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Design and operational optimisation of a combined cooling, heating and power plant to enable waste heat integration into an existing district heating network

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Abstract:

The substitution of fossil fuels in current energy systems is essential on the path to carbon neutrality. In the building sector, different renewable and waste heat sources could be used in district heating systems to replace fossil-based heating plants. However, if new heat sources are integrated into multi-energy systems, the profitability of present heating plants could decrease. At the Forschungszentrum Jülich, the waste heat from a new high-performance computer is to be integrated into the local district heating system in order to reduce overall CO_2 emissions. This waste heat integration will have an impact on the holistic multi-energy system of the campus, which is mainly supplied by a combined cooling heat and power plant (CCHP). This paper investigates the described waste heat integration using a bi-objective optimisation approach. The proposed model optimises the operation of the overall multi-energy supply system with waste heat integration. Furthermore, the optimisation model allows for the optimal design of the required heat pump system and additional absorption chiller capacity that enable efficient CCHP heat usage despite the waste heat integration. In addition, the effects of lowering district heating temperatures and changed energy prices are studied. The results show that integrating waste heat reduces the overall CO_2 emissions of the multi-energy system and even more if the integration is combined with a lowering of district heating temperatures. Furthermore, the optimisation shows that a cost reduction is feasible by increasing the absorption chiller capacity that uses the produced heat of the CCHP.

Keywords:

Waste Heat Integration, Bi-Objective Optimisation, Multi-Energy System, CCHP, District Heating

1. Introduction

The endeavour to decarbonise the building sector offers great potential for achieving the European Union's climate targets. The heat supply is mainly based on fossil fuels such as gas or oil to supply boiler systems in buildings. However, also many district heating systems are supplied by fossil-based energy plants, like 74 % of the combined heat and power plants (CHP) in Europe are based on coal and gas [1]. As an important contribution to the overall energy transition, heating plants in district heating systems need to be replaced by sustainable heat sources in order to reduce carbon dioxide emissions in the building sector. Renewable energy sources such as solar or geothermal energy as well as (low-temperature) waste heat sources from industry or cooling processes are examples of sustainable heat sources. Depending on the quality of the waste heat, the utilisation of waste heat sources could reduce CHP operation and, thus, save fuel and operating costs [2]. However, replacing existing, operating heating plants with sustainable heat sources could be challenging for many reasons.

Most heating plants in district heating systems have large nominal thermal capacities that cannot be easily replaced since the potential heat sources for replacement have limited heat capacities, are geographically inconveniently located, or the heat availability fluctuates due to scheduled processes. Zhang et al. show the difficulties of waste heat usage by optimising the utilisation rate for a district heating system and a cooling process depending on the availability of heat and the seasonal demand. Furthermore, they also consider how many consumers can be supplied with the available heat capacity [3].

The economic constraints make it challenging to replace current heating plants, as the profitability depends on different boundary conditions, such as the fuel prices or the investment required to integrate the sustainable heat source. Dorotić et al. perform an economic assessment of waste heat utilisation in an urban area by investigating the available waste heat from supermarkets and power substations. They show that the costs

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of waste heat integration into district heating systems depend not only on the waste heat process itself, but also on the waste heat temperature and the current temperature level of the district heating system [4]. In [5], the possibilities of integrating solar heat with the help of heat pumps into Helsinki's existing district heating system are examined and evaluated from an economic point of view. In this particular case, the operation of the CHP is less advantageous than the operation of the heat pumps due to the electricity price level. However, Durán et al. point out that the conversion of existing district heating systems towards sustainable systems is technically possible, but the substitution of CHP with sustainable heat sources is an economic challenge. Therefore, they propose to establish economic and political regulations to facilitate the economic realisation of such projects [6]. The challenging utilisation of sustainable heat sources depends on the boundary conditions of the respective use case.

Optimisation models are helpful in showing optimal adaptions of energy systems, from a design or an operational point of view, to e.g. enable the usage of sustainable energy sources. The consideration of different objectives is necessary in order to take into account ecological and economic interests. The objective functions of such mathematical optimisation problems can be the minimisation of emitted CO_2 emissions or the minimisation of total costs. Capone et al. develop a multi-objective optimisation model to optimise the operation of producers and consumers in a district heating system, taking into account different objectives, such as reducing CO_2 emissions or minimising the total costs [7]. However, the additional integration of sustainable heat sources in the existing district heating system is not considered.

The integration of a waste heat source into a fossil-fuelled district heating system takes place at the Forschungszentrum Jülich (FZJ), a research facility in Germany. On the campus of the FZJ, the integration of waste heat of an upcoming high-performance computer in the local district heating system is studied. However, the use of the waste heat source reduces the supply of the currently operated CHP units. Due to the fact that the CHP units are operated heat-led, the electricity production for the campus is lowered, which affects the economic profitability of the entire energy system. Therefore, the usage of the waste heat source in the energy system of the campus leads to ecological benefits, but may result in higher operating costs.

The impact of a possible waste heat utilisation at the FZJ is simulated for different shares of waste heat integration and evaluated for the ecological and economic effects in previous work [8]. In addition, [8] presents different measures on the energy system to improve the efficiency of waste heat utilisation are presented, such as lowering the district heating supply temperature and extending the absorption cooling production. However, as campus' heat and cooling demand fluctuates throughout the year, the operation of the existing energy plants is very dynamic, so the targeted waste heat utilisation could be further optimised. Therefore, we develop an optimisation model in this study to optimise the waste heat utilisation in the existing energy system design of the FZJ in order to show optimal system measures and optimal operation of the involved energy components under ecological but also economic aspects.

The paper is structured as follows: In Section 2., we first give an overview of the multi-energy system of the FZJ and describe the planned waste heat utilisation. Following, we describe the optimisation model and show the modelling approach of the energy components, which represent the different energy plants on the campus. Furthermore, we show the investigated scenarios and summarise the assumptions of the modelling approach. Section 3. shows the optimisation results for the different studied scenarios. After discussing the results and the limitation of the model in Section 4., Section 5. summarises the study.

2. Methods

In the following, we first explain the use case of waste heat utilisation on the FZJ campus. After that, we present the developed optimisation model and the objective functions. Thirdly, we show the scenarios studied and the corresponding boundary conditions.

2.1. Multi-energy system and waste heat utilisation

The campus of the FZJ is a research facility in North Rhine-Westphalia, Germany, with many buildings used as offices and laboratories. A local multi-energy system supplies the various energy demands on the campus with different energy components. The main energy plant of the multi-energy system is a gas-fired combined cooling, heat and power system (CCHP) consisting of three CHP units, two heat-only boilers (HOB) and an absorption chiller (AC). The CHP units supply electricity and heat to the campus and should operate at a high load for a cost-efficient operation. The electricity generated by the CHP is less expensive than the electricity supplied by the public power grid, which supplies the remaining electricity demand. The CHP units cover the heat demand in the base load. If the heat demand of the campus exceeds the capacity of the three CHP units, two HOB units support the heat supply. When the heat demand of the campus is low, the surplus heat from the CHP units is used to operate the AC to generate cooling for the campus. A district cooling network distributes the cooling to the buildings. Since the AC in the CCHP cannot meet the entire cooling demand of the campus, three additional compression chiller (CC) plants located on the campus also supply cooling to the

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district cooling network.

A new high-performance computer is being built on the FZJ campus, which generates a lot of waste heat through its operation. This waste heat source is being integrated into the multi-energy system of the campus to partially replace the heat supply from the gas-fired heating plants in the CCHP. However, the emitted waste heat will be available at a low-temperature level. Therefore, a heat pump (HP) system is required to raise the waste heat temperature to a higher level to make it usable in the local district heating system.

Different measures are described in [8] to enable more efficient waste heat usage. First, the supply temperature in the district heating system could be reduced to improve the efficiency of heat pump operation for waste heat integration. Second, the possibility to utilise more high-temperature heat by the CHP in the AC for cooling production is presented. Integrating waste heat into the district heating system reduces the supplied heat by the CHP and HOB units. Suppose the CHP units decrease their operation because the produced heat is not used anymore. In that case, electricity production will also decrease, leading to higher electricity consumption of the public grid and, thus, to higher operating costs. The CHP workload could be maintained at a high level by using the CHP surplus heat for additional AC cooling production. In addition, the extended AC operation partially replaces the cooling supply of the CC plants, which reduces the electricity demand for the cooling supply. However, as the ability to extend the operation of the current AC is limited, the construction of additional AC capacities can improve the ability to utilise high-temperature heat by the CHP units.

The dynamic operation of the various components of the energy system, in combination with the integration of waste heat, can be improved by optimising the multi-energy system at the campus. Therefore, an optimisation model is developed that both optimises the CCHP operation and takes into account possible design adaptation, such as the installation of heat pumps for waste heat utilisation and the expansion of the AC cooling supply. In the following, we describe the developed optimisation model.

2.2. Optimisation model

The campus' current energy supply system forms the basis for modelling the multi-energy system. However, the district heating and cooling network are not considered in the optimisation model, as we want to investigate the effects of waste heat utilisation on the overall energy production in this study. The main objective is the utilisation of waste heat in order to reduce carbon dioxide emissions taking into account the economic profitability of the overall energy system. Therefore, we apply a bi-objective optimisation approach that optimises the global warming impact (GWI) and the total annualised costs (TAC) of the multi-energy system, which are described more in detail in Section 2.2.3.

We use the COMANDO framework, which is written in Python [9]. COMANDO is an open-source modeling and optimisation framework for modelling energy components and linking them to an holistic energy system. The resulting energy system model is passed to a solver that optimises the design or operation regarding the set objective functions. The model in this study is based on a two-stage stochastic programming, which allows the design of components and the simultaneous operation optimisation based on a few typical time steps, i.e. operating points [9]. The typical operating points are determined by a clustering approach (see Section 2.3.).

In Fig. 1, the structure of the FZJ multi-energy system is shown. The different energy components, represented by submodels, are described in the following section. First, we give an overview about the main formulations and assumptions of modelling, followed by a more detailed description of the existing components and optional components for waste heat utilisation.

2.2.1. General model formulations

All energy components in the multi-energy system are modelled in terms of their operation efficiency η_{part}, which determines the quantity of energy output as a function of the amount of consumed energy. The general formulation of the components' part load efficiency is

$$\eta_{\text{part}} = \eta_{\text{base}} \cdot \mathcal{P}(out_{\text{rel}}), \tag{1}$$

where the base efficiency η_{base} is multiplied with $\mathcal{P}(out_{\text{rel}})$ that approximates the part load behaviour using two polynomial equations. The polynomials are determined by the specific energy components and depend on the relative energy output out_{rel}, which refers to the nominal capacity.

The modelling approach of the part load behaviour (1) leads to non-linear equations that increase the computation time for solving. Therefore, the resulting efficiency formulations of the energy components are simplified by using piecewise linear functions if necessary. The output of the components is an operational variable, and so is the efficiency, since it depends on out_{rel}. Thus, the input-output correlation is a multiplication of two variables and results in a quadratic equation. Since this correlation is set as a constraint in the energy components, the resulting optimisation problem is a quadratically constrained program.

The existing energy plants are modelled according to the currently installed components on site. The optional components, i.e. the HP for waste heat utilisation and the additional AC, can be built or not and are, there-

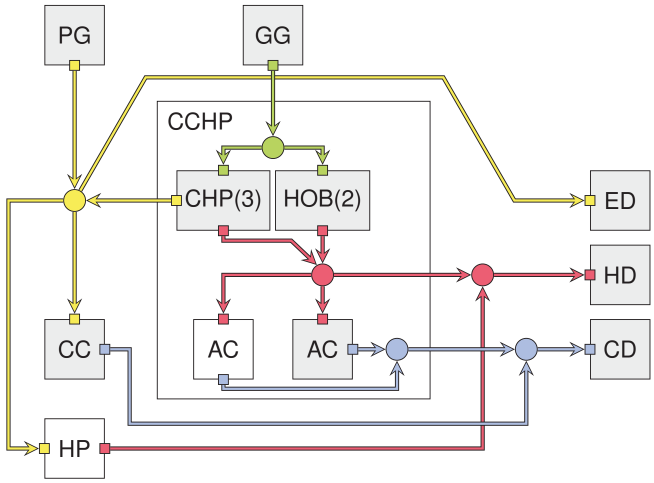

Figure 1: The different energy components of the multi-energy system are symbolised as grey boxes for existing and as white boxes for optional components. The CCHP includes three CHP units, two HOB units and an AC. The optional AC extension is shown as an additional AC in the CCHP. The CHP and HOB units are connected to the gas grid (GG). Electricity is supplied by the power grid (PG) and the CHP units to the CC and the electrical demand (ED) of the campus. The CHP and HOB units supply the heat demand (HD). The AC and the CC supply cooling to the cooling demand (CD). The AC is supplied by heat from the CHP units. A HP component is optional for waste heat utilisation, which consumes electricity from the PG and supplies heat to the HD. The waste heat source of the HP is not visualised.

fore, a design decision for the optimisation problem. In addition, the nominal output capacity of the optional components is a design variable.

For both existing and additional components of the energy system, the maintenance costs are taken into account through a maintenance coefficient and the initial investment of the component. The maintenance factors are based on [11].

2.2.2. Modelling of energy component

CHP

All three installed CHP units in the CCHP are identical in construction. The parameters set for the CHP model are based on manufacturer specifications. The nominal electrical output is 4.3 MW. At part load, the electrical efficiency decreases while the thermal efficiency increases. The manufacturer provides efficiency data for 100 % at full load (η_{heat}=0.437 and η_{el}=0.432) down to minimum part load of 50 %. The efficiency of the CHP between these operating points, with an additional available data point at 75 % part load, are linearly approximated.

HOB

The two HOB units in the CCHP have a nominal heat capacity of 16 MW each. The thermal efficiency is assumed to be constant at 80 % while considering a minimal part load of 20 %.

AC

The AC submodel is used for the installed AC in the CCHP and the optional AC capacity extension, i.e. an additional AC machine. For the already installed AC component, the design variable is set to one and the nominal cooling capacity to 5.7 MW. Furthermore, it is also considered that only the CHP units supply the AC, but not the HOB units.

The design variables for construction decision and dimensioning the nominal cooling capacity are used for the optional AC component. However, the minimal possible cooling capacity is set at 1 MW, as the investment for too small capacities is uneconomical for the studied energy system [12]. The part load efficiency of the AC components is modelled according to manufacture specifications, taking into account a minimal part load of 20 %. The specific investment of the AC is estimated following [12] at 200 EUR/kW.

HP

The waste heat utilisation in the multi-energy system is modelled as an optional HP. The HP increases the temperature of the waste heat to a sufficient level to integrate it into the local district heating system. Since the HP is not yet part of the multi-energy system, the HP component is a design decision subject to optimisation. In addition, the heat supply of the HP on the condenser side $\dot{Q}_{\mathrm{HP,con}}$ is an operational variable to determine the

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optimal amount of waste heat utilisation depending on the fluctuating demand.

The efficiency of the HP system is modelled by the coefficient of performance (COP). The COP of the HP COP_{HP} depends on the temperature difference between the heat source on the evaporator (eva) side, i.e. the waste heat source, and the heat sink on the condenser (con) side, i.e. the district heating system. The COP is calculated by

$$COP_{\mathrm{HP}} = \frac{T_{\mathrm{lm,con}}}{T_{\mathrm{lm,con}} - T_{\mathrm{lm,eva}}} \cdot \eta_{\mathrm{HP,system}} \cdot \eta_{\mathrm{HP,part}}, \tag{2}$$

where T_{lm} is the logarithmic mean temperature according to

$$T_{\mathrm{lm}} = \frac{T_{\mathrm{out}} - T_{\mathrm{in}}}{\ln T_{\mathrm{out}} - \ln T_{\mathrm{in}}}, \tag{3}$$

with the incoming (in) and outgoing (out) fluid temperature at the corresponding heat exchanger. The system efficiency $\eta_{\mathrm{HP,system}}$ is used to account for the system losses of the HP and is set to 0.5 [13]. The part load efficiency $\eta_{\mathrm{HP,part}}$ is based on [14] and linearised with the behaviour about 20 % part load. This linearised part load is considered down to the minimal set part load of 5 %. This is done, since the part load efficiency drops drastically below 20 % according to [14], however, the HP would not be operated in such inefficiently operating regimes in reality. The HP system is modelled as one component to reduce model complexity. In reality, however, the heat capacities required in this study would be realised by several HP units. The multiple HP units would allow for more efficient operation by avoiding the inefficient part loads under 20 %. Therefore, the linearised behaviour is used for the one HP system model.

The HP heat output $\dot{Q}_{\mathrm{HP,con}}$ is calculated by an energy balance and $COP_{\mathrm{HP}} = \frac{\dot{Q}_{\mathrm{HP,con}}}{P_{\mathrm{HP,el}}}$ to

$$\dot{Q}_{\mathrm{HP,con}} = \dot{Q}_{\mathrm{HP,eva}} + P_{\mathrm{HP,el}} = \frac{\dot{Q}_{\mathrm{HP,eva}}}{1 - COP_{\mathrm{HP}}^{-1}}, \tag{4}$$

where $\dot{Q}_{\mathrm{HP,eva}}$ represents the heat input of the waste heat source and $P_{\mathrm{HP,el}}$ the required electricity for operation.

Based on an anticipated waste heat capacity of 18 MW, a constant temperature level of the waste heat source at 44 °C [8], and the current supply temperature of the district heating system (see Section 2.3.), the upper limit of the design variable determining the thermal HP capacity is set to 22 MW. The lower limit of the HP capacity is set to 1 MW to avoid installing too small HP systems. The specific investment of the HP system is based on estimations by [15] and is set at 700 EUR/kW.

CC

The cooling demand of the campus is also met by three CC plants with a combined cooling capacity of 21 MW. Each CC plant comprises two or three CC units. In addition, no detailed manufacturer data of the individual chillers are available for these components. Since the district cooling network is not modelled and only the overall cooling supply is considered, all CC units on the campus are simplified into one CC component model. Therefore, a detailed analysis of the CC operational measurement data is performed to model the average behaviour of the summarised CC cooling supply.

The analysed measurement data of overall CC supply and consumed electricity for the CC operation does not show any significant correlation of the energy efficiency to the cooling load or the ambient temperature. The several CC units are from different years of construction, have various nominal capacities, and a control strategy for an optimal combined operation of the units is missing. Therefore, the analysed measurement data show a relatively constant COP over the year, which results from various superimposed COP characteristics of the individual CC units. Thus, the efficiency of the overall CC cooling supply is assumed to be constant and set at 3.7, as a COP formulation based on the temperature levels would not represent the actual CC operation on the campus.

The CC supply model consists of several small units, which is why the minimal part load of the comprised model is negligible. As no detailed information about the different CC units is available, the maintenance costs of the CC component are neglected.

GG, PG, ED, HD, CD

The external energy consumption by the GG and the PG (see Fig. 1) is modelled by considering specific energy prices and CO_2 factors that are defined in Section 2.3. Since the FZJ is not allowed to sell electricity to the grid, the energy flow from the PG model is limited to one direction. No restrictions on electricity and gas consumption are set for either grid model.

The demand models symbolise the consumption of the multi-energy system. The ED, CD and HD have a single input that represents the demand to be met (see Fig. 1). The energy demand symbolises the required supply by the energy plants, as the distribution losses are not considered. The assumed data for the energy demand is described in Section 2.3..

2.2.3. Optimisation problem and objective functions

The defined optimisation model is solved considering two objectives, minimising the TAC and the GWI of the multi-energy system. The TAC is expressed as

$$TAC = \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \cdot I + R, \tag{5}$$

with i for the interest rate of 0.7 %, n for the project duration of 20 a, I for the investment of HP installation and AC extension. The operational costs R are calculated according to the energy prices (see Section 2.3.) for energy consumption from the grids and the maintenance costs of the energy components. Gas is consumed to supply the CHP and HOB units, and electricity is consumed from the grid to cover the HP, CC and electricity demand of the campus that is not met by the CHP units.

Furthermore, the second objective GWI is formulated as

$$GWI = \dot{Q}_{\mathrm{GG}} \cdot CO_{2,gas} + P_{\mathrm{PG}} \cdot CO_{2,el}, \tag{6}$$

where $CO_{2,gas}$ and $CO_{2,el}$ represent the CO_2 emission factors for gas and electricity consumption supplied by the grids. The resulting bi-objective problem is solved by using the ε-constraint method.

The formulated energy system optimisation problem results in a Mixed Integer Quadratically Constrained Programming. The problem is passed to the Gurobi solver [16] via the implemented interface of COMANDO and solved for both objectives [9].

2.3. Studied scenarios

We define different scenarios for investigating waste heat utilisation in the FZJ multi-energy system. First, we optimise the energy system based on the current design without waste heat utilisation, i.e. an operational optimisation (Ref). Second, we consider the design option for an additional AC extension and HP installation for waste heat utilisation. Currently, the district heating network operates at high supply temperatures (HT) from 95 to 132 °C, controlled by a heating curve that depends on the ambient temperature. The first optimisation with optimal waste heat utilisation is carried out with these high supply temperature requirements at the HP system ($\mathrm{WH_{HT}}$).

The HP operates much more efficiently if the temperature difference between waste heat and network supply temperature is reduced. Therefore, we investigate another scenario with lower supply temperatures (LT) in the district heating network of 80 to 100 °C ($\mathrm{WH_{LT}}$). The technical feasibility of district heating operation and the sufficient heat supply to the connected consumers at these lower supply temperatures is already studied in [17].

In addition, we consider a changed energy price situation for gas and electricity consumption. As energy prices have changed significantly at the beginning of 2022, we estimate the changed energy prices for the FZJ supply ($\mathrm{WH_{HT,price}}$ and $\mathrm{WH_{LT,price}}$) in contrast to former energy prices used in [8]. Table 1 summarises all optimisation scenarios, including their considered option for waste heat utilisation, supply temperatures for HP operation and energy prices.

Table 1: Studied optimisation scenarios of the multi-energy system at the FZJ campus.

Scenario	Waste heat utilisation and AC extension	HP supply temperatures	Energy prices
Ref	No	95-132 °C	$c_{\mathrm{gas,old}}$ & $c_{\mathrm{el,old}}$
$\mathrm{WH_{HT}}$	Yes	95-132 °C	$c_{\mathrm{gas,old}}$ & $c_{\mathrm{el,old}}$
$\mathrm{WH_{LT}}$	Yes	80-100 °C	$c_{\mathrm{gas,old}}$ & $c_{\mathrm{el,old}}$
$\mathrm{WH_{HT,price}}$	Yes	95-132 °C	$c_{\mathrm{gas,new}}$ & $c_{\mathrm{el,new}}$
$\mathrm{WH_{LT,price}}$	Yes	80-100 °C	$c_{\mathrm{gas,new}}$ & $c_{\mathrm{el,new}}$

The energy prices in the period before 2022 ($c_{\mathrm{gas,old}}$=26.89 EUR/MWh and $c_{\mathrm{el,old}}$=149.54 EUR/MWh) are taken from [10] and used for the first scenarios. As the current energy prices of the FZJ were not made available, we estimate the energy prices increase based on the German gas and electricity prices of 2020 and calculate an average increase compared to December 2022. The average price increase for gas is calculated

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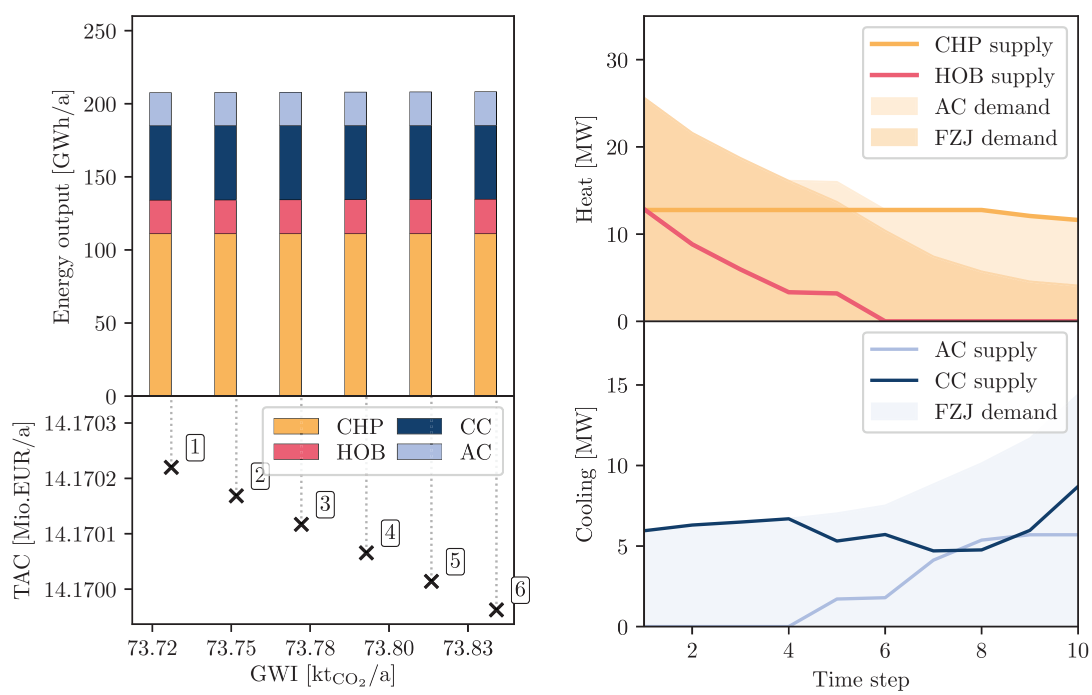
to 280 % [18] and to 126 % for electricity [19]. Thus, the increased energy prices for consumption from the energy grids are assumed to be $c_{gas,new}$=75.51 EUR/MWh and $c_{el,new}$=188.37 EUR/MWh, resulting in a lower price ratio between gas and electricity. Furthermore, the CO_2 emission factors are determined to $CO_{2,gas}$=201.24 kg/MWh for gas consumption and to $CO_{2,el}$=408 kg/MWh for electricity consumption [20, 21]. The energy demand data of the FZJ campus are taken from [10] since the consumption data from recent years are not representative due to the Corona-related basic operation with reduced on-site operation at the campus. Since the model is optimised for typical operating points that occur during one year of operation (see Section 2.2.), the demand data for heating, cooling and electricity are clustered. The demand data is clustered using the k-means algorithm [9]. The number of clusters is determined by the elbow-method, which evaluates the sum of squared errors within a cluster. Through this analysis, the number of clusters is set to ten. An additional cluster with a weight of zero represents the summed up nominal demand of the campus to account for the required design capacity [9]. The ambient temperature data, required for the district heating curve to calculate the HP condenser temperature, is matched to the identified clusters.

3. Results

We first present the optimisation results for the reference design of the multi-energy system. Then we show the results of waste heat utilisation with optional AC extension for both considered district heating supply temperatures. Finally, we show the influence of changed energy prices on the results of waste heat utilisation.

3.1. CCHP optimisation without waste heat utilisation

Figure 2a shows the multi-objective results of operational optimisation of the CCHP. The optimisation results are presented for both objectives resulting in multiple pareto-optimal solutions labelled as solution 1-6, with the resulting TAC on the vertical axis and the corresponding GWI on the horizontal axis. Solution 1 represents the minimal GWI, and solution 6 shows the minimal TAC. The energy output of the different energy components is presented in a stacked bar chart above each pareto solution.



(a) Pareto solutions (Ref)

(b) Operation over clustered time steps (solution 1)

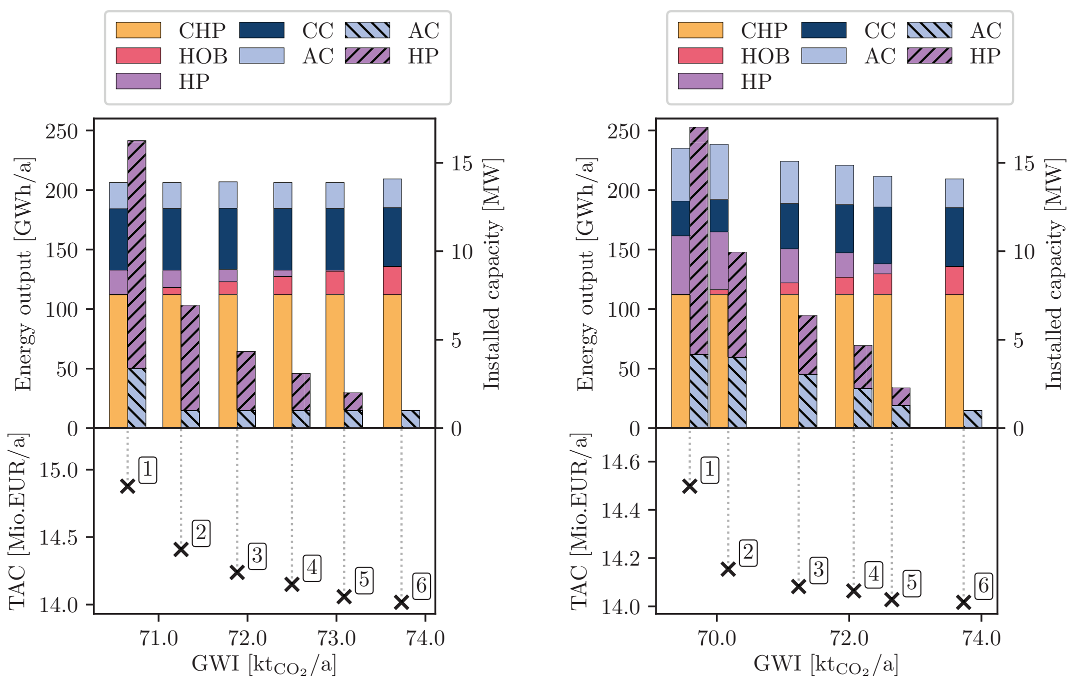
Figure 2: Operational optimisation of the CCHP without waste heat utilisation (Ref); Pareto solutions (6) for GWI, TAC and the corresponding energy output of the components (2a); Campus demand and supply of energy components for heat and cooling over clustered time steps of pareto solution 1 (2b).

The bi-objective optimisation shows only minor deviations between the solutions (see Fig. 2a) and therefore confirms that the current energy system is well designed to achieve the best economical and ecological result. Since the six solutions differ only minimally, the CCHP operational optimisation result is exemplary explained for solution 1.

In Fig. 2b, the energy demand of the campus and the energy supply of the different energy components over the clustered time steps are shown for solution 1. The clustered time steps are sorted from left to right by decreasing heat demand. The corresponding cooling demand is shown below the heat demand. The CHP units operate at full power to produce heat and electricity for the campus, while the HOB units cover the peak heat demands. Only in time steps 9 and 10 the CHP units operate in part load somewhat, as the heat demand of the FZJ and the AC demand are below the nominal heat output of all CHP units. The CC component covers the main cooling demand of the campus, especially when the heat demand is high. However, when the heat demand decreases, the heat from the CHP units is used to run the AC, which supplies cooling and replaces part of the CC supply (time step 7 and 8). In case the heat demand decreases and the cooling demand increases, the AC supply is extended as more CHP produced heat is available. At time step 8, the maximal cooling capacity of the AC is reached, so the CC cooling supply increases.

3.2. Waste heat utilisation and AC extension

The optimisation results for the additional waste heat utilisation, i.e. the optional HP installation and AC extension, are shown in Fig. 3a for the high supply temperature requirements at the HP system (WH_{HT}) and in Fig. 3b for the lowered supply temperatures (WH_{LT}). In addition, the installed system capacities for HP and AC extension are shown as stacked hatched bar charts above the corresponding solution.



(a) High-temperature requirements (WH_{HT}) **(b)** Low-temperature requirements (WH_{LT})

Figure 3: Optimisation of the CCHP with optional waste heat utilisation and AC extension.

The pareto solutions 1-6 differ significantly for the high supply temperature scenario WH_{HT} in Fig. 3a. For the lowest TAC, no waste heat is used. However, compared to the Ref results (see Fig. 2a), an additional AC capacity of 1 MW is installed to allow higher AC cooling production. When the GWI is lowered (solutions 5 to 2), the HOB heat supply is reduced while the waste heat usage, represented by the HP, increases. The HP supply increases for lower GWI, leading to an increased HP capacity installation and, thus, to higher TACs. The minimal GWI is reached at the maximal TAC (solution 1), leading to the largest installed HP capacity and increased AC capacity extension. However, the HP heat supply in solution 1 is not much higher than in solution 2. From solution 2 to 1, the HP even replaces peak supply of the HOB, but therefore additional HP capacity is

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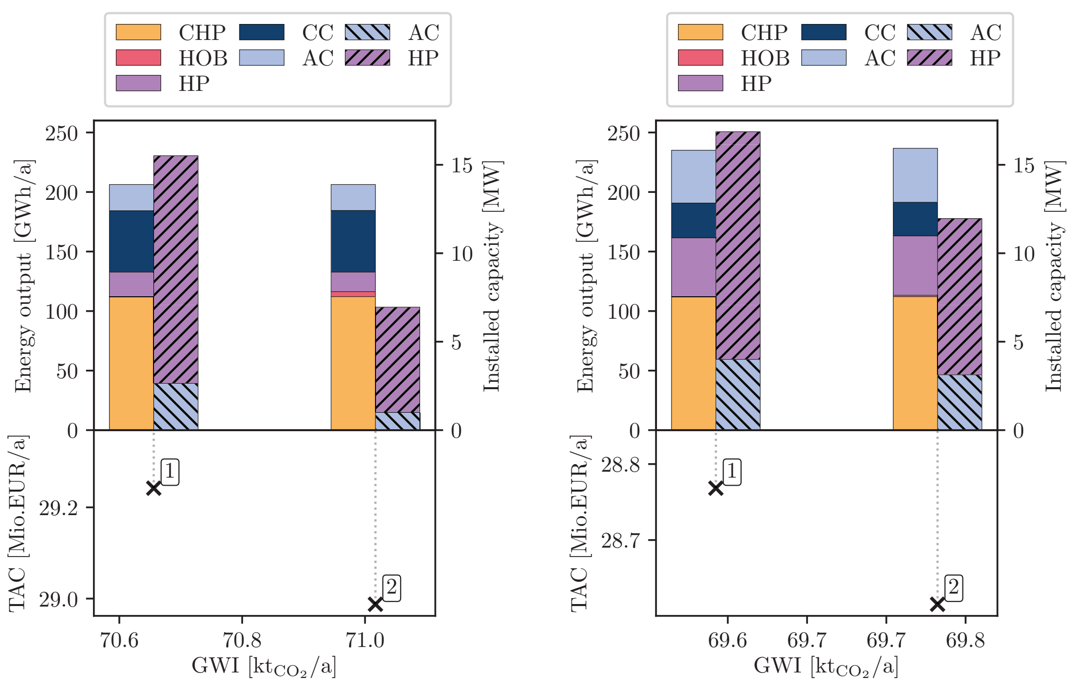
needed to cover the highest peak demands. The waste heat utilisation at high temperatures enables a GWI reduction of up to 4.2 % while the TAC increases by 4.7 % compared to the Ref scenario. However, although the waste heat utilisation is expanded to reduce GWI, waste heat does not replace the CHP heat supply. This is due to the high CO_2 factor of the power grid, which is why the HP heat supply still leads to relatively high GWI compared to the more ecological combined electricity and heat supply of the CHP units.

For lower supply temperatures in the district heating network (WH_{LT}) and thus more efficient HP operation, the HOB heat supply is replaced by the HP supply much earlier (see Fig. 3b). Compared to the WH_{HT} scenario, the HP heat supply is much higher for lower temperature requirements and therefore results in lower GWI values in WH_{LT}. In addition, the AC cooling supply rises for lower GWI while the CC cooling supply decreases. The CHP units continue to operate at full load as they produce priceless electricity for the campus. The high-temperature heat is not used to cover the heat demand as the HP supports the supply and is therefore used to supply the AC. Lowering the supply temperatures of the district heating network therefore leads to a more efficient use of waste heat and, thus, to an extended HP supply, while the high-temperature heat generated by the CHP units is used to operate the extended AC capacity. Compared to the current energy system design (Ref), the waste heat utilisation at low supply temperatures (WH_{LT}) lead to a GWI reduction of 5.6 % while the TAC increases by 2.3 %.

3.3. Changed energy prices

For the results of the changed energy price situation ($WH_{HT,price}$ and $WH_{LT,price}$), we show only two solutions (minimal TAC and minimal GWI) for each investigated supply temperature since the solutions only differ slightly and the effects for reaching lower GWI are the same as described before. The optimisation results of the changed energy prices are presented in Fig. 4a for the high supply temperatures and in Fig. 4b for the lowered supply temperatures.



(a) High-temperature requirements $WT_{HT,price}$ **(b)** Low-temperature requirements $WT_{LT,price}$

Figure 4: Optimisation of the CCHP with optional waste heat utilisation and AC extension and increased energy prices.

In scenario $WT_{HT,price}$, waste heat is already used in the case of minimising TAC (solution 2), despite the necessary investment for HP installation, which indicates an uneconomic operation of gas-fired plants. However, the peak heat demand is still supplied by the HOB to avoid the installation of large HP capacities. Whereas for minimal GWI (solution 1), the peak heat demand is also partly covered by the HP, accepting the high investment for the large HP capacity.

Lowering the supply temperatures in scenario $WT_{LT,price}$ also positively affects waste heat utilisation for increased energy prices (see Fig. 4b). For the minimal TAC (solution 2), a larger HP capacity is installed than in $WT_{HT,price}$ as the waste heat can be used more efficiently and, thus, already replaces the HOB heat supply to minimise the costs. To minimise GWI, the HP capacity installation is expanded to replace even the HOB peak supply (solution 1).

However, as the CHP units continue to operate at full load also for increased energy prices, the CHP heat is used to supply the extended AC. The AC capacity extension is more distinctive for lower supply temperatures, as waste heat utilisation is more efficient and, thus, more CHP heat is shifted to cooling production.

4. Discussion

The presented optimisation model confirms that the current CCHP is designed to operate at optimal ecological and economical performance, as the minimal TAC and GWI solutions are close to each other. The additional waste heat utilisation in the multi-energy system enables an increased ecological operation, as the waste heat replaces the HOB heat supply. However, the required investment for HP installation reduces the economic profit, as no waste heat is utilised for minimal TAC. Lowering the temperature in the district heating network has a positive effect on the efficiency of the HP, so that additional GWI and TAC savings can be achieved. Given the changed energy price situation, the waste heat is already being used for minimal TAC. As the gas price increases relatively more than the electricity price, the HP installation is more profitable for the HOB replacement in this price situation. Thus, the results show that a lower price ratio between gas and electricity strengthens the use of waste heat in the current energy system concept. To reduce the GWI, an extended HP heat supply becomes more attractive than a gas-fired heat supply. However, as the CHP units continue to operate at a high workload for producing electricity, additional AC capacity is installed to utilise the high-temperature heat of the CHP units. Thus, the option of AC extension enables continuous economic operation of the CHP units, as favourable electricity is produced, and the produced heat is used for cooling production and, thus, partially replaces the current CC supply.

The high CO_2 factor of the power grid leads to high emissions for waste heat utilisation, as the additional electricity for HP operation is supplied by the grid. In addition, the CHP produced electricity has a lower GWI than the electricity supplied by the power grid due to the assumed CO_2 factor. Thus, the waste heat does not replace the CHP heat supply, as the relative emissions of CHP produced heat and electricity, coupled with the cooling production via the AC, are lower than the emissions from the alternative supply by the HP and power grid. However, a changed electricity supply situation for the campus, e.g. through renewable electricity supply or a decreased CO_2 factor of the power grid, would reduce the emissions associated with waste heat utilisation and make the electricity supplied by the power grid more ecological than the electricity from the CHP plant. A more CO_2 neutral electricity supply by the grid could therefore increase the waste heat utilisation, as CHP operation would be replaced from an ecological point of view.

In the optimisation model, the CC component represents the total CC cooling supply from several individual CC units. The CC cooling supply model could be improved by collecting more detailed information about the installed CC units and parameterising several individual CC models to represent the different installed units. In this way, also the partially rather inefficient operation of the CC units on the campus could be improved. However, an adapted control strategy of the individual CC units, recommended by the optimisation, must be evaluated for a feasible district cooling operation, as the CC units are located decentrally on the campus.

5. Conclusion

In this study, we develop a model of a multi-energy system to optimise waste heat utilisation. Therefore, we model the existing components for heat, cooling and electricity supply and add an optional HP system to enable the usage of an available heat source. Additionally, we add the option to extend the AC cooling capacity to continue the CHP heat usage and, thus, maintain an economical CHP operation.

The optimisation model shows promising results for waste heat utilisation in the multi-energy system. To reduce the TAC, the CHP units operate at full load, and the HOB units cover the peak loads as these plants are already installed at the campus, and no investment is required. However, for minimal GWI, the waste heat utilisation by the installed HP system increases to replace the HOB heat supply. Lowering the district heating temperatures leads to a more efficient HP operation and, thus, to an increased waste heat usage to cover the heat demands of the campus. In contrast to the reference operation, the minimal GWI for the multi-energy system could be decreased by 4.2 % for high temperature requirements and by 5.6 % for lower supply temperature requirements at the HP system. The changed energy price situation leads to a smaller ratio between gas and electricity prices and strengthens the case of waste heat usage since, in this case, a HP installation is recommended to minimise costs as it replaces expensive gas-fired HOB heat supply.

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With the developed optimisation model, different adaptations to the multi-energy system could be additionally studied to improve waste heat utilisation. For example, a more CO_2 neutral electricity supply to the HP system would favorise an expansion of waste heat usage. Overall, the model is applicable for investigating the general effects and possible measures for waste heat utilisation in an existing multi-energy system.

Nomenclature

c	Specific costs, EUR/MWh
CO_2	Carbon dioxide factor, kg/MWh
COP	Coefficient of Performance, -
GWI	Global warming impact, t_{CO_2}/a
i	Interest rate, %
I	Investment, EUR
n	Project time span, a
P	Electric power, W
$\mathcal{P}$	Factor part load behaviour, -
$\dot{Q}$	Heat flow, W
R	Annual operating costs, EUR/a
T	Temperature, K
TAC	Total Annualized Costs, EUR/a

Abbreviations

AC	Absorption Chiller
CC	Compression Chiller
CCHP	Combined Cooling Heat and Power
CD	Cooling Demand
CHP	Combined Heat and Power
ED	Electrical Demand
FZJ	Forschungszentrum Jülich
GG	Gas Grid
HD	Heat Demand
HOB	Heat-Only Boiler
HP	Heat Pump
HT	High District Heating Temperatures
LT	Lower District Heating Temperatures
PG	Power Grid
WH	Waste Heat Utilisation

Greek symbols

η	Efficiency, -

Subscripts and superscripts

con	Condenser
el	Electricity
eva	Evaporator
in	Incoming quantity
lm	Logarithmic mean
nom	Nominal
out	Outgoing quantity
part	Part-load
Ref	Reference optimisation
rel	Relative

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