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Research paper

Bidding strategies for excess heat producers participating in a local wholesale heat market

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ABSTRACT

The heating sector of the European Union covers 80% of the household's final energy consumption, which shows its relevance for the energy transition to the carbon neutral society, as set out in the Green Deal. Since most of the heat demand is located in the high heat density areas, district heating shows to be a promising solution for reducing the environmental impact of this sector, as it enables the utilisation of renewable energy sources and the use of high efficiency production technologies. An especially interesting source for district heating is excess heat from various industries and tertiary sector buildings, which has a significant technical potential. However, to enable excess heat producers to supply their heat to district heating, third-party access needs to be granted, which calls for a deregulated heat market.

This work consists of analysing two different bidding strategies which can be applied on the heat market: total cost and marginal cost biding. The focus here is to research the feasibility of the excess heat sources when different bidding strategies are used, especially when low temperature excess heat is considered, which has variable hourly costs due to the electricity demand for operating a heat pump. The results show that, despite the increased capacity factor of low temperature excess heat when marginal cost biding is used, it remains infeasible when supplying heat to the high temperature district heating networks through a heat market. Therefore, lower temperature district heating is a necessity for a feasible utilisation of low temperature excess heat. Finally, the effect of the power market prices on the low temperature excess heat feasibility was analysed and it was shown that it is significant, which led to the conclusion that introducing a higher share of renewables into the power market could foster the utilisation of these heat sources.

1. Introduction

At the end of 2019 European Commission published the Green Deal, the plan to make the economy of the European Union sustainable (European Commission, 2019). This includes reducing the net greenhouse gases emissions to net zero levels, which cannot be achieved without the decarbonisation of the energy sector and specifically the heating sector, which is responsible for almost 80% of the final energy consumption in buildings (European Commission, 2021). District heating, especially when integrated with renewables and excess heat, is an obvious solution for decreasing the environmental impact of the heating sector and as such has been recognised by the Commission in the EU Strategy on Heating and Cooling (European Commission, 2016). This shows the potential and the need for further exploration of the low cost and low emission sources for district heating. Previous research has indicated that increasing the share of such systems would reduce indirect and direct heating system costs, while decreasing the emissions of the pollutants, with the optimal share being 70% for a country like Denmark (Lund et al., 2010). On the other hand, currently only around 13% of the overall heat demand in Europe is covered by district heating (Connolly et al., 2014) and the shares differ significantly depending on the geographical location. While northern and central Europe have higher shares, southern European countries like Spain lag behind despite the recent advances and the analysed potential (Balboa-Fernández et al., 2020). Also, there is a high diversity of energy sources currently being used, with a number of systems still using fossil fuels and high temperature networks resulting in considerable losses, the so called 2nd and 3rd generation (Čulig-Tokić et al., 2015). Other systems, especially in northern Europe, are much more developed and use significant shares of renewables, have low temperature networks and can be generally classified as 4th generation district heating (Sorknæs et al., 2020). Even the 5th

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generation is already being increasingly mentioned, as a system which has ultra-low temperature levels and which can therefore utilise low temperature sources (Lund et al., 2021) and provide bidirectional flow (Bilardo et al., 2021). Such sources are usually renewables, in the form of solar thermal or geothermal (Rutz et al., 2017, 2019).

However, another interesting source is excess heat from various activities, such as industrial processes, service sector buildings, data centres, etc. It may not be renewable at its source, but if not used in district heating, this heat would be wasted nonetheless and therefore it can be argued that it is neutral from the environmental perspective. It has already been shown that excess heat has a significant potential, when utilised from the industrial facilities (Papapetrou et al., 2018), thermal power plants (Colmenar-santos et al., 2016) or the low temperature sources such as service sector (Lygnerud et al., 2019). The benefits are considerable, from the environmental, as pointed out in the case of Sweden (Broberg Viklund and Johansson, 2014), but also from the economic perspective in certain cases. For example, it was shown that industrial excess heat, that has a temperature high enough to be utilised directly through the heat exchanger, can be feasibly utilised even if it is located several kilometres from the heat network (Doračić et al., 2018). On the other hand, the feasibility of excess heat source decreases with its temperature level, as shown in Doračić et al. (2020b), which brings in question the viability of low temperature sources, such as service sector facilities, in the existing 2nd and 3rd generation systems. Another issue which arises by using these sources is their low utilisation rate if the variable availability of the source is considered, which calls for the use of thermal storage systems, as shown by Fitó et al. (2020) and Doračić et al. (2020a). Additionally, in Doračić et al. (2020a) it was specifically concluded that thermal storage units used for increasing the excess heat capacity factor have a seasonal character due to non-decreasing availability of excess heat during the summer on the one hand and low heat demands on the other.

For excess heat to be utilised in district heating, usually there is a need for enabling third-party access, which requires a deregulated heat market. Currently, this is in most systems not the case since they are regulated as monopolies, which results in one utility being responsible for the whole process (Stennikov and Penkovskii, 2020). However, deregulation would facilitate competition, which in turn would enable a decreased environmental impact of the sector due to the penetration of cheaper renewable technologies and consequently lower prices. This was already shown in some countries like Lithuania (Jonynas et al., 2020) and Denmark (Bürger et al., 2019). The focus of this paper is on the implementation of the wholesale day-ahead heat market, which was developed as a model in the authors previous research (Doračić et al., 2021) and was already shown to be a good facilitator for adding new players, such as excess heat, to the existing systems. Still, to potentiate the feasible utilisation of various production units, in Doračić et al. (2021) authors considered only the total costs when defining the bidding prices. Total cost bidding was already proven as a good solution for increased feasibility of market producers in the power markets in Van Bracht et al. (2017), where authors debate using this approach for bidding on the European power markets due to the aforementioned reasons. They point out that in literature, power markets are usually modelled by utilising marginal cost bidding, but the situation in the real markets is different and incorporates strategic bidding. Similar statements are made in (Hogan, 2017), where it is argued that improved bidding strategies should be prioritised to decrease the impact of the missing money problem, a well-known issue in the power markets (Woo et al., 2019). In terms of heat markets, to the best knowledge of authors, total cost bidding has only been proposed and studied in Doračić et al. (2021). On the other hand, marginal cost bidding is the most widely used bidding strategy due to the reduced requirement of input data and consequently the simplicity. Heat markets are seldomly researched so far and are mostly modelled by using marginal cost bidding. For example, in Liu et al. (2019) authors use marginal cost pricing to simulate the heat market in the Plexos model, while in Moser et al. (2020) marginal cost was used to design the heat merit order to make the production costs transparent. However, the differences between the two bidding strategies on the heat market have not been studied so far. This is especially relevant from the perspective of the merit order of technologies with variable bidding prices, like low temperature excess heat sources, whose capacity factor and subsequently feasibility could significantly change in case of a different bidding strategy. Therefore, the key contributions of this paper are as follows:

- Total cost bidding is compared to the marginal cost bidding on the day ahead heat market by using the DARKO model to define the benefits of each bidding strategy from the producer and consumer side
- The impact of different bidding strategies on the utilisation of low temperature excess heat on such a market is analysed, focusing on the effect on the merit order due to its bidding price variability
- The impact of the electricity market prices on the bidding price of low temperature excess heat is studied, considering four consecutive years: from 2017 to 2020

2. Method

2.1. Day-ahead market clearing model

In this study an advanced open source (Pfenninger et al., 2017) day-ahead market clearing model DARKO (Pavičević, 2020) is used for optimal matching of the demand bids and supply offers under the total welfare maximisation principle. In the previous research of the authors (Doračić et al., 2021), the model was already validated and the results showed that such a heat market would facilitate the addition of new heat generation capacities such as excess heat or solar thermal and would decrease the final cost for the demand-side. On a further note, the additional benefit of implementing the heat market through the DARKO model was shown in the form of a positive total welfare for all the scenarios. This model features various market order types on demand and supply side under complex set of rules. E.g., heat market participants are allowed to place two different kinds of orders: complex (block and flexible orders) and simple orders. Furthermore, the market operator can optimally allocate the available storage capacities for additional increase of the social welfare through presence of storage orders and accompanying operational constraints. Topological features of the model are presented in Fig. 1. Bidding areas are linked by interconnections (lines) each representing a given topology. Energy between neighbouring areas can only flow through these lines. Lines are oriented from source to sink bidding areas (i.e. A->B, B->C etc.). A positive value indicates a flow from A->B whereas a negative value indicates a flow from B->A (the numbers in brackets of Fig. 1 represent examples of energy flows in MWh, to make it clearer for the reader). Lines are limited by the available transfer capacity (ATC), and other restrictions such as losses, tariffs, and flow variation between two consecutive hours or optimisation horizons (i.e. hourly/daily flow ramping rates). The ATC, mimicking energy flows between different zones; net positions, the upper and lower bounds on the market clearing fluctuations between consecutive time intervals; and zonal ramping rates, the increase or reduction in zonal output per minute, are limited on both hourly and daily basis. Moreover,

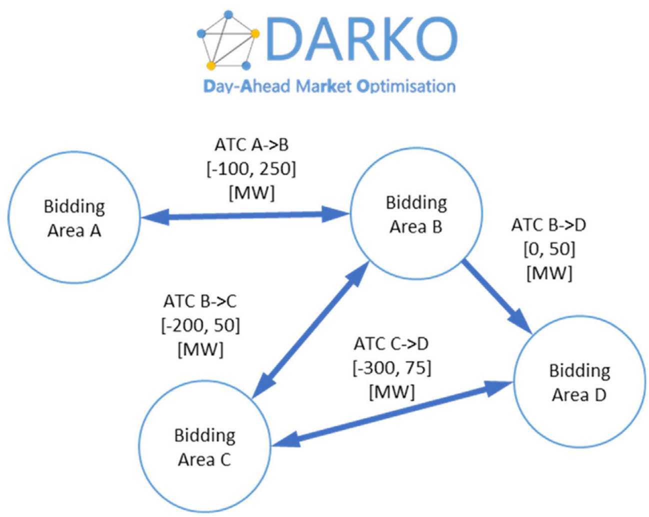

Fig. 1. ATC topology of the DARKO model.

the energy transactions between supply and demand orders from different bidding zones are encouraged and limited only by the network constraints (electricity, heat, gas etc.).

Formation of the intra zonal and intra temporal price equilibrium is presented in Fig. 2. Intra zonal price equilibrium can only be achieved if the ATC is sufficiently high to transfer excess production from a "cheaper" bidding area to the "more expensive" bidding area. Intra temporal price equilibrium can only be guaranteed if storage capacities inside the zones and ATC capacities between neighbouring zones are high enough to allow for price and energy shifts between them (i.e. if bidding zone A has an excess production of e.g. 100 MWh at the price of 10 €/MWh at time interval t = i after markets A and B are coupled and local storage is sufficient to store this excess "cheap" energy, this energy can be dispatched later on in time interval t = i+n at the price of 10€/MWh when the market clearing price is higher and energy required to achieve market coupling is equal to or lower than 100 MWh.).

For simplicity reasons, only the objective function and power balance constraints relevant for this study are assessed in the upcoming chapters. A more detailed explanation of the model and all the modelling constraints is presented in Doračić et al. (2021), Sebestyén et al. (2020) and Pavičević (2020).

2.1.1. Objective function

It is necessary to solve a Social Welfare Maximization Problem (SWMP) in order to obtain the market clearing price (MCP) in the wholesale day-ahead heat market. This must be done under the certain set of operational and storage related constraints which have to be followed at each time period in the optimisation horizon. As of today, energy markets which include storage orders do not exist. However, these can be fully exploited by the district heating sector, since the flows of energy, i.e. heat, between the production and consumption side are not instant due to the occurrence of thermal inertia in the distribution network. The objective function of the DARKO model is formulated as the Mixed Integer Linear Programming (MILP) problem with the aim of maximising the total social welfare w_{tot}, under the set of different primal decision variables: $V = \left\{x_{do}^i, x_{so}^i, f_l^i, p_n^t, p_n^{\prime t}, Q\_in_s^i, Q\_out_s^i, s\_lev_s^i, s\_spill_s^i, s\_ll_s\right\}$:

$$\max w_{tot} = c^{do} - c^{so} \qquad v \in V \tag{1}$$

Two functions comprise the total social welfare: First is the overall cost function of hourly demand orders:

$$c^{do} = \sum_{d\in D}\sum_{o\in O}\sum_{i\in I}\left(P_{do}^i Q_{do}^i x_{do}^i\right) \tag{2}$$

where, P_{do}^i, Q_{do}^i represent price quantity pairs of various demand orders in the trading period *i*. These are expressed in €/MWh and MWh, respectively. Furthermore, x_{do}^i represents the demand orders acceptance ratio in trading period i (%). Second function is the overall cost function of simple hourly orders:

$$c^{so} = \sum_{s\in S}\sum_{o\in O}\sum_{i\in I}\left(P_{so}^i Q_{so}^i x_{so}^i\right) \tag{3}$$

where, P_{so}^i, Q_{so}^i represent price quantity pairs of various simple orders in the trading period *i*. These are expressed in €/MWh and MWh, respectively. Furthermore, x_{so}^i represents the simple orders acceptance ratio in trading period i (%). Here it has to be noted that the demand quantities are always presented as negative values and the supply quantities as positive values, due to SWMP. Despite the fact that multiple types of orders can be calculated with the DARKO model (i.e. simple, block, flexible orders), the analysed heat market producers have no requirements for block production and therefore are bidding as simple order units on the heat market. Simple orders are the most flexible type of orders since their acceptance ratio (i.e., quantity supplied to the market) can have any value between 0 and maximum quantity being offered.

2.1.2. Power balance constraints

In this study, three power balance constraints are applied for different nodes, i.e. zones. Local production is calculated through the net position of the bidding zone n in the trade period *i*. Optimal decisions on thermal storage charging, if such a storage is available, are also made by considering this constraint. Heat is therefore stored in thermal storage in order to be used when more beneficial market situation is achieved. The variables in square brackets present the dual values, i.e. Lagrange multipliers, which are used to derivate the market clearing prices (MCP), which define the price at which the market is cleared, i.e., where the supply cost and demand cost curves cross.

$$p_n^i = \sum_{d\in D_n}\sum_{o\in O}\left(Q_{do}^i x_{do}^i\right) + \sum_{st\in ST_n}\left(Q_{in\,st}^{\;i}\right) - \sum_{s\in S_n}\sum_{o\in O}\left(Q_{so}^i x_{so}^i\right) - \sum_{st\in ST_n}\left(Q_{out\,st}^{\;i}\right) \quad \forall n \in N, i \in I \quad [\pi_{1\,n}^{\;i}] \tag{4}$$

To consider the energy flows between the adjoining zones, the temporary difference is calculated through the temporary net position of the bidding zone *n* in the trade period *i*. When there is a high enough interconnection capacity between two zones, it is expected that the MCP in these zones will be equal. This means the cheaper zone supply bids would satisfy the more expensive zone demand in case of a high enough interconnection capacities and surplus heat production capacities between the two zones. This can be presented by the following equations:

$$p_n^{\prime i} = -\sum_{l\in L_n}\left(f_l^i\right) \quad \forall n \in N, i \in I \quad [\pi_{2\,n}^{\;i}] \tag{5}$$

$$p_n^i - p_n^{\prime i} = -\sum_{l\in L_n}\left(f_l^i\right) \quad \forall n \in N, i \in I \quad [\pi_{3\,n}^{\;i}]$$

Finally, it needs to be mentioned that the temporary net position of two zones which are not connected equals to zero.

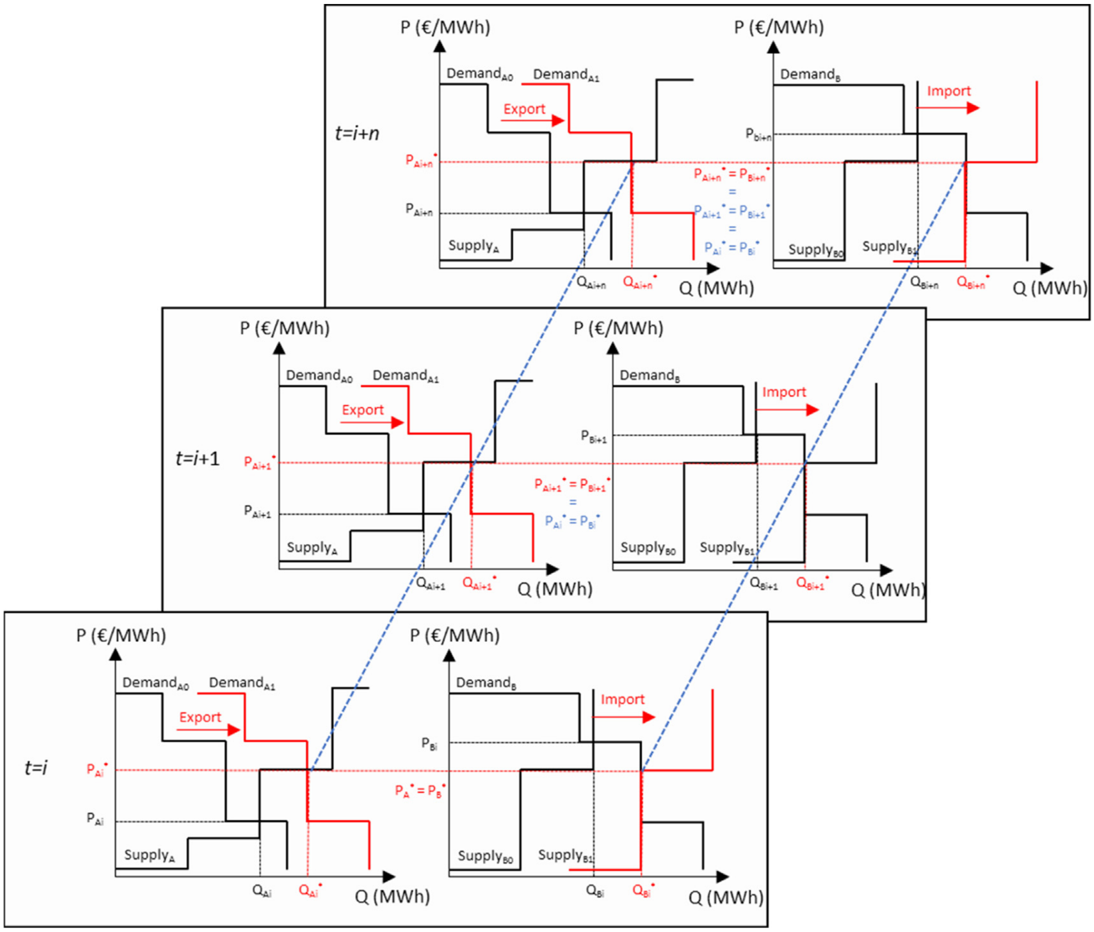

Fig. 2. Intra-zonal and intra-temporal price equilibrium formation in DARKO model. Red lines indicate shifts in the demand and supply orders due to available interconnections and blue lines indicate intra temporal price equilibrium due to storage. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Biding price formation

As mentioned earlier, two biding strategies will be analysed in this paper: total cost biding and marginal cost biding. In a case of a day-ahead power market, the majority of papers and simulations use marginal cost biding, for example Ma et al. (2020), Nitsch et al. (2021) and Banaei et al. (2021). However, it must be noted that the real bids on the market are not necessarily formed by using marginal costs, as debated in Van Bracht et al. (2017). They conclude that strategic biding is observed on the real power markets and therefore analyse different biding strategies, including total cost biding, marginal cost biding, next cluster biding and oligopoly biding as the means of ensuring the feasibility of the producers. Heating sector especially has its specifics which affect the possible biding strategies, as well as the profitability of the producers on such a heat market. Overall, it can be argued that heat market participants have limited additional income stream opportunities due to the lack of reserve markets where these producers could offer ancillary services, as opposed to the electricity market. Additionally, district heating are typically isolated, local systems which supply heat to separate cities or neighbourhoods, hence there are no opportunities for heat exchange between different regions and/or countries. Due to these reasons, total cost biding was used as a biding strategy in the previous work of authors (Doračić et al., 2021), but it is still necessary to compare it to marginal cost biding in terms of economic and energy parameters.

2.2.1. Total cost bidding

Total cost bids are calculated by considering all the costs associated to the individual technology, including the discounted investment, variable and fixed operation and maintenance costs and the costs for fuel. The equation is provided below.

$$c_{total\ cost} = \frac{I \cdot d}{8760 \cdot \left(1 - (1+d)^{-N}\right)} + \frac{O_{fixed}}{8760} + O_{variable} + c_{fuel} \qquad (6)$$

In the above equation, I are the investment costs in €/MW, d is the discount rate in %, N is the technology lifetime in years, O_{fixed} are fixed operation and maintenance costs in €/MW, $O_{variable}$ are variable operation and maintenance costs in €/MWh and c_{fuel} are fuel costs expressed per unit of heat in €/MWh. By taking into account all the discounted costs during the technology lifetime, total cost bidding contributes to the maximum feasibility of the producers participating on the heat market. On the other hand, this bidding strategy results in highest costs for the heat buyers, due to higher achieved market clearing prices on the market. Since the capacity factor of each production unit is not known at this stage, total costs are calculated by assuming the maximum production from all producers. As can be seen in the above equation, all the investment costs are discounted by taking into account the discount rate and the lifetime of each technology. The discount rate for all the technologies was assumed at 8% (Liu et al., 2019)

2.2.2. Marginal cost bidding

On the other hand, marginal cost bids are calculated by considering only the variable costs required to produce an additional unit of heat. The equation is provided below.

$$c_{marginal\ cost} = O_{variable} + c_{fuel} \quad (7)$$

It must be noted that the fuel costs represent the electricity costs in the case of low temperature excess heat sources, due to the need for a heat pump. However, these costs must be expressed per unit of heat, by taking into account the coefficient of performance of the heat pump, as explained in the previous work of authors (Doračić et al., 2020b). When compared to total cost bidding, marginal cost bidding results in lower feasibility of the producers but also lower costs for the heat buyers. However, this depends on the specific technology and has a higher effect on the low fuel cost technologies. In case of high fuel costs, the difference between total cost and marginal cost bids is significantly lower, as will be seen in the results section. Economic data for calculating the bids is provided in Table 1, while the resulting bids are shown in Section 3.

2.3. Numerical example

The numerical example has been used to analyse different biding strategies and their effect on the operation of the system in general and specifically low temperature excess heat sources. It is based on the existing district heating system in Sisak, which is located in central Croatia, and several assumptions related to the planned short-term expansion of the network, including the connection of new renewable powered supply technologies. This particular system configuration has been selected for the analysis due to several reasons: it was already used by the authors for previous analyses and therefore provides a good reference point and it uses the historical data. Hence, more details about previous work can be found in Doračić et al. (2021), The main technical information is provided in the following bullet points:

- The production units considered in the analysis consist of the existing biomass cogeneration (CHP_BIO) and natural gas boilers (HOBO_GAS), as well as the industrial excess heat (EH_IND), hospital excess heat (EH_HOSP), supermarket excess heat (EH_SMARK) and solar thermal (SOLAR). Apart from CHP_BIO and HOBO_GAS, no units currently exist and their capacities are assumed based on their theoretical potential (Doračić et al., 2021). Solar thermal and excess heat are enabled to store in the dedicated thermal storage units
- Existing heat demand can be divided to demand for industry and demand for household, amounting to 28 GWh and 70 GWh respectively
- In order to consider different heat transfer mediums and corresponding temperature levels, as well as the locations of production units and demands, these have been allocated to 3 different zones in the simulated heat market. In Z1, the heat transfer medium is steam, which is used to cover the industrial demand and only HOBO_GAS_1 and CHP_BIO can place bids there. On the other hand, in Z2 and Z3 the heat transfer medium is hot water used to cover the demand of households in these zones and all the available units can place bids there. Z2 represents the current district heating system of Sisak (excluding industrial demand), while Z3 represents the planned extension of the system (Vidak et al., 2015) and consists of household heat demand and HOBO_GAS_3

The economic and technical data of the supply units participating on the heat market in the elaborated numerical example are shown in Table 1. For all the units, a discount rate of 8% was used. Additional costs occur for CHP_BIO and HOBO_GAS in terms of fuel costs for biomass and natural gas. These were assumed at 15 €/MWh and 30 €/MWh, respectively. Additionally, when calculating total cost bids for CHP_BIO, the revenue from the sold electricity was taken into account, which is being sold at the fixed feed in tariff price. Furthermore, it has to be pointed out that for EH_IND, it was assumed that its temperature is sufficient to be utilised directly through the heat exchanger, while EH_HOSP and EH_SMARK represent the low temperature excess heat sources, assumed at 50 °C and 80 °C respectively. Therefore, these sources require the use of the heat pump to boost their temperature to the district heating supply level, which has been assumed at 85 °C. This means that the supplementary cost of electricity for the electric heat pumps needs to be included when calculating marginal and total costs of the low temperature excess heat (Doračić et al., 2020b). It must be pointed out that it was assumed that all the production units, including the high and low temperature excess heat supply their heat to the supply line. Supplying low temperature excess heat to the return line was not the focus of this paper.

3. Results and discussion

3.1. Merit order

When marginal cost and total cost bids have been calculated for each of the technologies participating on the heat market in the previously described numerical example, they have been compared to each other on the yearly level graphically, as shown in Figs. 3 and 4.

When total cost bidding is used, the technology with the lowest bids is solar thermal, followed closely by the high temperature industrial excess heat. These bids are assumed not to change during the year since all of their cost components are constant and do not contain any external variables. This is also assumed for the next technology in the merit order, the biomass cogeneration, whose fuel price is defined by multi annual contracts and therefore does not change during the year. However, in some hours of the year excess heat from the supermarket has a lower bidding price than the biomass cogeneration. Nevertheless, these bids differ on an hourly level due to different market prices on the electricity market which is needed for powering the heat pump and in most hours, it is a more expensive technology when compared to biomass cogeneration. Since even lower temperature of hospital excess heat is presumed, it always comes after the higher temperature supermarket excess heat in the merit order and its bids are even higher than the ones for HOBO_GAS in many hours during the year. This is the reason for a low capacity factor of low temperature excess heat in such a market, as already shown in Doračić et al. (2021). Additionally, it is necessary to further discuss the constant bidding prices of CHP_BIO throughout the year. Since bidding prices of low temperature excess heat sources vary from hour to hour, it could be expected that the cogeneration unit, whose bidding price is also affected by the sold electricity, would show the same variations. However, the reason why this is not the case in this example is that this particular power plant receives a feed in tariff for the produced electricity (as a renewable, biomass power plant) and therefore does not sell its electricity on the power market. In case it was selling its electricity on the power market, its bidding prices on the heat market would also be variable. However, this was not analysed in this manuscript and such configurations will be tackled in the future research of the authors.

On the other hand, when marginal cost bidding strategy is utilised, the situation changes as presented in Fig. 4. The proposed two bidding strategies have the lowest effect on HOBO_GAS, a technology with relatively low fixed and large variable costs (costs related to natural gas). Therefore, changing the strategy

Table 1
Economic and technical data of the heat production units in the numerical example.

Unit	Capacity	Investment	Fixed O&M	Variable O&M	Lifetime	Reference
CHP_BIO	12 MW	1,450,000 €/MW	71,250 €/MW	2.3 €/MWh	14 years	Energinet (2020) and Bogdan (2017)
HOBO_GAS_1	52 MW	60,000 €/MW	2000 €/MW	1.1 €/MWh	20 years	Energinet (2020)
HOBO_GAS_3	11 MW	60,000 €/MW	2000 €/MW	1.1 €/MWh	20 years	Energinet (2020)
EH_IND	3.7 MW	540,000 €/MW	2% invest	1.24 €/MWh	20 years	Hackl and Harvey (2013)
EH_HOSP	0.05 MW	1,240,000 €/MW	2000 €/MW	2.7 €/MWh	25 years	Energinet (2020)
EH_SMARK	0.4 MW	1,240,000 €/MW	2000 €/MW	2.7 €/MWh	25 years	Energinet (2020)
SOLAR	14,390 MWh	489 €/MWh	0.09 €/MWh	0.2 €/MWh	30 years	Energinet (2020)

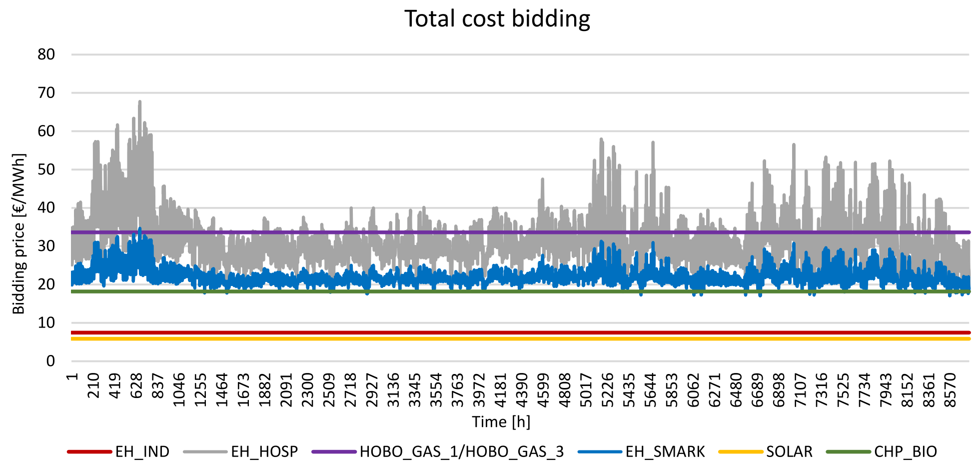

Fig. 3. Bidding prices of different heat production technologies when using total cost bidding.

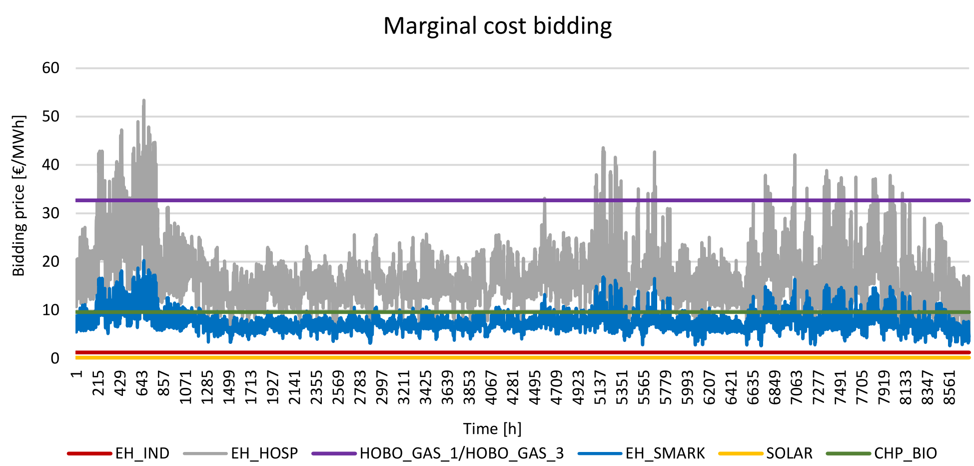

Fig. 4. Bidding prices of different heat production technologies when using marginal cost bidding.

from marginal cost bidding to total cost bidding results in only a 3% decrease of HOBO_GAS bidding price which is why it remains the most expensive technology in most hours throughout the year. However, the technologies with variable bidding prices, i.e. low temperature excess heat sources, decrease their bidding prices significantly when marginal cost bidding is used. This means that their merit order is significantly different and changes from the most expensive to a more affordable. While EH_SMARK had mostly higher bidding prices than CHP_BIO when total cost bidding was used, now it has lower bidding prices for the majority of time.

The same can be noticed for EH_HOSP, which now has mostly lower prices than HOBO_GAS and in some cases even lower than CHP_BIO. It is expected that this will increase the utilisation rate of the low temperature excess heat by quite some margin, which will be discussed in the next subsection. Furthermore, it can be noticed that use of different bidding strategies did not affect the merit order of already cheap solar thermal and industrial excess heat. These remain the production technologies with the lowest bids on the market. Also, when only the technologies with constant bids throughout the year are compared (SOLAR, EH_IND, CHP_BIO and HOBO_GAS), the merit order does not change in general. However, HOBO_GAS and CHP_BIO are affected by the variable cost technologies, as mentioned in the previous paragraph. As was already mentioned, HOBO_GAS was least affected by the two bidding strategies. However, other technologies were affected to a much higher extent. For example, the ones with no fuel, or other intensive variable costs like solar thermal and industrial excess heat decreased their bidding prices by more than 80% in marginal cost bidding. The others, however, had a much lower decrease due to the existence of rather high fuel costs in case of HOBO_GAS and CHP_BIO, or electricity costs in case of EH_SMARK and EH_HOSP.

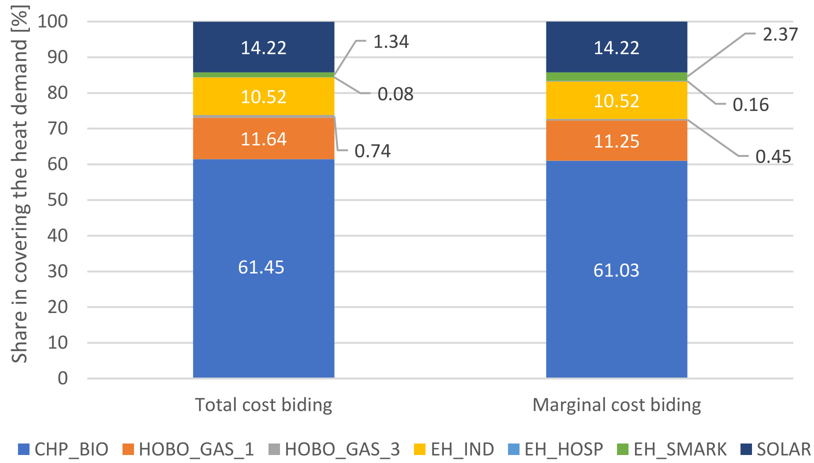

Fig. 5. Cleared production technology bids for two biding strategies, presented as the share in supplying the overall heat demand.

Table 2
Capacity factor of low temperature excess heat source in [%] when different biding strategies are applied.

	EH_SMARK	EH_HOSP
Total cost biding	37.70	17.80
Marginal cost biding	66.84	36.19

3.2. Heat market simulation results

In the next step of the analysis, two scenarios have been analysed, as previously elaborated: total cost biding scenario and marginal cost biding scenario. In this subsection, several indicators have been calculated and presented in order to compare these two biding strategies from different perspectives. First, the heat production analysis is shown in Fig. 5. This figure shows the cleared bids when total cost biding and marginal cost biding are used, presented as the share in supplying the overall heat demand. Immediately it can be seen that the number of cleared bids for SOLAR and EH_IND remains the same in both cases, since these two technologies remain the ones with the lowest costs, hence the lowest bids. Both are utilised to the maximum of their potential.

Changes can be noticed in terms of cleared bids of other production technologies, however in terms of covering the overall heat demand they seem rather small. This is because the theoretical potential of EH_HOSP and EH_SMARK is rather low compared to the overall heat demand. Nonetheless, it can still be noticed that the cleared bids from EH_HOSP practically double when marginal cost biding is used, while cleared bids for EH_SMARK also increase substantially. This results in the lower production from CHP_BIO, which is a base unit and therefore is not impacted by this change to a large extent. Finally, it can be argued that the biggest effect of different biding strategies in terms of heat production is on the low temperature excess heat. Therefore, Table 2 presents the comparison of these two strategies in terms of the capacity factor of low temperature excess heat.

From this, it can be seen that using marginal cost biding enables a much higher utilisation of the low temperature excess heat, due to their bidding prices going being below the prices of CHP_BIO, i.e. the merit order changes as already discussed. However, the overall capacity factor of these two low temperature sources is still not very high, due to the rather high variable costs, i.e. electricity costs necessary for the heat pump operation. Hence, the economic feasibility of low temperature excess heat for these two biding strategies will be analysed in more detail in the next subsection. The overall conclusion in terms of heat production analysis is that different biding strategies affect the number of cleared bids from different production technologies, however this effect is rather limited to the technologies with variable marginal costs. In the analysed numerical example, due to the rather low available amount of low temperature excess heat, this effect is not significant when overall heat production is considered.

In terms of economic analysis, the achieved hourly MCPs are presented by a box and whiskers diagram in Fig. 6. It is a graphical representation of aggregating hourly data on an annual level. The maximum and minimum values throughout a year are presented by the whiskers, the mean value is presented by the x, while the median is presented by the medium line. The bottom and top line of the box represent the first and the third quartile, respectively.

It can be seen that in all the zones, the mean value of MCP reduces significantly when marginal cost biding is applied. In Z1, this reduction is slightly lower at 30.2%, while in Z2 and Z3 it amounts to 33.4%. The minimal MCP in Z2 and Z3 also decreased meaningly due to the rather low marginal price of the cheapest technology (in this case SOLAR) at 0.2 €/MWh. However, the maximal MCP remained similar in all the cases, due to the demand for a peak load natural gas boiler, whose bidding price does not change much when different biding strategies are applied, as discussed previously. The effect of different strategies is lower in Z1 due to the fact that solar thermal and excess heat are not permitted to bid in that zone. However, the changes are still evident due to the high production from CHP_BIO, whose marginal costs differ significantly when compared to its total costs. Overall, from the perspective of the producers, total cost biding results in fairly higher MCPs and consequently higher revenues. As previously argued and shown in Table 2, marginal cost biding enables higher utilisation of the low temperature excess heat sources. However, Fig. 6 shows that alongside increased utilisation, the prices which can be achieved at the market are proportionally reduced, which brings in question the increased low temperature excess heat feasibility due to the use of marginal cost biding.

From the consumer side, the effect of different biding strategies can easily be shown by calculating the overall demand side costs. The calculation is performed by multiplying the MCP in every hour with the corresponding cleared demand in that particular hour. By summing up all the hourly values, overall annual cost of the demand side is presented in Table 3.

Logically, the overall demand cost is lower when the marginal cost biding is used. The difference between the two biding strategies amounts to 370,608€, i.e. 15%. This difference is not significant, which leads to a conclusion that the effect of different biding strategies is stronger on the production side than the demand side. It has to be pointed out that the costs from Table 3

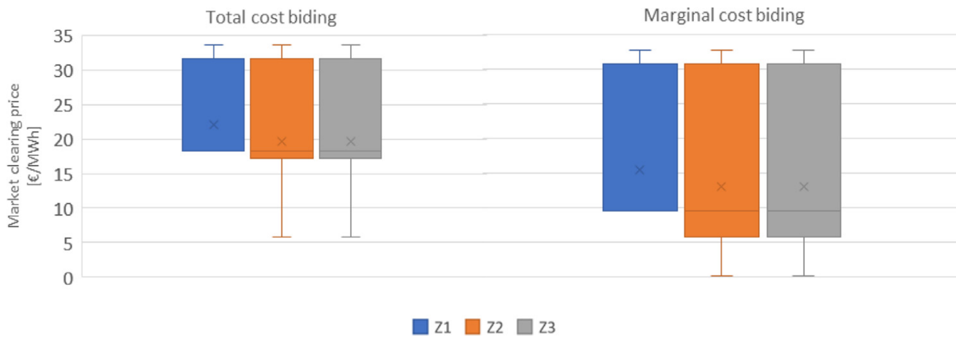

Fig. 6. Market clearing prices for different zones when total cost and marginal cost biding are applied.

Table 3
Overall cost in [€] for the demand side for different biding strategies in each zone.

	Total cost biding	Marginal cost biding
Z1 demand cost	626,356	471,064
Z2 demand cost	1,533,077	1,354,200
Z3 demand cost	312,293	275,855
Overall demand cost	2,471,727	2,101,119

present the costs at the supplier side, and not at the end user side since the end users cannot participate directly on the wholesale heat market. Therefore, marginal cost biding increases the benefit for the heat suppliers but the change of price for the end user depends on the business model of the supplier.

Finally, in terms of the overall social welfare, which is the objective function of the DARKO model used in this analysis, marginal cost bidding results in its increase by 29%. This happens due to the increased welfare at the demand side, but also due to the higher utilisation rate of the excess heat sources. Therefore, from the social welfare perspective, using marginal cost biding is a more optimal solution than using total cost biding.

3.3. Excess heat feasibility

In the previous subsections, it has been demonstrated that low temperature excess heat does not have a high utilisation rate when total cost biding is used, due to its high total cost and therefore unfavourable position on the merit order. It was already shown (Doračić et al., 2021) that this results in a significantly high levelized cost of excess heat (LCOEH), which cannot be matched by the achieved revenue of these sources on the market and which therefore results in their infeasibility. However, when marginal cost biding is used, the capacity factor of low temperature excess heat increases by almost double, which inevitably decreases LCOEH. Nevertheless, marginal cost biding also results in lower achieved prices on the market and therefore it is necessary to analyse the relation between LCOEH and achieved market price for the low temperature excess heat sources in order to see if the use of marginal cost biding might make these sources feasible on such a market.

LCOEH has already been defined as a criterion for feasibility calculation of excess heat (Doračić et al., 2018) and has been used in several studies for this purpose (Doračić et al., 2020b). It presents a minimum price that the excess heat needs to achieve on the market in order to be feasibly utilised. Therefore, if the average price that the excess heat source achieves on the market during the year is lower than the LCOEH, it is unfeasible to utilise this source. On the other hand, if the average price on the market is higher than LCOEH, it is feasible. LCOEH for excess heat sources using total cost and marginal cost biding is presented in Fig. 7. Since the utilisation rate of low temperature excess heat sources increased, LCOEH of both EH_SMARK and EH_HOSP decreased by 36.2% and 41.6% respectively. However, these figures are still rather high and it is impossible to achieve feasibility, especially when the lower MCP due to the marginal cost biding is taken into account. To prove this, the average achieved price on the market has also been calculated for the excess heat sources and plotted alongside LCOEH in Fig. 7. It has been calculated by multiplying the cleared bid in every hour by the MCP in that hour, summing up the values for the whole year and dividing by the overall production of each source. It can be seen that regardless of the biding strategy, the only source which achieves a higher price on the market than the LCOEH is high temperature industrial excess heat, while low temperature sources remain infeasible in both cases.

3.4. Electricity price variation

It was shown in the previous results that low temperature excess heat cannot be feasible when utilised in a wholesale heat market alongside other production technologies with lower production costs. Here it is important to point out that the presented numerical example has been focused on the 3rd generation district heating systems, which have higher supply temperatures and are still the prevalent generation of systems in many countries of Europe (Averfalk et al., 2017). The increased feasibility of low temperature excess heat with lower district heating supply temperatures was already shown in the previous research of authors (Doračić et al., 2020b) and will therefore not be the focus of this work.

The reason for the low utilisation rate and therefore low feasibility of low temperature excess heat in the presented numerical example is high variable costs of this source, which mostly consist of the cost for electricity for heat pumps. However, it has to be noted that the biding prices have been calculated by using the electricity prices from the Croatian Power Exchange (CROPEX) for 2017 (Croatian Power Exchange, 2021). More precisely, the hourly values of the day ahead prices on the CROPEX market were used for the whole year. Nevertheless, these prices can vary significantly on a year to year basis, due to several factors including the development of the power sector, meteorological conditions, economic situation, etc. For example, the average hourly electricity price on the CROPEX power market was 51.91€/MWh in 2017, 51.96€/MWh in 2018, 49.30 €/MWh in 2019 and 38.08 €/MWh in 2020 (Croatian Power Exchange, 2021). This shows a considerable reduction of average electricity market prices by 26.6% in 2020, compared to the reference year 2017. Therefore, an analysis of the biding prices for EH_SMARK and EH_HOSP has been performed with electricity prices from 4 consecutive years on the CROPEX day ahead power market, i.e. from 2017 to 2020. These are all publicly available at the CROPEX webpage. The results will be shown only for the marginal cost biding due to

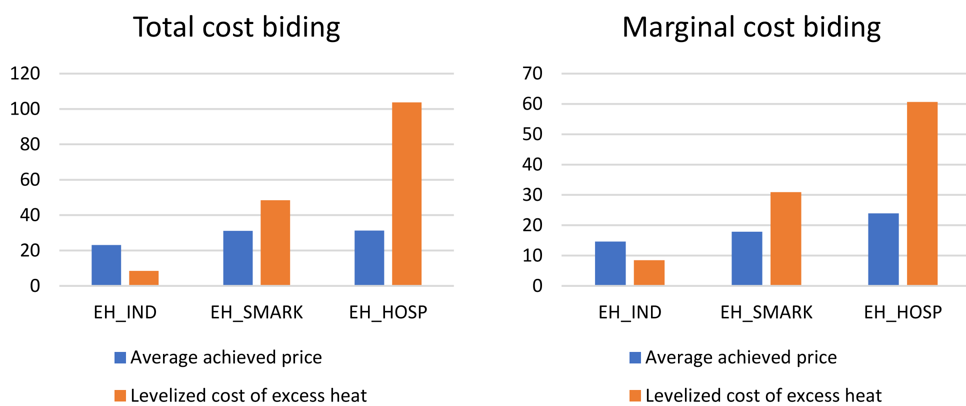

Fig. 7. Average achieved price and levelized cost of excess heat for two biding strategies.

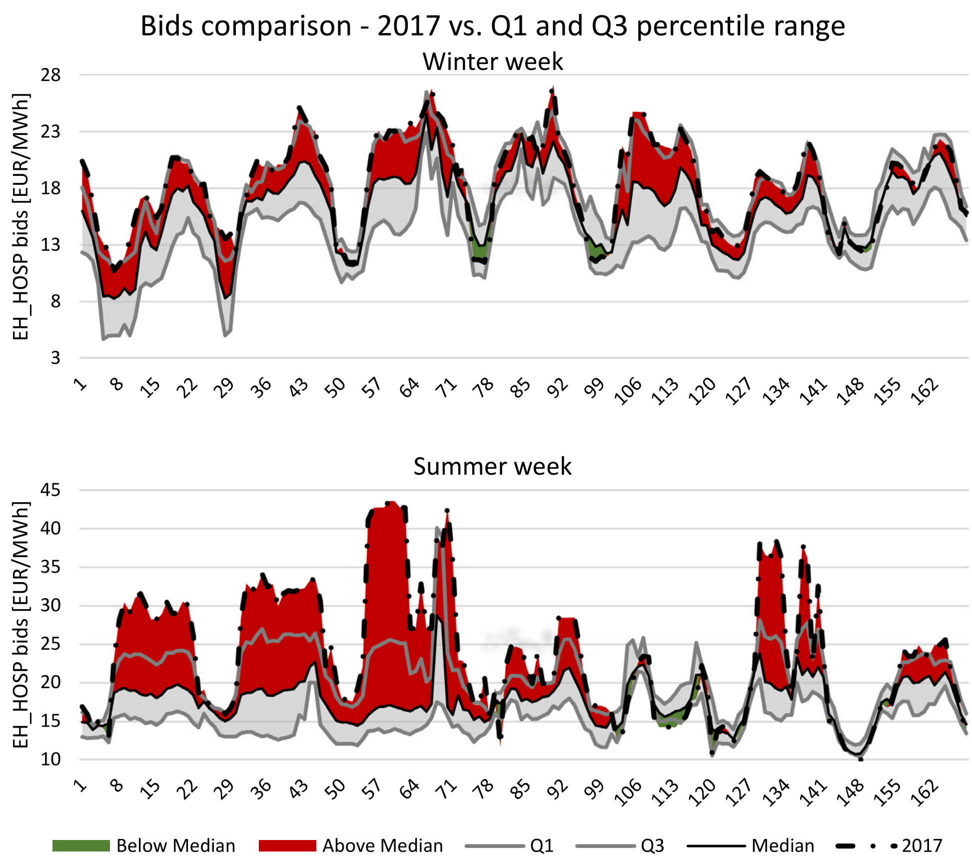

Fig. 8. Comparison of EH_HOSP bids for 2017 with the quartile and median values for the period 2017–2020, for a typical winter week (up) and a typical summer week (down).

higher total welfare values, as shown above. However, the same conclusions could also be applied to total cost biding since the bids would be reciprocally changed.

Fig. 8 compares the EH_HOSP bids for 2017 with the quartiles and median value of bids in the period 2017–2020. A typical winter week (1st January–7th January) and a typical summer week (1st August–7th August) have been visualised. It can easily be seen that the values for 2017 are much higher than the standard values in the analysed period, which shows a great effect of electricity prices in different years on the bids of low temperature excess heat. Throughout the majority of time, EH_HOSP bids in 2017 are higher than the median in the analysed period and are mostly in the 4th quartile (i.e. in the 25% of the most expensive bids). Since the qualitative effect of electricity prices on the EH_SMARK bids is the same as for EH_HOSP, it will not be presented graphically.

In order to make further analysis of the effect of different electricity prices on low temperature excess heat feasibility, market simulations with marginal cost biding have been performed and key performance indicators have been presented below. While the number of accepted bids of the other production units does not change, it does change for EH_SMARK and EH_HOSP, which consequently changes their capacity factor, as shown in Table 4. Here it must be noted that these changes affected only CHP_BIO, which changed its share of covering heat demand accordingly. However, due to a low available excess heat amount, this effect on CHP_BIO is rather insignificant, i.e. it ranges from 60.21% to 60% throughout the years.

Table 4
Capacity factor of low temperature excess heat sources in [%] for different years.

	EH_SMARK	EH_HOSP
2017	66.84	36.19
2018	64.33	38.66
2019	66.38	37.36
2020	69.42	43.71

It can be seen that decreased electricity prices, especially in 2020 lead to an increase of the capacity factor of EH_SMARK and EH_HOSP, but this increase is not significant, and it still remains too low for achieving a low enough LCOEH for these sources to be feasible. For example, in 2020 LCOEH of EH_SMARK reduced by 7.2% compared to 2017, while for EH_HOSP it reduced by 18.9%. Nevertheless, the average price these sources achieve on the market was also reduced and therefore they remained infeasible.

Despite this, it was proven that electricity prices affect the low temperature excess heat sources feasibility and that reduced prices on the electricity market could foster the feasibility and utilisation of this source. This is especially relevant from the perspective of the participation of renewable energy sources on the electricity markets since they have been shown to reduce the prices (Kolb et al., 2020). Therefore, increased utilisation of renewables could also foster the utilisation of low temperature excess heat, enabling a more efficient and sustainable heating sector.

4. Conclusions

This paper focused on the effect of different biding strategies on the low temperature excess heat feasibility, as well on the overall effect on the production and end user side. First of all, total cost biding and marginal cost biding have been compared in terms of their impact on the merit order in the analysed numerical example. While most production units kept the same position in the merit order in either of the biding strategies, low temperature excess heat sources were affected significantly, and they moved up in the merit order when marginal cost biding was used. This in turn changed the merit order of biomass cogeneration, which moved down in certain hours of the year. The highest effect of using different biding strategies was on the technologies with no fuel costs (solar thermal and high temperature industrial excess heat), while the others were affected to a much lower extent due to fuel costs in case of biomass cogeneration and natural gas boilers, or electricity costs in case of low temperature excess heat.

These two biding strategies were further compared by simulating the heat market operation on an annual level by using the DARKO model. It was shown that applying marginal cost biding results in a higher number of accepted bids from the low temperature excess heat, due to their improved position in the merit order. Therefore, the capacity factor of EH_SMARK increased from 37.7% in total cost biding to 66.8% in marginal cost biding, while the capacity factor of EH_HOSP increased from 17.8% to 36.2%. This mostly affected the production from CHP_BIO, which decreased from covering 61.5% of the demand to 61.03%. This decrease is not significant due to the low amount of available excess heat in the city. Furthermore, the MCP in all the analysed zones reduces by more than 30%, resulting in lower profits for the production side when marginal cost biding is applied. On the other hand, the benefits for the suppliers increase since the overall demand cost decreases by around 15%. However, it has to be pointed out that this cost decrease concerns only the suppliers and not the end users and therefore the effect on the end users would depend on the business model of the suppliers.

Since the focus of this paper was to see how different biding strategies affect low temperature excess heat feasibility, the average achieved price on the market for EH_HOSP and EH_SMARK was compared to the levelized cost of heat for both sources. It was shown that despite the increased capacity factor of these two sources when marginal cost biding is used, the lower prices on the market (due to lower MCPs) still lead to infeasibility of these low temperature sources on such a market configuration. This infeasibility is both due to low the excess heat source temperatures and therefore high electricity costs for boosting the temperature to district heating supply levels; as well as due to high temperatures of the analysed district heating system supply which presents the 3rd generation system (assumed supply temperature of 85 °C). Therefore, decreased district heating supply temperatures are still needed in order to increase the feasibility of low temperature excess heat. However, another option of increasing the feasibility of low temperature excess heat in the existing high temperature district heating systems would be by connecting these sources to the return line of the district heating network, which would remove the requirement of heat pump in cases of low temperatures of the return line. This way, the feasibility of the low temperature excess heat sources would correspond to the high temperature excess heat. This will be studied in further detail in the future research.

However, another parameter which effects the feasibility of low temperature excess heat is the electricity price, which varies on the power markets annually, depending on different conditions. For that reason, biding prices of low temperature excess heat were analysed by taking into account electricity prices from the Croatian Power Exchange in 4 consecutive years. Results have shown that electricity prices can have a strong effect on the increased utilisation and therefore increased feasibility of low temperature excess heat. This is especially important from the perspective of renewable energy sources which decrease the prices on the power market and could therefore also enable a more efficient and sustainable heating sector through fostering the utilisation of excess heat.

Nomenclature

Abbreviations		**Description**
ATC		Available transfer capacity
CHP_BIO		Biomass cogeneration
CROPEX		Croatian Power Exchange
DARKO		Day Ahead Market Optimisation
EH_HOSP		Excess heat from the hospital
EH_IND		Industrial excess heat
EH_SMARK		Excess heat from the supermarket
HOBO_GAS		Natural gas heat only boiler
LCOH		Levelized cost of heat
LCOEH		Levelized cost of excess heat
MCP		Market clearing price
O&M		Operation and maintenance costs
SOLAR		Solar thermal
SWMP		Social Welfare Maximisation Problem
Sets	**Units**	**Description**
i		Trading period
d		Demand
s		Simple

n		Node
l		Line
st		Storage
o		Order type
Variables	**Units**	**Description**
x_{so}^{i}	%	Acceptance ratio of simple orders in trading period i
x_{do}^{i}	%	Acceptance ratio of demand orders in trading period i
c^{do}	€	Total cost of demand orders
c^{so}	€	Total cost of simple orders
f_{l}^{i}	MWh	Flow in the interconnection lines in trading period i
p_{n}^{i}	MWh	Net position of bidding node n in trading period *i*
$p_{n}^{'i}$	MWh	Temporary net position of bidding node n in trading period i
$Q_{in_{st}}^{i}$	MW	Hourly storage charge rates
$Q_{out_{st}}^{i}$	MW	Hourly storage discharge rates
$S_{level_{st}}^{i}$	MWh	State of charge of the storage unit in trade period i
w_{tot}	€	Total welfare
$S_{spill_{st}}^{i}$	MWh	The amount of energy that is wasted or irreversibly thrown into the environment
Parameters	**Units**	**Description**
c_{fuel}	€/MWh	Fuel cost
$c_{totalcost}$	€/MWh	Total cost bid
$c_{marginalcost}$	€/MWh	Marginal cost bid
d	%	Discount rate
I	€/MW	Investment costs
N	years	Technology lifetime
O_{fixed}	€/MW	Fixed operation and maintenance costs
$O_{variable}$	€/MWh	Variable operation and maintenance costs
P_{do}^{i}	€/MWh	Price of demand orders in trading period i
Q_{do}^{i}	MWh	Quantity of demand orders in trading period i
P_{so}^{i}	€/MWh	Price of simple orders in trading period i
Q_{so}^{i}	MWh	Quantity of simple orders in trading period i

CRediT authorship contribution statement

Borna Doračić: Conceptualization, Methodology, Software, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Matija Pavičević:** Methodology, Software, Writing – original draft, Writing – review & editing. **Tomislav Pukšec:** Writing – review & editing, Supervision. **Neven Duić:** Writing – review & editing, Supervision.

Declaration of competing interest

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.

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