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PRODUCTION MANAGEMENT

Cascaded heat merit order for industrial energy systems to evaluate district heating potential

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Abstract

Industrial companies are undergoing a transformation to decrease energy costs and reduce emissions. The integration of renewables, sector coupling technologies, and industrial waste heat lead to complex interconnected industrial energy systems. As district heating systems play a decisive role for the integration of industrial waste heat in the building sector, barriers must be analyzed to overcome the gap between waste heat potential and waste heat use. Although data from production systems and their on-site energy supply are becoming available in the ongoing process of digitization, information deficits can be identified as one of the main barriers to couple industrial energy systems with district heating. We present a data-based methodology to evaluate the potential of industrial energy systems for connecting to district heating systems. Data from production systems, energy converters, thermal networks and necessary parameters of district heating systems are merged into a data model to determine a cascaded heat merit order and indicators for the energetic, economic and ecological potential. To set up the cascaded heat merit order, an algorithm for balancing complex industrial energy systems is integrated within the data model. In a case study, we apply the methodology to data of an industrial site. Besides increasing transparency through visualization of the cascaded heat merit order and corresponding indicators, the results show a base load potential of up to 0.8 MW over a year.

Keywords Industrial heating and cooling · Waste heat · District heating · Heat merit order · Potential analysis · Data-based methodology

1 Introduction

Industrial companies are faced with the challenge to decrease energy costs and reduce emissions. Besides energy efficiency of production systems, the on-site integration of renewables, sector coupling technologies, and industrial waste heat are promising measures, but lead to complex interconnected industrial energy systems (IES) [1, 2]. The industrial sector is responsible for about one third of the final energy demand worldwide [3]. In German IES, thermal energy demand accounts for about 70 % [4]. Besides providing thermal energy by using fossil fuels, substantial quantities of thermal energy are released as waste heat within production sites such as heat from furnaces, compressors or machine tools. In 2016, the annual industrial waste heat potential in Germany was estimated to be at least 127 PJ [5] and 1080 PJ in 2018 across the EU [6]. Both studies show a high dependency of industrial waste heat on temperature levels. Furthermore, on-site combined heat and power (CHP) is used to provide heat and electricity within production sites. Although the nominal thermal capacity of CHP plants above 1 MW in German industry was 30.3 GW in 2019, only 357.9 PJ of heat was utilized which accounts for only 37.5 %.[1]

Meanwhile, the building sector accounts for one third of worldwide final energy demand [3]. In Germany, 90 % of this demand is supplied for heating appliances [4]. District heating systems (DHS) are an efficient, climate-friendly, and

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[1] The nominal thermal capacity includes co-combustion of combined boilers in gas and steam turbines.

cost-effective way of distributing heat due to economies of scale effects and the potential to integrate renewables and waste heat over longer distances [7]. In Germany, the total heat demand supplied by DHS in 2020 accounts for 417.9 PJ [8]. Integration of industrial waste heat in DHS as the potential of reducing the emission impact of space heating, especially in urban areas. A study estimates 50–120 % of heat demand in specific urban areas can be met by integrated industrial waste heat [9]. Due to technical and organizational barriers only 7 % of DHS heat demand is supplied with waste heat [10].

As DHS play a decisive role in exploiting synergies between heat demand and supply of the industrial and buildings sector as well as the integration of waste heat, barriers must be analyzed and removed to overcome the gap between waste heat potential and waste heat use. Information deficits can be identified as one of the main barriers in coupling IES with DHS [11]. While Moser et al. present an economic approach to increase transparency by setting up a heat merit order in DHS [11], an analogous approach for creating transparency within the IES is needed. Through digitalized energy management systems and analyses, data from production systems and their on-site energy supply are becoming more easily available [12]. Thus, a heat merit order for more complex IES is proposed to increase transparency for a coordinated investment and operational planning between industrial sites and energy suppliers.

This paper is structured into a chapter laying out the foundations for analysing IES and DHS in terms of their viability for sector coupling, followed by a chapter wherein the state of the art in waste heat assessment and the heat merit order which this paper is based upon are presented. Subsequently, we present the methodology integrating the newly developed cascaded heat merit order as well as its underlying data model and algorithm. We close with an application of the cascaded heat merit order to an industrial site.

2 Fundamentals

In this section, fundamentals of IES and the integration into DHS are explained.

2.1 Industrial energy systems

IES consist of a variety of centralized and decentralized energy converters, distribution networks, and energy storage to supply production systems and buildings with energy [1, 2]. Central thermal networks which are supplied by typical energy converters such as CHP, gas or electric boilers, cooling towers, and compression chillers [13] can achieve high energy efficiency levels through economies of scale, efficient technologies, or integration of waste heat [14]. These central thermal networks can be characterized by temperature level and application (Table 1). The integration of heat exchangers (HEX) and heat pumps (HP) between thermal networks can further increase efficiency, but also complexity of such IES [2]. Highly integrated thermal networks of different temperature levels within IES are described as cascaded thermal networks in the following.

Table 1 Typical industrial thermal networks with flow and return temperatures [2]

Type	Flow [°C]	Return [°C]
High to low pressure steam[1]	120–240	80–160
High temperature[2]	90–120	70–90
Medium and low temperature[3]	50–70	30–50
Cooling[4]	10–30	15–40
Cold water[5]	1–6	6–12

Typical application

[1]Process heat for chemical processes, provision of hygienic steam for food industry, drying applications

[2]Metal washing, space heating, domestic hot water

[3]Space heating, cleaning processes, potential for waste heat uptake

[4]Cooling of industrial equipment, hot side of compression cooling, CHP generated heat, air conditioning

[5]Air conditioning, cooling of food products in food industry and supermarkets, chemicals

Waste heat occurring at industrial sites is often dissipated passively into the air or actively removed from cooling networks by cooling systems. Reusing waste heat can replace heat supply based on fossil fuels and thus reduce energy consumption of IES [13]. Within industrial processes, various sources generate waste heat which can be distinguished as follows:

- Waste heat at low temperature level that is dissipated via cooling processes, e. g. waste heat from machine tools. The implementation of HP is necessary to utilize this waste heat.
- Waste heat that is dissipated via cooling processes but can also be used directly for heating purposes according to the temperature levels, e. g. waste heat from compressors for pressured air.
- Waste heat that can be used directly which does not have to be cooled otherwise such as waste heat from heat treatment furnaces.

The possible uses of waste heat include in-process, in-plant, or external use. The first two options describe usage within the industrial site. If the potentials of these variants are exhausted - the internal heat demand is met -, potential waste heat integration can be increased by a connection to DHS [15]. Besides waste heat, excess heat from energy

Table 2 Generations of DHS [19]

Type	Flow [°C]
Generation 1: Steam	~ 200
Generation 2: Hot water	> 110
Generation 3: Warm water	< 100
Generation 4: Low temperature water	50–60

converters such as CHP units can be utilized for the use in DHS (see Sect. 1), thus a holistic view on surplus (waste and excess) heat must be obtained in order to evaluate the overall potential.

Due to the introduction of industrial energy management systems, e. g. in the course of implementing ISO 50001 [16], data on IES such as energy flows, volume and mass flows, or temperature levels are often digitally recorded and evaluated. Data analysis can also target measures for increasing energy efficiency, so that waste heat potentials are also investigated and corresponding information is provided [17]. These data can be used for the aim of this paper (Sect. 4).

2.2 District heating systems

District heating describes the supply of heat mainly for space heating and hot water in buildings over long distances, i. e., heat generation and consumption are spatially separated. Fossil fuel, biomass, or waste-fired CHP plants often serve as heat suppliers in DHS [18]. By separating generation and consumption, however, other heat sources such as waste heat or renewables can also be integrated. Depending on temperature levels, converter structures, and topologies, DHS are characterized in different generations (Table 2). Especially fourth generation DHS are able to integrate (industrial) waste heat [19].

The heat demand in DHS fluctuates seasonally and with the time of day. This results in load peaks in winter months as well as in the morning and afternoon. Depending on the network, the flow temperature is adapted to the ambient temperature on a sliding basis to achieve necessary thermal power [18]. DHS customers' retail prices are usually smoothed over the year including network costs, maintenance, cost for capacity provision, marginal cost, etc. [20]. For third parties such as industry which want to feed-in waste heat, the marginal costs of the network determine the maximum profit which can change over time depending on energy converters and energy prices, e. g. for electricity or gas from the energy supplier [11]. For feed-in from third parties, additional ecological requirements have to be met. DHS have to disclose a primary energy or emission factor which should not be worsened by third party feed in [18]. For feed-in planning, internal marginal cost and emission from potential surplus heat sources must be transparent, not only on DHS side, but also within IES.

3 State of the art

In the following, we present the state of the art for industrial waste heat assessment in general as well as DHS integration in particular. Furthermore, the heat merit order as a main concept of this paper is explained. From that, the aim for the paper is derived.

3.1 Industrial waste heat assessment

During IES planning and operation different methods can be applied to address the assessment and integration of waste heat. Woolrey et al. present a systematic approach for waste heat assessment within IES [21]. For systematic waste heat integration, pinch analysis is a common approach in process industry [22] already expanded to manufacturing [23, 24].

Current research on waste or surplus heat potential of IES for DHS mainly focuses on spatial or sector analysis. Here, the assessment of an overall potential within a certain region (e. g. in [25]), country (e. g. in [26, 27]) or sector (e. g. in [6]) can be seen as a top down approach not addressing IES in detail. For specific IES, model based research is conducted such as [28, 29]. These approaches model single waste heat sources and its potential for integration in DHS, often neglecting the complexity of IES. Lastly, technology driven approaches analyse how different technologies can be integrated to utilize, e. g. low temperature waste heat for DHS [30, 31].

3.2 Heat merit order

To increase economic transparency for potential decentralized heat suppliers in DHS such as industrial waste heat, Moser et al. present the heat merit order transferring the marginal cost approach from electricity markets to heating networks [11]. The heat merit order lists all heat generating units in DHS according to their specific heat costs and energy quantities per time unit (Fig. 1). According to the heating demand, the currently achievable price for a feed-in source can be determined. The profit of a feed-in can then be determined by the difference between the generation costs of the feed-in and the current price. From this, possible investment cost or operational planning can be derived [11].

For the simplified, transparent representation of the heat merit order, part load behavior and grid restrictions are omitted. Furthermore, compared to the electricity market, there are significantly fewer generation units in the merit order and CHP processes with corresponding electricity prices can also result in negative specific cost [11]. The approach is

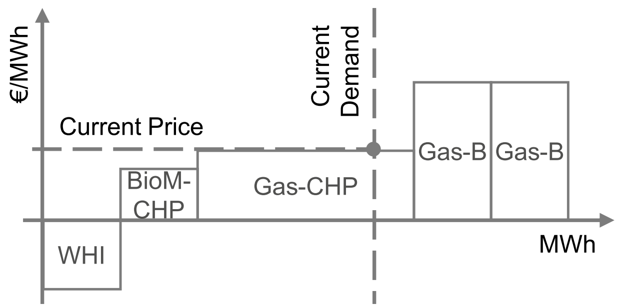

Fig. 1 Example of the heat merit order by Moser et al. for one time step [11]. WHI: waste heat incineration, BioM/Gas-CHP: bio mass/gas combined heat and power, Gas-B: gas boiler

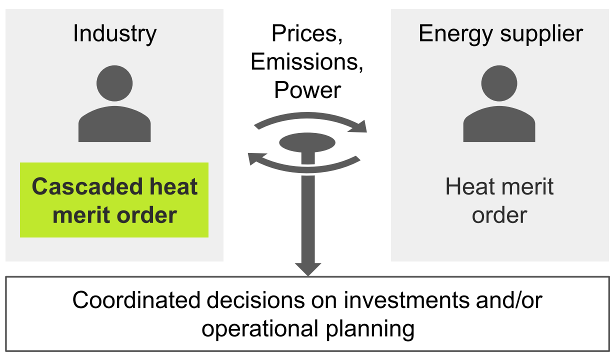

Fig. 2 Schematic depiction of communication and further steps between industry and energy supplier

based on the assumption that the supplier (industry) wants to evaluate a waste heat source in terms of economic potential, but omits the fact that IES have different (waste) heat sources, which should be investigated as a whole in terms of potential analysis. Furthermore, information about the ecological impact is only indirectly addressed.

4 Methodology

With the presented methodology, we close the information gap between energy supplier and industry by developing the heat merit order on the industry's side corresponding to the heat merit order on side of the energy supplier. Due to the cascading and interconnected nature of thermal networks in IES as well as the integration of waste heat, an algorithm for the calculation of the cascaded heat merit order is developed and integrated. By creating the cascaded heat merit order, a coordinated cooperation between industry and energy supplier for operational planning (e. g. day ahead) or investment planning can be initiated (Fig. 2).

In this section, the methodology to derive and embed the cascaded heat merit order for IES is presented. The method is split into seven steps (Fig. 3) roughly based on CRISP-DM [32]. The seven steps of the methodology are further described in the following with focus on "Data", "Quantification" and "Analysis".

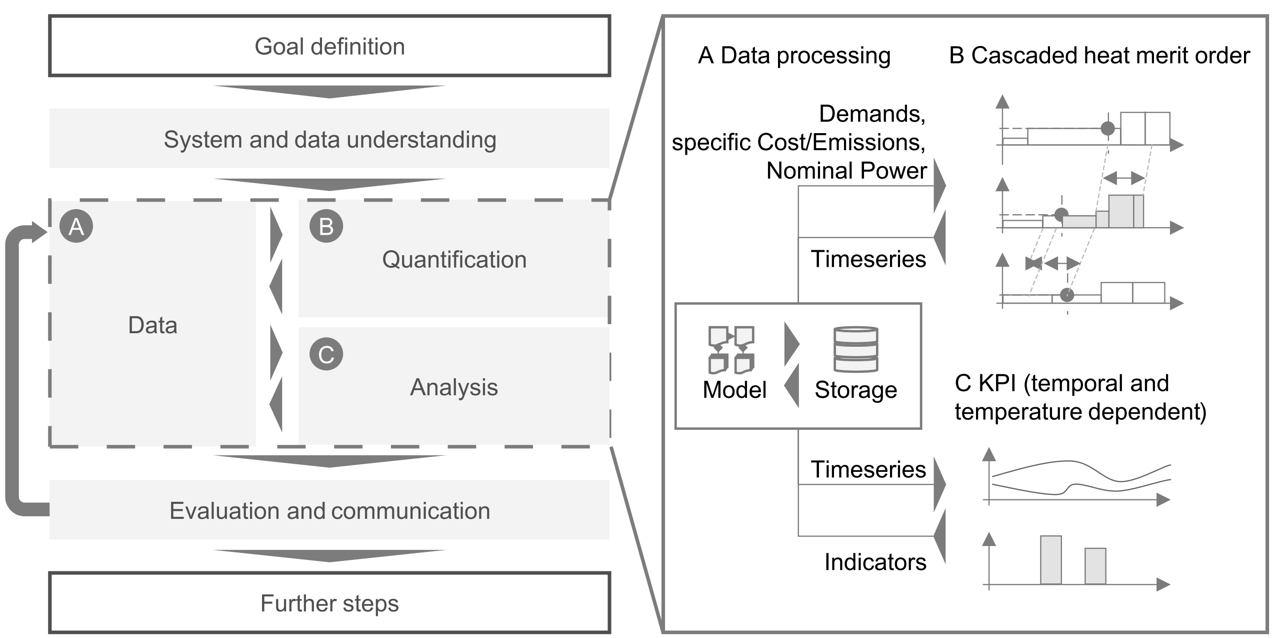

Fig. 3 Method for embedding and developing the cascaded heat merit order as well as evaluating the DHS potential of IES. KPI: key performance indicators

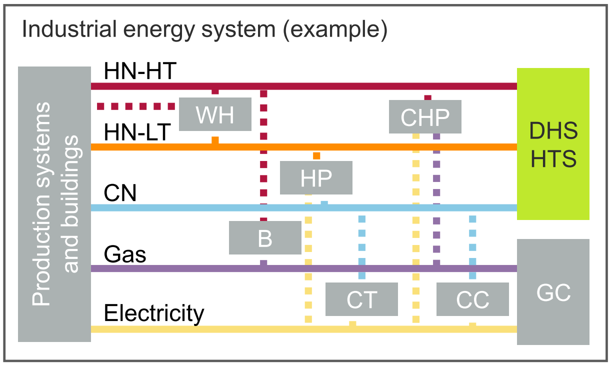

Fig. 4 Example of an industrial energy system. HN-HT: heating network high temperature, HN-LT: heating network low temperature, CN: cooling network, WH: waste heat, CHP: combined heat and power, HP: heat pump, B: boiler, CT: cooling tower, CC: compression chiller, DHS HTS: district heating system heat transfer station, GC: grid connection

4.1 Goal definition

As outlined in Sect. 1, industrial companies seek to reduce energy cost. By economizing industrial waste or excess heat through DHS, their overall site specific energy cost can be reduced [33, 34]. Moreover, due to ecological challenges, states provide incentives for increasing energy efficiency and emission reduction, e. g. taxation-benefits after certification within ISO 50001 [16]. After analysing and integrating industrial waste heat on-site, data on the amounts, specific cost, and specific emissions of surplus energy which can be traded with DHS must be obtained. As feed-in into DHS in operation depends on marginal cost, an estimation of time dependent available feed-in at a (potential) coupling point must be calculated and evaluated. The obtained information can be used to communicate with energy suppliers for operational or investment planning in order to develop business models around industrial waste heat (Sect. 4.7). The two main goals / business models can be described as follows:

- Operational planning: Offering industrial surplus heat on day ahead heating markets and optimizing operation of a heat transfer station. [34]
- Investment planning: Estimating the potential profits for an investment budget and optimizing investment in a heat transfer station. [11]

4.2 System and data understanding

In Sect. 2, the cascaded characteristics of thermal networks in IES are outlined. To apply the presented methodology, the specific network topology and characteristics such as temperature levels of an IES must be known. Figure 4 gives an example of a cascaded IES with a high and low temperature heating network as well as a cooling network to supply production systems and buildings with thermal energy.

Besides the network topology, data of available energy converters such as nominal power and efficiencies, thermal power of integrated waste heat sources from production processes and energy demands as well as prices for external energy supply such as gas and electricity have to be collected. These data are typically available in implemented energy management systems. If the methodology is applied for operational planning, e. g. day ahead, forecasting of energy demands and waste heat supply must be integrated.

Some thermal energy demands such as steam and cooling supply are usually recorded in other formats than power or energy. The former is often tracked in mass m (tons), the latter in volume V (m^3). In order to apply the heat merit order, the time dependent thermal demand of steam $\dot{Q}_t^{steam}$ and cooling supply $\dot{Q}_t^{cooling}$ must be converted as shown in Eqs. 1 and 2:

$$\dot{Q}_t^{steam} \cdot \Delta t = m \cdot \Delta h \tag{1}$$

$$\dot{Q}_t^{cooling} \cdot \Delta t = V \cdot \rho \cdot c_p \cdot \Delta T \tag{2}$$

The steam demand is calculated with the pressure dependent specific enthalpy of steam Δh while cooling demand is dependent on the temperature difference between flow and return temperature of the cooling network. Δt describes the time step length.

Lastly, information on the heat transfer station (HTS) between the IES and the DHS—especially on its subsystems—is necessary. For investment planning, potential transfer points must be evaluated. For operational planning, the IES is already connected via HTS to the DHS.

4.3 Data

To set up the cascaded heat merit order and store data for the analysis, a data model for each component of IES is generated. An overall factory model includes data models of thermal networks, energy converters, waste heat sources, energy demands, and the DHS as displayed in Fig. 5. The relational multiplicities are also illustrated.

The IES superstructure is represented in the data model by a *Factory* object which contains all thermal networks that are part of the IES as a list of *HeatNetwork* objects as well as a list of *NetworkConnector* objects which establish relations between the IES thermal networks, e. g. via HP or HEX. A *Factory* object must consist of a minimum of one *HeatNetwork* and one *DHS* object. *HeatNetwork* objects contain functions for establishing their internal heat merit order as well as a list of *EnergyConverter* objects and *Demand* objects.

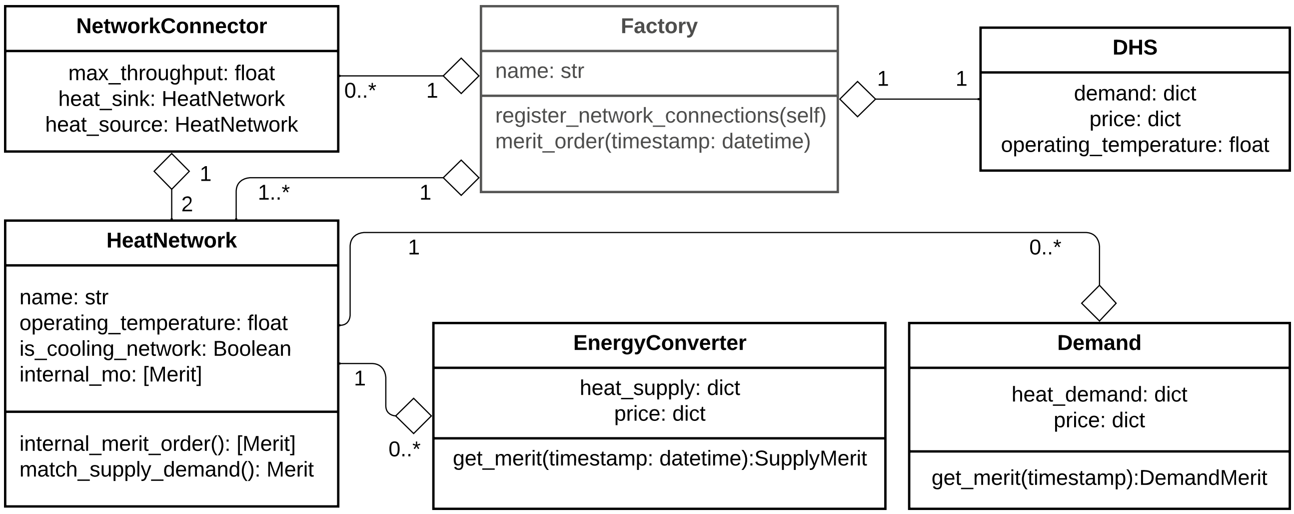

Fig. 5 Overall data model with subclasses, relations and multiplicities. DHS: district heating system

All typical thermal supply and demand systems are modeled as objects inheriting the base functionality of *HeatDemand* and *EnergyConverter* objects, respectively, and are extended with methods in order to represent their specific cost and supply structure. HP and HEX are modeled as subclasses of *NetworkConnector* objects and provide the necessary methods for applying penalties for transporting heat between thermal networks.

Necessary input parameters for the cascaded heat merit order are calculated and stored within the data model. These parameters include time dependent capacities $\dot{Q}_{i/j,t} \cdot \Delta t$ of energy converters i and waste heat sources j as well as their marginal cost $c_{i/j,t}$ and specific emissions $e_{i/j,t}$. Moreover energy demands $\dot{Q}^{dem}_{n,t}$ for each thermal network n are calculated as the sum of all demands in this network.

The marginal cost of heat sources such as energy converters or waste heat from production processes can include the following variable cost parameters [11]:

- Energy input cost with taxes and network tariffs $c_t^{gas/el}$ (e. g. for gas and electricity),
- Electricity output revenues or savings for CHP units depending on feeding into the electric grid $c_t^{el,sell}$ or self-use c_t^{el},
- Cooling cost which is replaced by the use of HP $c_{n,t}^{cooling}$ or direct waste heat use $c_{j,t}^{cooling}$,
- Additional cost $c_{j,t}^{add}$, e. g. operation-dependent maintenance or electricity for pumps.

The following equations show the basic calculations for energy converters such as boilers (Eq. 3), CHP units (Eq. 4), HP (Eq. 5), and a single waste heat source (Eq. 6) with corresponding efficiency measures ($\eta_i^{th/el}$ and COP_i):

$$c_{i,t}^{B} = \frac{c_t^{gas}}{\eta^{th}} + c_{j,t}^{add} \tag{3}$$

$$c_{i,t}^{CHP} = \frac{c_t^{gas}}{\eta^{th}} - \frac{c_t^{el,sell} \cdot \eta^{el}}{\eta^{th}} + c_{j,t}^{add} \tag{4}$$

$$c_{i,t}^{HP} = \frac{c_t^{el}}{COP_i} - c_{n,t}^{cooling} + c_{j,t}^{add} \tag{5}$$

$$c_{j,t}^{WH} = -c_{j,t}^{cooling} + c_{j,t}^{add} \tag{6}$$

The specific emissions *e* for each energy source are calculated in the same way as energy cost (Eqs. 7–10).

$$e_{i,t}^{B} = \frac{e_t^{gas}}{\eta^{th}} + e_{j,t}^{add} \tag{7}$$

$$e_{i,t}^{CHP} = \frac{e_t^{gas}}{\eta^{th}} - \frac{e_t^{el} \cdot \eta^{el}}{\eta^{th}} + e_{j,t}^{add} \tag{8}$$

$$e_{i,t}^{HP} = \frac{e_t^{el}}{COP_i} - e_{n,t}^{cooling} + e_{j,t}^{add} \tag{9}$$

$$e_{j,t}^{WH} = -e_{n,t}^{cooling} + e_{j,t}^{add} \tag{10}$$

The calculated specific emission can be used to integrate cost for CO_2 certificates by multiplying with the CO_2 price. If the direct waste heat source does not need to be cooled such as waste heat from heat treatment furnaces, the term for cooling in Eqs. 6 and 10 is set to zero.

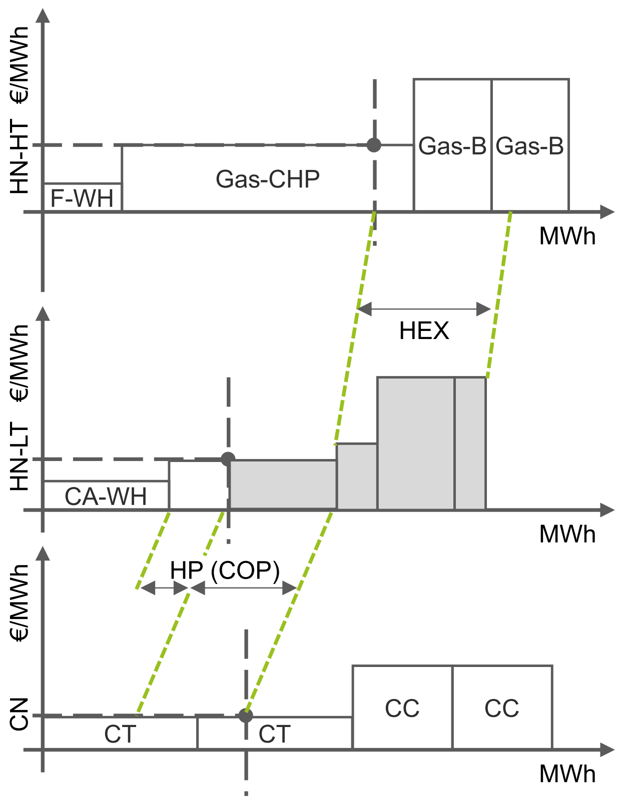

Fig. 6 Exemplary cascaded heat merit order for three networks. Grey: DHS Potential if the IES is coupled through HN-LT. HN-HT: heating network high temperature, HN-LT: heating network low temperature, CN: cooling network, F-WH: furnace waste heat, Gas-CHP: gas combined heat and power, Gas-B: gas boiler, CA-WH: compressed air waste heat, CT: cooling tower, CC: compression chiller

4.4 Quantification

By applying the cascaded heat merit order, the waste and excess heat potential for every time step is quantified. How the heat merit order is set up for a single thermal network is described in Sect. 3.2 and [11]. As IES can consist of several interconnected thermal networks, the cascaded heat merit order must be set up for each network after which the heat exchange between networks must be evaluated. Figure 6 shows the cascaded heat merit order exemplarly for three networks. The high temperature heating network (HN-HT) is connected via HEX to the low temperature heating network (HN-LT). Thus, depending on maximum power of the HEX, thermal energy can be transferred from HN-HT to HN-LT. Moreover, heat from the cooling network which contains waste heat from production processes can be integrated into the HN-LT via HP. Depending on the COP of the HP, the heating power differs from the cooling power. If the DHS is connected to the HN-LT of the IES, a heat merit order for the transfer station can be derived. The parameters of the heat sources are calculated as stated in Sect. 4.3. As explained in [11], the cascaded heat merit order must neglect part load behavior of energy converters to enable a linear calculation for single networks with focus on the maximum potential output of surplus heat.

To calculate a generic cascaded heat merit order for *n* heating and cooling networks with *i* energy converters and *j* waste heat sources, an algorithm as displayed in Fig. 7 is developed and integrated. The algorithm is divided into two levels, the factory level and the thermal network level. First, the factory is initialized with all components such as thermal networks, network connections, energy converters, waste heat sources, and energy demands. Then, on the network level, iteratively for each thermal network, the supply merit order (energy converters and waste heat sources) is set up for each thermal network which can supply into the current thermal network (parent networks). Thus, all thermal sources to meet the internal demand are considered to match supply and demand for each thermal network. For example, in a heat network which is connected to a higher temperature steam network via HEX, all internal sources are considered as well as all sources within the connected steam network. On the factory level, overall demand and supply matching can be conducted. Due to the network connections, some energy supply sources may appear more than once in the total set of all network-level merit orders. This is why in the next step only the cheapest match between supply and demand is subsequently chosen. The transferred energy amount is then subtracted from both the energy supply source as a capacity reduction and from the energy demand. If the specific energy demand is met or the full capacity of an energy supply source is exhausted, these are removed from the factory. The merit orders of the networks within the resulting factory with adapted energy supply sources and energy demands are then recursively calculated again until no matching energy demands and energy supply sources are left.

The resulting heat merit order is stored to be analysed with further data in the analysis block.

4.5 Analysis

The results of the cascaded heat merit order calculation can be used for different applications. Depending on whether the heat merit order of the DHS is known or unknown as well as if an operational or investment planning is the goal, different analyses can be conducted.

For investment planning and if the heat merit order of the DHS is known, time dependent values of both merit orders can be compared as described in [11]. Depending on the marginal cost in the DHS which can be replaced by the surplus heat of the IES, a maximum profit can be calculated. This way, maximum investment cost for a heat transfer station can be derived e. g. on the basis of one year of data. If the DHS heat merit order is unknown, the results

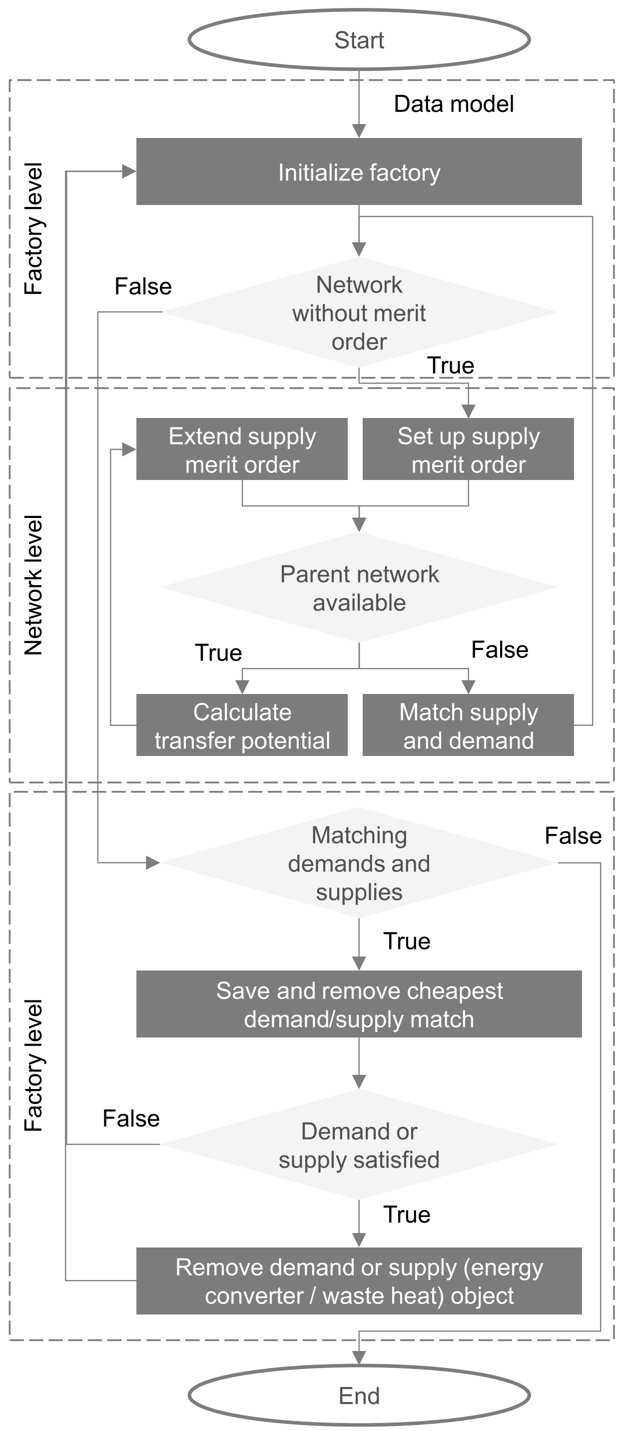

Fig. 7 Flowchart of the algorithm to calculate the cascaded heat merit order

of the cascaded heat merit order can be analysed regarding the energetic potential of single energy sources, e. g. the cooling network, as well as the base load potential of the IES. The base load potential describes how much energy the IES can supply continuously over a certain time period, e. g. a month, a quarter or a year. The base load may vary depending on price of emission restrictions. Compared to a uncertain feed-in, base load supply ensures security of supply for the energy supplier.

For operational planning and if the DHS heat merit order or if a pricing scheme is known, as in Stockholm Open District Heating,[2] the industrial company can plan which amount of energy it will provide based on the profits it can make. If the pricing scheme is not known, the cascaded heat merit order can be used to communicate offers to the energy supplier. These offers can be used in direct communication with the energy supplier in order to establish a long-time cooperation or to participate in dynamic heat market structures.

Exemplary analysis of the cascaded heat merit order are presented in Sect. 5.2

4.6 Evaluation and communication

The analysis of the cascaded heat merit order can provide indications whether it is economically viable to feed in surplus heat. In an exchange with the energy supplier, further information can be requested, e. g. the merit order of the DHS. Based on this information, feed-in potentials can be specified—if necessary with iterative repetition of the merit order calculation—and further steps can be initiated together with the energy supplier (Fig. 2).

4.7 Further steps

After deciding on traded energy amounts, further steps can be initiated. Depending on the application, further steps can be the technical planning (engineering) of the heat transfer station (investment planning) or setting up control signals for operational planning.

5 Application

In this section, the application of the methodology to data of an industrial site and its results are outlined. Moreover, the potential and challenges of the approach are discussed.

5.1 Use case

The following use case represents an industrial company which is planning a connection to a nearby DHS, thus aiming to utilize and trade waste and excess heat. The presented methodology can support the goal by creating transparency about the potential of connecting the IES to the DHS.

[2] www.opendistrictheating.com.

The IES of the industrial company consists of five thermal networks:

- Steam with CHP and gas boilers to supply production processes with heat.
- High temperature water with CHP to supply production processes and buildings with heat.
- Low temperature water to supply buildings with heat and to integrate waste heat.
- Cooling water with cooling towers to provide cooling for production processes and buildings.
- Cold water with compression chillers to provide cooling for production processes.

The steam network is connected to the high temperature network via HEX and the high temperature network to the low temperature network, respectively. Waste heat, e. g. from production processes within the cooling and cold water network are connected to the low temperature network via HP. The efficiency of the HP depends on the temperature difference between low temperature network and the respective cooling or cold water network. The provision of heat from cooling or cold water networks via HP can be a cost-effective source for space heating in low temperature networks [35]. Moreover, waste heat from compressors for compressed air is integrated into the low temperature network. It is assumed, that a potential coupling point to the DHS is via low temperature heating network. Surplus heat is upgraded via HP to meet the temperature requirement in the DHS. Through the coupling point via low temperature heating network, excess heat from the two CHP units as well as waste heat from the compressors, cooling network and cold water network is available for the integration into the DHS. Depending on internal energy demands, the potential of the energy sources changes over time. Parameters on cost, energy converter capacity and energy demands of the networks are known and data for one year is available. For the IES, the data model is set up and necessary parameters to calculate the cascaded heat merit order are derived.

5.2 Results

In the case study the cascaded heat merit order was calculated on an hourly basis for 2021. In the following, resulting heat merit order diagrams are exemplarily shown and discussed. The identified heat supply potential throughout the year within the case study is analysed. Based on all hourly merit orders, the base load potential of the IES is evaluated and discussed.

Figure 8 shows an exemplary heat merit order during production times in a summer month. The main heat source at this time stems from coupling the cooling demand of the cold water and cooling networks into the low temperature heat network and upgrading the resulting heat surplus to the temperature requested by the DHS. A remaining CHP waste heat potential which is not used up internally can be provided at the lowest specific price. The price of the cooling and cold water demand result from the difference of HP expenses and avoided cooling costs such as from cooling towers and compression chillers. The increased cooling cost within the cold water network results in a lower specific price compared to heat provided via the cooling network even though HP expenses are higher for cold water sources. It should be noted that the resulting heat merit orders can vary within a day and between days, depending heavily on plant operation and ambient temperatures. The effects of this dependence are discussed at a later point within this section.

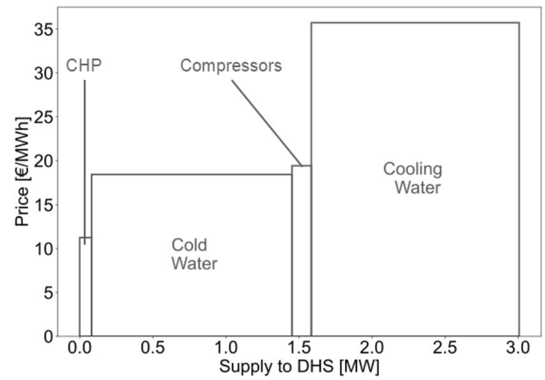

Fig. 8 Merit order for the 1st of June 2021, 10:00. CHP: combined heat and power plant

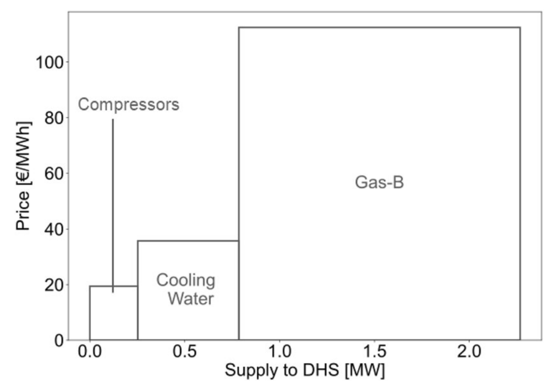

Fig. 9 Merit order for the 9th of February 2021, 10:00. Gas-B: gas boiler

A merit order for a colder month is presented in Fig. 9. The cooling demand and thus potential for this date is significantly reduced, mainly due to the difference in ambient temperature compared to the summer date discussed above. Waste heat resulting from air compressors is similar in amount to operation in the summer months and can be provided here at the lowest price. For this date, all CHP

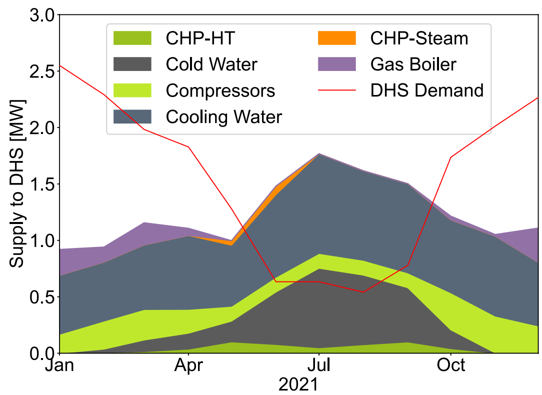

Fig. 10 Stacked heat merit order for 1 year on the basis of monthly mean values. CHP-HT: combined heat and power in high temperature network, CHP-Steam: combined heat and power in steam network

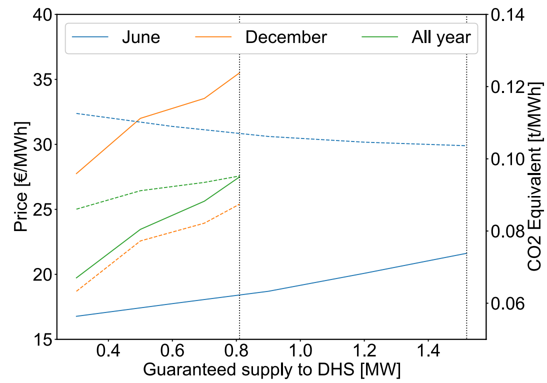

Fig. 11 Potential base load depending on price level and time frame. The dashed lines represent the corresponding specific CO2 emission equivalents

waste heat was used internally and is thus not provided to the DHS. Instead a more expensive gas boiler supply can use the available HEX capacity and cover some of the supply difference compared to the summer case discussed above.

In application of the methodology presented in this paper, the potential surplus heat throughout the year is of interest to the industrial company and the local energy supplier. Figure 10 shows the monthly mean supply potential after applying the cascaded heat merit order for 2021. To provide a clear representation, the supply is averaged over each month. In further steps of investment planning, heat storage sizing can be used to smooth the available supply. The different heat sources are stacked by their price from bottom to top. A clear trend of heat surplus in the summer months due to increased cooling operation is visible. This inversely corresponds to the decreased DHS demand during summer months as previously shown in [11]. Available waste heat from the IES compressed air source is steady throughout the year. During the winter months, boiler operation can cover some of the deficiencies from missing cooling demand. From this graph, a first conclusion of available waste heat throughout the year can be drawn.

Due to the variable nature of the available heat, an indicator to assess constantly available heat for a given time frame is presented in the following. This metric is of especial interest for communication, as a guaranteed base load is often part of bilateral agreements between industrial sites and energy suppliers. For this approach, all merit orders within a specified time frame are taken into account. The minimum available amount of heat that can be provided for each time step defines the maximum supportable base load for a given time frame. The average specific heat price is calculated for n grid points and plotted over the corresponding heat supply. The resulting graph for the whole year of 2021, June of 2021 and December of 2021 is shown in Fig. 11.

The graph shows a clear difference in marginal cost between the summer and winter months. This information can be taken into account by an industrial company in finding a profitable pricing model for year-round feed in. A continuous supply of 0.8 MW can be achieved by the IES over different heat sources for marginal cost of around 27 €/MWh. If the DHS only needs base load over winter months marginal costs rise to 35 €/MWh. The cascaded merit order was calculated in an economic manner so that it does not necessarily suggest the most CO_2 effective feed-in. Thus, in the summer month, the specific CO_2 emissions decrease with increasing base load.

5.3 Discussion

The presented methodology for deriving and analysing the cascaded heat merit order for IES can increase transparency in an economic and ecological view for the coupling with DHS. The marginal cost, specific emissions, and time dependent energetic potential of heat sources for DHS are integrated into the heat merit order to achieve a holistic view on the energetic potential. The economic view corresponding to [11] follows the goal of profit maximization in industrial companies. As the supply of surplus energy is not the main business of industrial companies, the approach aims to support the industrial energy management and to decrease information deficits for a more effective communication with energy suppliers.

The presented algorithm can handle the complexity of several thermal networks with potential waste and excess heat sources for DHS. As the heat merit order assumes that the energy demands of the internal production systems are met before energy is traded with the DHS, the internal security of supply is ensured.

Due to the high level economic and ecological focus, technical requirements are simplified such as part load behavior of energy converters, heat storage or flexibility in production processes. The cascaded heat merit order gives a first impression of the potential feed-in regarding energy amount and base load potential. Further engineering in investment planning must be conducted subsequent to the approach. Although the use case focuses on a potential estimation for investment planning, the approach can be used for both operational and investment planning.

6 Summary and outlook

In this paper, we present a data-based methodology to evaluate the potential of industrial energy systems for connecting to district heating systems. Due to the cascading and interconnected nature of thermal networks in industrial energy systems as well as the integration of waste heat, an algorithm for the calculation of the cascaded heat merit order is developed. Data from production systems, energy converters, thermal networks, and necessary parameters of district heating systems are merged into a data model to determine a cascaded heat merit order and indicators for the energetic, economic, and ecological potential. By creating the cascaded heat merit order, a coordinated cooperation between industrial sites and energy suppliers for operational planning (e. g. day ahead) or investment planning can be initiated. In a case study, we apply the methodology to data of an industrial site with five thermal networks. The cascaded heat merit order is used to visualize the feed-in potential over a year and calculate a cost-dependent potential base load. Besides increasing transparency through visualization of the cascaded heat merit order and corresponding indicators, the results show a base load potential of up to 0.8 MW over a year.

Some technical details of the industrial energy system discussed within the case study have been simplified due to the economic and ecological focus. In further research, the possibility of integrating further technical requirements can be discussed. Moreover, within an ongoing research effort the cascaded heat merit order will be integrated into a digital heating market as a way of providing offers in day ahead heat trading.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

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