanger. As mentioned above, the size of the compressor heat exchanger is reflected by the nominal power of the compressor. The available data of compressor heat exchanger systems showed that on average the usable heat power is around 87 % of the nominal power of the compressor (KAESER, 2012).

In the absorption circuit the following tubes are chosen: medium weight, seamless threaded tubes according to DIN EN 10255-Serie M made of S195T for nominal diameters below 50 mm (DN 50) and seamless steel tubes according to DIN EN 10216-1 made of P235TR2 for pipes above DN 50. The pipes are insulated with mineral wool sheathing resulting in a heat conductivity of 0.035 W/mK.

Heat Distribution Circuit

The distribution circuit connects the absorption circuit with the district heating grid. It consists of the heat transfer station and the pipes outside of the industrial site. Part of the return pipe of the district heating system is branched off and directed to the heat transfer station. After the heat absorption it is returned to the flow pipe of the district heating system.

The heat transfer station is designed in order to be able to transfer the available waste heat power at any moment of the year. Therefore the highest available waste heat power is taken for the dimensioning of the heat transfer station. For the pipes outside of the industrial plant flexible pre-insulated pipes underground are assumed, as these are commonly used.

Dimensioning of pipes and pumps

For the calculation of the diameter of the pipes used in the system the following definition is made. In case of the highest volume flow in the year the flow rate shall not exceed 5 m/s. The highest volume flows in the year appear when a low temperature difference between return and flow of the district heating grid occur in combination with a high available industrial waste heat power.

The power demands of the pumps in the absorption and distribution circuit depend on the volume flows V_{flow} that are transported, on the vertical heights H to be overcome, the density of the transport medium ρ, and on the efficiency of the motor and pump system η. It is calculated according to the following formula:

$$P_{Pump} = \frac{V_{flow} H \rho\, g}{\eta}$$

For this study the vertical heights to be overcome are defined with 15 m inside the industrial site and 5 m in the external area between the transfer station and district heating grid. For the pump as well as the motor an efficiency of 85 % is assumed. The overall efficiency of the motor and pump system therefore results in 72 %.

Heat losses in the pipes

In the transportation of the heat from the waste heat sources to the district heating grid heat is lost to the ambient. For the analysis it is assumed that the pipes of the absorption circuit are above ground and inside of the industrial building, the pipes of the distribution circuit are buried underground. To determine the heat losses in the pipes two different methods are used: for the losses in the pipes of the distribution circuit literature values are taken, while the losses in the pipes of the absorption circuit are calculated based on an approach shown in (Wossog, 2003). The heat lost in 1 m of the pipe (q_{loss}) are given as a function of the temperature difference between the fluid medium in the pipe (T_p) and the ambient temperature (T_{amb}), the inner (d_i)and outer (d_o) diameter of the pipe, the heat conductivity λ and the heat transfer coefficient α_a as follows:

$$q_{loss} = \frac{\pi\,(T_P - T_{amb})}{\frac{1}{2\lambda}\, ln\frac{d_o}{d_i} + \frac{1}{\alpha_a d_o}}$$

The heat transfer coefficient α_a consists of two factors, the convection coefficient α_c and the radiation coefficient α_r. As these coefficients are functions of the temperature of the outer surface of the pipe T_{OS} all values are calculated iteratively starting with an estimated temperature T_{OS}.

$$\alpha_c = 1.22\sqrt{\frac{(T_{OS} - T_{amb})}{d_o}}$$

$$\alpha_r = C_{12}\frac{(\frac{T_{OS_{abs}}}{100})^4 - (\frac{T_{amb_{abs}}}{100})^4}{T_{OS} - T_{amb}}$$

The losses in the pipes of the distribution circuit are determined according to (Siebrasse, 1999). He calculates the losses in underground heat distribution pipes with the following specifications: flow temperature 90 °C, return temperature 70 °C, ground temperature 5 °C, distance between flow and return pipes is 10 cm and cover height is 80 cm. The resulting values are used as the basis for the calculations in this paper. For return temperatures lower than 70 °C a correction factor is used (-10 % for 60 °C, -20 % for 50 °C and -30 % for 40 °C).

METHOD FOR THE ASSESSMENT OF THE ECONOMIC EFFICIENCY

In order to quantify the economic performance of investments in waste heat integration systems the concept of the Levelized Costs according to e.g. (Branker et al., 2011) is used. The idea of the Levelized Costs of Heat Generation (LCOH) is to compare the costs of the heat supply (C) with the resulting heat supplied by the system (E). Since both the costs of the heat supply and the supplied heat itself are subject to the time preference of the investors, the costs as well as the energy amounts are discounted at the interest rate r with an economic assessment period of τ. The following equation is used to calculate the LCOH:

$$LCOH = \frac{\sum_{t=0}^{\tau} C_t\,(1+r)^{-t}}{\sum_{t=0}^{\tau} E_t\,(1+r)^{-t}}$$

Description of relevant input data

COST DATA OF THE WASTE HEAT INTEGRATION SYSTEM

To integrate waste heat from the defined processes into existing district heating grids the following components are necessary: heat exchangers to collect the waste heat from the different sources, a heat transfer station to integrate the collected waste heat into the district heating grid, and pipes to transport the collected heat from the waste heat sources to the district heating grid.

In order to reuse available waste heat from the process water, flue gas and cooling compressors different types of heat exchangers are needed. Furthermore, to integrate the collected waste heat into the district heating grid a transfer station is necessary. Based on data from Austrian retailers for each of these equipment a cost curve is derived according to the following equation:

Table 2. Heat Exchanger types and cost data used in the calculations.

heat exchanger	connection between	base value in the cost curve	parameters of the cost curve		
			a	b	c
plate heat exchanger	process water - absorbtion circuit	heat transfer surface [m²]	410	-0.30	200
compressor heat exchanger	compressor - absorbtion circuit	rated motor power [kW]	199	-0.32	21
tube bundle heat exchanger	flue gas - absorbtion circuit	heat transfer surface [m²]	363	-0.10	265
transfer station	absorption circuit - distribution circuit	transfer power [kW]	1,048	-0.63	3

$$c_{invest} = a\ Base^b + c$$

The characteristic base values and the constants a, b and c resulting from the regression are shown in the following Table 2. The yearly operation and maintenance (O&M) costs of the heat exchangers are estimated with 3 % of the investment costs.

The investment costs of the piping of the absorption circuit consists of the costs for the pipes itself and the costs for the insulation. Based on prices from an Austrian retailer of pipes and a large insulation retailer we calculated investment costs between €27 per meter for a nominal diameter of 25 mm and €213 per meter for a nominal diameter of 150 mm. The costs of the transportation of the heat from the plant to the district heating grid outside the industrial site depend on a variety of different factors: the type of pipes used, the diameter of the pipes, the method of construction, the planning and the local conditions such as geography and administration procedures. For the analysis we estimated the investment costs for the external piping based on data for realised projects in Austria. Using flexible pre-insulated pipes we calculate investment costs between €300 and €500 per meter of the distance between plant and grid for nominal diameters of the pipes between 25 and 150 mm. The major cost component is the laying of the pipes accounting for 55 to 60 % of the total costs. The surface restoration accounts for 23 to 28 % and the ancillary costs account for 18 to 21 %.

For the absorption and the distribution circuit vertical dry-running pumps are selected. We calculated with calculated with cost from an Austrian retailer being between €1,500 for a nominal diameter of 32 mm and €6,900 for a nominal diameter of 150 mm. The running costs of the pumps are calculated with an electricity price of 11 ct.EUR/kWh.

In general it was experienced to be difficult to receive cost data for the various parts of the waste-heat-to-grid system. This is mainly due to the fact that piping and heat exchanger solutions in industry as well as district heating grid connections are highly individual and general information is given very seldom from the retailers. Most of the cost data presented in this paper is based on information from one or two retailers in Austria.

PROCESS DATA

Three sources of industrial waste heat are investigated in this analysis: process water, a cooling compressor and flue gas. The temperature levels are shown in the description of the heat absorption circuit. It is assumed that these temperature levels are constant whenever the plant is in operation. Furthermore in order to calculate first results we assumed that all processes have the same load profile. Then the available power of the industrial waste heat system is reflected through the plant operation times. For the reference case we chose a 2-shift production plant starting operation at 6 a.m., not operating weekends and producing all over the year. For the sensitivity cases we varied between 2-shift and 3-shift, production on weekends or not and between one week plant holidays or no holidays.

The assumption that all processes are constantly running while the plant is in operation is a major constraint of this analysis, as this is likely not to be expected in existing plants. Differing load profiles would imply the need for heat storage and probably lead to lower cost effectiveness of other parts of the system. These costs and the resulting influence on the LCOH are therefore not reflected in this study.

DISTRICT HEATING GRID DATA AND PRICES FOR DISTRICT HEAT

In this calculation the district heating grid is mainly characterised by the temperatures of the return and the flow. The return temperature is varied in the analysis between 40 and 60 °C. The flow temperature is assumed to range between 70 and 90 °C, depending on the actual heating demand. These temperatures reflect common values for small local heating networks as well as the secondary parts of large district heating networks of big cities. Concerning the capacity of the district heating grid to absorb the industrial waste heat no limitation is assumed for this study.

The prices for district heat differ between utilities and users. In several countries of the European Union they lie in the range between €40 and €50/MWh (in 2009)[1].

Assessment results

With the model and system design described in the previous part of the paper we perform an assessment of the Levelized Costs of Heat (LCOH) for different input parameter sets. The aim is to identify important factors determining the economic viability of industrial waste heat systems designed for the integration of the heat into existing district heating networks. We define a reference case for the analysis and calculate sensitivity scenarios for different input parameters. The following Table 3 shows the values chosen for the reference case and the range defined for the parameter variation.

The usable waste heat power of the plant is determined for the different waste heat sources according to the designed temperature differences at the heat exchangers. In case of the lowest return temperature of the district heating grid (40 °C) all waste heat sources can be used with the temperatures as defined in Table 1. For the return temperatures of 50 and 60 °C the waste heat of the process water cannot be used as the temperature difference is too low or even negative. For these cases no heat

1. See e.g. the RES-H Policy or ENTRANZE projects (www.res-h-policy.eu, www.entranze.eu).

Table 3. Defined settings for the calculation of the reference case and range of parameters for the sensitivity calculations.

parameter	unit	reference case	range of sensitivity analysis
available waste heat power	MW	1	0,5 - 3
$T_{return, district heating grid}$	°C	50	40, 50, 60
$T_{flow, district heating grid}$	°C	70 - 90	no variation
economic assessment period	a	10	1 - 20
interest rate	%	7	no variation
distance between the transfer station and the grid	m	250	100 - 1000
load profile	-	2 shifts, no weekends, no holidays	2 / 3 shifts, weekends yes/no, holidays yes/no

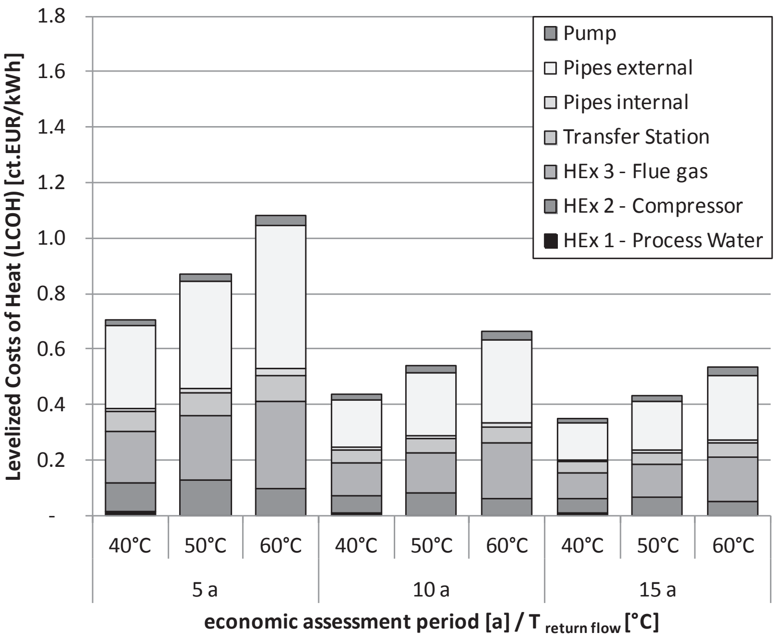

Figure 2. LCOH for different return temperatures of the district heating grid and economic assessment periods.

exchanger for this source is considered. Furthermore in case of 60 °C return temperature less waste heat power can be used from the compressor heat exchanger, as the usable temperature difference is lower compared to the higher return temperatures of 40 and 50 °C. As a result the usable waste heat power decreases with increasing return temperatures to 80 % (in case of 50 °C) and 60 % (in case of 60 °C) compared to the return temperature of 40 °C. Figure 2 shows the Levelized Costs of Heat (LCOH) for the three cases of calculated return temperatures for different economic assessment periods. We see that the decrease of usable waste heat power due to higher return temperatures leads to remarkable increases in the LCOH.

In Figure 2 the LCOH is split into the components resulting from the different parts of the waste heat integration system. We can see that the plate heat exchanger to use the waste heat in the process water is cheap compared to the other waste heat source heat exchangers. Although a fifth of the power is delivered by this heat exchanger in case of 40 °C return temperature, the lower investment and maintenance costs lead to a comparably lower increase in overall LCOH for this case. The highest fractions of the total LCOH of the waste heat integration system are caused by the tube bundle heat exchanger to use the waste heat contained in the flue gas and by the external pipes. These two components account for between 66 and 77 % of the overall LCOH. In Figure 2 we can further see a high influence of the LCOH to the economic assessment period. This is due to the fact that the main cost component of the waste heat integration system is the investment cost. Operation and maintenance (O&M) costs and the energy costs for the pumps are the only running costs in this system. The waste heat from the industrial processes doesn't have to be paid. This is the main reason for the low overall running costs of this heat supply system.

In Figure 3 the sensitivity of the increase of the LCOH between a return temperature of 40 °C and a return temperature of 50 and 60 °C is illustrated in detail. In average of all calculated sensitivity scenarios the increase of the LCOH from 40 °C to 50 °C is 23 %, from 40 °C to 60 °C it is 56 %. While the results show a low sensitivity of the described increase in LCOH to the economic assessment period and to the available waste heat power, a remarkable sensitivity was calculated for the distance

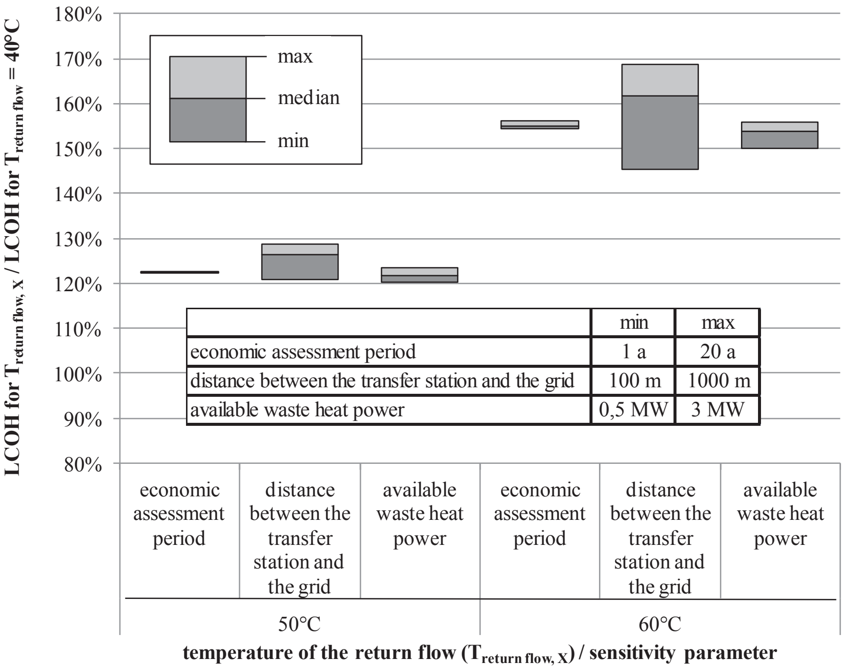

Figure 3. Relative change of the LCOH due to changes in the input parameters.

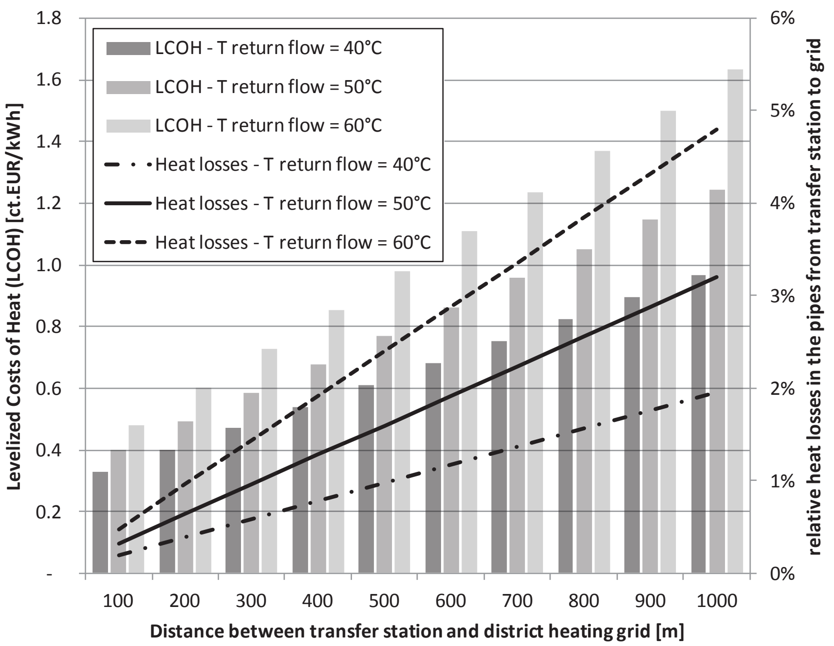

Figure 4. LCOH for different return temperatures of the district heating grid and distances between the transfer station and the district heating grid.

between the transfer station and the district heating grid. Comparing return temperatures of 40 and 60 °C the increase lies in the range of 46 to 69 % varying the distance between 100 and 1,000 m. For short distances comparably lower increases can be found, while at the same time they rise remarkably already for small distance increases (compare median values in Figure 3).

The influence of the distance between the transfer station and the district heating grid on the overall LCOH is shown in Figure 4. We can see that the heat supply costs rise with increasing distances between the transfer station at the industrial site and the integration point into the district heating grid. The reason is that the investments into the external pipes grow with the increasing distance, but at the same time the amount of waste heat that can be integrated into the district heating grid declines due to the increasing heat losses in the external pipes. In practice, this has to be balanced against the higher district heating demand potential which might be exploited with longer distances. As the amount of heat losses depend on the temperature level inside of the pipes, a stronger increase in costs for higher return temperatures of the district heating grid can be found.

In Figure 5 we can further see a remarkable influence of the available waste heat power on the overall costs. Compared to the reference case of 1 MW, in case of only 0.5 MW available waste heat power the costs increase between 47 and 49 % for the different load profiles. In case of 3 MW of available power the LCOH decrease between 35 and 36 %.

Additionally also the investigated load profiles of the waste heat sources show to have important influence on the heat supply costs. The lowest LCOH occur in case of a 3-shift production all over the year, the highest LCOH in case of a 2-shift production where the plant is not being operated on weekends and it is shut down for two weeks of the year due to company holidays. This is reasonable as the available waste heat power appears to be the same for all load profiles leading to the same investment and O&M costs, but the total amount of waste heat that can be integrated into the district heating grid over a year depends on the hours of operation of the plant. The higher the full load hours of the waste heat integration system, the lower are the LCOH of the system. Figure 5 shows this relation. Compared to the 3-shift operation running 8,760 hours a year, a reduction of the full load hours between 64 and 67 % (in case of the 2-shift operation running also the weekends) the LCOH increase between 46 and 54 %. A reduction of the full load hours between 46 and 48 % (in case of the 2-shift operation not running the weekends) leads to an increase between 102 and 114 % in the LCOH.

Discussion and Conclusions

For the analysis in this paper we built up a simplified model of the technical parts of an industrial waste heat integration system to feed into existing district heating grids. According to the concept of Levelized Costs of Heat (LCOH) we analysed the influence of various parameters on the heat supply costs of waste heat integration. We found that the return temperature of the district heating grid, the distance between the transfer station and the district heating grid, the economic assessment period, the available waste heat power as well as the full load hours of the waste heat supply system have a high impact on the resulting costs of such projects. Furthermore for many combinations of the stated parameters we calculated LCOH remarkably below 1 ct.EUR/kWh. The energy costs that have to be paid for district heat in many European countries are above 4 ct.EUR/kWh. This shows that with favourable conditions a cost effective integration of industrial waste heat into existing district heating grids can be expected. However, the calculations in this paper do not cover the whole range of possible process and district heating grid characteristics. Further research is needed to quantify these effects on the costs of such projects.

The load and temperature profiles of industrial processes as well as their combination on site vary a lot between different branches and even between different plants of the same branch producing similar goods. Therefore it is necessary to analyse the economic viability of waste heat integration on the basis of exemplary plants. This is furthermore important as the available waste heat potential, which can possibly be integrated into district heating grids, depends also largely on the potential of the integration of waste heat in the processes at the plant itself. As we showed in the analysis the external transfer of the heat to the grid is costly. And also from the technical perspective it makes sense to primarily integrate available waste heat streams into processes and other heat demand at the plant itself, as the losses are expected to be lower compared to the integration in the external grid. In this paper we didn't analyse the effect of

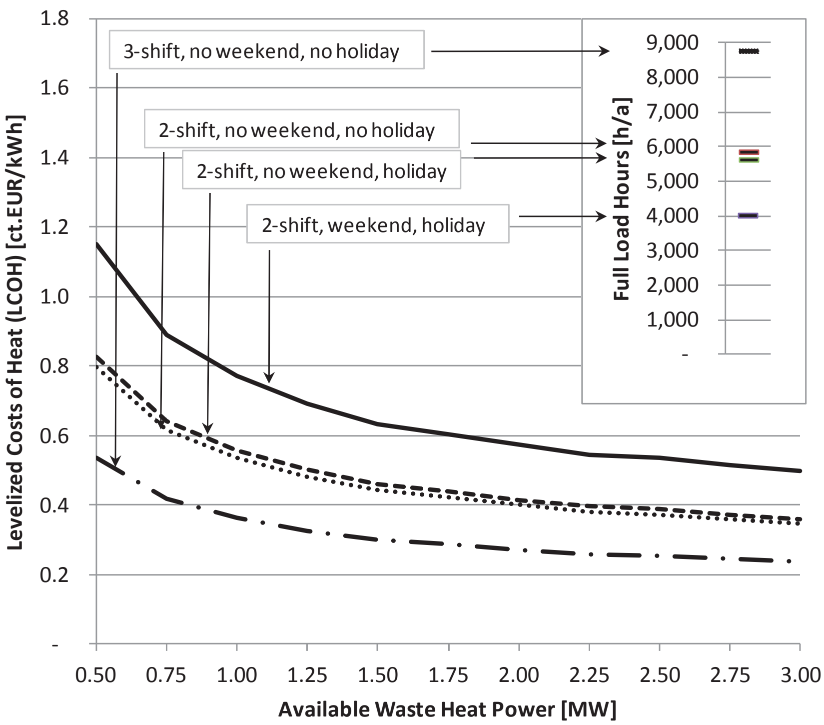

Figure 5. LCOH for different available waste heat powers and load profiles of the waste heat sources.

differing load and temperature profiles of the various processes in the plant. Furthermore, in order to calculate first results we assumed that all processes have the same load profile, which is likely not to be expected in existing plants. In order to draw sound conclusions on the influence of differing load and temperature profiles of the processes at the industrial site on the possible heat supply to the district heating grid and on the resulting LCOH of such projects a detailed storage tank model has to be used. Even though there are storage tanks with low investment costs compared to the storage capacity they provide, we expect the LCOH to increase remarkably for largely differing load profiles of possible process combinations.

In the context of the district heating grid we assumed a flow temperature between 70 and 90 °C depending on the ambient temperature. This reflects common values for small local heating networks as well as for the secondary parts of large district heating networks of big cities. In order to be able to draw conclusions on a general economic viability of such projects a sensitivity analysis for flow temperatures up to 110 °C should be performed, as these temperatures occur in the primary parts of large heating networks nowadays. Furthermore the overall integration capacity of industrial waste heat into existing district heating networks has to be discussed in detail. Empirical load data of existing heating grids show that in summer only about 10 % of the maximum power in winter is needed. In general industrial plants do not have higher production rates in winter than in summer, this means that only a comparably small part of the power demand is accessible for industrial waste heat. Moreover the industrial waste heat then is in competition with a possible heat supply from waste incineration being constant all over the year. E.g. in the Viennese district heating grid nearly the whole base load in summer is provided by waste incineration, leading to a very limited integration potential for industrial waste heat.

Industrial plants have very differing characteristics not only concerning their hourly profiles of the processes, but also concerning the materials that are treated. As a result the heat exchangers that are possibly integrated to use available waste heat streams differ a lot in construction and in the materials necessary to avoid erosion. This of course affects the associated investment costs. In general it was difficult to find reliable cost data of heat exchangers for the theoretical calculations in this paper. Therefore the cost curves used in this study are based on a relatively low number of data points, leading to a significant uncertainty of the calculated LCOH. It should further be noted that the costs and time for approval procedures as e.g. for laying the pipes outside of the industrial site are not taken into account.

The technical and economic feasibility of the integration of waste heat into district heating grids has to be analysed for each possible project in detail and depends as we have shown on many different influencing factors. However, based on this theoretical estimation a significant number of technically and economically feasible waste heat integration projects are likely to be expected in Europe.

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