

Liberalized market designs for district heating networks under the EMB3Rs platform

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ABSTRACT

Current developments in heat pumps, supported by innovative business models, are driving several industry sectors to take a proactive role in future district heating and cooling networks in cities. For instance, supermarkets and data centers have been assessing the reuse of waste heat as an extra source for the district heating network, which would offset the additional investment in heat pumps. This innovative business model requires complete deregulation of the district heating market to allow industrial heat producers to provide waste heat as an additional source in the district heating network.

This work proposes the application of innovative market designs for district heating networks, inspired by new practices seen in the electricity sector. More precisely, pool and Peer-to-Peer (P2P) market designs are addressed, comparing centralized and decentralized market proposals. An illustrative case of a Nordic district heating network is used to assess the performance of each market design, as well as the potential revenue that different heat producers can obtain by participating in the market. An important conclusion of this work is that the proposed market designs are in line with the new trends, encouraging the inclusion of new excess heat recovery players in district heating networks.

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1. Introduction

1.1. Motivation

Over the years, DHC systems have been proliferating in many countries [1]. In Denmark, according to EUROHEAT & POWER, 65% of citizens were served by District Heating Networks (DHNs) in 2017, accounting for more than 30 000 km of pipelines in DHNs. Most European DHC systems follow a monopolistic approach due to heat demand sparsity, the market power of a single generating unit that often owns the DHN, the lack of DHN linking all possible customers, and long-term return on investment. These reasons pull back new investors and market liberalization, which could foster the reuse of waste heat as an extra source in DHNs [2,3]. In fact, DHN is a natural monopoly due to the large infrastructure and operation costs, concerning the production and distribution of heating and cooling. Therefore, the heat production plants and the network are commonly owned, operated and managed by the same company, which is the main obstacle to the complete liberalization of the system [4]. Overall, DHC systems are

heavily regulated and price competitiveness for consumers is disregarded.

Nevertheless, governments (through energy regulators and policymakers) are enforcing the liberalization of heat markets (similar to what happened in the power system), as it becomes easier to monitor the whole process of energy systems, aiming to drag the prices down through competition, once the energy providers are competing with each other, leading to economic benefits for consumers [5–9]. Therefore, DHC market liberalization is gaining momentum in some European countries, aiming to replicate and adapt the good experience with electricity markets, bringing their capacity to improve system efficiency [7,10,11]. This disruptive paradigm shift will increase competitiveness through the inclusion of new players in the system. That is, several agents from different industry sectors can play an active role in the DHC market by buying and selling energy from different sources, increasing competitiveness and bringing financial benefits to everyone involved [6,12].

1.2. Literature review

The authors in [10,13] present case studies suggesting that a large amount of heat demand can be supplied by industries, e.g., by supplying waste/excess heat of industry processes to neighboring consumers, but no business or market assessment is

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Nomenclature**Sets and Indexes**

Ω_c	Set of consumers c
Ω_m	Set of agents m
Ω_n	Set of agents n
Ω_p	Set of producers p
$\Omega_{ln,m}$	Set of pipes in the path between agents n, m
Ω_k	Set of communities k
i	Pipe index
k	Community index
m	Agents index
n	Agents index
t	Time period index
S^L	Set of loads in DHN
S^S	Set of heat sources in DHN
S^{no}	Set of nodes in DHN
$S_{in}^{p,e}$	Set of pipelines ending at node in
$S_{in}^{p,s}$	Set of pipelines starting at node in

Parameters

λ_b	Heat transfer coefficient of pipeline
$\underline{P}_n, \overline{P}_n$	Lower and upper bounds of agent n
C_n	Price offer by agent n
C_p	Specific capacity of water
$c_{exp,k}$	Cost of heat export
$c_{imp,k}$	Cost of heat import
$C_{n,k}$	Price offer by agent n from community k
$C_{n,m}$	Product differentiation cost applied to the trade between agents n and m
$c_{n,m}$	Initial penalty between agents n and m
$D_{i,n,m}$	Influence of agents n and m in the total heat flow in pipe i (%)
$d_{i,n,m}$	Distance of pipeline i in the path between agents n and m
E_n	CO ₂ Signals Coefficient by agent n
$h_{in,t}^L$	Energy demand of heat losses
$l_{n,m}$	Thermal losses of pipeline i in the path between agents n and m
T_t^a	Ambient temperature at period t
$TotDist$	Total pipeline distance in the network
$TotLoss$	Total pipeline losses in the network

Variables

$\alpha_{n,k'}$	Imported heat by agent n at the community k
$\beta_{n,k'}$	Exported heat by agent n at the community k
$\dot{m}_{b,t}^{p,s}/\dot{m}_{b,t}^{p,r}$	Mass flow rate in supply/return pipeline
$\dot{m}_{in,t}^S/\dot{m}_{in,t}^L$	Mass flow rate of heat source/load

$\tau r_{b,t}^{p,in}/\tau r_{b,t}^{p,o}$	Temperature at inlet/outlet of return pipeline
$\tau s_{b,t}^{p,in}/\tau s_{b,t}^{p,o}$	Temperature at inlet/outlet of supply pipeline
$\tau s_{in,t}^L/\tau r_{in,t}^L$	Supply/return temperature of heat source
$\tau s_{in,t}^{no}/\tau r_{in,t}^{no}$	Mixture temperature at supply/return node
$\tau s_{in,t}^S/\tau r_{in,t}^S$	Supply/return temperature of heat source
$h_{in,t}^S$	Generation of heat source
$P_{k,k'}$	Bilateral trade between communities k and k'
$P_{n,k}$	Total heat production/consumption of agent n from community k
$P_{n,m}$	Bilateral trade between agents n and m
P_n	Total heat production/consumption of agent n
$Participation_{p,t}$	Binary variable indicating market participation
$q_{exp,k}$	Heat exported by a community k
$q_{imp,k}$	Heat imported by a community k
$q_{n,k'}$	Internal trade by agent n at the community k

yet ignoring their prosumer behavior in a competitive energy market. On the other hand, the works in [16–18] show the benefits of the synergies between the power and DHC systems, modeling centralized dispatches to improve the efficiency of the entire energy system, however, disregarding market competition. In addition, consumers can also play an active role in the DHC system, providing demand flexibility in response to dynamic tariffs, thereby improving market competition [19–22], but no prosumers participation is considered.

DHC markets inspired by the electricity sector, applying conventional market designs and approaches (as the pool/merit-order), are growing [11,13,23–27]. An example of a running DHC market is the Open District Heating project [28], operating at Stockholm's DHN, which encourages industrial businesses to sell their excess heat to the DHN at a uniform price cleared in the proposed day-ahead heating market. In Denmark, there is a centralized day-ahead heat market, where producers and consumers submit their offers for the following day. The market is dispatched by the operator based on the merit-order, considering the technical aspects of the heating system [29]. However, none of these markets are designed for prosumers (e.g., supermarkets equipped with heat pumps).

In fact, the literature is scarce in innovative DHC market designs to bridge the gap of prosumers integration in the DHN and participation in current energy exchange heat markets. An innovative market idea is the adaption of consumer-centric market designs, inspired in the power sector, allowing prosumers to supply surplus heat to the DHN by exchanging energy in the market. Recently, this concept through the P2P subject, has been brought up by some researchers [30,31]. The authors in [30] proposed a decentralized energy management, enhancing the energy trade without supervision from other identities. This approach turns aside the usual monopoly in the heat management systems. The model is a multi-layer architecture, and each peer aims to maximize its profit. With the directly energy trade between agents, the authors state the energy cost can be reduced by 61%. Similarly, the work presented in [31] also highlights the P2P

introduced. Similarly, the authors in [14,15] also demonstrate the benefits that prosumers (proactive consumers who can consume and produce heat at different time steps by taking advantage of heat pumps, waste heat and renewable heat technology) bring to the DHC system if they supply their excess heat to the DHN,

benefits. In a wider perspective, the electricity and heat market are addressed. The thermal agents operate as price makers and the electricity agents as price takers. The market is based on a linear optimization through an iterative algorithm. The main outcomes point to benefits for all the involved agents, but also to small-scale heat producers, which can engage new players. Both studies present a fully distributed and iterative P2P market approaches for heat exchange, yet disregarding a fair comparison with the centralized market approach (pool-based market). The studies do not assume the same general market structure and incentives, which may benefit their P2P market approaches. In addition, the transition between the today's centralized system and the expected decentralized system, as well as the settlement structure for each market type, is disregarded.

1.3. Main contributions

Specifically, this work contributes to the literature by modeling alternative market designs for the negotiation of heat in DHNs, considering local energy communities. More precisely, three distinct market designs are modeled and compared, namely, the pool-based, the P2P, and the community-based market designs. The markets are adapted from the current and future trends in electricity markets. Additionally, consumers preferences (e.g., distance, losses and CO₂) through product differentiation are applied to the P2P market design, enabling consumers to choose sources they prefer to be provided from. An illustrative DHN based on Nordic countries is used to test the applicability of the proposed solution. The main contributions of the present work are fourfold:

- To implement, analyze and compare, different market models in the EMB3Rs platform;
- To model new market designs for heat exchange in the DHN, namely, the pool-based, P2P, and community-based market designs;
- To explore competitiveness in DHC markets, enabling producers and industrial businesses with excess heat recovery systems to inject excess heat in the DHN;
- To improve market options for consumers by introducing product differentiation in the P2P market design.

Note that the present work aims to provide the most significant advances in the market module of the EMB3Rs platform, which includes the design, formulation and settlement of new markets. DHN operation and control is out of the scope of the market module and of the current work.

In addition to this introductory section, this paper is organized as follows. Section 2 describes the EMB3Rs platform for the simulation of different DHC market designs. Section 3 presents the detailed mathematical models of the proposed market designs. Section 4 assesses the proposed market models considering an illustrative case of Nordic DHNs, while Section 5 gathers the conclusions of the study.

2. EMB3Rs platform for DHC market simulation

This section provides an overview of the EMB3Rs platform that will incorporate current and new market designs, adapted to the context of DHC systems. In addition, it provides a brief review of the actual situation of the DHC markets in the Nordic countries.

2.1. Current DHC market situation in Nordic countries

The current situation of DHC markets varies on a country basis, as the deregulation of DHC systems has been carried out in different ways [32]. In Denmark, the DHN is still a natural monopoly, as the network and heating plants are mostly owned by energy companies, municipalities or consumer cooperatives. The regulation dictates that the heat supply works under non-profit rules, which means that the supplier must provide heat to consumers at marginal cost. This non-profit rule benefit everyone, as any profits are distributed to consumers to reduce costs [33]. In this case, industries with excess heat are encouraged to self-consume and only then to sell excess heat to the market, since the sale of excess heat comes with a tax to prioritize energy efficiency [32].

Similarly to Denmark, DHNs are also heavily regulated in Norway. DHNs are mostly private and municipal owned, with mandatory connections to consumers decided by the municipalities, while the operator is forced to expand the network [32]. The energy price from different producers are set on a competitive market, but prices for consumers with mandatory connections are regulated and cannot exceed the price of electric heating within the supply area [34]. Alternatively, consumers without mandatory connections are free to choose their heating source (e.g., electric heating or heat pump), so the supply price will follow the electricity price [34,35].

In contrast, Sweden was one of the first European countries to deregulate the heating market, however, that deregulation was not as robust as expected. According to [36], the prices of the different Swedish utility companies are not similar, meaning that these companies behave as price-makers. The costs are related to heating production and DHN operation, while what was expected was marginal-based pricing. On the other hand, Finnish utility companies have a monopoly on certain DHNs. Consumers have no open market to select their DHC utility [37]. Some Finnish companies have been trying to change this paradigm, i.e., offering seasonal tariffs, but these measures also do not shape the fair price for customers [19]. For further details on the situation of DHCs systems in European countries, interested readers are referred to [32,38].

Nonetheless, the transition to sustainable, efficient and competitive markets is unavoidable and future DHC markets will require new market approaches suitable to the integration of renewable energy sources in DHNs [39].

2.2. EMB3Rs platform overview

The EMB3Rs platform has been designed to assess the reuse and trade of excess thermal energy in a holistic perspective within an industrial process, energy system environment, or in an DHN under regulated and liberalized market environment [40]. The platform empowers industrial users and stakeholders to investigate the revenue potential of using industrial excess heat and cold as an energy resource, based on the simulation of supply-demand scenarios. Therefore, the platform simulates multiple business and market models, proposing innovative solutions in the sector.

From the large variety of options, users can: (i) map new and existing supply and demand users with geographic relevancy and enable their interlink; (ii) assess costs and benefits related to the excess heat and cold utilization routes, considering existing and new network infrastructure (e.g., DHN); (iii) explore and assess the feasibility of new technology and business scenarios; and (iv) compare and analyze distinct market models applied to the DHN to dynamically create new business models and identify potential benefits and barriers under specific regulatory framework conditions.

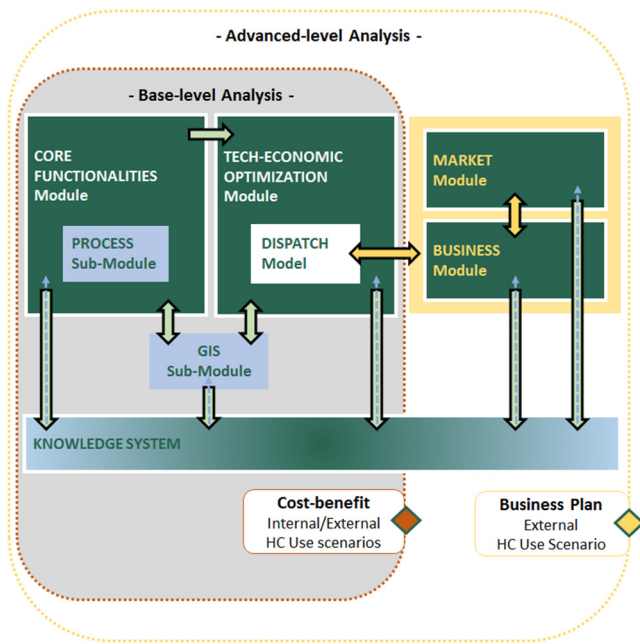


Fig. 1. EMB3Rs architecture and main functionalities.
Source: Replicated with authorization from [40].

To overcome all the above features, the platform is composed by individual functional modules (presented in Fig. 1) that connected are able to provide a cost-benefit analysis and solutions for excess heat and cold recovery in industry. More precisely, the core functionalities module relates all the parameters of the users (e.g., geographical location, temperature and amount of energy available). In addition, it includes the process sub-module and geographical interface system sub-module that provides the characterization of the individual industrial processes. The techno-economic module performs long-term simulations assessing investment and maintenance costs considering new technologies for heat recovery. The market module simulates different market designs following regulated and liberalized approaches. The business module defines the main conditions for exploitation of excess heat in industry, considering regulatory framework, investment goals, existing infrastructure, etc. This module communicates with the other main modules, (mainly, the techno-economic and market modules) to ensure that all business specifications are included in the cost-benefit analysis of the tool.

The integration of a dedicated market module in EMB3Rs platform allows users to perform market analysis considering multiple existing market designs, regardless of the DHN operation and control. Therefore, users can create, test and validate different market structures for selling and buying energy in the DHN, identifying barriers and risks, as well as regulatory framework conditions required to ensure that the implementation of such market solutions are economically feasible. That is, the market analysis enable users (e.g. industries, supermarkets and data centers) to estimate potential revenues from selling excess heat and cold. This is especially important for users who have invested (or are considering investing) in waste heat recovery technology to assess the potential economic and environmental savings of their investment. In this scope, the market module of EMB3Rs platform considers the market specifications and operation for the exchange of heat and cold energy. The technical operation of each asset, including the DHN operation is disregarded in this market module, as it concerns to other modules within the EMB3Rs platform. Thus, the present work focuses specifically on the market designs implemented on the EMB3Rs platform.

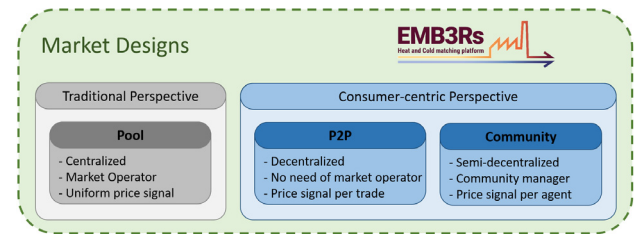


Fig. 2. Market designs under EMB3Rs platform.

2.3. Market approach for heat exchange

On the EMB3Rs platform, users must be able to explore different market designs, from centralized to the decentralized designs, allowing them to analyze the best market framework for their interests, which can be economic, environmental or social.

In this regard, three distinct market designs are adapted in the present work to be included in the EMB3Rs platform, as presented in Fig. 2. The conventional pool market, the innovative P2P and community-based market designs are addressed to ensure that the platform's users (e.g., industries, supermarkets and data centers) can assess their business models under different levels of market decentralization for the exchange of thermal energy in DHNs. All the three market designs are inspired in the electricity sector, and therefore, need to be adapted to the underlying characteristics of DHC systems.

The pool market follows a systemic perspective of the whole market by applying the merit order mechanism and performing the intersection of production and demand curves. This mechanism, known as uniform price, results in a market clearing price that is used for the settlement of producers and consumers. That is, each producer and consumer scheduled in the market will receive and pay for the energy at the market clearing price, respectively. This market design requires an independent central entity to operate it, usually referred as market operator.

In contrast, consumer-centric market designs (such as P2P and community-based market designs) follow a more decentralized and consumer-focused perspective. The P2P market enables producers and consumers to exchange energy directly with each other, subject to certain specific conditions defined by consumers. In this market design, no central facilitator is needed to verify energy exchanges, being usually referred to as a fully distributed market. On the other hand, the community-based market requires the use of a central entity (usually referred to as community manager) that coordinates energy exchanges within the energy community, well as the imports and exports to other energy communities and DHN players. It is worth to mention that these kind of decentralized markets can empower consumers and prosumers to play a more active role in the DHN. For instance, local supermarkets are emerging thermal prosumers that can provide and consume heat in different hours, making them a flexible player to reuse excess heat and even selling surplus heat to other consumers in the DHN.

3. District heating market designs

The DHC market designs discussed in this work, represent insights into the future of heat exchange in DHNs. There is still a long way to go regarding infrastructure and legislation for the implementation of liberalized markets. In this context, the first steps in what we believe could be the DHC systems of tomorrow are given in this work. In this way, pool, P2P and community-based market approaches are addressed. Note that for the rest of

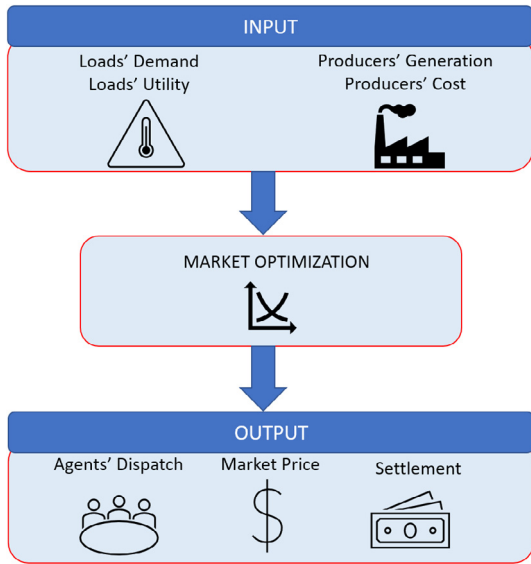


Fig. 3. Market framework overview.

the work, it is assumed that the heat sources are considered producers and the heat sinks are consumers. Prosumers are agents in the system that can both produce and consume energy at different times of the day, e.g., supermarkets. Even so, at every hour of market simulation, the prosumer behaves as producer or consumer, not both at the same time step. Therefore, the market formulation considers producers and consumers roles at every simulating hour. The prosumer's role in the market is updated every simulating hour depending on whether the prosumer participates as a producer or consumer, which is established through its individual expected net balance. It is noteworthy that the market does not consider network management, which is a problem to be solved aside.

3.1. General market framework

All the DHC market designs covered in this work follow the general stages of market operation illustrated in 3. In the input data stage, the market requires that all market participants (producers, consumers and prosumers) submit their offers (demand and production offers) for each time interval. In this case, it is assumed that the market is cleared on a hourly basis. Each prosumer must identify its role in the market, every hour, so that its offer is recognized as producer or consumer. All offers contain information about the expected amount of thermal energy that the player wants to buy or sell on the market, as well as the cost it is willing to pay or expecting to receive.

In the market optimization stage, the market algorithms, namely, the pool (Section 3.2), P2P (Section 3.3) and community-based market (Section 3.4) designs, can be used to clear the market and find a solution to the problem. Note that the market algorithm runs for every single hour. The market optimization returns the energy dispatched for each agent in the market, as well as the market clearing price used to perform the settlement in the output stage.

3.2. Pool market design

The pool market design (represented in Fig. 4) consists of matching all producers and consumers offers (price and quantity) through aggregated supply and demand curves, following the



Fig. 4. Pool market design.

merit order mechanism [29]. More precisely, heat producers submit offers to sell heat that are aggregated into the supply curve in price ascending order. Conversely, heating consumers and retailers submit bids to buy heating, which are aggregated into the demand curve in price descending order. The matching (intersection) of the supply and demand curves determines the offers that were scheduled in the market and establishes the market-clearing price. These steps are commonly known as the merit-order mechanism in the electricity sector [41,42]. Therefore, the market has the goal of maximizing social welfare, meaning that lower offers from producers and higher offers from consumers are scheduled. Since the network is not considered for clearing the pool market, there is only one market-clearing price, which is the same for all scheduled agents. The time gap between sessions associated with the pool market is usually one hour, but it may depend from country to country [41,42]. In theory, the pool market design is the best approach to obtain the highest social welfare, however, market scalability, communication burden and privacy concerns are the main drawbacks. In what concerns privacy, all peers in the market have to share their information with the market operator, which exposes the privacy of each peer in the system [43].

Mathematically, this market can be presented as:

$$\min_D \sum_{n \in \Omega_n} C_n P_n \quad (1a)$$

$$\text{s.t. } \underline{P}_n \leq P_n \leq \bar{P}_n \quad p \in \Omega_n \quad (1b)$$

$$\sum_{n \in \Omega_n} P_n = 0 \quad : \lambda \quad (1c)$$

$$P_n \leq 0 \quad n \in \Omega_c \quad (1d)$$

$$P_n \geq 0 \quad n \in \Omega_p \quad (1e)$$

where $D = \{P_n \in \mathbb{R}\}_{n \in \Omega_n}$ correspond to the energy traded by each agent n . C_n represents the agents' bid price; $\underline{P}_n, \bar{P}_n$, represent the lower and upper bound of the agents' energy offer, respectively; Ω_c represent the consumers sets, Ω_p represent the producer sets. Eq. (1b) set the agents offers boundaries. Eq. (1c) sets the market balance, where the supply must equal the demand. (1d) sets that the consumption is non-positive in the system, while (1e) sets that production variable from producers is non-negative. The dual variable λ sets the market price. The settlement, i.e., the revenue for the heat producers or the payment for the consumers in the pool market, is defined by the energy traded and the market price. The mathematical formulation is as follows:

$$\sum_{t \in T} \lambda^{*,t} P_n^{*,t} \quad (2)$$

3.3. P2P market design

Regarding the P2P approach, it is proposed that two different peers can trade heat on a bilateral basis, without a third party (coordinator) supervision [44], as represented in Fig. 5. That is, each peer n can exchange with another peer m on an individual basis, defining the amount of energy to be bought or sold at a given price. Note that prosumers can trade with both producers

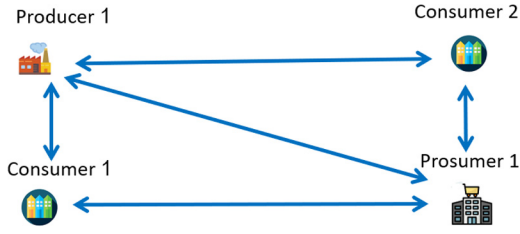


Fig. 5. P2P market design.

and consumers, but such interaction is limited by the type of offer they submit on the market. It is assumed that, at each hour, the prosumer can only present offers as a producer or consumer, and not both, to avoid energy arbitrage. The main advantage is that the privacy of peers is protected, as peers share limited information with those they want, taking full control of their own facilities [45]. The main disadvantage of this decentralized market is that the efficiency of the market is often reduced, especially when considering consumer preferences. Another potential disadvantage is the predictability of this market for network operators (due to the inconsistent bilateral exchanges between peers), which can make network operation even more complex to manage [43].

This problem can be mathematically formulated as follows:

$$\min_D \sum_{n \in \Omega_n} C_n P_n \quad (3a)$$

$$\text{s.t. } P_n = \sum_{m \in \Omega_n} P_{n,m} \quad n \in \Omega_n \quad (3b)$$

$$P_n \leq P_n \leq \bar{P}_n \quad n \in \Omega_n \quad (3c)$$

$$P_{n,m} + P_{m,n} = 0 \quad \{n, m\} \in \{\Omega_n\} : \lambda_{n,m} \quad (3d)$$

$$P_n \leq 0 \quad n \in \Omega_c \quad (3e)$$

$$P_n \geq 0 \quad n \in \Omega_p \quad (3f)$$

where $D = \{P_n \in \mathbb{R}\}_{n \in \Omega_n}$ represents the heat traded by each agent n . Like in the pool market, the goal is to minimize the cost associated with the agents' transactions (3a). The total heat traded by an agent n must equal the sum of the heat exchanges from that agent n to the other agents m (3b). Also, a reciprocity is expected in the bilateral trades (3d), where $P_{n,m}$ and $P_{m,n}$ must be symmetric. In this design, the market price is defined by transaction P_{nm} , here expressed through $\lambda_{n,m}$. The settlement is defined as:

$$\sum_{t \in T} \sum_{m \in \omega_m} \lambda_{n,m}^{*,t} P_{n,m}^{*,t} \quad (4)$$

Looking at the peer-to-peer formulation, one can see that it yields the trade between agents. Thus, a preference can be added to each of these trades, which can be translated into a penalty or benefit. This is called product differentiation, meaning that a certain trade can be advantageous or harmful to the system management. In this way, the objective function is willing to benefit or penalize the trades that deserve such consideration. The distance between agents, the thermal losses and the CO₂ emissions are preferences that can be placed within this scope. There is also the option where the agents can choose the penalty that best suits their ideology. For instance, on the EMB3Rs platform, three different penalty options are provided to the consumers. One option is the physical network distance between agents. For example, an agent can select the distance penalty if he wishes to trade with the nearest neighbor. Another option is thermal losses, where an agent can select the thermal losses penalty if it is

concerned about the system energy efficiency. Alternatively, the CO₂ penalty is proposed if an agent has environmental concerns. Conventionally, the product differentiation is represented as:

$$C_{n,m} = P_{n,m} c_{n,m} \quad (5)$$

where $C_{n,m}$ represents the final penalty applied to the trade between agents n and m . $P_{n,m}$ represents the energy trade between agents n and m , and $c_{n,m}$ represents the initial penalty between these agents.

In order to apply product differentiation, the objective function must account with the penalty from Eq. (5). Thus, the objective function takes the following form:

$$\min_D \sum_{n \in \Omega_n} C_n P_n + \sum_{n \in \Omega_n} \sum_{m \in \Omega_n} C_{n,m} \quad (6)$$

where $D = \{P_n, C_{n,m}\} \in \mathbb{R}_{n,m \in \Omega_n}$. Hence, the formulation is completed, since Eqs. (3b)–(3f) keep unchanged. Nevertheless, the determination of the product differentiation penalties may follow different ways.

3.3.1. Physical network distance preference

In the distance preference, the network distance between the selected agents is determined. The penalty implies the sum up of all the pipes that make the path between agents. Note that Dijkstra's algorithm [46] is used to find the shortest path between agents. Thus, the penalty associated to the network distance is given by:

$$c_{n,m} = \sum_{i \in \Omega_{i,n,m}} d_{i,n,m} / \text{TotDist} \quad (7)$$

where $d_{i,n,m}$ represents the pipe distance along the path between agents n and m , while TotDist is the total network distance.

3.3.2. Network thermal losses preference

The thermal losses penalty between two agents is given by the share that each agent has in the system losses considering the thermal flow in each pipe. In this case, it is required to determine the thermal flow in the DHN and, therefore, the losses in each pipe. To determine the thermal flow and losses in the DHN based on the initial market results, the thermal control algorithm in [47] is used and briefly described below:

$$h_{in,t}^S = c_p \dot{m}_{in,t}^S (\tau_{in,t}^S - \tau_{in,t}^L) \quad (8a)$$

$$h_{in,t}^L = c_p \dot{m}_{in,t}^L (\tau_{in,t}^L - \tau_{in,t}^S) \quad (8b)$$

$$\tau_{b,t}^{p,o} = (\tau_{b,t}^{p,in} - T_t^a) e^{\frac{-\lambda_b L_b}{c_p \dot{m}_{b,t}^{p,s}}} + T_t^a \quad (8c)$$

$$\tau_{b,t}^{p,o} = (\tau_{b,t}^{p,in} - T_t^a) e^{\frac{-\lambda_b L_b}{c_p \dot{m}_{b,t}^{p,r}}} + T_t^a \quad (8d)$$

$$\sum_{b \in S_{in}^{p,e}} (\tau_{b,t}^{p,o} \dot{m}_{b,t}^{p,s}) + \sum_{j \in S_{in}^{p,s}} (\tau_{j,t}^S \dot{m}_{j,t}^S) = \tau_{in,t}^{no} (\sum_{b \in S_{in}^{p,e}} \dot{m}_{b,t}^{p,s} + \sum_{j \in S_{in}^{p,s}} \dot{m}_{j,t}^S) \quad (8e)$$

$$\sum_{b \in S_{in}^{p,s}} (\tau_{b,t}^{p,o} \dot{m}_{b,t}^{p,r}) + \sum_{h \in S_{in}^{p,r}} (\tau_{h,t}^L \dot{m}_{h,t}^L) = \tau_{in,t}^{no} (\sum_{b \in S_{in}^{p,s}} \dot{m}_{b,t}^{p,r} + \sum_{h \in S_{in}^{p,r}} \dot{m}_{h,t}^L) \quad (8f)$$

$$\tau_{b,t}^{p,no} = \tau_{in,t}^{no}, \tau_{h,t}^L = \tau_{in,t}^{no} \quad (8g)$$

$$\tau_{b,t}^{p,in} = \tau_{in,t}^{no}, \tau_{j,t}^S = \tau_{in,t}^{no} \quad (8h)$$

where Eqs. (8a) and (8b) present the thermal energy provided by heat producers and consumed by heat consumers, respectively. Due to the heat losses, temperature drops along the pipeline are expressed by Eqs. (8c) and (8d). Eqs. (8e) and (8f) express the temperature at confluence nodes, for both supply and return pipelines. Finally, the temperatures of leaving mass flows are equal to the temperature during mixing at the node (Eqs. (8g) and (8h)).

Therefore, the impact that each agent has on the thermal flow and losses of each pipeline is determined using Bialek's downstream looking algorithm [48]. Finally, the thermal losses penalty for the transaction between two peers is given by:

$$c_{n,m} = \sum_{i \in \Omega_{i,n,m}} l_{i,n,m} D_{i,n,m} d_{i,n,m} / \text{TotLoss} \quad (9)$$

where $l_{i,n,m}$ represents the thermal losses in each pipe along the path between agents n and m ; $D_{i,n,m}$ represents the n, m peer impact in each pipe of the system determined by the downstream looking algorithm presented in [48]. In this way, a fairly penalty allocation for the transaction between two agents is achieved, accounting for the cumulative impact that such transaction has in the thermal losses in the system.

3.3.3. CO₂ emissions preference

The last option proposed for product differentiation is to penalize transactions through CO₂ emissions. This penalty consists of penalizing peer transactions that may, consequently, emit higher emissions into the atmosphere. The EMB3Rs platform can provide standard levels of CO₂ per technology, and therefore, penalties between agents n and m consider such levels. Here, the penalty is only associated with the heat source. Hence, the CO₂ penalty between agents n and m is given by the quotient between agent n emissions and the total system emissions:

$$c_{n,m} = E_n / \sum_{n \in \Omega_n} E_n \quad (10)$$

where E_n represents the CO₂ emissions by agent n .

3.4. Community-based market

The community-based market design (represented in Fig. 6) intends to represent a more hierarchical structure of bilateral peer trades. In general, a community is composed by members who share common interests or are geographically close. In this semi-decentralized model, there is a community manager responsible for the community's energy management. In terms of privacy, it requires less information than the pool market model, but more than the P2P market model. This system is often seen as a compromising solution between the centralized and decentralized approaches [49].

This manager supervises all the trading activities within the community, as well as works as an intermediary in the heat trade with other communities or with the main grid [50]. The mathematical formulation is presented as:

$$\min_D \sum_{n \in \Omega_n} \sum_{k \in \Omega_k} C_{n,k} P_{n,k} - C_{exp,k} q_{exp,k} + C_{imp,k} q_{imp,k} \quad (11a)$$

$$P_{k,k'} + P_{k',k} = 0, \forall (k, k') \in (\Omega_k) \quad (11b)$$

$$q_{exp,k'} = \sum_{k \in \Omega_k} P_{k',k}, \forall k' \in \Omega_k \quad (11c)$$

$$q_{imp,k'} = \sum_{k \in \Omega_k} P_{k',k}, \forall k' \in \Omega_k \quad (11d)$$

$$\sum_{k \in \Omega_k} P_{k',k} = q_{exp,k'} - q_{imp,k'}, \forall k' \in \Omega_k \quad (11e)$$

$$P_{n,k} + q_{n,k} + \alpha_{n,k} - \beta_{n,k} = 0, \forall (n, k) \in (\Omega_n, \Omega_k) \quad (11f)$$

$$\sum_{n \in \Omega_n} q_{n,k} = 0, \forall k \in \Omega_k : \lambda_k \quad (11g)$$

$$\sum_{n \in \Omega_n} \beta_{n,k} = q_{exp,k}, \forall k \in \Omega_k \quad (11h)$$

$$\sum_{n \in \Omega_n} \alpha_{n,k} = q_{imp,k}, \forall k \in \Omega_k \quad (11i)$$

$$\underline{P}_n \leq P_n \leq \bar{P}_n \quad (n, k) \in (\Omega_n, \Omega_k) \quad (11j)$$

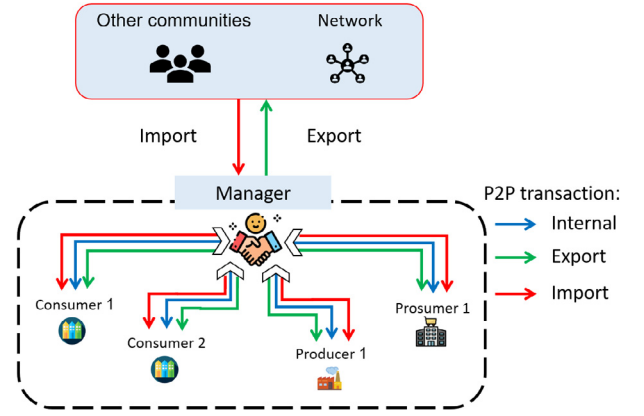


Fig. 6. Community market design.

where $D = \{P_{n,k}, q_{exp,k}, q_{imp,k} \in \mathbb{R}\}_{(n,k) \in \Omega_n, \Omega_k}$. $P_{n,k}$ represents the internal trade of agent n within its own community k . (11b) represents the symmetry when communities exchange heat. Eq. (11c) balances the exported heat by a community with other communities. The same is valid for (11d), regarding the imported heat. Also, the sum of one community bilateral trades must equal the exported heat minus the imported heat (11e). Eq. (11f) sets agents' balance, i.e., the purchase/consumption, the heat traded within the community and the heat exchanged with other communities must reach an equilibrium in each time period. Within a community, the purchase/consumption of all involved agents must be equal to zero (11g). Furthermore, the heat exported by each community agent must equal the total heat exported by the community (11h). The same holds true for the imported heat (11i). Like in the previous market designs, heat boundaries ought to be kept (11j). The market price per community is defined by λ_k . In the community-based, the settlement is defined as:

$$\sum_{t \in T} \lambda_{k,n}^{*,t} P_n^{*,t} \quad (12)$$

4. Case study

In this section, a case study is presented considering an illustrative Nordic DHN with several producers and consumers. This illustrative example has been developed to assess different market designs on the EMB3Rs platform. All the input data and results of this study, including demand and supplier offers for an entire year (from April 2018 to March 2019) are available at Mendeley Data [51].

4.1. Case characterization

A DHN has been built considering several producers and consumers with different characteristics and patterns.

Note that the DHN operator must ensure that the temperature is within the levels required by the heating demand, and that the flow rates in the DHN must be kept at a reasonable low level in order to avoid water velocities above 2 m/s. To this end, it is assumed that this DHN operates similarly to most Danish DHNs, which work within annual averages temperatures of 77.6 °C supply and 43.1 °C return [52]. In addition, it is assumed that all heat suppliers (producers and prosumers) comply with the network rules, and therefore, have installed a plate heat exchanger to convert its excess heat into the network; remote meters in the primary circuit (to measure the flow rate, pressure, and supply and return temperatures); and their own pumping group to circulate their excess heat.

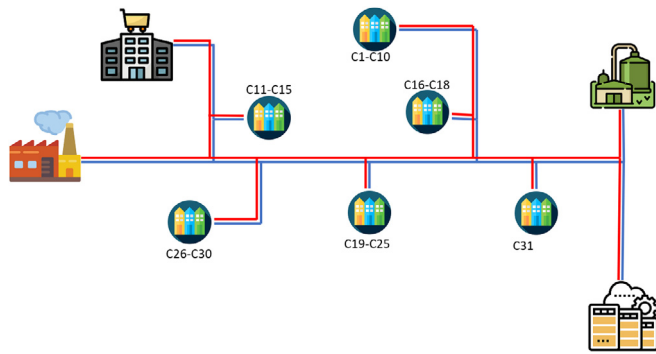


Fig. 7. Illustrative district heating network.

Fig. 7 shows the schematic diagram of the DHN, where 31 row houses and 3 potential producers and one prosumer are considered. The consumption of 31 row houses for a entire year (from April 2018 to March 2019) has been generated considering a typical demand pattern taken from [53]. The price that the row houses are willing to pay for the demand in the market follows a normal distribution, in which the base price is the heat tariff in Copenhagen, Denmark [54]. In order to suppress basic consumption needs, at least 70% of the heat demand of each house must be supplied at all periods.

A 15 kW industrial ammonia heat pump is located in the DHN and can provide heat at some time of the day at a certain cost. The heat pump generation profile considers a Coefficient of Performance (COP) ranging from 3,3 to 5, providing hot water via a heat exchanger at 80 °C, based on [55,56]. The cost curve of the heat pump is based on the electricity spot price in 2018 and 2019 in DK2 area in Denmark, taken from [57].

In addition, a 0.4 MW data center is included in the DHN. Commonly, data centers follow a relatively constant pattern of excess heat recovery to inject into the DHN, although the temperature of their excess heat from the condenser cooling towers is usually between 35 °C and 45 °C. Thus, an industrial ammonia heat pump, similar to the one referred above, would be required to upgrade its heat to inject into the DHN. This data center has been modeled producing 71,6 kWh on average, in which the calculus for the heat recovery profile is based on [58,59]. To this value, it would be added the energy used in the ammonia compressor. The cost curve for the data center sell recovered heat energy in the DHN has been modeled following a normal distribution and the monthly excess heat procurement costs presented in [59]. A 500 kW Combined Heat and Power (CHP) unit is included in the DHN being the main producer in the system. This CHP is designed to provide the entire consumption of the system, being therefore the most expensive generation resource. The CHP is not included in any community, as it is seen as an external agent, so that other agents can import heat, ensuring that there is always at least one heat source available throughout the year. The cost curve for a entire year follows the behavior of the natural gas spot price for years 2018 and 2019, available in [60]. Note that the prices were normalized for the Nordic context.

Besides this, a supermarket with heat pump technology and 50 kW capacity is included in the system behaving like a prosumer. That is, the supermarket may consume heat from the DHN or inject recovered heat into the DHN, taking into account the hour of the day and the outdoor temperature. The generation and consumption profile depends on the outdoor temperature. It has been considered the outdoor temperature in Copenhagen for the entire year (April 2018 to March 2019), available at [61]. Then, the prosumer profile of the supermarket is determined following a typical COP (around 3.0) for heat recovery in supermarkets, and

Table 1
DHN distance between agents.

Agent	Distance (m)			
	CHP	Supermarket	Data Center	Heat Pump
C1–C10	266,24	181,25	206,15	174,96
C11–C15	190,76	20,47	168,58	199,06
C16–C18	228,66	143,67	230,27	137,38
C19–C25	175,25	90,26	158,21	127,01
C26–C30	196,37	111,38	224,52	193,31
C31	259,32	174,33	122,23	94,28
SM	201,37	–	240,87	209,67

Table 2
DHN nominal losses between agents.

Agent	Losses (W/m)			
	CHP	Supermarket	Data Center	Heat Pump
C1–C10	17,31	16,40	17,31	14,02
C11–C15	18,35	17,23	16,83	17,43
C16–C18	17,90	17,12	17,73	17,58
C19–C25	18,10	18,01	17,78	17,49
C26–C30	17,24	16,51	17,41	16,43
C31	17,39	16,99	17,05	16,66
SM	18,64	–	16,87	17,86

Table 3
CO₂ emissions by heat producer.

CO ₂ Signals (g/kWh)			
CHP	Supermarket	Data Center	Heat Pump
225	225	166.1	34.6

a typical supermarket consumption pattern, detailed in [62]. The cost curve for the supermarket to inject recovered heat in the DHN depends on the outdoor temperature and is based on [63].

All supply offers from all producers and prosumers already consider the cost of electricity to be spent on the pumping group, which is necessary to inject the recovered heat into the DHN.

It is noteworthy that different market designs may require the use of different data or configurations. For example, the community-based market design requires the configuration of the energy community, that is, who are the community members. For the community-based market, two communities were created, based on the aforementioned energy resources, namely:

- Community 1: Data Center and all consumers from 19 to 31;
- Community 2: Supermarket, Heat Pump, and consumers from 1 to 18.

Regarding the P2P market model via product differentiation, the required data were retrieved based on the THERMOS project tool [64]. This tool is able to provide the distance (Table 1) and nominal losses (Table 2) between agents, based on the supply and return temperatures, and on the maximum heat flow in the pipelines.

The CO₂ signals for the CHP were obtained from [65], while for technologies that rely on the electricity mix were retrieved from [66] considering the Nordic zone. Table 3 presents the CO₂ signals for all heat producers.

4.2. Results

This section presents the main results and indicators for comparing the different market designs. All simulations were performed for an entire year of market operation.

4.2.1. General results

Table 4 presents the social welfare and the revenue achieved by each agent over the simulated year. For the pool market, the

Table 4
Agents' revenue by market design.

Revenue (€)	Pool/Full P2P	P2P Distance	P2P Losses	P2P CO ₂	Community
Social Welfare	175250	115560	166422	175040	110407
CHP	89328	69179	78094	85115	185057
Supermarket	5615	6162	5813	5352	6093
Data Center	85090	77614	84670	86931	77452
Heat Pump	6610	13413	5338	7007	14113
Load	361893	281928	340338	359446	366479

Table 5
Agents' dispatched heat by market design.

Dispatched Heat (kW)	Pool/Full P2P	P2P Distance	P2P Losses	P2P CO ₂	Community
Load	682941	532850	642078	678188	687215
CHP	217191	120623	180546	205486	275674
Supermarket	39937	43255	43255	38173	42758
Data Center	411472	338954	408897	419155	336219
Heat Pump	14341	30018	11522	15372	32564

achieved results are the same as the Full P2P, so these are not discussed in detail. As expected, the Full P2P market design is the one presenting the best solution, since there are no limitations on heat exchanges between agents, opposite to what happens in P2P with product differentiation where penalties (consumer preferences) are considered. Note that social welfare represents the objective function without penalties, i.e., once the objective is defined, the penalties are removed and all heat transactions are kept. Within the P2P markets, the P2P with distance as product differentiation (P2P Distance) is the one achieving the lowest social welfare (65.9% compared to Full P2P), since it is the one that most penalizes the transactions between agents. P2P CO₂ is the one reaching the social welfare closest to the Full P2P (more than 99.8%). The Full P2P and the community-based are the market models supplying more load, reaching 90% of the total load demand. Other models have a smaller delivery capacity and the minimum is reached for the P2P Distance where only 70% of the entire load demand is met. Although the community performs the poorest social welfare (63% compared to the Full P2P), it is worth stressing that it is the market that allocates the most load. In terms of heat production, the CHP and the data center are the ones producing the most heat throughout the year. The CHP has the largest thermal energy producing capacity and is the most expensive resource. Thus, it is often used to cover the remaining energy demand, which other producers cannot cover. On the other hand, the high dispatch of the data center is related to its high nominal capacity and low bid price offered in the market. The CHP shows a drop of about 45% in production at P2P Distance when compared to the Full P2P, which is linked to the fact that it is the producer that is more distant from the consumers.

It is worth mentioning that the heat pump reaches high dispatched heat levels and, consequently, high revenue in the P2P Distance and Community-based markets. The heat pump is located very close to the consumption points, which helps to explain the heat pump performance in the market design that considers the distance between agents. With respect to the community-based, the heat pump results are related to the community structure. The heat pump is a member of Community 2, where only the supermarket compete to meet the demand. As the supermarket behaves as a prosumer, the heat pump or imported heat are often the only available heat sources for that community, leading to a higher market share for the heat pump. As the heat pump and the data center are the two sources with the lowest CO₂ emissions, these are also the only agents presenting an increase in the heat supplied (1.8% and 6.7%, respectively), when comparing the P2P CO₂ with the Full P2P (see Table 5).

4.2.2. Single hour assessment

Table 6 shows each agent's revenue for the hour 8248, as in this period there is a proper market participation mix among all producers in all markets designs. Herein is detailed the effect each market design has on individual agents. For instance, the CHP presents the higher revenue in the Full P2P for that hour, while for the P2P distance, P2P CO₂ and Community no heat is dispatched. In this hour, the supermarket provides waste heat to the system. Actually, it is the only agent that supplies heat in all market designs, achieving the highest revenue of all agents in the P2P models. The data center collects the higher revenue in the community, whereas the heat pump only participates in the market in the P2P Distance, highlighting again the shorter distance to the consumer peers. The consumers, represented by C1, have the most linear behavior once all the demand is met, except in the P2P Distance due to a high penalty when settling the market.

4.2.3. Average dispatched heat and successful participation in the market

In addition to the general results, two key performance indicators (namely, the Average Dispatched Heat (ADH) and the Successful Participation in the Market (SPM)), were introduced. ADH represents the amount of heat that is dispatched from a source on average, i.e., the mean percentage of dispatched heat from the total capacity of the source. The values are presented in percentage (%) and determined through:

$$ADH(n) = \frac{\sum_{t=1}^T \frac{P_{n,t}}{\bar{P}_{n,t}}}{T}, \forall n \in \{\Omega_p\} \quad (13)$$

where $P_{n,t}$ represents the heat dispatched by source n in time period t and $\bar{P}_{n,t}$ represents the maximum capacity of source n in time period t .

Regarding the SPM, it indicates the level of participation by an agent n in the market, which is given by:

$$SPM(n) = \frac{\sum_{t=1}^T Participation_{(n,t)}}{T} \times 100, \forall n \in \{\Omega_p\} \quad (14)$$

where $Participation_{n,t}$ is a binary variable indicating whether a source n is or not dispatched in the market, in time frame t .

In addition to the annual results, seasonal results are also presented, once the sources and loads have seasonal behaviors. As one can see in Table 7, the heat dispatched is generally higher in the winter, which is linked to lower external temperatures, hence larger levels of heat demand are required. However, the

Table 6
Agent's revenue for hour 8248 (Friday)

Revenue (€)	Pool/Full P2P	P2P Distance	P2P Losses	P2P CO ₂	Community
CHP	1.28	0	0.54	0	0
Supermarket	4.12	3.5	4.12	4.12	2.71
Data Center	0	0	0.69	1.33	4.07
Heat Pump	0	0.43	0	0	0
C1	1.29	0.90	1.29	1.29	1.29

Table 7

Annual and seasonal index of average dispatched heat for each heat producer and market design.

	Year			
	CHP	Supermarket	Data Center	Heat Pump
Pool/Full P2P	72%	97%	62%	25%
P2P Distance	71%	100%	51%	64%
P2P Losses	71%	98%	61%	14%
P2P CO ₂	72%	96%	63%	28%
Community	30%	100%	51%	91%
Summer				
	CHP	Supermarket	Data Center	Heat Pump
Pool/Full P2P	84%	97%	48%	1%
P2P Distance	83%	100%	29%	36%
P2P Losses	87%	98%	48%	1%
P2P CO ₂	84%	96%	49%	4%
P2P Community	34%	100%	31%	92%
Winter				
	CHP	Supermarket	Data Center	Heat Pump
Pool/Full P2P	60%	98%	76%	50%
P2P Distance	58%	100%	73%	92%
P2P Losses	54%	98%	76%	28%
P2P CO ₂	60%	97%	77%	53%
Community	26%	100%	71%	90%

CHP presents lower ADH in the winter when compared to the summer period. This is connected to the higher bidding prices offered by this resource in that period of the year, which enhances other resources participation in the market. Also note that the supermarket is the resource with the highest ADH, being fully dispatched most of the time. It is also noteworthy that the heat pump is less dispatched in the summer than in the winter, not only due to the increase of the bid offer, but also due to the lower production capacity during this season.

Regarding the SPM indicator, the results clearly point to a high successful participation of the supermarket and data center in all market designs. When it comes to the data center, these results are justified by its steady heat production and low offer price, being one of the first sources that all consumers want to exchange with. It is important to highlight the contrast exhibited between SPM and ADH in relation to the CHP, since in the summer there is less heat demand that can be met by other agents with better offers, thus reducing this agent overall participation (see Table 8).

4.2.4. Fairness indicators

Fairness indexes are also assessed in this work. The methodology of [67,68] was followed to evaluate the resource allocation in each market design. These indicators are not meant to measure quantities, but rather to assess the relationships between the different agents and the impact that each of them brings to the whole system. To do so, Quality of Service (QoS), Quality of Experience (QoE) and Min-Max Indicator (MiM) were determined. QoS represents how all the agents impact the heat distribution in the system, i.e., if all involved agents trade the same amount of heat, then the QoS would be equal to 100%. This index assesses

Table 8

Annual and seasonal index of successful participation in the market for each heat producer and market design.

	Year			
	CHP	Supermarket	Data Center	Heat Pump
Pool/Full P2P	36%	91%	89%	26%
P2P Distance	61%	100%	100%	64%
P2P Losses	37%	99%	100%	16%
P2P CO ₂	35%	88%	90%	28%
Community	81%	100%	100%	92%
Summer				
	CHP	Supermarket	Data Center	Heat Pump
Pool/Full P2P	13%	83%	93%	1%
P2P Distance	56%	100%	99%	37%
P2P Losses	15%	99%	100%	1%
P2P CO ₂	12%	75%	95%	4%
Community	71%	100%	100%	93%
Winter				
	CHP	Supermarket	Data Center	Heat Pump
Pool/Full P2P	60%	95%	85%	51%
P2P Distance	66%	100%	100%	93%
P2P Losses	59%	98%	100%	31%
P2P CO ₂	59%	93%	86%	54%
Community	91%	100%	100%	91%

the equilibrium in the system and is expressed as:

$$QoS = \frac{[\sum_{n=1}^n |P_n|]^2}{n \sum_{n=1}^n P_n^2} \quad (15)$$

QoE points out the consumer satisfaction related to the heating price when trading with other agents. To do so, $\lambda_{n,m}$ is calculated for each transaction n, m through (16):

$$\lambda_{n,m} = \frac{C_n P_{n,m}}{P_n} \quad \forall \{m, n\} \in \Omega_n \quad (16)$$

Afterwards, σ is defined as the standard deviation of $\lambda_{n,m}$ and the QoE for each time frame is calculated as:

$$QoE = 1 - \frac{\sigma}{\lambda_{n,m} \max - \lambda_{n,m} \min} \quad (17)$$

The MiM indicator stands for the fairness in the prosumers and consumers field, where the ratio between the minimum and maximum values for each time period is calculated. If all the consumers trade the same amount of heat, then this index equals 100%. For each timestamp, the MiM is calculated as:

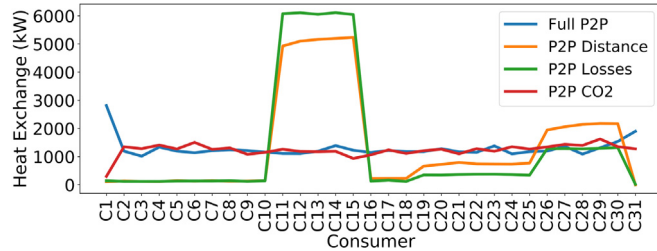
$$MiM = \frac{\min P_n}{\max P_n} \quad \forall n \in \Omega_c \quad (18)$$

Table 9 gathers the fairness indicators results. As one can see, in general, the market modules present a QoS around 20%, meaning that there are agents with larger capacities when compared to other. This discrepancy leads to lower levels of QoS. When looking at community 2, this index is even lower which is related to the heat pump impact in this community. For most of the year, this player is in charge of supplying the whole community, creating a huge impact, attracting a large part of the exchange within

Table 9

Fairness indicators for each market model.

	QoS		QoE		MiM	
Pool/Full P2P	21%		78%		4%	
P2P Distance	17%		83%		4%	
P2P Losses	21%		79%		5%	
P2P CO ₂	20%		79%		4%	
Community	Com 1	Com 2	Com 1	Com 2	Com 1	Com 2
	26%	14%	48%	23%	2%	16%

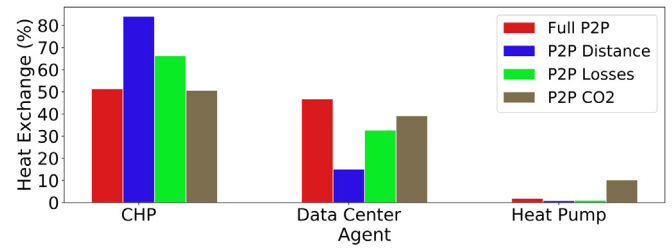
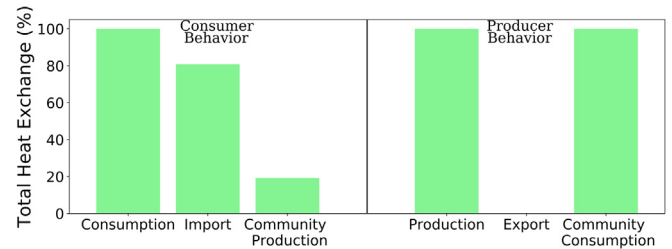
**Fig. 8.** Cumulative annual heat exchange of the supermarket as a heat producer in the P2P designs.

the community. The QoE, related to the user viewpoint, presents similar values for all P2P designs. When analyzing the communities, these values are substantially lower, due to the fewer competitiveness existing in each community. Therefore, agents are compelled to exchange with players who do not offer prices as favorable as their competitors at certain times, as in the P2P market models. The low values presented by MiM point to the significant difference between the heat values that are exchanged among the different agents.

4.2.5. Supermarket individual analysis

The supermarket is the only prosumer in the system, which means that it is the only player capable of behaving as a producer or consumer in different periods of time, being important to analyze its individual trades with other peers. When the supermarket is behaving as a producer, it is able to sell heat to the loads. Fig. 8 depicts the cumulative heat trade over the year between the supermarket and the loads for each of the considered P2P market designs. More precisely, Fig. 8 points to a steady supply to all consumers by the supermarket in the Full P2P design, which was expected, since there are no preference constraints for any heat consumer. On the other hand, the product differentiation effect is clear in the P2P Distance and P2P Losses, since consumer preferences (namely, distance and losses) encourage trading with closest peers. Thus, the consumers (C11–C15) are strongly encouraged to trade with the supermarket, as it is one of the closest producers. In fact, most of the supermarket heat production goes directly to these consumers (about 59.2% and 73.9% for P2P Distance and P2P Losses, respectively), supplying other consumers with residual heat, or not at all. In the P2P considering the CO₂ signals, there are no major fluctuations once the CO₂ emissions value of the supermarket (225 g/kW) is similar to that of the CHP and Data Center, and much higher than that of the Heat Pump. In this way, the differentiation criterion is minimal relative to the CHP and Data Center with consumers giving priority to trade with the Heat Pump. More precisely, as both the supermarket and the Heat Pump have a low capacity to influence the system, the changes in the exchanges between the supermarket and the consumers are relatively small compared to the Full P2P market design.

Notwithstanding, there are periods in which the supermarket does not have sufficient self-generation of heat and needs to

**Fig. 9.** Cumulative annual heat exchange of the supermarket as a heat consumer in the P2P designs.**Fig. 10.** Supermarket heat exchange in the Community design.

consume from the DHN, behaving as a consumer in the market. In this case, Fig. 9 depicts the annual percentage of heat supplied by the heat producers to the supermarket. In general, the supermarket is mainly supplied by CHP and the data center, since these agents have a large thermal capacity. As the supermarket is closer to the CHP, when considering the distance criteria (P2P Distance), the heat supplied by this resource, reaches its peak. Hence, as the data center is the farthest resource from the supermarket, the heat exchange reaches its low. The same line of thought is true for the P2P Losses. Conversely, as the heat pump is the resource with the lowest CO₂ emissions, this resource reaches its maximum when considering the P2P CO₂ market design.

Looking at the community-based market design (Fig. 10), one can see that as a consumer, the supermarket is compelled to import about 80% of the heat, the remaining 20% being supplied by the community itself (heat pump). As a heat producer, all production is shared with the community itself, and no heat is exported.

5. Conclusion

District heating still has a long way to go, especially regarding the way heat is exchanged and the infrastructure needed for this transformation. Within this scope, new market models for district heating have been proposed in this work, encouraging direct heat exchange between peers. The network characteristics and impact on heat exchange were also assessed through product differentiation, giving to the peers and network operators the possibility to define and test criteria that best fits their interests. All markets designs were simulated, compared and incorporated in the market module of the EMB3Rs platform.

The results point to the feasible implementation of this type of market structure in DHNs. The Full P2P model presents the best results, since it disregards any limitations of the DHN for the heat exchanges between the different players. This work, also proves that it is possible to impact the way heat is distributed according to preferences that may be associated with distance, minimizing losses or mitigating CO₂ emissions. As an example, analyzing the market design of P2P Distance, one can see that the supermarket can increase by 500% the heat supply to closest consumers when compared to the Full P2P market design. In

addition, the Community-based market design also reveals the possibility to divide agents into communities, allowing them to manage their own community and exchange heat with other communities, through heat import or export. Overall, if looking at the equilibrium between the agent participation in the market, the quality indicators do not show a balanced system. This is linked to the different heat technologies and prices, that change over the year according to several factors as the weather. The MiM also highlights this point, as a low value for this indicator means a big difference between the maximum and minimum heat traded amongst the agents.

Future work will focus on full network thermal characterization and comparison with the main findings here presented. Also larger networks will be explored in order to test the solutions in a real-world like environment.

CRediT authorship contribution statement

António S. Faria: Software, Writing – original draft Preparation, Data curation, Investigation. **Tiago Soares:** Conceptualization, Methodology, Visualization, Writing – review & editing, Data curation. **José Maria Cunha:** Data curation, Writing – review & editing, Investigation. **Zenaida Mourão:** Supervision, Writing – review & editing.

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.

Data availability

Datasets related to this article can be found at <http://dx.doi.org/10.17632/ydbcpb73t2.1>, an open-source online data repository hosted at Mendeley Data (António, Tiago, Zenaida, José, 2020).

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