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Utilizing excess heat through a wholesale day ahead heat market – The DARKO model

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ABSTRACT

District heating has already proven to be a suitable solution for the decarbonisation of the most energy intensive energy sector in Europe, heating and cooling. However, to achieve this, it needs to incorporate renewable and sustainable energy sources into the generation mix which is still dominated by fossil fuels in many countries. Alongside traditional renewables like solar thermal, geothermal and biomass, excess heat from the industrial and service sector has a high untapped potential. Nonetheless, to utilize it in district heating, third party access must be granted. For that reason, a wholesale day ahead heat market has been modelled in this study and validated on a case study in the city of Sisak in Croatia. The idea was twofold: to evaluate the functionality of such a heat market and its effect on the existing system, as well as to analyse the integration of high and low temperature excess heat sources in different conditions, including the use of thermal storage, as well as the competition with low-cost renewables, i.e. solar thermal. The results have shown that the introduction of a wholesale day ahead heat market would ensure the positive total welfare in all the scenarios. The benefit for the demand side and the total welfare would increase even more if excess heat sources are integrated in the system and especially if they are combined with a thermal storage to increase their capacity factor, which would also decrease the competing effect of solar thermal. Finally, it was shown that low temperature excess heat is not feasible in the high temperature district heating and the transfer to the 4th generation district heating is required to feasibly utilise low temperature sources.

1. Introduction

Heating and cooling is one of the most important energy subsectors, since it amounts to approximately 50% of the overall final energy consumption in Europe [1]. This shows that there are great potentials to increase the efficiency of this sector and subsequently decrease its environmental impact. An obvious solution are district heating systems, an efficient way of heating, which currently amounts to around 13% of the heat supply in Europe [2] and shows significant benefits over the individual fossil fuel heating solutions [3]. Despite a relatively low share on the European level, certain countries like Denmark, Iceland, Sweden, Lithuania, etc. already have a high share but still show significant potential to expand it even more. For example, a research has shown that an increase of district heating share in covering heat demand of Denmark to 70% would be an optimal solution [4]. Nonetheless, this can only be the case if these systems transform to a 4th generation [5] since numerous systems throughout Europe are still 2nd or 3rd generation of district heating, having high supply temperatures, using fossil fuel sources, encountering high losses, etc., as was shown in the comparison between the Danish and Croatian systems [6]. This would mean that district heating will have to use renewable and sustainable sources like solar thermal [7], geothermal, power to heat technologies and biomass in certain cases, when sustainability of its use can be proven [8]. Especially their combination and integration into an interconnected energy system with the use of storage technologies will lead the way towards the 4th generation, as was shown for the case of combining heat pumps, solar thermal and seasonal heat storage in Spain [9]. The benefits of using renewables over fossil fuels are significant, both from the economic and environmental point of view [10], which increases the willingness of the end users to connect to such a system [11]. Excess heat is an additional source which is interesting for sustainable district heating solutions and which can be utilized from various locations, including service sector buildings, industries, and thermal power plants. Its potential has been broadly researched, including the industrial excess heat [12], excess heat from thermal power plants [13] and the service sector

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Nomenclature

Abbreviations Description
CHP_BIO Biomass cogeneration
DARKO Day Ahead Market Optimization
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
MCP Market clearing price
O&M Operation and maintenance costs
SOLAR Solar thermal
SWMP Social Welfare Maximization Problem
TS_EH Thermal storage for excess heat
TS_SOLAR Thermal storage for solar thermal

Sets Units (Description)
i trading period
d Demand
s Simple
b Block
f Flexible
n node
l line
st storage
o Order type

Variables Units (Description)
x^i_{so} % (acceptance ratio of simple orders in trading period i)
x^i_{do} % (acceptance ratio of demand orders in trading period i)
x_{bo} % (acceptance ratio of block orders)
u^i_{fo} - (clearing status of flexible hourly orders in trading period i)
c^{do} € (Total cost of demand orders)
c^{so} € (Total cost of simple orders)
c^{bo} € (Total cost of block orders)
c^{fo} € (Total cost of flexible orders)
f^i_l MWh(Flow in the interconnection lines in trading period i)
p^t_n MWh (Net position of bidding node n in trading period *i)*
p'^t_n MWh (Temporary net position of bidding node n in trading period i)
${Q_{in}}^i_{st}$ MW (hourly storage charge rates)
${Q_{out}}^i_{st}$ MW (hourly storage discharge rates)
${S_{level}}^i_{st}$ MWh (state of charge of the storage unit in trade period i)
w_{tot} € (Total welfare)
${S_{spill}}^i_{st}$ MWh the amount of energy that is wasted or irreversibly thrown into the environment)

Integer Variables Units (Description)
u_{bo} (binary status of block orders)

Parameters Units (Description)
P^i_{do} €/MWh (price of demand orders in trading period i)
Q^i_{do} MWh (quantity of demand orders in trading period i)
P^i_{so} €/MWh (price of simple orders in trading period i)
Q^i_{so} MWh (quantity of simple orders in trading period i)
P_{bo} €/MWh (price of block orders)
Q^i_{bo} MWh (quantity of block orders in trading period i)
P_{fo} €/MWh (price of flexible orders)
Q_{fo} MWh (quantity of flexible orders)
R^{min}_{bo} % (minimum acceptance ratio of block orders)
R^{up}_{so} %/h (hourly ramp up of simple orders)
R^{down}_{so} %/h (hourly ramp down of simple orders)
F^{max}_{li} MW (maximum energy flow rates in the interconnection lines)
F^{min}_{li} MW (minimum energy flow rates in the interconnection lines)
F^{up}_{li} %/h (hourly ramp up rate in the interconnection lines)
F^{down}_{li} %/h (hourly ramp down rate in the interconnection lines)
C^{up}_{li} %/h (maximum hourly increase rate of the net positions in individual zones)
C^{down}_{li} %/h (maximum hourly decrease rate of the net positions in individual zones)
$\eta_{discharge}$ % (Storage charging efficiency)
η_{charge} % (Storage discharging efficiency)
$S_{max\,st}$ MWh (upper boundary of the state of charge of the storage unit)
$S_{min\,st}$ MWh (lower boundary of the state of charge of the storage unit)
$S_{final\,st}$ MWh (minimum state of charge at the last time interval of the optimization horizon)
${S_{inflow}}^i_{st}$ MWh (externally imposed storage inflows)
${S_{outflow}}^i_{st}$ MWh (externally imposed outflows)

and other low temperature sources of excess heat [14]. These researches show the significance of this source, especially when its relatively low environmental effects, in terms of global CO_2 reductions are taken into account, as has been shown for the case of Sweden [15]. Further benefit is its low cost, which enables its integration into district heating even when the source is located further from the heat demand [16]. However, this depends also on the temperature level of the excess heat, as discussed in [17], where it was shown that the feasibility of low temperature heat questionable in the existing high temperature networks, which further potentiates the need for the 4th generation district heating. Also, due to the variability of the excess heat source its utilisation can be decreased significantly because of the mismatch with heat demand, which decreases its feasibility. Therefore, in most cases there is a need for a thermal storage, as shown in e.g. [18] and [19].

Despite all the benefits mentioned above, district heating is still regulated as a monopoly in many cases, with one company being responsible for production, distribution, and supply of heat [20]. In these cases, there is no competition, which would decrease the cost and the environmental effect of this sector. Some countries have already deregulated their district heating sector which in theory should enable competition, but practically the situation has not changed much and there is still a large number of monopolies throughout Europe. A good example of deregulating the heat market is the Lithuanian district heating sector, where independent heat producers can supply their heat to the district heating network if their price is lower than the production costs of other units [21]. This also decreased the costs for the end users. Some other examples of a deregulated market include Sweden [22], Germany [23], and Denmark [24], among others.

This paper focuses on modelling the wholesale day-ahead heat market to determine the benefits of such a deregulated market in terms of costs for the production and the demand side, but also enabling access to additional players to increase the sustainability of the system. From that perspective, the feasibility of utilizing industrial and service sector excess heat sources in such a market is analysed, through the case study based on the system in Croatia. The heat market is modelled in a similar manner to the electricity spot market [25], but taking into account the specifics of heat and the district heating systems. Some papers have already researched the possibilities of a deregulated wholesale heat market but none, to the authors' best knowledge, have modelled in detail the full wholesale day ahead heat market and the research in this

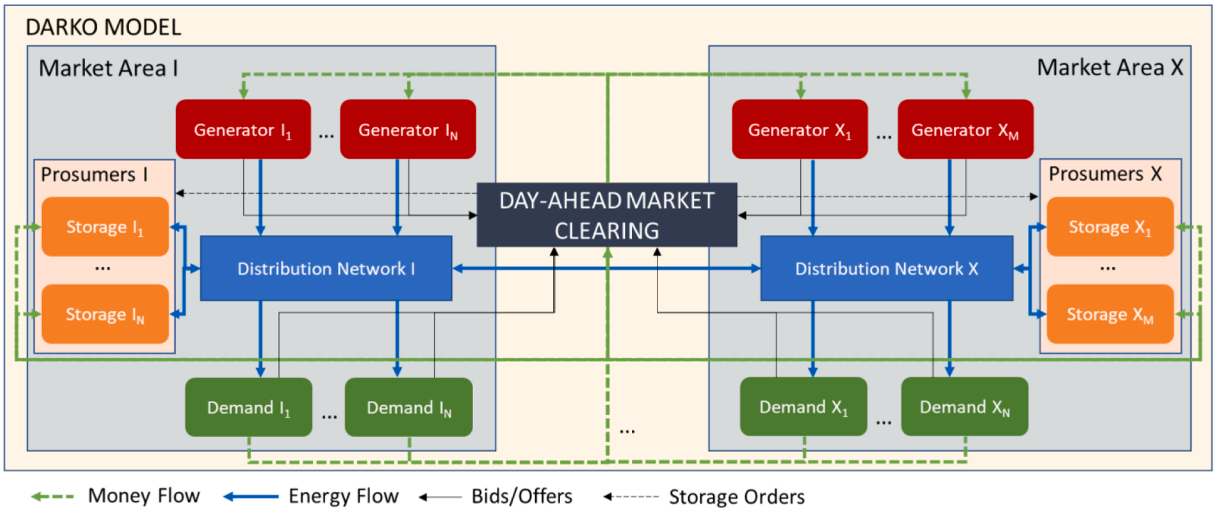

Fig. 1. Graphical representation of the DARKO model. Flows between different market participants are color-coded based on the type of commodity (energy, money) and information being exchanged.

area is scarce. For example, in [26] Plexos model is used to simulate the wholesale market based on marginal cost pricing, while in [27] heat merit order is designed to make the production costs transparent. On the other hand, different parameters of the spot electricity market have been widely researched. For instance, in [28] the authors have developed a graphical approach for power-to-x scheduling in the spot electricity market in order to reduce the costs and CO_2 emissions of the electricity sector. Furthermore, in [29] the effect of photovoltaics and wind power on the spot market electricity prices is shown, concluding that these sources will reduce the price on the wholesale market, regardless of the scenario analysed.

Based on the previous gap analysis, the main contributions of this paper are as follows:

- A novel open source day-ahead heat market clearing model with optimal storage scheduling is presented and validated.
- It is shown that excess heat can and should be allowed to participate on the market as the benefits, in terms of the increase of the total social welfare, are significant.
- The feasibility of low and high temperature excess heat sources utilized in high temperature district heating systems (2nd and 3rd generation) is analysed by comparing the LCOH with the achieved price on the day ahead heat market.

2. Day-ahead market model (DARKO)

DARKO model [30] is an advanced open source [31] energy market model that incorporates different types of market orders on both sides (supply and demand) of the chain. For example, market participants can place two types of orders, simple orders, and complex orders. A graphical summary of the proposed modelling framework and energy, money and information (i.e. price and quantity of supply bids, demand offers and information related to operation of storage units) flows is presented in Fig. 1. The model is highly generalized, meaning that there are no preset limits on the number of participants (supply, demand and storage/prosumers sides) on the day ahead market. The only limitation is the availability of the computational resources. The model obeys the following hierarchical structure: In each market area there is a single distribution network (i.e a district heating, gas or electricity network) that interlinks all the market participants (demands, generators and storages/prosumers) within that market area; each market area can also be interconnected with other neighbouring market areas through a set of transmission lines (i.e. pipes, wires etc.). These interconnection lines can positively impact the market clearing prices of neighbouring zones by shifting the merit order supply curves to the right in case of excess availability of cheap orders when the transmission capacities are high enough to accommodate the cleared energy flows from market area I to the market area X. Further information about the DARKO model can be found in the official documentation of the model [32].

2.1. Order types

2.1.1. Simple orders

Simple orders are usually being referred to as the building blocks of the market. They are formulated in a simple way with limited number of linear constraints. Simple orders are linked to a single time step, meaning that price and quantity (availability) pair needs to be specified for each time step of the optimization horizon. 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. Most orders on the energy markets are indeed simple orders.

2.1.2. Complex orders

Contrary to the simple orders, complex orders are subjected to a more complex set of constraints. These constraints are unique because one of the optimization variables is either integer or binary. Without complex orders, market clearing optimization is completely relaxed and purely linear. There are two main types of complex orders supported by the DARKO model. Block orders are the simplest type of market orders linking two or more consecutive time-intervals. They are defined as a specific quantity offered at a specific price for certain number of consecutive time intervals within the same optimization horizon (i.e., 24 h in a day-ahead market). Block orders are also constrained by the minimum quantity that needs to be accepted by the market clearing algorithm (i.e., 20% of the total volume). Second type of complex orders is called flexible order. This group of orders is, in its core, analogous to block orders. The main difference between those two is that flexible order can be supplied for a maximum duration of i-1 time intervals present in the optimization horizon. Second difference is related to the way of how the order is being cleared. Flexible orders are only cleared in one time-interval providing the best social welfare (i.e., the time period is not decided by the user but by the optimization algorithm itself).

2.2. Mathematical formulation

Generally, the market clearing solution of the day-ahead markets is found by solving the Social Welfare Maximization Problem (SWMP). The aim of the SWMP is to maximize the social welfare (i.e., the economic benefits from the demand and the production side) and ensure that operational and storage constraints are obeyed at every time period of the optimization horizon. Mathematically speaking, these are well defined problems used by different market operators on a daily basis. However, currently there are no energy markets that incorporate storage orders. This addition can be fully utilized by the heating sector where energy flows between the producers and consumers are not instantaneous due to the presence of the thermal inertia in the heating and cooling networks.

2.2.1. Objective function

The objective function is formulated as the MILP problem aiming at maximization of the overall social welfare w_{tot}, under the set of primal decision variables: $V = \left\{x^i_{do}, x^i_{so}, x_{bo}, u_{bo}, u^i_{fo}, f^i_l, p^i_n, p'^i_n, Q\_in^i_s, Q\_out^i_s, s\_lev^i_s, s\_spill^i_s, s\_ll_s\right\}$:

$$\max w_{tot} = c^{do} - \left(c^{so} + c^{bo} + c^{fo}\right) \tag{1}$$

Thus, the social welfare comprises of the following functions.

Total hourly demand order cost function:

$$c^{do} = \sum_{d\in D}\sum_{o\in O}\sum_{i\in I}\left(P^i_{do}Q^i_{do}x^i_{do}\right) \tag{2}$$

where, P^i_{do}, Q^i_{do} is a price quantity pair of demand orders in trading period i, in €/MWh and MWh, respectively, and x^i_{do} is the acceptance ratio of demand orders in trading period i in %.

Total hourly simple order cost function:

$$c^{so} = \sum_{s\in S}\sum_{o\in O}\sum_{i\in I}\left(P^i_{so}Q^i_{so}x^i_{so}\right) \tag{3}$$

where, P^i_{so}, Q^i_{so} is a price quantity pair of simple hourly orders in trading period i, in €/MWh and MWh, respectively, and x^i_{so} is the acceptance ratio of simple orders in trading period i in %.

Total block order cost function:

$$c^{bo} = \sum_{b\in B}\sum_{o\in O}\sum_{i\in I}\left(P_{bo}Q^i_{bo}x_{bo}\right) \tag{4}$$

where, P_{bo}, Q^i_{bo} is a price quantity pair of block orders in trading period i, in €/MWh and MWh, respectively. The quantity of block orders might, based on the maximum availability, differ in each trading period i. The x_{bo} represents the acceptance ratio of block orders. It is important to note that block orders are, opposed to simple orders, cleared only as a binary variable for the entire optimization horizon (i.e. either all consecutive trading periods i where block order is present are cleared or not).

Total flexible hourly order cost function:

$$c^{fo} = \sum_{f\in F}\sum_{o\in O}\sum_{i\in I}\left(P_{fo}Q_{fo}u^i_{fo}\right) \tag{5}$$

where, P_{fo}, Q_{fo} is a price quantity pair of flexible hourly orders in €/MWh and MWh, respectively, and u^i_{fo} is the clearing status of flexible hourly orders in trading period i. Flexible hourly orders are cleared only once per trading horizon, optimal trading period is chosen by the optimization algorithm.

It should be noted that since the proposed mathematical formulation is a SWMP the demand quantities for simple and complex offers are always negative, while supply quantities for simple and complex orders are always positive. Furthermore, the objective function is subject to the following set of primal (Power balance, Order clearing, Energy flows, Net positions, Ramping rates and Storage related) constraints. More detailed descriptions are provided in the upcoming sections. The Lagrange multipliers (the dual values) of individual constraints (shown in brackets next to the respective constraints) are used for the derivation of the market clearing price (MCP).

2.2.2. Power balance constraints

There are three power balance constraints applicable for each node (zone). Net position of bidding node n in trading period i computes the local generation in each node. It also utilizes the intertemporal possibility to either charge energy into the local storage (if available) for later use or discharge it in case of favourable market conditions.

$$p^i_n = \sum_{d\in D_n}\sum_{o\in O}\left(Q^i_{do}x^i_{do}\right) + \sum_{st\in ST_n}\left({Q_{in}}^i_{st}\right) - \sum_{s\in S_n}\sum_{o\in O}\left(Q^i_{so}x^i_{so}\right) - \sum_{b\in B_n}\sum_{o\in O}\left(Q^i_{bo}x_{bo}\right) - \sum_{f\in F_n}\sum_{o\in O}\left(Q_{fo}u^i_{fo}\right) - \sum_{st\in ST_n}\left({Q_{out}}^i_{st}\right)\forall n\in N, i\in I\left[{\pi_1}^i_n\right] \tag{6}$$

Temporary net position of bidding node n in trading period i (p'^i_n) computes the temporary change due to the flows happening between neighbouring nodes (i.e. if the cross-zonal interconnection capacity is high enough, market clearing prices in both zones are expected to be equal, meaning that the demand in a more expensive node would be satisfied by the supply bids from the cheaper node if the excess local generation capacities are high enough). This translates into the following two equalities:

$$p'^i_n = -\sum_{l\in L_n}\left(f^i_l\right)\forall n\in N, i\in I\left[{\pi_2}^i_n\right]$$

$$p^i_n - p'^i_n = -\sum_{l\in L_n}\left(f^i_l\right)\forall n\in N, i\in I\left[{\pi_3}^i_n\right] \tag{7}$$

It should also be noted that when two nodes are not connected temporary net position of area equals zero.

2.2.3. Order clearing constraints

The following order clearing constraints denote the upper limits of the hourly demand and simple supply orders:

$$x^i_{do} \le 1\forall d\in D, o\in O, i\in I$$

$$x^i_{so} \le 1\forall s\in S, o\in O, i\in I \tag{8}$$

The following order clearing constraints denote the lower and upper limits of block orders. They enforce the block orders to either be zero or between their minimum and maximum acceptance ratios. In literature this is also referred to as "fill-or-kill" constraints.

$$R^{min}_{bo}u_{bo} \le x_{bo}\forall b\in B, o\in O$$

$$x_{bo} \le u_{bo}\forall b\in B, o\in O \tag{9}$$

Where R^{min}_{bo} is the minimum acceptance ratio of block orders, in %, and u_{bo} binary status of block orders, either 0 or 1. The clearing condition of flexible hourly orders is equal to:

$$\sum_{i\in I}u^i_{fo} \le 1\forall f\in F, o\in O \tag{10}$$

Besides, simple orders are also constrained by the hourly ramping rates. These constraints are necessary for imposing intra temporal operational limits of thermal generators (i.e. the speed at which the thermal output can be increased between two consecutive hours).

$$\sum_{o\in O}\left(Q^i_{so}x^i_{so}\right) - \sum_{o\in O}\left(Q^{i-1}_{so}x^{i-1}_{so}\right) \le R^{up}_{so}\forall s\in S, i\in I-\{i_1\}$$

$$\sum_{o\in O}\left(Q^{i-1}_{so}x^{i-1}_{so}\right) - \sum_{o\in O}\left(Q^i_{so}x^i_{so}\right) \le R^{down}_{so}\forall s\in S, i\in I-\{i_1\} \tag{11}$$

Where $R^{up}_{so}, R^{down}_{so}$ are hourly ramp up and ramp down rates of simple orders, in %/h.

2.2.4. Energy flow constraints

The energy (heat) flow constrains denote the heat transfer limitations between different regions (zones) as follows:

$$f_l^i \leq F_{li}^{max}$$

$$F_{li}^{min} \leq f_l^i \quad (12)$$

Where $F_{li}^{min}, F_{li}^{max}$ are the minimum and maximum energy flow rates in the interconnection lines (pipes), in MW. Furthermore, hourly, and daily energy flow limits are imposed to mimic the realistic behaviour of heating networks (i.e., thermal inertia, heat, temperature and pressure drop(increase) rates etc.).

$$f_l^i - f_l^{i-1} \leq F_{li}^{up} \forall l \in L_n, i \in I - \{i_1\}$$

$$f_l^{i-1} - f_l^i \leq F_{li}^{down} \forall l \in L_n, i \in I - \{i_1\}$$

$$\sum_{l \in L_n} f_l^i \leq F_l^{up} i \in I$$

$$F_l^{down} \leq \sum_{l \in L_n} f_l^i i \in I \quad (13)$$

Where $F_{li}^{up}, F_{li}^{down}$ are hourly ramp up and ramp down rates in the interconnection lines, in %/h. Propagation times are neglected in this modelling framework.

2.2.5. Net position constraints

Analogous to the energy flow constraints, net position constraints limit the price volatility in individual regions:

$$p_n^i - p_n^{i-1} \leq C_{li}^{up} \forall n \in N, i \in I - \{i_1\}$$

$$p_n^{i-1} - p_n^i \leq C_{li}^{down} \forall n \in N, i \in I - \{i_1\}$$

$$\sum_{l \in L_n} p_n^i \leq C_l^{up} i \in I$$

$$C_l^{down} \leq \sum_{l \in L_n} p_n^i i \in I \quad (14)$$

Where $C_{li}^{up}, C_{li}^{down}$ are maximum hourly increase and decrease rates of the net positions in individual zones, in %/h. These inequality constraints also guarantee that the sudden and drastic heat drops (increases) (heat is chosen because of the way how the heat is being traded on the heat market, pressure, temperature, and other heat network related parameters are all directly related to the heat being supplied) between two consecutive time periods are prevented and security of the network is guaranteed.

2.3. Heat market features and storage constraints

Additional uniqueness of the heat networks opposed to the power networks is the slower response rate to the sudden increase(decrease) of heat supply(demand) which is mainly caused by the heat inertia in the networks. Thus, each branch of the network needs to be modelled as a small but expensive (low efficiency) thermal storage that can shift some portion of the oversupply to a consecutive time period.

2.3.1. Storage charging and discharging

The amount of energy that can either be charged or discharged in a given time period is limited by the state of charge of the storage unit and by the predetermined inflows and outflows (i.e. in the power sector the equivalent for this can be observed in hydro dams, while in heating sector this refers to a solar thermal or some other generation that is directly connected to the storage unit but that is not participating on the market).

$$\frac{Q_{out_{st}}{}^i}{\eta_{discharge}} \leq S_{level_{st}}{}^{i-1} + S_{inflow_{st}}{}^i \forall st \in ST, i \in I - \{i_1\}$$

$$Q_{in_{st}}{}^i \bullet \eta_{charge} \leq S_{max_{st}} - S_{level_{st}}{}^{i-1} + S_{outflow_{st}}{}^i \forall st \in ST, i \in I - \{i_1\}$$

$$Q_{in_{st}}{}^i \leq Q_{max}^{charge} st \forall st \in ST, i \in I$$

$$Q_{out_{st}}{}^i \leq Q_{max}^{discharge} st \forall st \in ST, i \in I \quad (15)$$

where $Q_{in_{st}}{}^i, Q_{out_{st}}{}^i$ are hourly charge and discharge rates, in MWh, $\eta_{charge}, \eta_{discharge}$ are charging and discharging efficiencies, in %, $S_{level_{st}}{}^i$ is the state of charge of the storage unit, in MWh, $S_{inflow_{st}}{}^i, S_{outflow_{st}}{}^i$ are externally imposed inflows and outflows (i.e. from external energy source not participating in the market) in MWh and $Q_{max}^{charge}, Q_{max}^{discharge}$ are maximum hourly charging and discharging capacities, in MW.

2.3.2. Storage boundary

Besides charging and discharging constraints, storage units are also constraint by the storage minimum state of charge. It is especially important that storage level at the end of the optimization horizon (i.e. at the last hour of each day) is always at a certain (predetermined or optimized) level:

$$S_{final_{st}} \leq S_{level_{st}}{}^i \forall st \in ST, i \in I = N$$

$$S_{min_{st}} \leq S_{level_{st}}{}^i \forall st \in ST, i \in I$$

$$S_{level_{st}}{}^i \leq S_{max_{st}} \forall st \in ST, i \in I \quad (16)$$

where $S_{final_{st}}$ is the minimum state of charge at the last time interval of the optimization horizon, in MWh, and $S_{min_{st}}, S_{max_{st}}$ are lower and upper boundaries of the state of charge of the storage unit, in MWh.

2.3.3. Storage balance

Besides all previous constraints, energy stored in a given time period is also limited by the state of charge from the previous period as follows:

$$S_{level_{st}}{}^{i-1} + S_{inflow_{st}}{}^i + Q_{in_{st}}{}^i \bullet \eta_{charge} \leq S_{level_{st}}{}^i + \frac{Q_{out_{st}}{}^i}{\eta_{discharge}} + S_{spill_{st}}{}^i \forall st \in ST, i \in I - \{i_1\} \quad (17)$$

where $S_{spill_{st}}{}^i$ stands for the amount of energy that is wasted or irreversibly thrown into the environment (i.e., this might be the case if the bidding price of storage units is so high that its cheaper to just release it into the air) and is expressed in MWh.

3. Case study

In order to validate the model described in the previous section, a case study was analysed through five different scenarios. The selected city is the city of Sisak, located in central Croatia. Here it must be noted that the case study consists of the real heat demand data, real data on the existing production units, but also the assumed data on excess heat potentials from various actors, as well as assumed data on solar thermal plant, due to the lack of any detailed information on these actors. The details of the case study are elaborated in the next paragraphs.

The city of Sisak is a mid-sized city in the central Croatia, with a population of 47 768. District heating is already present in Sisak, covering the heat demand of around 22% of the households. The existing production units consist of natural gas cogeneration, natural gas heat only boilers and a biomass cogeneration plant. For this analysis, the natural gas cogeneration plant is excluded since it operates based on the electricity demand, i.e., its primary purpose is selling electricity. Therefore, only the heat only boilers (HOBO_GAS_1) and the biomass cogeneration (CHP_BIO) are considered in the analysis in terms of existing district heating units. The overall demand of district heating connected customers equals to 59 GWh for households and service sector, and 28 GWh for the industrial facilities. The hourly demand profile is shown in the appendix, in Fig. A1.

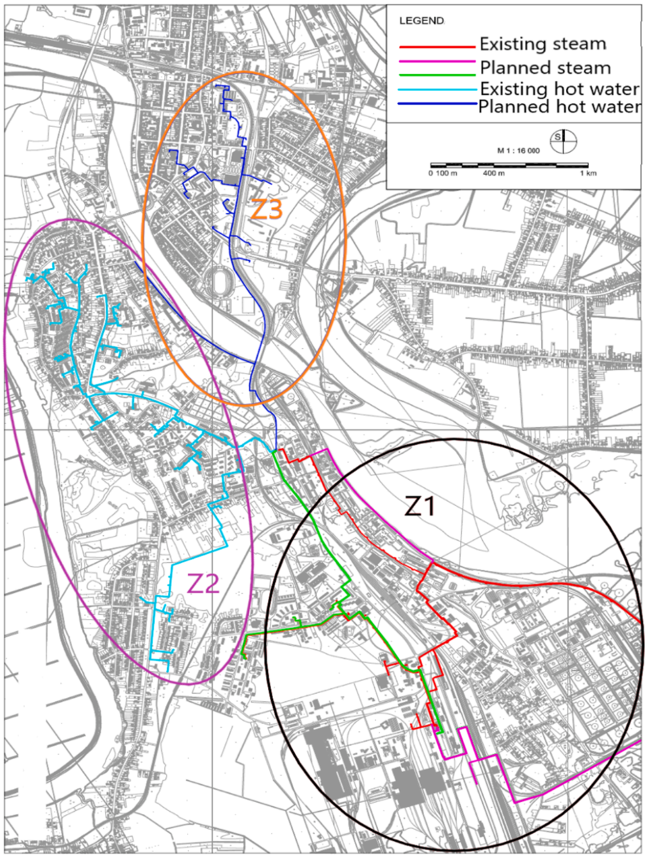

Fig. 2. The location of the main zones analysed in this study, map based on [33].

For this analysis, three different zones have been defined to take into account different temperature levels of the industrial and household heat demand, as well as different heat transfer mediums. The existing district heating production plants have been allocated to the Zone 1 (Z1), along with the industrial demand, based on their physical location and the heat carrier. In Z1, steam is used as a heat carrier for covering the industrial demand. Also, all the heat produced in Z1 for the district heating system (households/service sector) is in a form of steam and it is being transported to the main heating station, where the heat is exchanged with the hot water system, used for covering the demand of households/service sector buildings. Therefore, the heat demand of these users is allocated to the Zone 2 (Z2), where hot water is used as a heat carrier. The overall length of the distribution network in Z1 is 8350 m, while the length in Z2 is 21 600 m.

Furthermore, an additional district heating demand is added for this analysis and allocated to Zone 3 (Z3). It is based on the assessment of the potential for expanding the district heating system of Sisak across the river Sava, to the old part of the city [33]. Currently, this demand is being covered either by the individual natural gas boilers or the central natural gas heat only boiler. This heat only boiler actually represents a small district heating system since it covers the demand of several buildings, however, in Croatian law smaller systems are not regarded as district heating, but rather closed heating systems. It is planned to connect this demand, as well as the natural gas boiler (HOBO_GAS_3) to the district heating system of Sisak in the near future and therefore both were included in the analysis as a part of Z3. The planned length of the distribution network in Z3 is 2066 m. The temperature level of Z2 and Z3 has been assumed constant throughout the year and averages 85 °C. Therefore, the system presents a 3rd generation district heating, which is a standard in many European countries, including Denmark, Sweden, Latvia and Poland among others [34].

The map of the city of Sisak, with the existing and planned distribution networks and the allocated zones is shown in Fig. 2. This map is based on the map elaborated as a part of the report on the potential for expanding the district heating system of Sisak [33]. A more detailed explanation of the existing production units and demands will be provided in the next subsection, focused on the individual scenarios.

3.1. Scenarios

In order to validate the heat market model and study the effect of integrating different excess heat actors in the heat market under various circumstances, five scenarios have been developed. In Scenario 1, the idea was to assess the impact of implementing the wholesale heat market in the current situation, i.e., taking into account the current demands and production units and assuming that the demand in the old part of the city (Z3) is connected to the main district heating system of Sisak. This scenario would then act as a reference for other scenarios. It must be noted that there is currently no thermal storage in the system, but it was necessary to model the short-term storage capacity of the distribution network itself. This was done through calculating the overall volume of the network, for which the average pipe diameter was assumed based on [35]. Therefore, for Z1 the calculated network storage capacity is 1.13 MWh, for Z2 2.47 MWh and for Z3 0.42 MWh. These values have been validated through literature since they correspond to the networks of similar length calculated in [36].

In Scenario 2, three excess heat facilities are added to the market as additional production units. These include industrial excess heat from the refinery located in Z1 (EH_IND), service sector excess heat from hospital in Z2 (EH_HOSP) and service sector excess heat from the supermarket in Z3 (EH_SMARK). To represent these sources in the market, several assumptions needed to be made, since no detailed data on the excess heat potential is available at the moment. First of all, the available excess heat from the refinery has been calculated by combining the Heat Roadmap Europe method presented in [37] and the maximum available excess heat potential from chemical industry in Croatia presented in [12], giving the maximum availability of this source 10.3 GWh. Its availability has not been assumed constant but variable (Fig. A3) , by applying the variation presented in the previous research of the authors [18], while the temperature level has been assumed high enough for the direct utilization through the heat exchanger. Service sector excess heat facilities have been added to the analysis to also consider the low temperature excess heat sources, which need a heat pump to increase the temperature level to the required district heating supply temperature. Since there was no real data on the excess heat potentials from the hospital and the supermarket, this was assumed based on the literature. The available excess heat from the hospital has been assumed based on the ReUseHeat project at 450 MWh [38], while from the supermarket it has been assumed at 3.5 GWh, based on the average capacity of heat that can be recovered from a supermarket in Sweden [39]. The temperature levels of these sources have been assumed at 80 °C for the supermarket (based on high excess heat temperatures from the freezing processes using CO_2 as a medium [40]) and 70 °C for the hospital. The availability has been presumed constant throughout the year.

Through the previous research of the authors, mainly Refs. [17] and [18], it has been concluded that the main competitors of excess heat sources in terms of feasibility are low cost technologies like solar thermal. Furthermore, there is a plan in development to include solar district heating into the system in Sisak in the near future. For these reasons, Scenario 3 presumes the inclusion of a solar thermal field to the heat market of Scenario 1, in order to define the differences of using solar thermal instead of excess heat. This technology was modelled in such a way that its annual production roughly corresponds to the available excess heat potential from all the sources. The production from solar thermal, as well as the required capacity of the dedicated thermal storage unit (TS_SOLAR) was modelled in the energyPRO software [41].

Table 1
Available capacities on the heat market for each of the scenarios in [MW] for heat production technologies and [MWh] for thermal storage technologies.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
HOBO_GAS_1	8	8	8	8	8
HOBO_GAS_2	44	44	44	44	44
HOBO_GAS_3	11	11	11	11	11
CHP_BIO	12	12	12	12	12
EH_IND	–	3.7	–	3.7	3.7
EH_SMARK	–	0.4	–	0.4	0.4
EH_HOSP	–	0.05	–	0.05	0.05
SOLAR	–	–	14.3	14.3	14.3
TS_SOLAR	–	–	44	44	44
TS_EH	–	–	–	–	4500

This provided the maximum production from this technology in each hour (Fig. A3), the charging/discharging profile of thermal storage and the capacities of both solar thermal and thermal storage. These data were used as an input in the DARKO model.

The final step in the analysis was assessing the impact of using both the solar thermal and excess heat units in the heat market, alongside the existing district heating production plants. Therefore, in Scenario 4, all the available heat production units are participating in the heat market, while in Scenario 5, an additional seasonal thermal storage unit (TS_EH) is added in order to increase the production from excess heat. This storage can be used only by the excess heat sources and it was chosen as a seasonal pit storage based on the results from the previous research of authors which showed the necessity of such a unit when utilizing excess heat in combination with solar thermal [18]. Its charging/discharging behaviour is optimized by running the heat market model with a 365-day time horizon (i.e., full year in advance), providing an optimal state of charge of all storage units for this scenario. This profile is shown in the Appendix, in Fig. A4. The expected impact of storage units, run by the market operator, can be summarized as follows:

- More exploitation opportunities for variable technologies – during the off-heating season (i.e. summer months) when variable technologies such as solar thermal or variable excess heat have the highest availability, the state of charge of seasonal storage units at the start and at the end of each optimization horizon increases. This consequently impacts the demand in that particular zone (i.e., demand rises because storage unit must charge certain amount of energy in order to reach the minimum state of charge at the end of the optimization horizon)
- Price variability decreases – during the off-heating season market clearing price would mimic the price of cheapest technology (i.e., solar thermal), however, if the storage capacity is high enough to absorb all the excess heat being generated, market clearing price would mimic the second cheapest unit etc. During the heating season, the opposite situation would be true. The cheap energy accumulated during the off-heating season can be released lowering the demand. This would also be reflected on the market clearing price diminishing the clearing opportunities for the more expensive technologies (i.e., backup gas unit)
- Total welfare increases – combined effect of previous two points is reflected on the increase of the total welfare.

An overview of the installed capacities of the production units participating on the market in each of the scenarios is shown in Table 1, while the system scheme for scenario 5 (when all the available technologies are allowed to participate on the market) is presented in the appendix, in Fig. A5. Since there are no requirements for block production from none of these units, all of them are bidding as simple order units, as defined in Section 2.1. For offers on the heat market, prices were defined in such a way that they are slightly above the bidding price of the most expensive existing technology, in order to make sure that the demand will be satisfied in each hour of the year. Bidding prices of the heat production units were calculated by taking into account the discounted investment, operation and maintenance (O&M) costs and fuel costs in order to consider all the expenses for the heat production. Exceptions are HOBO_GAS_1 and HOBO_GAS_3, since it is assumed that these units are already amortized due to their age and therefore their bidding price includes only the fuel costs. The main motivation behind this approach is due to the particularities of the district heating sector. For example, district heating systems are usually isolated systems supplying heat to individual neighbourhoods or cities, and only in rare cases to larger regions with over a million consumers. Opposed to electricity sector, there are no opportunities to exchange heat with neighbouring regions or countries. This means that each district heating system is rather unique and acts as a standalone system. Thus, generalizations that would be applicable to all systems are hard if not impossible to make. Opposing to the electricity sector where ancillary services are provided by the same units on the reserve markets, in the heating sector the existence of these services is rather limited (i.e., heat can be supplied even if temperature levels are not 100% satisfied).

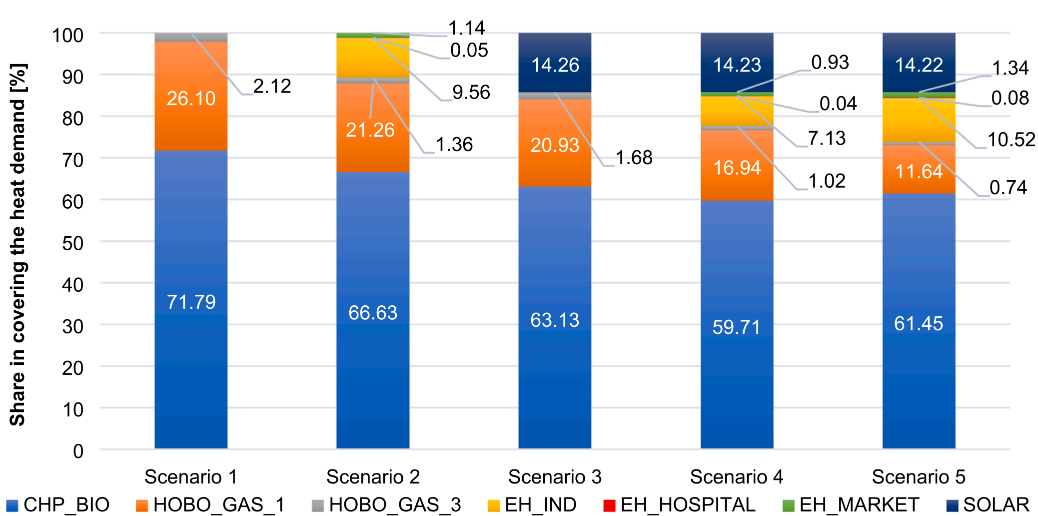

Fig. 3. Cleared bids from different heat production technologies in five scenarios, expressed through the share in covering the heat demand.

Table 2
The capacity factor of different excess heat sources in [%] for Scenario 2, 4 and 5.

	EH_SMARK	EH_IND	EH_HOSP
Scenario 2	31.96	90.22	10.85
Scenario 4	26.20	67.51	9.03
Scenario 5	37.70	99.94	17.80

Furthermore, revenues from capacity additions in form of government subsidies observed in the electricity sector are limited and outdated. Thus, due to all these reasons, opportunities for additional income streams are limited and not uniquely spread among different market participants. By using the bidding prices which include the discounted fixed costs, the aforementioned facts are taken into account and the chance of achieving feasibility of the market actors is increased, all the while the merit order is kept the same. This has also been discussed for the electricity markets, e.g., in [42] where authors debate using the same approach for bidding on the European markets in order to ensure the feasibility of the producers. They point out that day ahead electricity markets are usually modelled by using marginal cost bidding, but that this does not reflect the situation in real markets, in which strategic bidding is observed . Furthermore, this could prevent the missing money problem, which is a well-known issue in the electricity markets [43]. Similar propositions have been made in [44], where authors argue that the better energy price formation should be prioritized to reduce the effect of the missing money. The economic data for calculating the bidding prices are presented in the Appendix, in Table A1, while the prices used for bidding and offering have been shown in Fig. A2.

4. Results and discussions

In the following subsections, the results of the scenario analysis will be presented and discussed. These are divided to the energy part (role of different technologies in covering the demand), economic part (achieved prices on the market) and the detailed analysis of the excess heat feasibility in the wholesale heat market.

4.1. Cleared bids

The first requirement of the heat market is that the heat demand is satisfied in every hour of the year. Since the current heat offer prices are modelled in such a way that they are higher than the highest bidding price of the existing technologies, the demands of each zone are satisfied in every hour. The cleared bids from the heat production technologies are shown in Fig. 3. The results of Scenario 1 are expected and show that most of the demand is covered by the biomass cogeneration plant, while the peak load boilers, especially HOBO_GAS_3 have a rather low production. This happens due to the much lower price of the cogeneration, which results in the capacity factor of almost 70% for this unit.

When excess heat units from industry and service sector are added to the market as additional players, the share of fossil fuel units and the biomass cogeneration decreases. This is presented as Scenario 2 and shows that approximately 10.7% of heat demand is covered by these units. However, not all the available excess heat is cleared in Scenario 2, especially due to the high costs of the low temperature excess heat from the hospital, which sold only 10.9% of the available amount. Despite the assumed higher temperature of the supermarket heat which results in lower bidding price, only 31.9% of its available heat has been sold. This is due to the fact that in certain hours of the year all of the heat demand is covered by the cheapest units (CHP_BIO and EH_IND) and there is no need for additional heat, despite the fact that it is cheaper than the fossil fuel boilers in a number of hours. Even the excess heat from industry sold only 90.2% of the available heat regardless of being the cheapest unit in this scenario, because of its variability which results in the mismatch with the heat demand in the summer months. This shows the need for a thermal storage system to increase the amount of cheap heat on the market, which was analysed in Scenario 5. The capacity factor of excess heat in the three scenarios where these sources are included in the analysis is shown in Table 2. It represents the amount of sold heat in relation to the maximum available amount.

On the other hand, the aforementioned is prevented from happening in Scenario 3 where instead of excess heat, solar thermal collectors are added to the market. This is because of a dedicated thermal storage which was modelled alongside solar collectors. Furthermore, the bidding price of solar collectors is the lowest of all the technologies, even when the costs of the storage system are taken into account and therefore almost all its available heat is sold to the market in this scenario, which results in a further decrease of operation of the existing units.

Scenario 4 shows how the excess heat sources are completely underutilized when there are other low bidding price technologies available on the market, such as solar thermal, and no thermal storage is available for the excess heat. On the other hand, the number of accepted bids from solar thermal practically remains the same as in Scenario 3. It clearly shows that solar thermal is a direct competitor to the excess heat, since it reduces its capacity factor to 67.5% for the industrial source, 26.2% for the supermarket and to just 9% for the hospital. However, this scenario does result in a lower number of cleared bids from the fossil fuel units, causing the lower environmental effect of the system. These results further potentiate the need for a storage unit which would act as a seasonal storage to increase the utilization of excess heat.

When a seasonal thermal storage is added, it can be seen in Fig. 3 and Table 2 that almost all of the bids from the industrial excess heat source are accepted, while the production from solar thermal remains mostly the same. This results in the further decrease of the operation of fossil

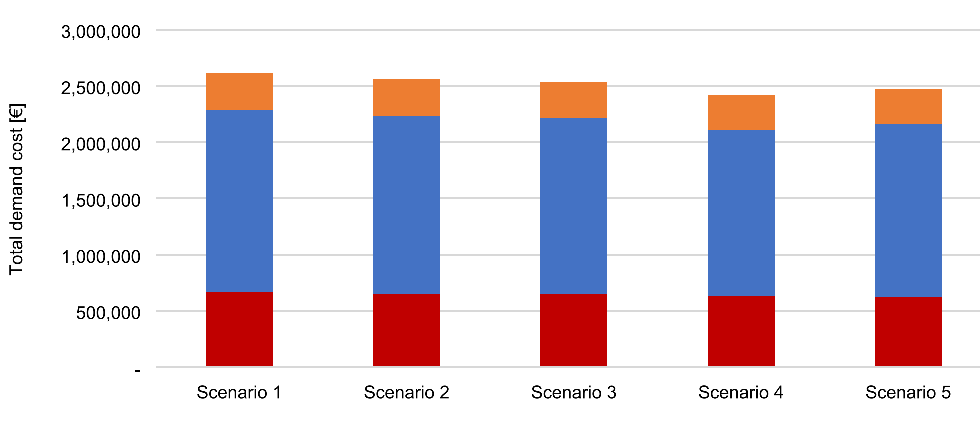

Fig. 4. The total costs of the demand side divided per zones for each of the scenarios.

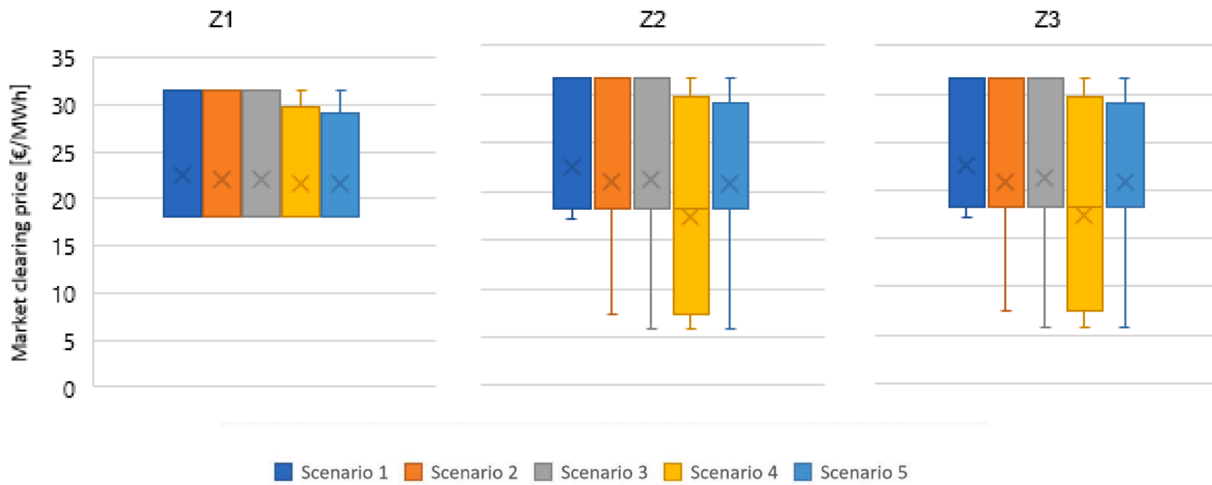

Fig. 5. Market clearing price for each zone and scenario.

fuel units from more than 28% of heat production in Scenario 1 to just above 12% in Scenario 5. It enables a decrease of the environmental effect of the district heating sector by a large margin since all the other technologies used for heat production can be deemed sustainable, but also renewable (the emissions of pollutants from the excess heat sources are usually considered to be zero, since they are already attributed to the industrial or service sector from which the heat is extracted and the heat would be produced anyway and wasted in the air or water [16]). However, despite the complete utilisation of the industrial excess heat, the low temperature excess heat sources show no major increase of their utilisation due to the high costs, which brings into question their overall feasibility. This will be discussed in the next sections, where the focus will be on the economics of the analysed scenarios. The reasons for this are mainly to define which scenario results in the lowest costs for the demand side, what is the effect of different technologies on the MCP of the existing zones, what effect does the implementation of the seasonal thermal storage have on the costs of the system, etc.

4.2. Market clearing price

The most important economic indicator of the heat market is the hourly market clearing price, which defines the price at which market is cleared, i.e., where the supply cost and demand cost curves cross. MCP can then be used to analyse various other factors, which will be done in the following paragraphs. First, the effect of implementing the heat market will be analysed from the perspective of the demand side. This is done by multiplying the MCP with the demand in each hour of the year in the 3 zones, which gives the total cost for the demand side when all the values are summed up on the annual level. The results are shown in Fig. 4 and illustrate the effects of integrating industrial and service sector excess heat through the heat market on the costs of the end users.

If the current production plants and demands in Sisak are integrated in a day ahead heat market, the total cost for the demand side would amount to 2,616,398 € (Scenario 1). This does not represent the total cost for the end users, but rather the wholesale costs which would be marked up with supplier costs and the distribution costs to achieve the final end user cost (tax excluded). When excess heat is integrated in Scenario 2, the demand costs decrease slightly by 2.2% and are even more decreased when solar thermal is integrated alongside excess heat in Scenario 4, by 7.6%. Here it can be observed that Scenario 5 has a bit higher costs than Scenario 4, which happens due to the thermal storage unit which enables accepting more bids from the excess heat sources and therefore the cost (i.e., the average MCP in that case) is increased. However, Scenario 5 still has the second lowest cost of all the analysed scenarios. When considering the environmental effect of having the lowest production from fossil fuel technologies, the advantages of Scenario 5 prove to be the highest among the analysed scenarios. Finally, the results show the high benefit of introducing the wholesale heat market for the end users, in terms of reducing their costs especially when low bidding price technologies are used, such as solar thermal and

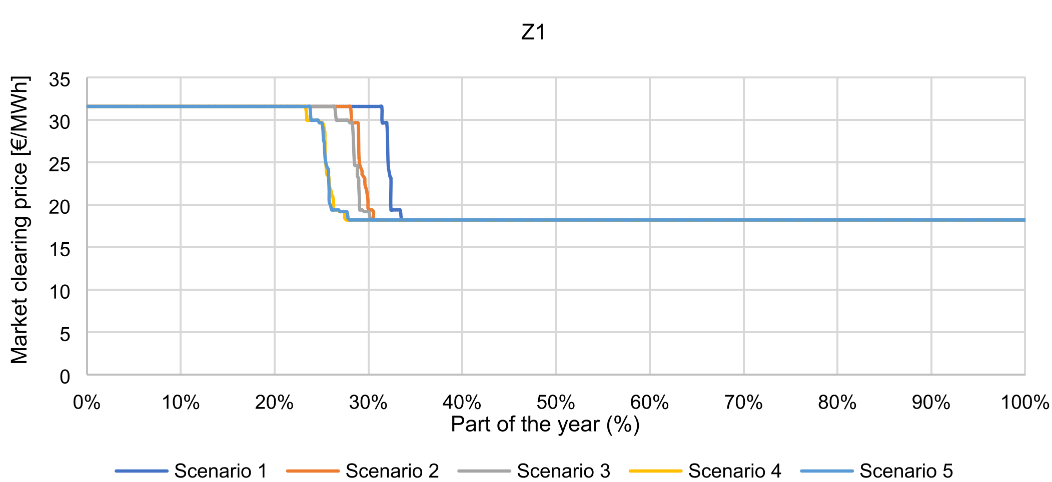

Fig. 6. Load duration curve of the market clearing price for Z1.

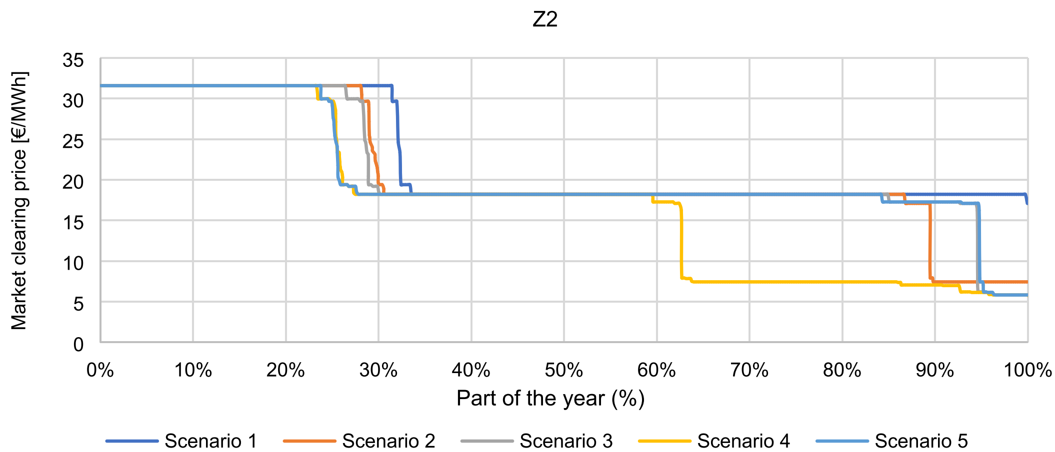

Fig. 7. Load duration curve of the market clearing price for Z2.

excess heat.

The MCP of each zone is shown by a box & whiskers diagram in Fig. 5, which aggregates the hourly values of the whole year. In this diagram, the whiskers represent the minimum and the maximum value that occurs in the selected period, the × represents the mean value and the middle line represents the median value. The bottom line of the box represents the first quartile, while the top line of the box represents the third quartile. The figure shows that the mean MCP in Z1 decreases slightly from Scenario 1 to Scenario 5, but the differences are rather small between all the scenarios. This is because excess heat and solar thermal cannot bid in Z1 since its demand is for industrial processes and its temperatures are assumed too high for these sources. However, they do affect the MCP in this zone indirectly through reducing the need for HOBO_GAS units in other zones, which enables increased production of cheaper CHP_BIO for covering Z1 demand.

On the other hand, the changes of the MCP between the different scenarios in Z2 and Z3, where excess heat and solar thermal are allowed to place bids, are much more evident. It can be seen that with the introduction of excess heat in Scenario 2, the minimum achieved MCP is reduced significantly, which reduces the mean value of MCP in Z2 from 22.52 €/MWh in Scenario 1 to 20.96 €/MWh in Scenario 2. This value is a bit higher in Scenario 3, at 21.27 €/MWh because of the variable availability of solar thermal, which is unavailable in most hours during the winter, while excess heat is available throughout the whole year.

Scenario 4 shows the highest variations in MCP for Z2 and Z3, as well as the lowest mean MCP of all scenarios at 17.44 €/MWh. This happens because there is no thermal storage for excess heat and therefore its bids are accepted only in those hours when it has the low price, which has a significant effect on the overall cost, but results in a low share of excess heat in the overall generation mix as was already shown in Fig. 3 and Fig. 4. Scenario 5 on the other hand results in the second lowest mean MCP. It should be noticed that in Z1, Scenario 5 has the lowest MCP of all the scenarios, as the share of utilized excess heat is increased and the need for expensive fossil fuel boilers is reduced. Therefore, the demand of Z1 can be covered by a lower cost CHP_BIO throughout the longest period of time. Finally, the differences between Z2 and Z3 prices are existent due to the changes in distribution network storage capacity of two zones but these are practically negligible. For that reason, in the following figures, only Z1 and Z2 will be illustrated.

Fig. 6 and Fig. 7 show the duration curve for the market clearing price in Z1 and Z2 respectively. For Z1 it can clearly be seen that Scenario 1 results in the lowest number of low MCP hours in the year, while Scenario 5 results in the highest. However, MCP does not fall below 18.21 €/MWh in none of the scenarios due to the lower impact of excess heat and solar thermal on Z1, as previously elaborated, and the lowest cost MCP corresponds to the bidding price of CHP_BIO. On the other hand, the results for Z2 show that even lower MCP can be achieved, especially for Scenario 4 in which the price is below 8 €/MWh for 3233 h in the year. Scenario 2 and Scenario 3 also achieve MCP below 8€/MWh but for a much shorter time period, i.e., 919 h for Scenario 2 and 475 h for Scenario 3. In contrast, the MCP of Scenario 5 is at 18.21 €/MWh through most of the year and falls below that for a much shorter period of time. This higher price, compared to Scenario 4, is due to the thermal storage unit, which enables the higher utilisation of excess heat but also

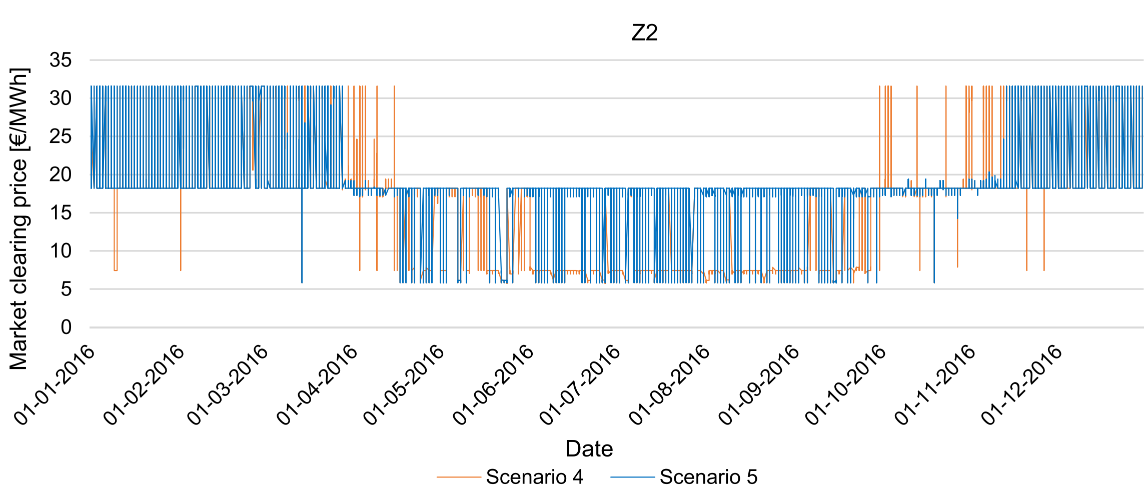

Fig. 8. Hourly market clearing price of Scenario 4 and Scenario 5 in Z2.

Table 3
Total welfare of all the scenarios, on an annual level.

Scenario	Total Welfare [€]
Scenario 1	3,681,941
Scenario 2	4,022,894
Scenario 3	4,175,062
Scenario 4	4,444,681
Scenario 5	4,604,915

Table 4
Levelized cost of heat in [€/MWh] for excess heat sources and solar thermal in different scenarios.

	Scenario 2	Scenario 3	Scenario 4	Scenario 5
EH_IND	9.42	–	12.59	8.50
EH_SMARK	60.40	–	72.05	48.46
EH_HOSP	184.00	–	218.50	103.80
SOLAR	–	6.39	6.42	6.23

storing this heat during the hours in which it would otherwise be directly used on the market and reduce the need for CHP_BIO. Therefore, by implementing TS_EH, the production of CHP_BIO as a marginal production technology increases.

The difference between MCP of Scenario 4 and Scenario 5 in Z2, which are the most interesting for this study, is shown on an hourly level in Fig. 8. Here it can easily be seen at which hours Scenario 4 has a lower MCP than Scenario 5. The differences can be most easily observed during the summer period, i.e., outside of the heating season. Because of the thermal storage unit, the MCP of Scenario 5 remains below the bidding price of HOBO_GAS in autumn for approximately 1.5 months longer than in Scenario 4, meaning that HOBO_GAS does not need to be turned on before the middle of November. The same can be observed in the spring, when HOBO_GAS turns off already at the end of March in Scenario 5, while in Scenario 4 it is still needed until the middle of April. On the other hand, the MCP of Scenario 5 is much higher on average during the non-heating season, when compared to Scenario 4 because of the need for the CHP_BIO operation in times when thermal storage is being charged. This figure clearly shows the effect of the thermal storage operation on the market clearing price. While in Scenario 4, the lower price is achieved during the summer due to the demand being covered mainly by solar thermal and industrial excess heat, Scenario 5 enables the utilisation of a higher amount of excess heat sources through the implementation of thermal storage, and reduces the number of high MCP periods, which translates to the reduced use of HOBO_GAS units.

Finally, since the objective function of the day ahead heat market optimizes social welfare, it is necessary to provide the analysis of this parameter. Overall social welfare on the annual level is shown in Table 3.

The figures show that the total welfare is maximal in Scenario 5, due to the fact that the highest amount of excess heat and solar thermal bids are accepted in the market. Taking into account both the production and the demand side benefits, Scenario 5 is obviously the most optimal solution, even when environmental effect is not considered. Furthermore, it can be seen that all the scenarios have a positive total welfare providing the further benefit of implementing the wholesale day ahead heat market.

4.3. Levelized cost of heat

As previously mentioned, these scenarios have been based on the current situation in the city of Sisak, where HOBO_GAS and CHP_BIO already exist. Their feasibility will therefore not be discussed in more details since they are already built. On the other hand, excess heat units and solar thermal have not been built yet and therefore it is necessary to analyse whether their participation on the heat market would be feasible, i.e. should these units be built in the first place. This is done by calculating the levelized cost of heat (LCOH) for these production units and comparing it to the average achieved price on the market. LCOH is used based on the previous research from authors [16], which showed that it is a good criterion for calculating the feasibility of excess heat. From the perspective of this paper, LCOH provides a minimum price at which excess heat and other market actors can feasibly participate on the heat market. It has been calculated by using the equation provided in the previous research from the authors [16,17] and is presented in Table 4. Here, the difference between the bidding price in the market and LCOH needs to be pointed out. While both use discounted investment, fixed and variable O&M, fuel costs and other sources of costs, LCOH uses data on the real utilisation, i.e. the capacity factor of the unit for which it is calculated. Therefore, it can be calculated only after the results from the heat market are acquired.

Table 5
Achieved average price in [€/MWh] of the excess heat sources and solar thermal on the heat market in various scenarios.

	Scenario 2	Scenario 3	Scenario 4	Scenario 5
EH_IND	22.49	–	23.45	23.18
EH_SMARK	30.32	–	30.93	31.16
EH_HOSP	31.18	–	31.16	31.33
SOLAR	–	19.81	15.42	18.37

The results show that the lowest LCOH is achieved for SOLAR, due to its high capacity factor and low costs. On the other hand, LCOH of excess heat varies significantly depending on the source. If the source is an industrial facility, where there is no need for a heat pump due to the high temperature level, LCOH is rather low in all the scenarios. This is not the case for the excess heat from the supermarket and the hospital due to the need for an additional heat pump. Especially high LCOH is calculated for the hospital excess heat due to its lower temperature level and therefore lower coefficient of performance of the heat pump. Even in Scenario 5, where thermal storage is available, the high price does not enable higher utilization of these sources and therefore results in high LCOH.

As mentioned earlier, these values need to be compared with the average achieved price of these units on the market, which is shown in Table 5. It was calculated by multiplying the cleared bid of each technology with a MCP in every hour of the year, summing these values and dividing them with the overall production from this technology. Based on Table 5 it can be concluded that solar thermal is a very feasible solution in such markets. The same can be said for the excess heat from the industry since the achieved average price was significantly higher than the LCOH in every scenario. However, low temperature excess heat sources have such a high LCOH in Scenario 2, 4 and 5 due to the low capacity factor that despite achieving a higher average price they still remain infeasible. These results are in line with the previous research [17] which showed the infeasibility of the low temperature excess heat sources.

A couple of facts can be discussed based on these results. First, it can be seen that the lower temperature excess heat sources are currently not suitable for the traditional high temperature district heating systems since the low COP of the heat pump results in high electricity costs and therefore low feasibility of this source. On the other hand, high temperature industrial excess heat has a high feasibility, regardless of its capacity factor since there is no need for a heat pump and the costs in general are much lower. Solar thermal has proven to be a big competitor to the low temperature excess heat due to its low costs and it was shown that in most cases it will reduce the operation of excess heat sources. This leads to the fact that thermal storage is required for excess heat in situations when there is a competition with low bidding price technologies like solar thermal, but also when these sources operate alongside traditional production units, due to their variable availability. However, the feasibility of low temperature excess heat would increase significantly if the supply temperature of the district heating network would decrease. This shows the necessity of transforming the existing 2nd and 3rd generation systems to the low temperature 4th generation district heating to utilize various low temperature sustainable heat sources.

5. Conclusion

The main idea of this paper was to analyse the functionality of a wholesale day ahead heat market and specifically to investigate the feasibility of excess heat utilisation from different temperature level sources when it participates in such a market. For that purpose, an open source energy market model (DARKO) was developed, which was validated on a case study based on a mid-size city in Croatia, the city of Sisak. The results of the analysis showed that a day-ahead 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. The lowest costs for the demand side turned out to be in Scenario 4, when excess heat from industry, supermarket and hospital, as well as solar thermal collectors are added to the current system, resulting in a decrease of costs by 7.6% compared to Scenario 1. However, in this scenario solar thermal reduces the capacity factor of the excess heat sources significantly (industrial excess heat 67%, excess heat from supermarket 26% and excess heat from hospital 9%) due to its low bidding cost. Therefore, from the environmental perspective, Scenario 5 provides better results since the utilization of excess heat is increased, while the utilization of solar thermal remains roughly the same. This can only be achieved if a seasonal thermal storage is built, which was proven to be a precondition for achieving a high capacity factor of the excess heat utilization. Despite not being the cheapest solution (although it is the second cheapest solution with just 2.3% higher costs compared to Scenario 4) for the demand side, the total welfare of Scenario 5 turned out to be the highest at 4,604,915 €, meaning that it is the most optimal solution from the perspective of the model, which maximizes the total welfare of the system.

By taking a closer look at the feasibility of different excess heat sources when participating at the heat market, it can be concluded that low temperature excess heat sources, like service sector facilities (supermarkets and hospitals in this paper) are not feasible in the existing high temperature district heating systems. This has been analysed by calculating the levelized cost of heat for each of the excess heat sources and solar thermal and comparing it to the average achieved price on the market. In Scenario 5, where the capacity factor of all these technologies was the highest, both the excess heat from industry and solar thermal heat were feasible. However, excess heat from hospital and the supermarket, which were assumed to have a low temperature, were still not feasible, with levelized cost of heat being higher than the achieved price by 72.5 € and 17.3 € respectively. This shows the need for the low temperature 4th generation district heating systems, which would decrease the costs of low temperature excess heat sources and make them a viable solution in the heat market.

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. **Sylvain Quoilin:** 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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Appendix

Figs. A1–A5
Table A1

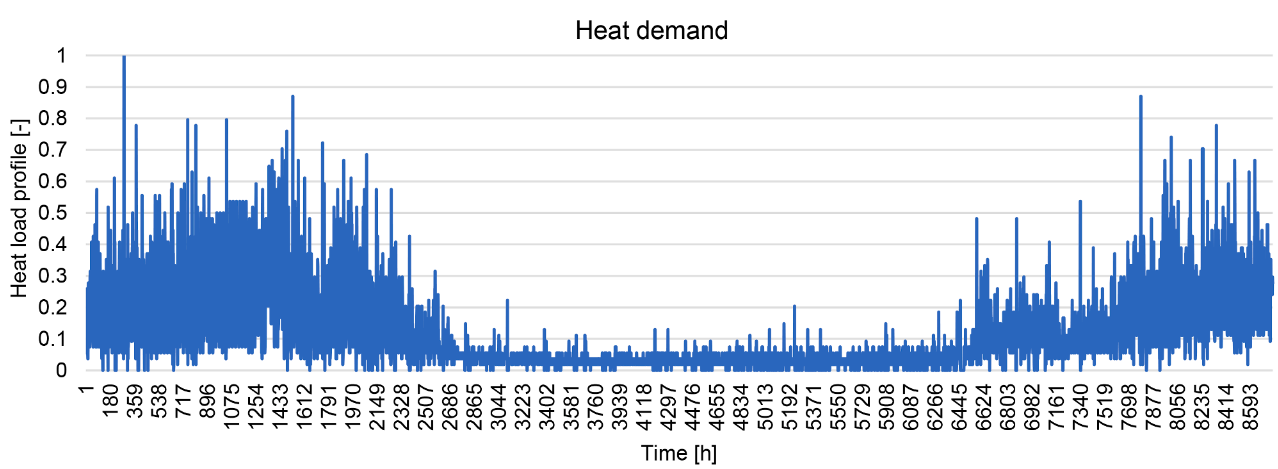

Fig. A1. Heat demand profile for Z2, also applied to Z3.

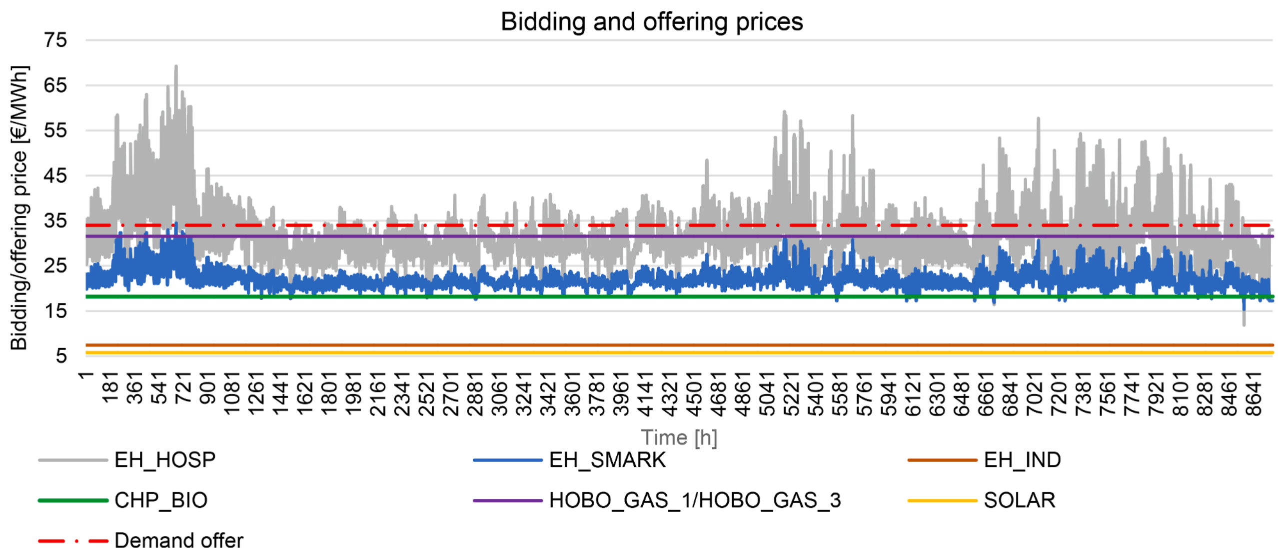

Fig. A2. Bidding prices of different technologies and demands analysed in the paper.

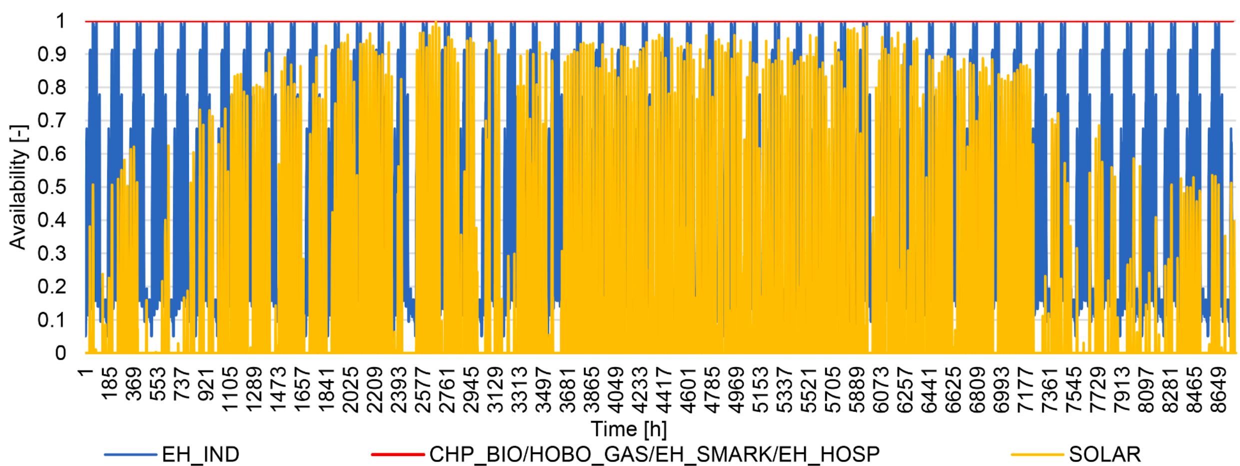

Fig. A3. Availability factor for the technologies participating on the market.

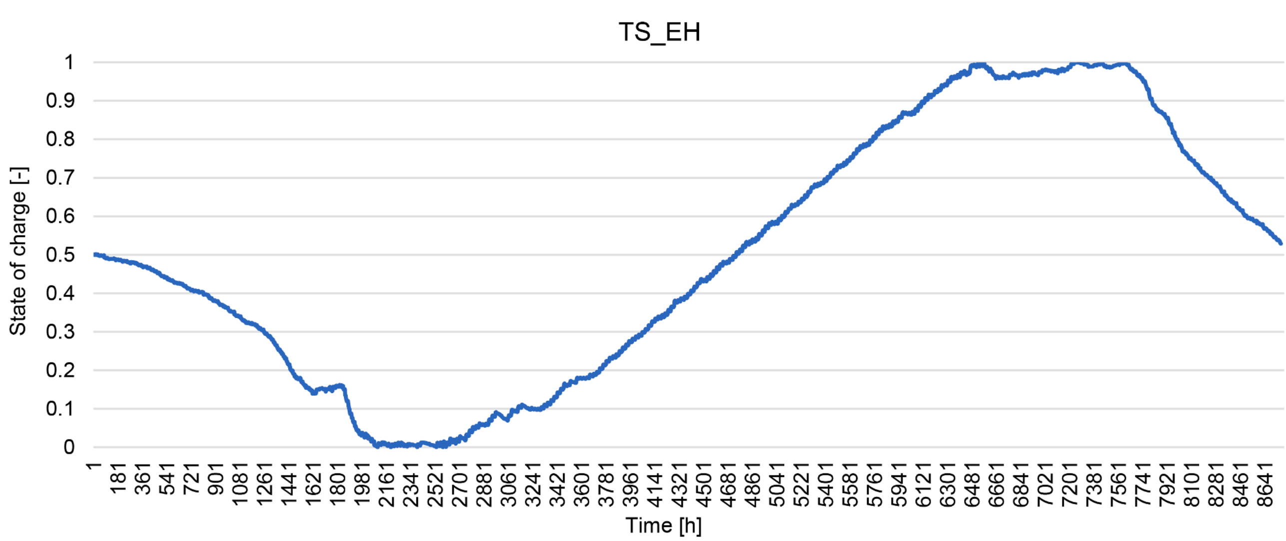

Fig. A4. Optimized thermal storage profile used for the seasonal storage in Scenario 5.

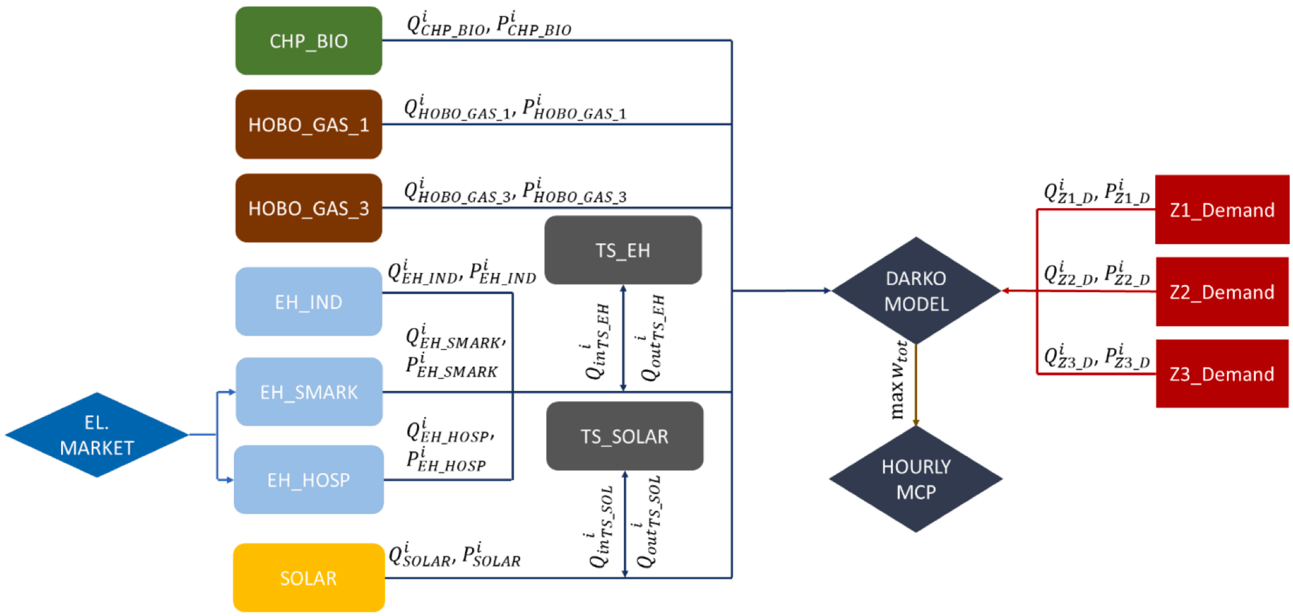

Fig. A5. System schematic for Scenario 5.

Table A1
Economic data for the analysed heat production technologies.

Technology	Investment cost	Fixed O&M cost	Variable O&M cost [€/MWh]	Discount rate [%]	Lifetime[years]	Fuel cost [€/MWh]	Reference
HOBO_GAS	60,000 €/MW	2000 €/MW	1.1	8	20	30	[45]
CHP_BIO	1,450,000 €/MW	71,250 €/MW	2.3	8	14	15	[45,46]
EH_IND	542,000 €/MW	2% invest.	–	8	20	–	[47]
EH_SMARK	1,240,000 €/MW	2000 €/MW	2.7	8	25	–	[45]
EH_HOSP	1,240,000 €/MW	2000 €/MW	2.7	8	25	–	[45]
SOLAR	489 €/MWh	0.09 €/MWh	0.2	8	30	–	[45]

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