Energy 200 (2020) 117579

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Designing the Heat Merit Order to determine the value of industrial waste heat for district heating systems

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A R T I C L E I N F O

Article history:
Received 4 November 2019
Received in revised form
4 March 2020
Accepted 6 April 2020
Available online 11 April 2020

Keywords:
District heating
Heat merit order
Industry
Marginal costs
Third party feed-in
Waste heat

A B S T R A C T

Using industrial waste heat increases primary energy efficiency and may reduce costs. District heating networks are a promising sink as temperatures are relatively low. Usually only the end-use prices are public; but these include network infrastructure costs, maintenance costs etc. The value of a certain kWh fed in, i.e. the current marginal costs for the generation of heat, are not transparent. However, current marginal generation costs are decisive for the use of waste heat as the accumulated producer surplus determines the profitability of investment. To make marginal generation costs transparent, a “Heat Merit Order” is constructed. Based on conversion factors, fuel prices, network tariffs, etc. the maximum remuneration payed by the district heating operator at a certain point of time is made calculable. For a case study, the applicability to estimate maximum investment costs is proven. In conclusion, the Heat Merit Order makes local heat generation prices transparent and allows to calculate the profitability of integrating waste heat, other heat sources and storages; it enables companies to estimate the value of waste heat and if investments are profitable. Finally, the Heat Merit Order avoids information asymmetries and thus generally supports the efficiency and penetration of district heating.

1. Introduction

Primary energy efficiency is a key element of the transition towards a sustainable energy system [1] and the exergy-oriented supply of customers with the adequate quality of energy [2] can contribute to this by using low-temperature thermal sources instead of (renewable) fuels [3]. Using industrial waste heat for space heating probably is the most prominent and the most promising example [4]. In order to achieve a sustainable energy system, district heating systems need to expand, [5,6]. One third of global energy consumption accounts to the consumption of the industrial sector [7]. It has been shown that the awareness of the energy-intensive industry for the topic of sustainability is rising sharply [8]. Once a given industrial company has ruled-out or maximized the “internal” alternatives for waste heat recovery, the system boundaries can be expanded (see Simeone et al. for a “Decision Support System” [9]). Therefore, the waste heat could be used outside the company for heating purposes. From a technical point of view, implementations are feasible in the short-to medium-term [10].

Of course, the temperature of the waste heat must be compatible with the temperature of the district heating system. To some extent, preparation of the waste heat with heat pumps is cost-effective, [11–13]. In principal, the lower the temperatures of district heating networks are, the more industrial waste heat can be integrated [14]. For example, waste heat is commonly low-grade from the food and beverages industry [15]. Aside of other benefits like avoidance of heat losses, low temperature district heating is especially advantageous when a low temperature heat source is available [16]. Return temperatures can be reduced by implementing a cascaded use of the flow, allowing waste heat sources to feed into the return pipe [17]. Today’s technology deployment is in line with the third generation of district heating technology [18]. The stereotype third generation district heating network uses pressurized water with temperatures of about 100 °C and lean components [19]. The fourth generation is not only operated at temperatures lower than 100 °C, but the district heating network is an integral part of the renewable energy system [20]. District heating is a low-risk investment which does not require short payback periods (especially in cities, but in low heat density areas competitiveness may be at risk [21]). However, if waste heat provides heat cost-effectively, it can also contribute to the economic

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https://doi.org/10.1016/j.energy.2020.117579

operation in suburban systems [22]. Thus, industrial waste heat does not imply sunk costs for district heating companies' cogeneration plants which replace expensive hot water boilers [23] and serve as backups, while waste heat covers the base load [24].

1.1. Non-transparent value of waste heat

When considering the use of waste heat in district heating networks, the waste heat potential (MWh/year) is often compared with the volume of heat consumed. This is an improper simplification as space heating demand occurs in winter and industrial waste heat is available the whole year, but especially in summer. The provision of industrial waste heat only in winter means that revenue can only be generated in winter. This increases the payback period and often makes the integration of waste heat economically infeasible [25]. It was shown that district heating companies are local natural monopolies [26], but this attribute is demonstrably only subordinate for the integration of waste heat, [23,27].

Normally, the energy carriers' costs are officially known, e.g. for crude oil, natural gas, electricity, and also for biomass. Market prices are defined by the demand on the one hand and the marginal costs on the other. In line with economic theory, these suppliers' costs are illustrated by the "supply curve" [28]. In electricity markets this curve has become known as the Merit Order Curve. Any actor intending to feed in/sell electricity can analyze this data and estimate its turnover. The (marginal) heat generation costs of district heating systems are not transparent, i.e. they are only known to the district heating operator and eventually to contracted heat providers. Only the smoothed retail prices in Euros per kWh are officially known. These retail prices are normally the same for the whole year; they include network costs, markups, etc. and definitely do not reflect the actual marginal costs at a certain point of time [29]. Any third party intending to feed in cannot estimate its turnover.

1.2. Aim of the paper

The intention of this paper is to provide a basis for estimating the turnover of feeding in industrial waste heat. In order to do so, a "Heat Merit Order" tool is developed. The authors suggest that the Heat Merit Order is still unknown to many researchers and practitioners (Google Scholar finds one publication on "Heat Merit Order" which is not co-authored by this paper's authors). However, the Heat Merit Order is not new as it is applied for generation dispatch. The innovative aim of this paper is the backward calculation of the maximum investment cost of feeding in industrial waste heat into district heating networks. Please find a demarcation to existing, similar, but not congruent approaches below.

The Heat Merit Order shows the marginal costs of the district heating system's generation unit. It therefore illustrates the district heating system's actual supply curve. If cogeneration or power-to-heat plants are part of the generation portfolio, electricity market prices (which are transparent) can be included. The Heat Merit Order tool intends to enable third parties to evaluate their potential feed-in into the local district heating system. The characteristics and composition of the generation units is network-specific but is usually commonly known. Finally, the Heat Merit Order is derived for a case study example.

In some related literature, similar but not congruent approaches are applied: Brückner et al. apply the maximum costs approach to evaluate the profitability of company-internal recovery and reuse of industrial waste heat [30]. Difs and Trygg calculate the marginal costs of district heating in order to supply industry (as a consumer) with an alternative source of energy, predominantly replacing electricity and gas [29]. Sun et al. also focus on the demand side and calculate the marginal costs of a district heating system in order to construct a basis for developing a new dynamic pricing mechanism [31]. Sjödin and Henning use the marginal costs approach to analyze changes in energy carrier prices and to derive recommendations with regard to demand-side mobilization (i.e. time-of-use pricing) [32]. Zhang et al. analyze a pricing model for the heat supply side; this model is also marginal cost oriented but includes a second market for capacity, covering the fixed costs; thus, the model is hardly applicable for European company-operated district heating networks [33].

2. Method

In the following, the basic assumptions and methods are described.

2.1. Assumptions

The intention of the paper is to design the marginal cost curve of a local network's heat generation which we call "Heat Merit Order". It shall enable companies to evaluate the feed-in of waste heat into a district heating system. Thus, it is assumed that a district heating system exists and that it has sufficient heat generation units/capacity at its deposal.

As explained in the introduction, "waste heat" is complex to be defined and its existence does not automatically imply technical and economic usability. As the Heat Merit Order evaluates the waste heat from an economic perspective, it is assumed that the preconditions are met, in other words it is assumed that the waste heat, which is intended to be fed in, meets the requirements of the heating network in terms of temperature, water quality, pressure, etc.

2.2. Microeconomic theory-based assessment

In a first step, a sound basis must be set up for the application of the Heat Merit Order. The main actors (i.e. the district heating operator and the industry/third party willing to feed in) are described. It is explained how they act on the market and how they earn money. In a microeconomic theory assessment, their intentions are identified and, based on these, their incentives and expected actions are derived. It will be shown that the Heat Merit Order directly reflects these intentions and actions.

2.3. Expert interviews

Expert interviews were conducted in order to receive feedback on the results elaborated during desk research. Interviews were conducted with six Austrian companies which considered or intended to feed (more) waste heat into the local district heating networks. The companies belong to different industry branches: steel making, foundry, petrochemicals, chemicals, food & beverages, pulp & paper. Further interviews were conducted with four major Austrian district heating system operators.

3. Description of main actors: situation and intention

This chapter presents the interests of the two main players. From this, their ideal-type decisions are derived.

3.1. Situation of the industry/third party willing to feed in

The industry with technical waste heat potentials is the third party willing to feed in. The heat source is located at the company's site/property.

Profit maximization. Private companies are aiming to maximize profit and minimize costs. Even if a private enterprise is restricted by regulation (for example, with regard to environmental or market issues), the company aims for profit maximization and cost minimization within the given limitations [28].

Scope of core business. The argument of profit maximization and cost minimization implies that an industrial enterprise wants to utilize its waste heat potential to achieve additional income and reduce net energy costs, even if this is not its core business or core competency. Depending on the temperature level, the waste heat provision for district heating competes with potential other uses, e.g. as electricity or internal process or heating energy. If these potentials are maximized or ruled-out, still, some major limitations were identified. These limitations differ in their intensity depending on the size, situation and culture of the enterprise. The following barriers for waste heat recovery in industries are identified as the most relevant ones among others [34]:

- Information deficits: unknown waste heat sources, unknown heat sinks, unknown revenue potentials. Moreover, the potentials of optimization of sub-processes are hardly considered with regard to external waste heat usage.
- Restrictions with regard to human resources: availability and responsibility of staff.
- Guaranteed continuation of the core process, which ensures the economic viability of the company. Payback of waste heat recovery must be guaranteed before the core processes'/plants' expected end of life. Industrial enterprises usually wish to provide waste heat whenever it is available and expect remuneration. They do not intend to guarantee feed-in at a certain point of time and for a certain minimum period.
- Indirect costs associated with system changes, e.g. the need to redesign the installation in accordance with the IED Directive 2010/75/EU.

Payback periods. Due to their international orientation, industrial enterprises are exposed to price developments on the international commodity and sales markets and thus to high market pressure. The price risks are reflected in the owners' high expectations on return. For investments outside the core process, minimum amortization times between one and seven years are required, with three years being mentioned most often in the expert interviews (depending on company, site, and size of waste heat stream).

In many businesses, a large part of the total costs is associated with the operation of the plant; if variable costs change, operation is adopted. However, waste heat recovery and usage are almost exclusively associated with investment costs and therefore fixed costs. Market or price changes cannot be cushioned by an intensified or reduced operation of the plant. The initial investment costs ("upfront costs") are therefore subject to market risks, which increase the requirement for short payback periods (risky investments usually offer higher interest rates). Of course, operation is expected to continue after the payback period so that the investment is profitable.

Economic theory often describes capital as a perfectly mobile production factor. Capital is thus given to the investment which promises the best return on investment, with due regard for all risks. In practice, companies make investments with up to 15 years of amortization. In the areas of energy efficiency and waste heat recovery, the above-mentioned three years usually apply. From a research point of view, this raises the question of whether there are really high risks, which can explain these differences, or whether other market and non-market barriers exist. Some projects are currently elaborating this issue (e.g. TrustEE https://www.trust-ee.eu/).

Summary. Industrial enterprises are willing to invest when their (expected) sales are greater than costs. However, the calculation period is short as payback periods of usually approximately three (one to seven) years apply. Additionally, risks need to be considered.

3.2. District heating company

The district heating operator owns the district heating network and supplies the end-users. In most cases, the operator owns the heat generation units and conducts the heat sales activity. To be precise, it is assumed that the district heating operator is a private company which is vertically integrated, i.e. owns the heat generation units, the network and does the sales business.

Profit maximization. Private companies are aiming to maximize profit and minimize costs. Even if the company is owned by the local/regional government (as it applies for the largest operators in Austria) or is restricted by regulation (as it applies with regard to customer pricing in Austria, c. f. prize law 1992) an enterprise aims for profit maximization and cost minimization within the given limitations [28]. Of course, companies in public ownership are subject to (political) objectives, implying that there is some trade-off between the political aims of the owner and the company's profits. However, the argument of cost minimization implies that a heat network operator accepts a third party feeding in heat if this has a positive effect on the profit and cost development of the vertically integrated company. In other words, the net benefit of all steps in the supply chain are considered.

Network cost recovery. The costs of the district heating network must be recovered via network charges or as an integral part of end-user prizes. These costs include investment and running costs. Otherwise, no long-term operation of the heating network is possible for economic reasons, and thus no integration of the waste heat sources would be possible. Especially if any regulation is in place, the recovery of costs is essential for the district heating network. Similarly, the costs of the regulated European electricity and gas networks are recovered via network charges.

Security of supply. In the current status there is no statutory obligation of the heating network operator to guarantee the security of supply (at least in Austria [23]). The commitment to a secure supply results from the supply contracts with end customers or solely from the long-term economic interest of the heating network operator. In order to maintain security of supply, the feed-in of heat is not possible at every location of the heating network, and in any case, certain technical requirements must be met [37].

Backup capacity. As described above, it is assumed that the waste heat is fed into an existing district heating network. Thus it is to be assumed that sufficient generation capacities already exist. In order to maintain security of supply, the waste heat usage from an industrial company that does not guarantee the feed-in must go in parallel with the provision of adequate backup capacities. This backup can be provided by the existing generation plants (in particular the gas-fired plants).

Heat generation. The generation of heat is a core competency of most integrated district heating operators. More than that, these district heating operators are one branch of integrated (municipal) utility companies, which are also active at the electricity or gas market and can make use of interactions (e.g. cogeneration). Most of the heat generated over the entire year is currently being generated in combined heat and power (cogeneration) plants in most municipal district heating systems. Experts argue that up to a few years ago, electricity generation was the focus, with the residual heat generated being the “waste heat” of electricity generation. At the present time, or at least in the years around 2015, most of the cogeneration plants were operated for heat generation. In other words, the cogeneration plants were operated when district heating demand existed and not necessarily when electricity prices were high. In any case, the production of district heating represents a flexibility of the cogeneration system. If the electricity prices allow for a cost-covering generation of electricity with gas, district heating is an added value waste product. If the costs of electricity generation are not covered by electricity market revenues, district heating is an essential source of revenue for refinancing of the cogeneration plant.

Acceptance of feed-in. The district heating operator has the generating capacity necessary to meet the current (for example hourly) demand. Even if the demand is covered by third parties, these generation capacities are available (possibly as a backup). Therefore, the fixed costs of these plants are incurred, only the variable costs (fuel, variable operating costs) are avoided by the external feed. Consequently, a feed-in of one MWh by a third party is beneficial to the district heating operator if its cost is (at least minimally) below the variable cost of the most cost-effective existing generation plants. It should be noted that other criteria can be defined as part of the contractual solution: If the compensation for the feed-in is significantly more favorable than the variable costs, the district heating operator can in some cases also accept costs that are higher than the variable costs. Conforming to the above described requirements (profit maximization), there must be a positive net effect which results from the sum of the individual MWh benefits. From this perspective, the justification for applying the Heat Merit Order arises. The Heat Merit Order describes the marginal (variable) costs of the existing generation capacities and thus the maximum remuneration per MWh fed in from a third party.

Maintaining negotiation power. Heating network operators have a monopoly on the supply of heat as soon as the developer or owner of the apartment or the house has decided to connect to the district heating system. The existing connection creates a lock-in effect (as switching to another heating system causes sunk costs) which binds the end-users. Generally, in order to be economic, district heating aims to supply as many end-users as possible in a certain area. Ideally, one network operator is the local single supplier. This end-user monopoly creates a strong bargaining power for the heating network operator with regard to the feed-in of third parties. The bargaining power may result in the possibility of negotiating a higher share of the pension resulting from a third party feed-in. One district heating operator facing many third parties intending to feed-in corresponds to a monopsony situation. However, due to economies of scale and easier coordination, especially large alternative sources of heat are of economic interest. Thus, these few third parties which have economically interesting sources of heat also have strong bargaining power. Consequently, negotiations are expected to be “normal” business-to-business deals without a partner, who can generally be defined as dominant [27].

Payback periods. Non-regulated district heating operators have a high long-term security of the capital backflow due to long-term contracts with end-users and the local monopoly status. Thus, risks are low and experts mention maximum payback periods of ten to twelve years. District heating market regulation may increase the payback period as (i) it obliges companies to accept them, but also (ii) install a long-term perspective which minimizes risks (as it is the case for electricity network operators) [34]. The longer payback periods also imply longer planning horizons. The long-term development of heat demand over the coming years and decades is significant for investment decisions; policy makers should take into account the least-cost approach to decarbonize the building sector, which could be measures at the supply side via district heating instead of exclusive and expensive insulation measures and building standards at the demand side; note that insulation measures are necessary and buidlings may be technically able to cope with lower supply temperatures, [5,35]. However, the use of third party heat sources also means that there are short-term (process modification) or medium-term (relocation of site) risks, jeopardizing economic feasibility and long-term security of supply. Thus, also district heating operators require to face short payback periods when evaluating industrial waste heat feed-in. District heating market regulation may define how to handle these risks. The interviewed experts did not commit themselves: The expectation depends on the current status of the industrial enterprise, for example, whether in recent years or currently a large investment in the site has been made. (On the basis of said periods of two to eight years, a period of about five years can be assumed.) The maximum remuneration within this payback period is derived from the sum of maximum current remunerations for one MWh, which is described by the Heat Merit Order.

Summary. The district heating operator’s existing heat generation capacities must remain as these capacities are used as backup and depreciation of capacities is guaranteed (no sunk costs). Given these requirements, the maximum remuneration for a third party feed-in is defined by the variable/marginal costs of the district heating operator’s existing capacities. Marginal costs of individual plants can change, reflecting the input energy carriers’ current market prices. Moreover, 15-min electricity prices influence the marginal heat costs when heat is generated in cogeneration plants. Finally, the cost-benefit-analysis of accepting a third party feed-in considers risks and expected differences in the costs of network operation.

4. Designing the Heat Merit Order

The order of operation of the electricity power plants is called the “merit order”. The order is determined by the marginal costs of electricity generation. Based on this denomination, in this paper the order of operation of the heat generation units is referred to as a “Heat Merit Order”. Thus, analogously, the order of operation is determined by the marginal cost. From an economic theory point of view, the Heat Merit Order is the short-term supply curve/marginal cost curve for the local district heating market [28].

There are various examples of applying the merit order curve in research, e.g. for analyzing the impact of renewables, see Ref. [38,39], or energy efficiency [40] on the spot power market. A similar application and method of constructing a cost curve is McKinsey’s greenhouse gas abatement cost curve [41]. From these examples, the following descriptions/explanations of marginal cost curves are derived:

As with all cost curves, the vertical axis depicts the price. The unit of the horizontal axis is MW, which is the current output, not the amount of energy (MWh). This designation is due to the rapid change of influencing parameters: On the European electricity market, the usual time interval is 15 min; as both markets are linked through combined heat and power (cogeneration) plants, this time interval is also transferred to the supply curve of the district heating market. Consequently, MW is used as the horizontal axis unit, although MWh per 15 min would be more accurate.

The merit order curve ranks the generation units according to their current variable costs, starting at the left with the least cost unit. In economic theory, usually a very high number of market participants is assumed. As a result, individual generation units are no longer visible and the single supplier "disappears" in a steadily increasing line. Due to the comprehensible number of relevant heat generating plants in a local district heating system, the individual generation units can be identified in the merit order curve. They are usually represented as a rectangle. One side of the rectangle is congruent to a part of the horizontal axis. The width of the rectangle indicates the "normal output" of the unit when it is operated. It is assumed that always this normal output is supplied, i.e. partial load operation is neglected. This is a simplification especially for heat generation units in district heating networks, which often have a low number of generation plants. Furthermore, the rectangular form assumes that the marginal cost of production is the same for the first and the last MW supplied by the plant.

Restrictions resulting from the general conditions of the market (in the energy sector these are mainly restrictions of the network) are ignored when creating the merit order curve. While the horizontal axis starts at zero, i.e. generation is always positive, prices may become negative. Prices vary, especially for the cogeneration plants, due to the rapid changes in energy (electricity) market prices (see below). Given the merit order curve, its intersection with demand defines a market clearing price. Due to the demand of the heat customers being unaffected by the market, demand is primarily temperature-dependent and easily calculable [32].

The current market clearing price defines the current value of heat. Every MWh fed into the district heating network is worth this price, even if generation costs are lower. (Of course, this is only true if the unit is left to the equilibrium.) The generation units cheaper than the market clearing price earn the producer surplus, which is the difference between the price and the unit's costs. The producer surplus serves to cover fixed costs and to generate profits [28].

4.1. Parameters of unit generation costs

The capacities of the heat generation plants are usually known. From this, the width of the rectangle can be deduced directly. For the representation of the single rectangle the calculation of the height is the central challenge: The variable costs of the heat generation plants are included in the marginal cost curve. The fixed costs of the heat generation plants are not included. Fixed costs are, in particular, the investment/erection costs, and also personnel, which is indispensable also during a standstill. The exclusion of fixed costs is also the essential difference of the Heat Merit Order approach to the LCOE approach (e.g. Ref. [42,43]).

The following variable cost parameters were identified and included in the development of the Heat Merit Order:

- Energy input costs of the heat generation unit (e.g. gas costs)
- Electricity output revenues of the cogeneration unit (e.g. electricity spot market)
- CO_2 certificate costs (e.g. emission trading scheme)
- Energy taxes: taxes on energy inputs (e.g. gas tax)
- Variable network tariffs for energy inputs (e.g. gas network)
- Variable network for energy outputs (e.g. electricity network)
- Costs directly linked to generation (e.g. disposal of ash, operation-dependent maintenance)
- Subsidies linked to the volume of energy consumed or produced (e.g. green electricity act subsidies for electricity produced in the biomass cogeneration plant)

Of course, the parameters were adjusted with the technology-specific conversion efficiencies. If these are not known for the local district heating system, values from literature must be used. All the cost and efficiency factors were combined by the authors in Microsoft Excel for all common generation technologies. In this file, a good overview is possible and the 122 parameters are easy to control or adapt to the specific district heating system. Furthermore, conversion factors are included. The above-mentioned parameters are summarized in Microsoft Excel, but calculation is to be preferred in a more method-oriented program when there are frequent changes (i.e. the electricity market influences the local Heat Merit Order). For example, the Heat Merit Order has already been applied using Matlab, [25,44].

4.2. Application: maximum waste heat investment costs

With the tool, it is possible to compare the savings from avoided energy carrier consumption or power plant operation with the exogenous investment costs on the basis of the marginal cost approach (merit order). Instead of evaluating if an implementation is profitable or not, it is derived how much the implementation is allowed to cost in order to be competitive. This takes into account the annual operating hours and the revenues generated/costs avoided during these hours.

A district heating system supplies a local market and has a unique network (size, loads, etc.) and set of heat generation units [45]. Thus, the merit order must be created individually for each district heating network. However, a potential investment of recovering industrial waste heat and feeding it in a district heating system is case-specific.

The current heat generation price, made transparent by the Heat Merit Order, minus the variable costs of the waste heat, equal the 15 min producer surplus. The accumulated 15 min producer surpluses result in the contribution margin over one year. The contribution margin is used to pay back the fixed costs. Based on the maximum payback period required by the investor, the added up annual (discounted) contribution margins equal the maximum investment. Thus, the output of the economic analysis are maximum feasible investment cost. (For another paper choosing the same approach for company-internal investments in waste heat recovery and reuse see Ref. [30].)

As it is true for any other investment decision, the realization of a waste heat feed-in project is subject to the risk of input energy price changes (or electricity price changes when cogeneration plants are present). This may lead to disruptions with regard to the position of the waste heat feed-in in the Heat Merit Order. In practice, high electricity prices lead to low or negative waste heat costs. This power plant excess heat may eliminate the demand for third party/industrial waste heat. However, the Heat Merit Order can support decision making as it allows to estimate the impacts of price changes.

5. Case study Linz/Austria

In the following, the Heat Merit Order will be exemplarily applied for a case study. The information presented has been derived from two project reports and one reviewed paper (see Refs. [23,25,46]). Linz is Austria's third-largest city with 200,000 inhabitants. Linz is one of Austria's major industrial areas. The energy consumption of the companies located in Linz is approximately 30 TWh. As of 2016, 70% of households are connected to the district heating system of the two local suppliers. This paper focuses on the network of the main supplier, which accounts for 1.1 TWh/a or 80–90% of energy provided via district heating in Linz. The "Linz Mitte" heat generation park comprises one waste incineration cogeneration plant, one biomass cogeneration plant, two gas-fired cogeneration plants and three gas boilers. For simplicity, but almost according to the real values, the waste incineration plant and the biomass cogeneration plant each have 35 MW thermal output. Electricity generation by the biomass cogeneration plant has been subsidised by the federal government. Also simplifying, but almost equivalent to reality, the heat generation capacity of the two gas-fired cogeneration plants is assumed to be 100 each. The three boilers are assumed to generate 35 MW each.

The data on the parameters were collected in 2015. In the fictitious calculation, temperature-based demand of the year 2012 was used. The waste incineration plant shows negative variable costs as it earns money for the waste burned. The electricity generation of the biomass cogeneration is subsidised, but revenues from district heating are important for economic profitability. The variable heat costs of the gas-fired cogeneration plants depend heavily on the electricity market. They are negative if electricity prices are high enough. However, at the time of analysis, market prices were low and the cogeneration plants' variable heat costs were positive most of the year. The gas boilers, being subject to energy taxation, showed the highest variable costs.

The network-specific Heat Merit Order was developed to analyze a potential project: 40 MW of waste heat from industry could be fed in. The variable costs (here alternative revenues) of feeding in the waste heat were low. Thus, the waste heat would have been the second cheapest heat source, just after the waste incineration plant (or third, depending on the position of the gas-fired cogeneration units). Fig. 1 shows the most common position of the gas cogeneration plants in winter based on the 2015 parameters. Fig. 2 shows the position of the gas cogeneration plants in those (few) hours the electricity prices were high. Fig. 3 shows a peak demand situation in winter. Fig. 4 shows how demand is satisfied usually in the summer months, i.e. with variable costs around zero. Fig. 5 shows a summer situation when waste heat is valuable as the waste incineration CHP and the biomass CHP plant undergo maintenance.

Based on the 15-min extracts of the Linz Heat Merit Order, shown in Figs. 1–5, the following implications are derived:

- Figs. 4 and 5: It is not possible to feed in the waste heat in summer. The must-run waste incineration plant covers summer demand. In summer, no contributions to payback the waste heat investment can be achieved. One exemption is when the waste incineration plant and/or the biomass CHP plant undergo maintenance.
- Fig. 1: It is possible to feed in the full capacity of waste heat in the usual winter situation. In the Linz case and given the year 2015 data, feed-in was possible 5000 h per year.
- Fig. 2: The investment is subject to high risks with regard to changes at the electricity market. If prices are high in the long term, there will be no feed-in even in winter.
- Fig. 3: Especially during peak demand on cold winter days, waste heat is definitely accepted due to the high costs of heat-only-boilers.

The producer surplus calculated based on the Linz Heat Merit Order and the year 2015 data was approximately, on average, 12.5 euros/MWh fed in. Given the hours/year and the capacity, a contribution margin of 2.5 million euros per year can be achieved. If a payback period of four years is required (combining the requirements of industry and district heating operator), approximately 10 million euros can be invested.

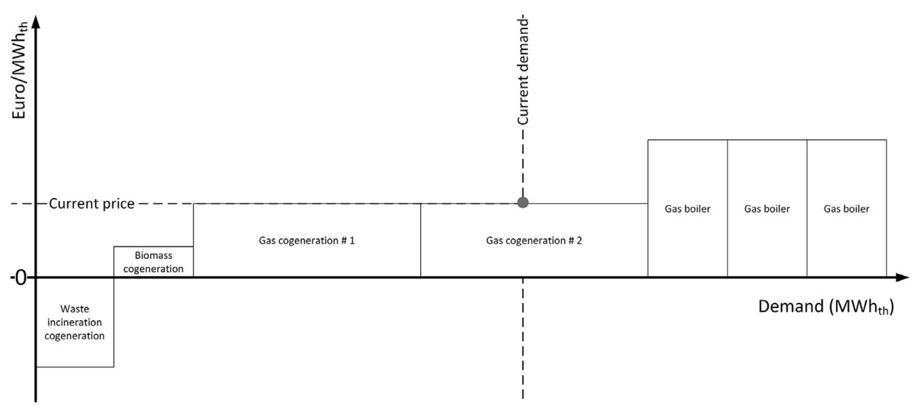

Fig. 1. The predominant 15-min "Linz Mitte" Heat Merit Order in winter months. Status of parameters: 2015.

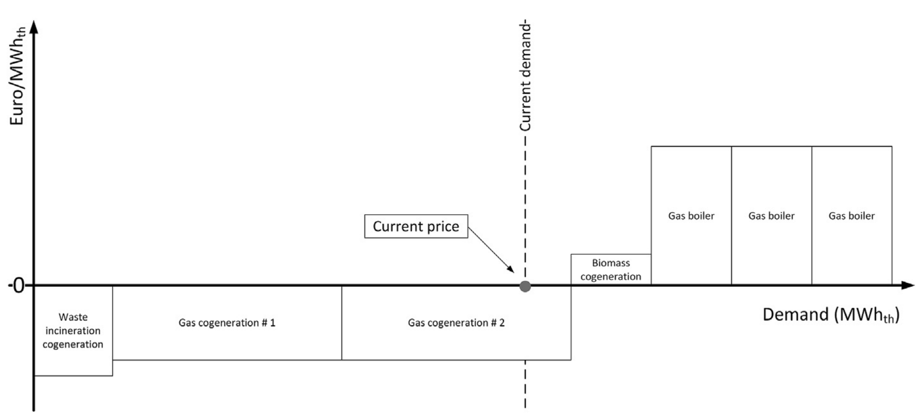

Fig. 2. The 15-min "Linz Mitte" Heat Merit Order curve when electricity prices shift gas-fired CHP to the second rank. Status of parameters: 2015.

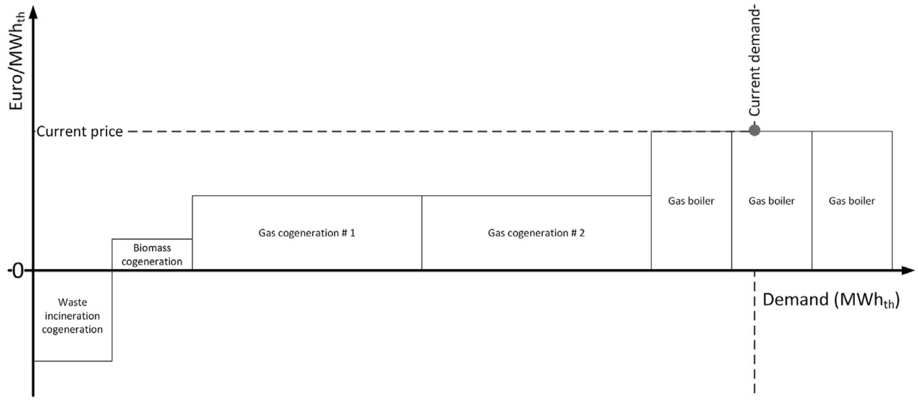

Fig. 3. The 15-min “Linz Mitte” Heat Merit Order curve in winter peak. Status of parameters: 2015.

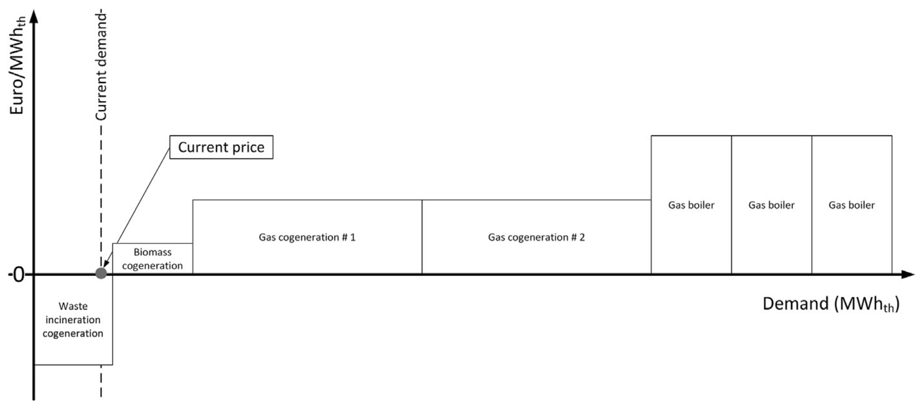

Fig. 4. The 15-min “Linz Mitte” Heat Merit Order curve in mid-summer. Status of parameters: 2015.

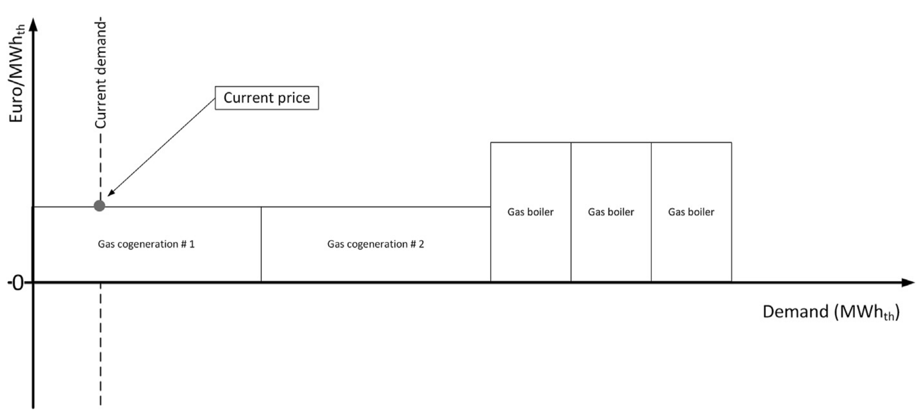

Fig. 5. The 15-min “Linz Mitte” Heat Merit Order curve in mid-summer when the low-cost CHP plants undergo maintenance. Status of parameters: 2015.

6. Conclusions

To make marginal generation costs transparent, a “Heat Merit Order” is constructed. Based on conversion factors, fuel prices, network tariffs, etc. the maximum remuneration payed by the district heating operator at a certain point of time is made calculable. For a theoretic case study example, the applicability of the Heat Merit Order to estimate maximum costs of waste heat utilization is proven. Based on these previous steps the following conclusions can be derived:

1. The Heat Merit Order makes local heat generation prices transparent and allows to calculate the profitability of waste heat, other heat sources and storages.

Designing the Heat Merit Order is an effective approach to overcome the missing transparency of heat generation prices in the local district heating network. Therefore, the Heat Merit Order is not only applicable to industrial waste heat, but for the feed-in of any potential third party. These may include, for example, biomass cogeneration or heat from solar thermal plants. (Seasonal) heat storages use low-cost energy in order to provide the energy again when prices/costs are higher. Thus, the Heat Merit Order also is an effective tool to evaluate the profitability of heat storage systems (for applying the Heat Merit Order on heat storages, see Ref. [25,44]).

2. The Heat Merit Order enables companies to estimate the value of their waste heat and if investments are profitable.

The “forward approach” for an industrial company is to determine and proclaim estimated investments costs of waste heat recovery and making it useable. Based on these, in order to be profitable, a minimum kWh remuneration is derived based on the volume fed in. However, many companies hesitate to proclaim estimated investment costs as in bilateral negotiations, proclaiming the minimum remuneration necessary may be disadvantageous. As district heating operators intend to pay as little as possible for the waste heat and are likely to recognize waste heat as a source with variable costs of zero, their remuneration offer is likely to be too low.

Using the “backward approach” by designing the local Heat Merit Order and deriving the maximum investment costs, the industrial company has available a mighty tool to compare its estimated investments costs and thus the profitability of waste heat delivery. In conclusion, the Heat Merit Order can be applied by many companies which have excess heat to estimate their waste heat valorization potential and to become active towards cooperation.

3. In general, the Heat Merit Order avoids information asymmetries and thus indirectly supports the efficiency and penetration of district heating.

Ideally, the Heat Merit Order will contribute to enforcing waste heat usage and industry awareness. In addition, district heating network operators can proactively search for cost-effective waste heat sources by publishing the quarter hourly “feed-in tariffs”. The Stockholm “Open District Heating” (www.opendistrictheating.com) project is market-going and exactly follows this approach by publishing the hourly feed-in remuneration one day in advance. Authorities and policy makers may consider to enforce publishing the current variable generation costs as economic theory states that markets work best when information is transparent to all participants. Thus the availability of the Heat Merit Order indirectly contributes to district heating efficiency and penetration.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This paper resulted from a research project funded by the Austrian Ministry for Transport, Innovation and Technology (grant number 845161), a research project funded by the Austrian Climate and Energy Funds (grant number 853169), and a research project funded by the state of Upper Austria (‘Fernwärme-Übertragungsnetze’).

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