Identification of waste heat potentials and their integration into a district heating subgrid

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Abstract

The University Campus of Kassel is supplied by a district heating subgrid using district heating (DH) and a gas combined heat and power (CHP) unit. To make the transition to a climate neutral heat supply possible, the network temperatures need to be lowered and local renewable energy sources need to be integrated into the DH network. Waste heat potentials can play an important role here. Therefore, waste heat potentials from a data center, chillers and compressor units were investigated. The data center and chillers show high potential for an integration into the DH network. Two of the chiller's waste heat potentials can be used when their temperature level is risen by heat pumps. These could supply about 15 % of the heat needed in the subgrid. Even though the waste heat is economically competitive to district heating, the revenues from electricity sales of the CHP unit are high enough to make the heat demand scenario more expensive than with just CHP unit and DH. This stands in contrast with the transformation to a renewable energy system. With changing energy prices this dilemma might resolve itself, if the relation between gas and electricity price changes.

Keywords: district heating, waste heat, heat pumps, chillers, University Campus

1. Introduction

On the University campus “Holländischer Platz” in Kassel a district heating subgrid supplies 20 buildings (19 substations) with district heating from the local city network and a gas CHP unit. The buildings on campus include laboratories, lecture halls, office space and a library, as well as some student accommodation. The DH subgrid of Kassel University was built in the 1980s and therefore requires renovation. This offers the possibility for structured planning to achieve efficiency gains and lower greenhouse gas emissions. Currently, measures for temperature reduction in network and building temperatures are being developed.

One approach to lower greenhouse gas emissions is the integration of waste heat sources into the energy supply of the DH network. The local district heating supplier plans to decarbonize the district heating network (Städtische Werke Energie + Wärme GmbH) additionally the city of Kassel plans to be climate neutral by 2030 (Stadt Kassel). The renewable energy sources inside the city are limited, therefore it is reasonable to identify potentials on the University campus. Essentially these are solar energy and waste heat potentials. The existing sources for waste heat at the University Campus are a data center, compressor units and chillers. In this paper it will be evaluated which sources can be used and weather this is profitable. If the integration of renewable sources should prove not profitable in present conditions, the focus should lie on the transformation to profitable conditions.

2. Methodology

2.1 Current heat supply

As discussed before, the current heat supply of the subgrid at the University campus “Holländischer Platz” in Kassel consists of gas-powered CHP unit and district heating from the local city network. A current typical share of district heating is about 80 %, while the CHP unit makes out about 20 % (data from 2019). The share of the CHP unit is lower than possible since there were some breaks in operation. The network temperatures in the subgrid are rather high, 115 to 75 °C supply temperature and 65 C return temperature, as shown by the straight lines in Figure 1. The current and future return temperature (RT) and supply temperature (ST) are shown in dependence of the outdoor temperature. The supply temperature is dependent on the city network since currently no hydraulic separation between the subgrid and the city network exists. In future, the modification of the substation to achieve

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hydraulic separation will be realized, additionally measures to reduce the supply and the return temperature are planned. The resulting estimated operating curves are shown by dashed lines. These two temperature levels are an important parameter that influences the efficiency of renewable energy sources and are used as a basis for further calculations.

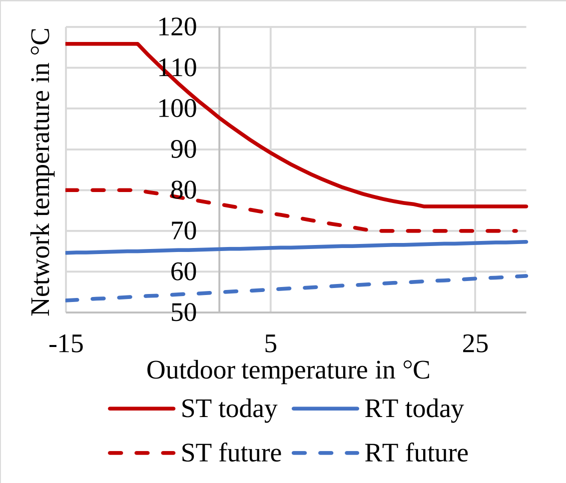

Figure 1:Operating curve of network temperatures

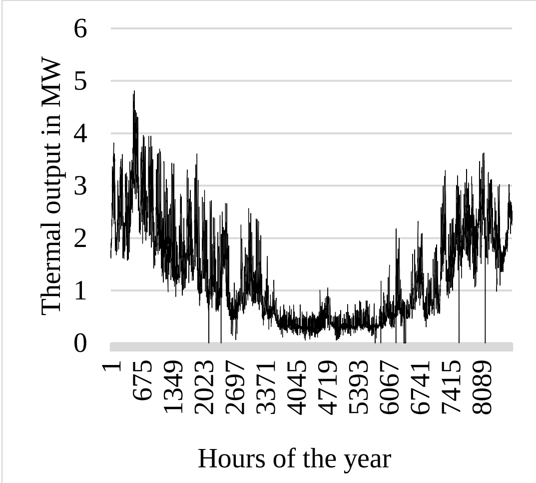

Figure 2: Heat use profile subgrid

Figure 2 shows the heat load profile from the year 2019 that had typical weather conditions and operation of the CHP unit. The heat load profile shows a well-defined seasonality with a peak demand of 4.8 MW and a heat demand in summer of around 0.4 MW.

2.2 Selection of suitable waste heat sources

As described before the waste heat potentials at the University campus “Holländischer Platz” consist of a data center, compressor units and chillers. The compressor units supply laboratories with compressed air, however the waste heat from these units proved to be unusable since the waste heat temperatures fluctuate strongly, due to start-stop operation of the compressor units. The data center is the biggest available waste heat source, but only part of the potential waste heat can be utilized since the data center is currently air cooled. Additionally, the data center is still undergoing reconstruction and has not yet reached its peak demand. Therefore, the current analysis is focused on the chillers as a waste heat source. The chillers supply laboratories with cooling water and air conditioning systems. To determine the best integration of the waste heat potentials from the chillers, the following steps were taken:

- measurements at condenser cooling circuits (several weeks in summer 2021)
- rough calculation of energy efficiency ratios (EER) of chillers depending on cooling demand (whole year)
- assessment of temperature level: possibility of direct use of waste heat?
  → heat pump (HP) to raise temperature necessary?
- estimation of seasonal coefficient of performance (SCOP) of a heat pump to decide on hydraulic integration
- calculation of actual possible waste heat that can be used to substitute district heating and gas CHP
  → possible share of waste heat

To determine waste heat potentials and temperature levels, measurements were conducted for several weeks in summer at the condenser cooling water circuits of three different chillers. The temperature level in these circuits is around 35 to 40 °C, so a direct utilization is not possible, thus the temperature level needs to be raised by a heat pump. As described in (Rühling, K. et al. 2019) the integration of renewable energy sources, in this case heat pumps, into DH networks can be achieved by different configurations. They can reach from direct use in the building on the secondary side of the substation to direct feed-in into the district heating grid. Direct use of the waste heat can be limited when the potential is higher than the building demand, while the feed-in into the district heating network ensures maximum use of waste heat potential. The three chillers that were investigated all showed significant waste heat potential, but for one of them the integration into the district heating network proved too difficult due to the local conditions. Therefore, two of the chillers remain as potential waste heat sources. Table 1 shows some defining parameters as well as the chosen hydraulic configuration.

Table 1: Heat pump integration and parameters

	Heat pump 1	Heat pump 2
Chosen hydraulic configuration	feed-in into DH network	direct use in building behind substation
Source temperature	35 °C	40 °C
Yearly waste heat potential (source)	372 MWh	1303 MWh
Sink temperature	supply temperature (95-76 °C)	80 °C
SCOP	4.24	3.98
Yearly waste heat potential (sink)	486 MWh	1195 MWh

To calculate the SCOP, the following Equation 2-1 was used, it was deduced from operational data of standard heat pumps and high temperature heat pumps with hydrofluorocarbons and hydrofluoroolefin refrigerants (Jesper, M. et al. 2021). In the case of a changing sink temperature, the mean value of the various COPs is the SCOP.

$$COP = a \cdot \left(\Delta T_{lift} + 2 \cdot b\right)^{c} \cdot \left(T_{h,out} + b\right)^{d}$$ (eq. 1) (Jesper, M. et al. 2021)

COP	Coefficient of performance	a	$1.4480 \cdot 10^{12}$
ΔT_{lift}	Temperature lift between source and sink	b	88.730
$T_{h,out}$	output temperature sink	b	-4,9460
		d	0

Once the decision for the integration of waste heat from two chillers was made, a profile for the hourly waste heat usage of the heat pumps was calculated based on an assumed future operating curve for the grid temperatures, see Figure 1 (dashed lines). To calculate the SCOP of the heat pumps, see Table 1, eq. 1 was used on an hourly basis and the average value represents the SCOP.

2.3 Heat supply scenarios and additional renewable potentials

In order to evaluate the integration of the waste heat sources, their combination with other heat sources, existing as well as additionally built, has to be assessed. Especially the CHP operation is an important factor, since it produces the highest amount of greenhouse gas emissions. District heating will provide the heat that can't be generated by other sources. The main focus lies on the integration of the waste heat sources and other renewable energy sources. In addition to waste heat sources solar thermal potentials were investigated. They are the only other usable renewable heat source. However, most roof areas are already used for PV-plants or unsuitable due to constructive reasons. One large roof area could be identified, it has an area of about 1400 m² and could contain 700 m² of flat plate collector area.

To determine the best heat supply scenario, input data was fed into an energyPRO-model, where an hourly heat generation profile for each scenario is determined. The investigated scenarios relating to heat sources are:

- DH + CHP (reference)
- DH + CHP +HPs
- DH + CHP + HPs + ST
- DH + HPs + ST

To determine which heat source is used when, the priority of heat sources needs to be defined. A high priority means that the heat source will be used first and at maximum possible level. Only then the next source can generate heat as well. The use of this approach is that some heat sources have production costs e. g. for gas or electricity. If the heat sources exist in the scenario, their priority from high priority to low priority is as follows: Solar thermal energy, waste heat pumps, CHP and district heating. In addition to the variations in heat sources the temperature operation curve was varied between the current network temperatures and the future network temperatures.

3. Results

3.1 Contribution of heat sources to the heat supply over the course of a year

To give some insight into the simulation results the scenario DH + CHP + HPs + ST with future network temperatures will be discussed in detail as an example. Figure 3 shows the share of energy sources when solar thermal and the waste heat pumps are integrated into the subgrid. The mayor part is still supplied by district heating (49 %) while the CHP plant reaches about a third (34,5 %) of the total supplied energy. The amount of solar thermal is limited by the available collector area and therefore supplies only a small portion (2.0 %) while the two waste heat pumps can supply 14,5 % of the required heat.

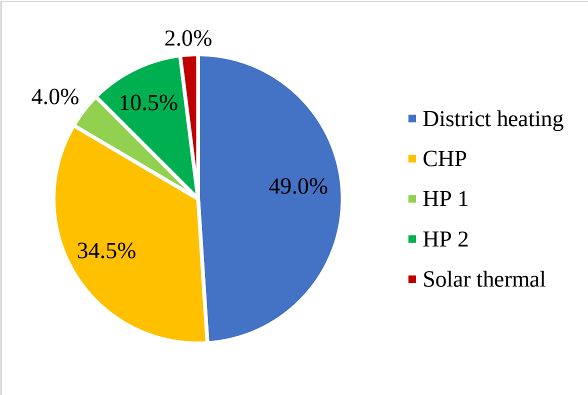

Figure 3:Share of energy sources to supply the subgrid's heat demand (future network temperatures)

The contribution of the heat sources to the heat demand over the course of a year is shown in Figure 4. Additionally, a sorted annual load curve is displayed in Figure 5. Both diagrams show that the heat demand in summer can be supplied largely by the renewable energy sources that therefore operate at base load. During summer the CHP unit is only active for short intervals to fill the storage, this can be seen very clearly in Figure 5 by yellow peaks above the total heat use line and empty spaces below. During the rest of the year the CHP unit operates continuously, whenever possible at nominal load and DH supplies the peak load for the subgrid.

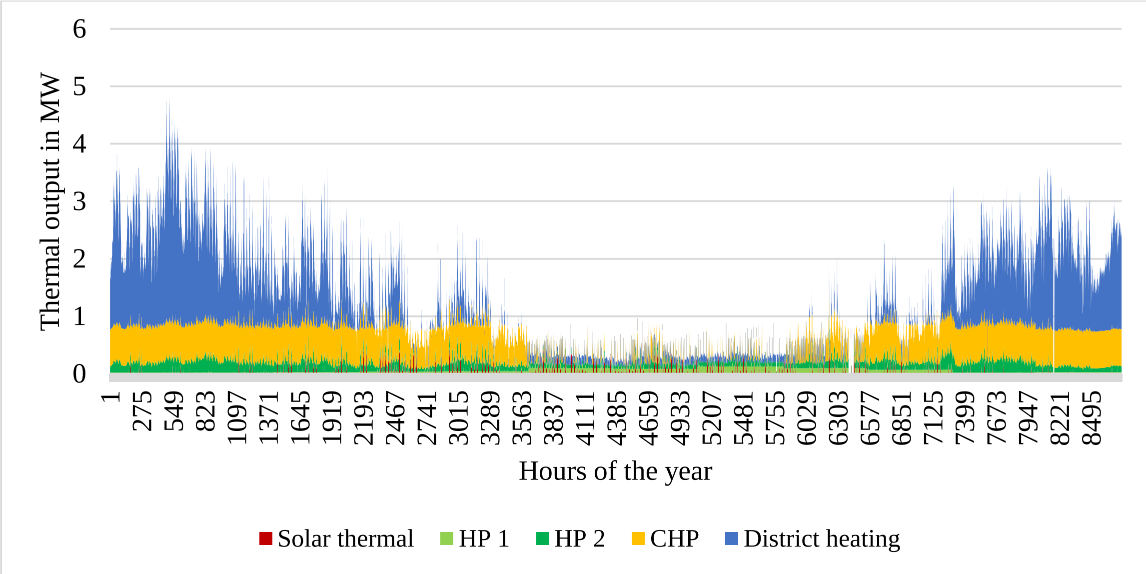

Figure 4: Thermal output of energy sources over the year with waste heat integration (future network temperatures)

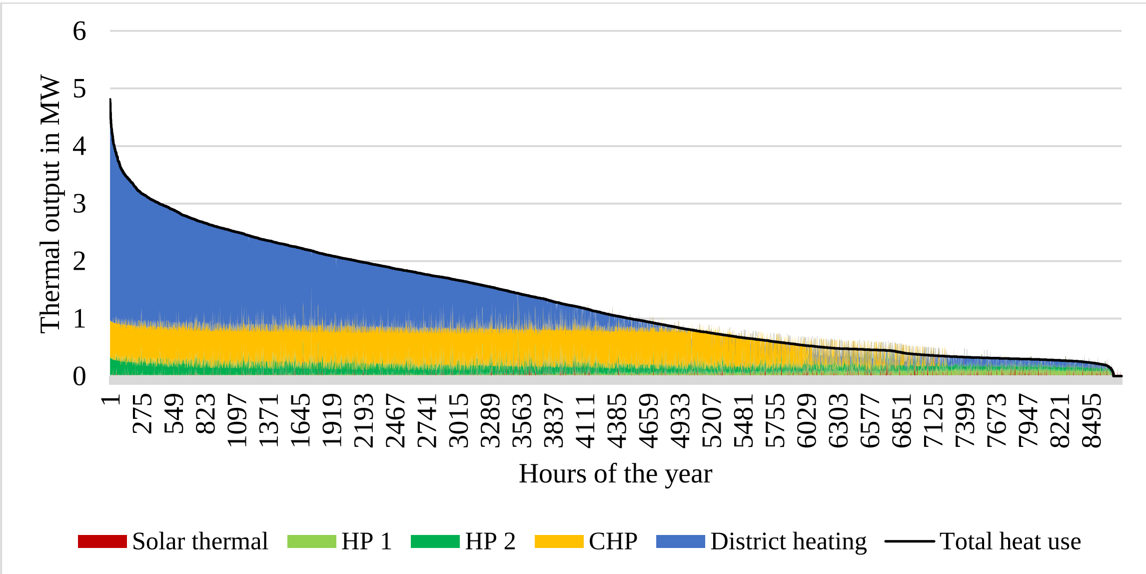

Figure 5: Thermal output of energy sources sorted by total heat use (future network temperatures)

3.2 Comparison of heat supply scenarios

Figure 6 shows how the contribution of heat sources changes from scenario to scenario, in this example it is shown for future network temperatures. When waste heat sources are integrated into the network, the amount of heat generated by the CHP plant is reduced. If solar thermal energy is integrated additionally, it further replaces the CHP plant and to a lesser degree the waste heat provided by heat pumps. Without the CHP plant its former share is replaced by district heating.

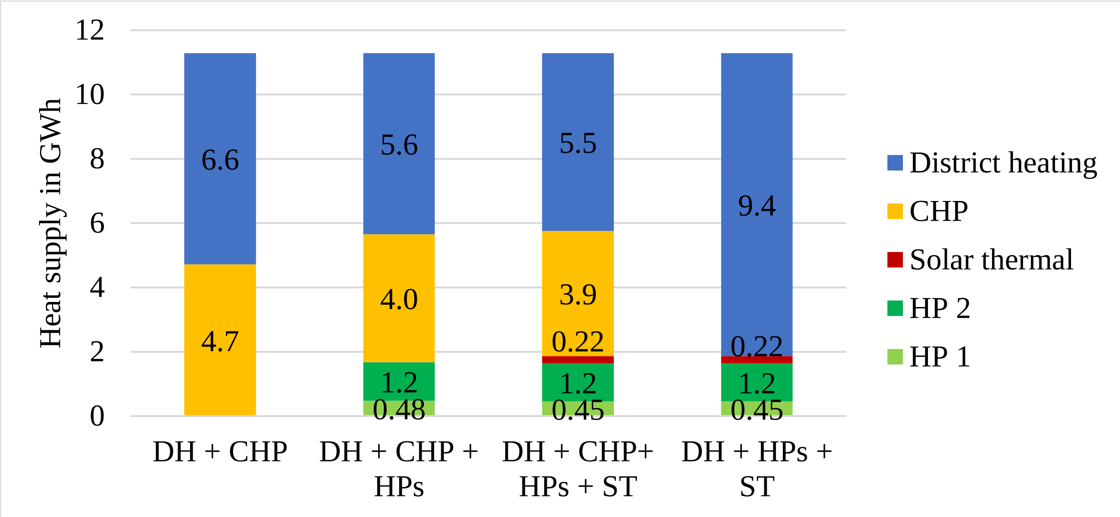

Figure 6: Thermal output of heat supply scenarios (future network temperatures)

3.3 Economic analysis

The levelized cost of heat (LCOH) is composed of investment costs for the integration of heat sources and operation costs, such as energy or fuel costs and maintenance in relation to the generated heat. The approaches to estimate cost components are summarized in Table 2. To merge investment costs with operational costs annuities for the investment costs have been calculated with a weighted average capital cost (WACC) of 8 % and a period under review of 15 years. In the case of the CHP plant proceeds from the electricity have been deducted from the costs. The investment for the solar thermal system and the waste heat pump was reduced by 40 % due to subsidies from the "Bundesförderung für effiziente Wärmenetze" (BEW) (Bundesministerium für Wirtschaft und Klimaschutz 2022).

Table 2: Approaches for cost components for LCOH calculation

Cost category	Cost approach (standardized to 2021)	Source
Investment CHP retrofitting	200000 €	(Building department University of Kassel 2022)
Investment Solar thermal high temperature flat collector (rooftop)	649.06 €/m^2	(Heymann, M. et al. 2019)
Investment HP (main component and integration)	$1649.1 \cdot x^{-0.363}$ x = thermal power output	(Wolf, S. 2017)
Maintenance CHP	6.33 €/operating hour	(Building department University of Kassel 2022)
Maintenance solar thermal	2.5 €/MWh	own assumption
Maintenance heat pump	2 €/MWh$_{th}$	(Große, R. et al. 2017)
Price electricity (2021)	0.22 €/kWh	(Building department University of Kassel 2022)
Price district heating (2021)	0.085 €/kWh	(Building department University of Kassel 2022)
Price gas (2021)	0.05 €/kWh	(Building department University of Kassel 2022)

Table 3 shows the calculated LCOH for each heat generation technology. The LCOH for the CHP plant is negative and its use therefore very profitable. The LCOHs for waste heat and solar thermal heat need to be evaluated in relation to the district heating price. The solar thermal LCOH of 11.5-14.4 €ct/kWh$_{th}$ is higher than the district heating price and solar thermal therefore not profitable with current energy prices. The waste heat pumps reach a LCOH of 6.4-8.2 €ct/ kWh$_{th}$ below the DH price and are therefore profitable in comparison.

Table 3: LCOH by energy source

LCOH energy sources in €/kWh$_{th}$	**DH + CHP**		**DH + CHP + HPs + ST**		**DH + CHP + HPs**		**DH + HPs + ST**	
	Operation curve present	**Operation curve future**	**Operation curve present**	**Operation curve future**	**Operation curve present**	**Operation curve future**	**Operation curve present**	**Operation curve future**
ST (after subsidies 40 % of investment)	-	-	0.144	0.115	-	-	0.144	0.115
CHP fuel	0.093	0.093	0.098	0.098	0.098	0.098	-	-
CHP balance (costs minus profits)	-0.061	-0.061	-0.056	-0.055	-0.055	-0.056	-	-
Waste heat HP 1 (after subsidies 40 % of investment)	-	-	0.082	0.064	0.081	0.061	0.082	0.064
Waste heat HP 2 (after subsidies 40 % of investment)	-	-	0.065	0.065	0.065	0.065	0.065	0.065
Waste heat total (after subsidies 40 % of investment)	-	-	0.069	0.065	0.069	0.063	0.069	0.065
DH price	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085

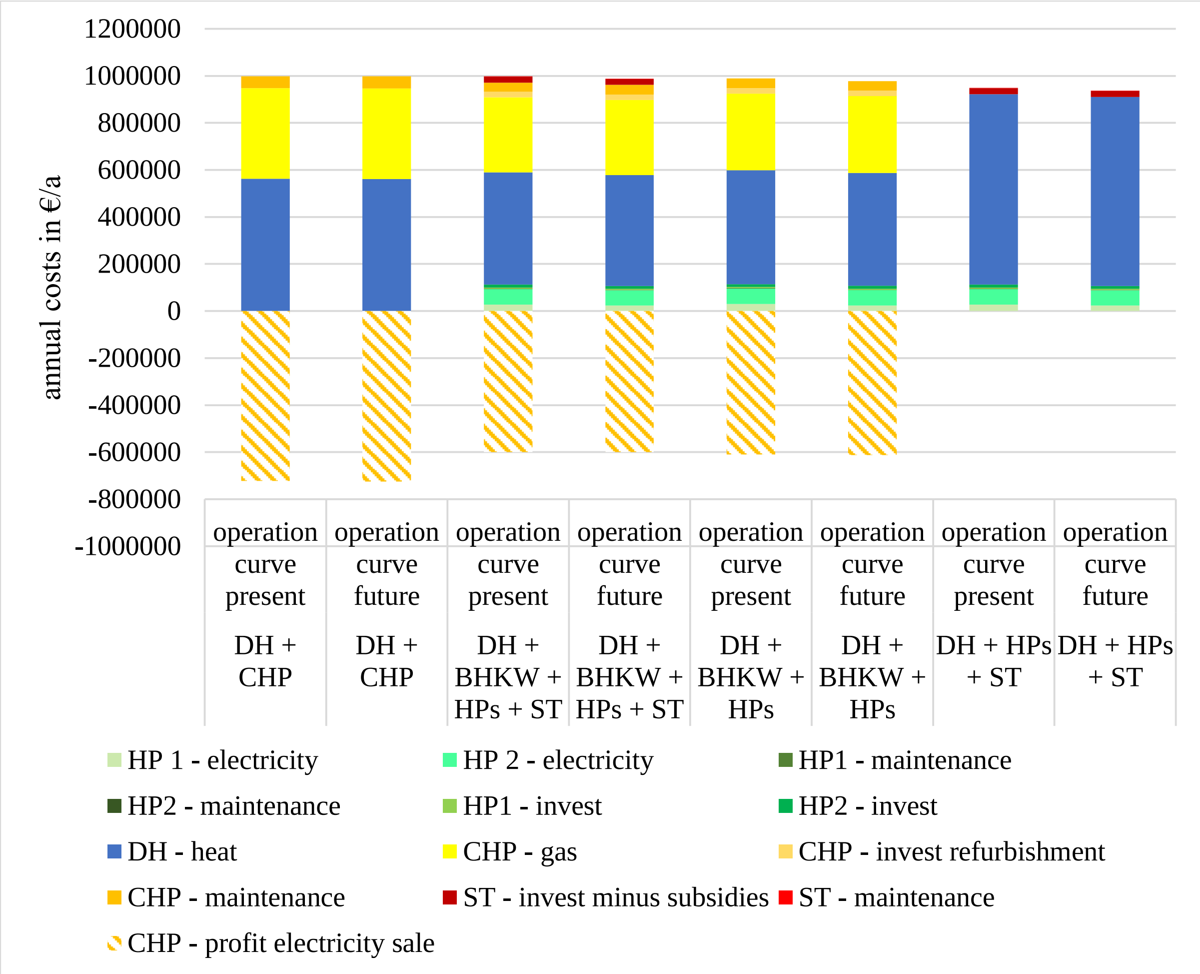

Figure 7: Annual costs and profits different scenarios

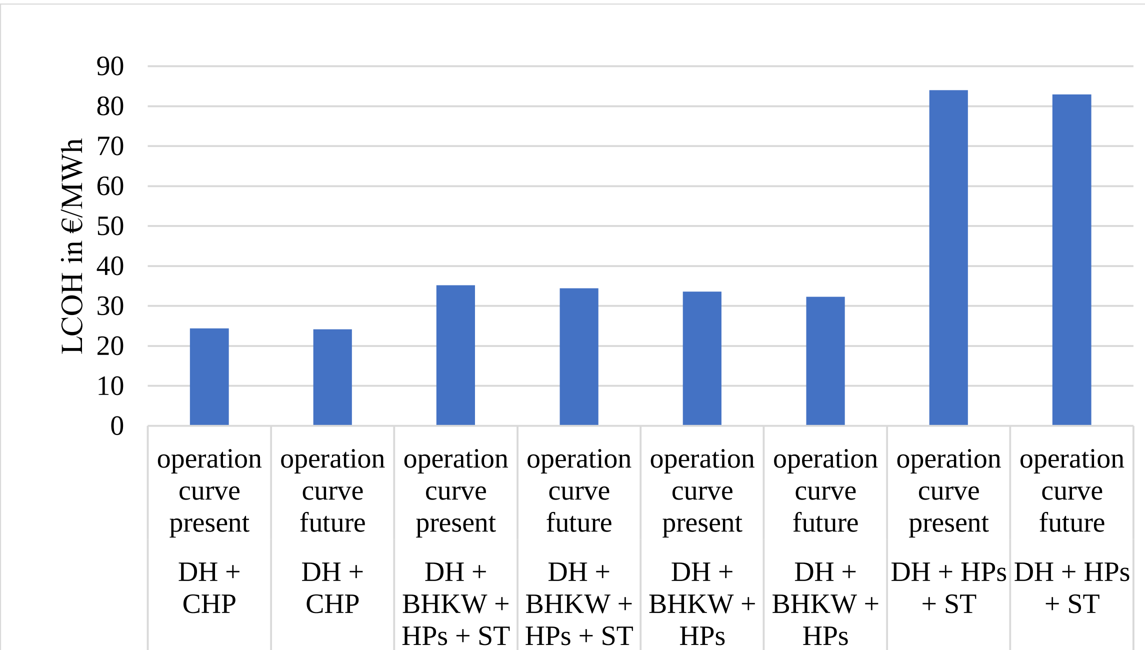

Figure 8: LCOHs of different scenarios

In addition to the economic evaluation of the heat generation scenarios the environmental impact can be assessed by comparing greenhouse gas emissions. In this case the scope for greenhouse gas emissions focusses on the emissions generated by the energy sources used. The greenhouse gas emissions of the energy sources use a CO_2-equivalent of 202 g/kWh for gas, 0 g/kWh for green electricity (HPs) and 133 g/kWh for the local district heating network (Building department University of Kassel 2022). Figure 9 shows the LCOH and CO_2-equivalents for the heat generation scenarios with future network temperatures. Both parameters are contrary to each other, a low LCOH corresponds to a high CO_2-equivalent and the other way around. This means that the current economic framework for renewable heat sources in this context does not reflect the environmental impact. Particularly the relation between gas and electricity prices has a big influence.

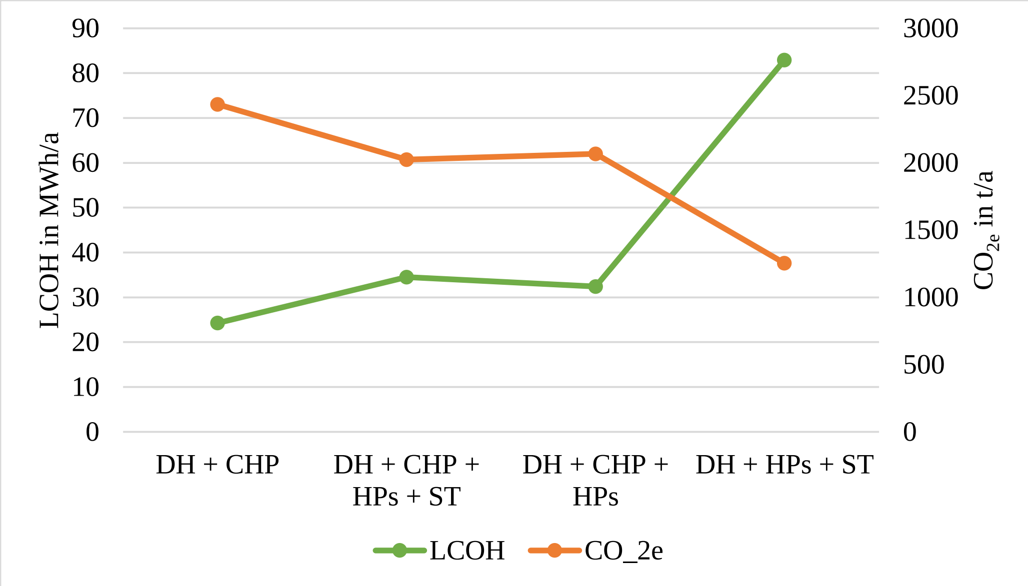

Figure 9: LCoH and CO_{2e} (future network temperatures)

4. Conclusions and outlook

Significant waste heat potentials from the chillers could be identified. Two of the waste heat sources can be used by raising their temperature level with heat pumps. Heat pump 1 can use the waste heat potential directly inside the building behind the substation while heat pump 2 would feed the waste heat directly into the district heating subgrid. The also investigated solar thermal potentials are not profitable under current conditions. The waste heat pumps are economically competitive to district heating and could supply about 15 % of the heat needed in the district heating subgrid. However, heat supply scenarios that use the waste heat pumps are less profitable than scenarios that use more heat from the CHP unit, this is due to the high revenues from the electricity sale. This stands in contrast to the greenhouse gas emissions where the gas-powered CHP unit is responsible for most. This dilemma can only be overcome if the relation between gas and electricity price changes. In further research, it could be interesting to calculate the LCOH under different pricing conditions, especially since gas prices have risen dramatically since the war in Ukraine started this year.

5. Acknowledgements

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6. References

Building department University of Kassel 2022.

Bundesministerium für Wirtschaft und Klimaschutz. Richtlinie für die Bundesförderung für effiziente Wärmenetze „BEW“. 2022. https://www.bundesanzeiger.de/pub/de/amtliche-veroeffentlichung?1. Accessed 23

Sep 2022.

Große R., Christopher B., Stefan W., Geyer R., Robbi S. Long term (2050) projections of techno-economic performance of large-scale heating and cooling in the EU: External study performed by ILF Consulting Engineers Austria GmbH, and AIT Austrian Institute of Technology GmbH for the Joint Research Centre; 2017.

Heymann M., Rosemann T., Rühling K., Hoppe S., Wudenka E., Hafner B. Kostenreduktionspotential beim Ausbau der Solarisierung von Fernwärmenetzen durch Standardisierung: Koordinierter Schlussbericht - SOLSTAND (FKZ: 0325553A+B). Dresden, Allendorf; 2019.

Jesper M., Schlosser F., Pag F., Walmsley T. G., Schmitt B., Vajen K. Large-scale heat pumps: Uptake and performance modelling of market-available devices. Renewable and Sustainable Energy Reviews. 2021;137:110646. doi:10.1016/j.rser.2020.110646.

Rühling K., Gnüchtel S., Felsmann C., Heymann M., Rosemann T. Kostenreduktionspotential beim Ausbau der Solarisierung von Fernwärmenetzen durch Standardisierung: Koordinierter Schlussbericht – SOLSTAND; 2019.

Stadt Kassel. Die Klimaschutzziele. https://www.kassel.de/buerger/umwelt_und_klima/umwelt_und_klimaschutz/klimaschutz/inhalt-klimaschutzziele.php. Accessed 6 Aug 2022.

Städtische Werke Energie + Wärme GmbH. Wir über uns. https://www.ew-kassel.de/10/.

Wolf S. Integration von Wärmepumpen in industrielle Produktionssysteme: Potentiale und Instrumente zur Potentialerschließung [Dissertation]. Stuttgart: Universität Stuttgart; 2017.