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DOI
10.1016/j.apenergy.2022.118572

Publication date
2022

Document Version
Final published version

Published in
Applied Energy

Applied Energy 311 (2022) 118572

Contents lists available at ScienceDirect

Applied Energy

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

A peer-to-peer market mechanism incorporating multi-energy coupling and cooperative behaviors

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ARTICLE INFO

Keywords:
Peer-to-peer energy trading
Local energy market
Cooperative game
Integrated energy system
Distributed energy resource

ABSTRACT

As the use of distributed energy resources increases, peer-to-peer (P2P) energy trading is becoming a promising way to harmonize the decarbonization and decentralization transformations in the energy sector. P2P markets give households the autonomy to make individual decisions and thus they may cooperate with each other to obtain economic benefits. However, existing studies on cooperative behaviors in P2P markets focus mostly on the electricity sector and P2P multi-energy markets are rarely studied. In fact, other energy carriers not only constitute a large part of the total energy demand, but their coupling can potentially benefit the system as well as the end-users. In this paper, we propose a P2P multi-energy market mechanism that allows peers to trade both electricity and heat. Two trading coalitions, i.e., an electricity-only trading coalition and an electricity–heat trading coalition, are predefined. The peers will join one of the coalitions based on their potential benefits and will trade energy inside the coalition. The energy markets are cleared separately per coalition and per energy carrier and hence, multi-energy markets are modeled. The proposed mechanism is a first-of-its-kind that explores the integrated effects of the multi-energy coupling and the cooperative behaviors in the P2P market. It is illustrated by a case study on a neighborhood in the Netherlands using realistic data. Results show that the mechanism is prosumer-centric as peers choose to join different coalitions at different time steps which benefit them the most. Compared to the reference scenario where there is no P2P trading, the P2P multi-energy market leads to higher economic benefits for all the peers altogether and benefits most individuals. The case study also demonstrates a benefit transfer from service-sector peers to residential peers.

1. Introduction

1.1. Background and motivation

The energy sector is undergoing an accelerating transformation to decarbonization and decentralization. Firstly, decarbonization concerns various energy carriers. The coupling of electricity, heat, gas, and transport sectors can improve the technical, economic, and environmental performance of the overall system [1]. The integration of energy carriers provides system flexibility compared to an electricity-only system. The need to integrate different energy systems has been highlighted by [2] and new methods and tools to analyze such integrated energy systems (IES) are called for [3,4]. In the residential sector particularly, electricity and heat account for the predominant energy use. Domestic heating takes up 69% of the residential energy consumption while the remaining 25% is use for electric lighting and appliances [5]. Secondly, as the share of distributed energy resources (such as residential solar panels) increases, there is a surge in prosumers [6], i.e., households that both produce and consume energy, as well as increased interest in peer-to-peer (P2P) energy markets that allow direct energy trading between prosumers (see the comprehensive review in [7]). The advantages of P2P energy trading are twofold. On the one hand, a P2P market enables the peers to increase their income by trading based on their diverse demand profiles, generation portfolios, and preferences [8]. On the other hand, as P2P markets mostly work in the distribution grid rather than the transmission grid, they help to alleviate issues such as reduced transmission network investment [9] and congestion by peak shaving [10,11].

These two trends in the energy transition call attention to study the role of the sector coupling in P2P markets in order to unravel how the integration of energy carriers affects the design of P2P markets and accordingly, if and how the households would benefit from trading multiple energy in P2P markets. Especially, the high residential electricity and heat consumption requires studying the coupling effects of electricity and heat under a multi-energy market scenario. However, existing literature on P2P energy trading is mostly limited to the electricity sector. How P2P markets should work in an IES is yet to be explored. The lack of research in this direction gives rise to questions

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https://doi.org/10.1016/j.apenergy.2022.118572
Received 14 August 2021; Received in revised form 8 December 2021; Accepted 16 January 2022
Available online 5 February 2022

Nomenclature

Parameters

α	Proportionality constant between P2P heat and electricity price
cop	HP coefficient of performance
e^{bas}	Base electricity demand [kWh]
e^{pv}	Electricity generation from PV [kWh]
e^{wt}	Electricity generation from WT [kWh]
hg^{hp}	HP annual heat generation [kWh]
ic^{hp}	HP initial investment cost [€]
l^{hp}	HP lifetime [yr]
om^{hp}	HP annual operation and maintenance cost [€]
$p^{e,buy,euc}$	Electricity buying price from EUC [€/kWh]
$p^{e,sel,euc}$	Electricity selling price to EUC [€/kWh]
$p^{h,buy,th}$	Threshold price for buying heat [€/kWh]
$p^{h,sel,th}$	Threshold price for selling heat [€/kWh]
$p^{hp,f}$	HP degradation cost of unit generation [€/kWh]
p^{mid}	Mid-market rate[€/kWh]
q^{bas}	Reference base heat demand [kWh]
$q^{hp,max}$	Maximum generation of the HP [kWh]
r	Discount rate
u	Preference coefficient of heat demand utility
v	Scaling factor of heat demand utility

Sets

$\mathcal{HB}$	Set of heat buyers hb
$\mathcal{HS}$	Set of heat sellers hs
$\mathcal{N}$	Set of peers n
$\mathcal{T}$	Set of time steps t
$\mathcal{X}$	Set of peers x in coalition $\mathcal{X}$
$\mathcal{Y}$	Set of peers y in coalition $\mathcal{Y}$

Superscripts and subscripts

$e, h, \mathcal{X}, \mathcal{Y}$	Superscripts to represent the P2P trading market: electricity market, heat market, market in coalition $\mathcal{X}$, market in coalition $\mathcal{Y}$
n, hs, hb, x, y	Subscripts to represent the index of peer category: any peer, heat seller, heat buyer, peer in coalition $\mathcal{X}$, peer in coalition $\mathcal{Y}$
t	Subscript to represent the time step. Note it is used in the algorithm when more time steps are considered.

Variables

B	Net benefit [€]
C^{hp}	HP generation cost [€]
E^{buy}	Electricity buying volume [kWh]
E^{imb}	Electricity imbalance [kWh]
E^{sel}	Electricity selling volume [kWh]
p^{buy}	P2P buying price [€/kWh]. The guiding price is a parameter, in case of adjustment, the price becomes a variable.
p^{sel}	P2P selling price [€/kWh], The guiding price is a parameter, in case of adjustment, the price becomes a variable.
Q^{*}	Optimal heat consumption level [kWh]
Q^{bas}	Elastic base heat demand [kWh]
Q^{buy}	Heat buying volume [kWh]
Q^{cur}	The curtailment per volume of heat selling or buying [kWh]
Q^{imb}	Heat imbalance [kWh]
Q^{sel}	Heat selling volume [kWh]
R	Revenue [€]
U	Utility [€]

such as: What is a proper P2P multi-energy market mechanism to accommodate the trading of both electricity and heat in an IES? How can the economic benefits of such IES (both on the system level and on the individual level) be evaluated? With such questions in mind, this paper, therefore, focuses on the P2P energy trading in an IES. In the next subsection, we will review the relevant literature.

1.2. Literature review

A P2P energy market mechanism regulates the peers' trading behaviors and decides on the market-clearing process [12]. It matches energy demand with supply and settles the time, price, and volume of the trades.

Wang et al. (2020) reviewed the mechanisms and classified them into cost-sharing mechanisms, auction-based mechanisms, and bilateral contracts [13]. The cost-sharing mechanism allocates the cost and benefit after the market-clearing has taken place. An example of such mechanisms can be Shapley value distributions in cooperative games [14]. Moreover, various pricing schemes such as mid-market rate [8,15], supply–demand ratio [15,16], and discriminate pricing [17] also fall into this category. In the auction-based mechanism, peers submit price–quantity pairs either for the demand or for the generation to a market operator who then clears the market while facilitating the financial transactions. Commonly-used examples are the double auction mechanism and its variation [18,19]. Bilateral contracts include over-the-counter and long-term agreements as results of direct negotiations between the peers [20]. In comparison to the cost-sharing mechanism, the auction-based mechanism grants the peers full autonomy to conduct trading strategies. Li and Ma (2020) proposed to mimic a self-interested rational peer using methods such as zero-intelligence and its variations and eye on the best price[1] [20]. Nevertheless, other strategies, coalition formation, in particular, are rarely modeled. In that respect, Tushar et al. (2020) proposed a model to simulate the trading strategies of the peers and coalitions are formed [21]. In their study, the mid-market rate was used as the pricing scheme which mitigates the trading complexity as it was simple to implement. Nevertheless, this study only discusses the P2P electricity market while multi-energy coupling was not investigated. Given the importance of IES, there is a need to develop a model for multiple energy carriers while taking the peers' preferences and their trading strategies into account [22].

Some studies summarizes peers' trading preferences from economic [23], psychological [24], and social perspectives [25]. Hahnel et al. (2020) identified three types of prosumers in the German market, namely price-focused, autarky-focused, and heuristic prosumers[2] [23].

[1] Eye on the best price refers to the strategy where agents actively adjust bids or offers based on information from the real-time market. The best price is targeted and the agent changes the valuation to gain more benefits.

[2] Heuristic prosumers refer to prosumers who apply a rule-of-thumb trading strategy. Such prosumers are sensitive to the state-of-charge of their energy storage instead of the market prices.

Morstyn and McCulloch (2018) also proposed three energy classes based on the preferences of low-income consumers, philanthropic prosumers, and green prosumers [24]. To model such peers in a P2P market, coalitional games in game theory [26] are often used. The rationale is that peers with common preferences or geographical proximity may choose to cooperate. Lee et al. (2014) applied a canonical coalitional game to explore the cooperation between prosumers. They proposed a pricing scheme using a Shapley value for a fair revenue allocation [27]. Amin et al. set up a two-step market mechanism with a non-cooperative game for the main trading and a grand coalition game to deal with the uncontracted prosumers [28]. Tushar et al. (2020) proposed a trading scheme based on a coalition formation game to explore the social cooperation between prosumers [21].

Now that we have reviewed the literature on market mechanisms and peers' preferences, we focus on the literature on electricity and heat trading in P2P markets. Although these studies have justified the physical feasibility of multi-energy trading, it will now be further argued to provide more background information. In an IES, P2P multi-energy trading is feasible when the peers are connected by the infrastructures for the different energy carriers [29,30]. While electricity networks are mostly present for electricity trading, district heating networks or heating networks within buildings could be utilized for heat trading. In 4th-generation district heating systems, a (ultra) low supply temperature as low as 35 °C integrates well with heat pumps and renewable energy sources [31]. Furthermore, in 5th-generation district heating systems, active substations could be expected to interact and exchange heat with a price [31]. Despite the proven feasibility in such systems, in the literature, only a few studies consider the coupling of electricity and heat trading in the P2P market. Zhu et al. (2020) investigated the synergies between electricity, heat and hydrogen but only electricity is traded [32]. Wang et al. (2020) proposed a bi-commodity electricity and heat market mechanism with a multi-leader multi-follower Stackelberg game and motivated the participants with a discriminatory pricing scheme [17]. However, in their work, the peers' cooperative behaviors were not studied. Jing et al. (2020) coupled the electricity and heat trading between a residential community and a commercial community and reached a fair pricing strategy using a non-cooperative Nash game [33]. Nonetheless, this study only considered two peers and the emergent cooperation between multiple peers was neglected.

1.3. Research gap and contributions

Based on the background and the literature review, we found that although a few existing studies have addressed the coupling of multiple energy carriers using P2P markets in an IES, there has been little attention on the multi-energy trading in its energy form taking into account the cooperative behaviors of the peers. Considering the sector coupling in the energy transition, multi-energy market scenarios in a P2P context are crucial to study. Such a study would evaluate the performance of an IES (both for the system and for the individual peers) in a market context and unravel the effect of the interactions between multiple energy carriers as well as the effect of the cooperative behaviors of the peers. To that end, a new market mechanism considering both aspects is needed.

Therefore, in this paper, we propose a P2P multi-energy market mechanism that exploits both the electricity–heat coupling and coalitional trading between the peers. This paper aims to fill the knowledge gap by designing and evaluating a P2P market mechanism that integrates multi-energy coupling and cooperative behaviors, where a techno-economic modeling perspective is taken to evaluate the IES under a P2P market.

The contributions of this study are as follows:

- We propose a multi-energy market mechanism for P2P energy trading to facilitate electricity–heat coalitional trading. The market mechanism is a first-of-its-kind that explores the synergies of multiple energy carriers in an IES by considering the trading of electricity and heat in the P2P market while incorporating cooperative behaviors among the peers.
- We present a trading process where the decision-making of each peer and of the market operator is simulated and the corresponding algorithm is developed. Each peer is able to optimize their economic benefit by autonomously selecting their trading strategy. The strategy includes which trading coalition the peer wants to join, what heat consumption is optimal, and the volumes of trades for electricity and/or heat.
- We conduct a case study using realistic data from the municipality of Apeldoorn in the Netherlands. A geographic information system has been used to obtain the locations and the types of the buildings, where the households within geographical proximity are clustered and the relevant spatio-temporal information is used.

This paper is structured as follows. Section 2 describes the system by showing the research scope and the system components. Next, Section 3 presents the system model including the peer's model, the market operator's model, and the P2P trading process. After that, Section 4 conducts a case study to showcase the model and the algorithm in a realistic setting. Reflections of the approach are also given to warrant future research. In the end, Section 5 concludes with some interesting findings and observations.

2. System description

This section aims to describe the considered system and the underlying assumptions. Meanwhile, the system components are introduced briefly to give an overall picture while the details will be elaborated in the subsequent sections.

This paper models the proposed market design in an IES as illustrated in Fig. 1, in which electricity and heat (in the form of hot water) are used and traded in an energy community. In this system, households (also referred to as peers in this study) generate, consume, and trade energy, while a P2P market operator coordinates the electricity and the heat market. The proposed market design is prosumer-centric, meaning that it empowers each peer to optimize their own economic benefit. The starting point of this research is that the peers are proactive and self-interested in the market and conduct the optimal trading strategy based on their demand, generation, and preferences. The system operator only acts as a facilitator and no system-level optimization is performed.

Electricity is generated by roof-top solar PV and wind turbines (WT), heat is generated by heat pumps (HP). In principle, when heat pumps are used for heat generation without heat exchanges, they are often connected to energy storage so that the portfolio of generation and storage could be optimized to the prosumer's benefit [34]. In this study, we expand the trading commodities from electricity-only to electricity and heat (in the form of hot water). In this way, without storage, peers can proactively increase or decrease their heat generation levels as well as their heat trading levels to optimize their benefits. This focus avoids the investment cost of energy (especially electric) storage at the consumer side but requires local district heating networks for hot water exchange as discussed in Section 1.2. Although water tanks that are often found in existing heating systems could be used as thermal storage, whether the existing capacity is enough or not to play an important role in determining peers' benefits is not yet known. In this study, we focus the work on the integrated effects of multi-energy coupling and cooperative behaviors, while evaluating the effects of storage systems is left for future studies (see reflections in Section 4.6 as well). We assume that solar PV and HP are owned by individual peers, but WT are owned by an energy community collectively where each

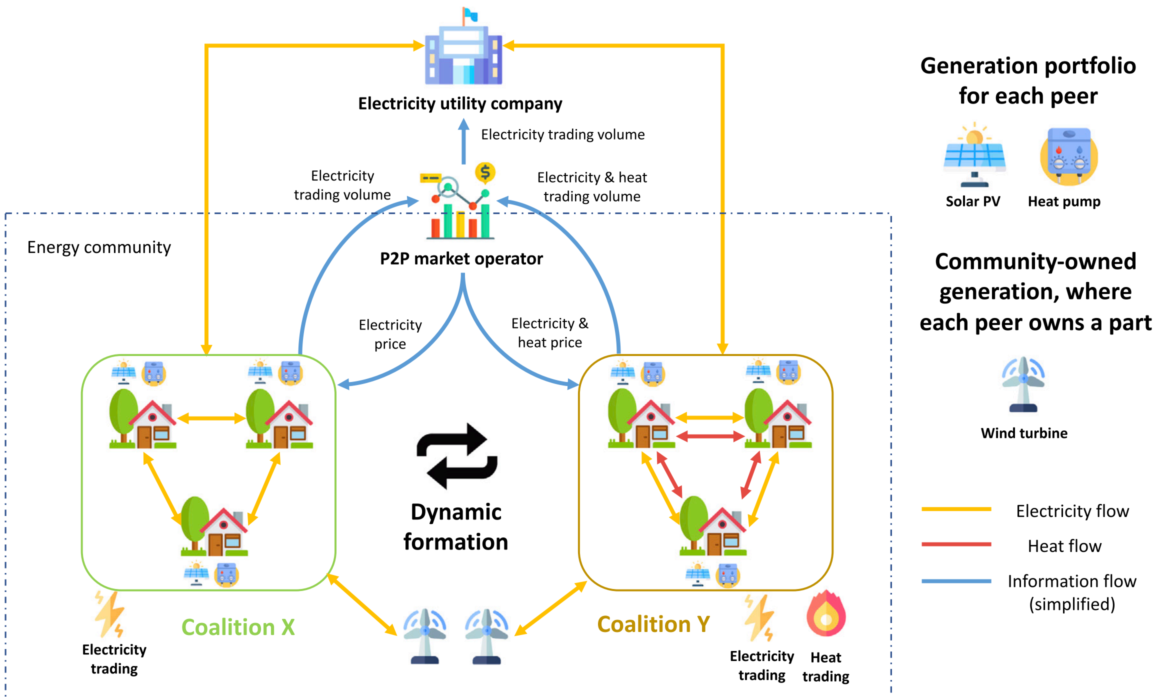


Fig. 1. Schematic of the integrated energy system, where the information flow is simplified.

peer owns a part. On the demand side, the heat demand is assumed to be elastic. In this paper, elastic heat demand means the peers are willing to make a trade-off between heat comfort by consuming heat and economic benefit by trading heat (which will be further elaborated in Section 3.4), but the heat demand will not be shifted. This choice is made in order to avoid extra model complexity for additional storage investments. However, it could be interesting to include energy storage in future studies. The electricity demand is assumed to be inelastic to reduce model complexity.

A P2P multi-energy market facilitates electricity and heat trading between peers. The heat supply and demand must be balanced within the community, as heat grids are typically local in contrast to electricity grids. Surplus or deficient electricity in the community can be exchanged with the connected grid. To that end, an electricity utility company (EUC) is introduced. This is a new role that combines retailers and wholesalers in the future energy system who trades electricity with prosumers on the distribution level. A P2P market operator is responsible for the market-clearing and deriving the energy prices. In this paper, the market operator is assumed to be independent of other players and is virtual (such as an algorithm). It runs the P2P market within the community and communicates with the EUC outside the community. Hence, it lies on the interface between the energy community and the outside world. It is a facilitator instead of a profit-maker, hence, it is assumed to not extract any benefits from the transaction process.

The proposed market mechanism empowers the peers to form coalitions. The peers are assumed to be benefit-driven prosumers and although they are all electricity and heat users, they may have trading preferences (i.e., whether to only trade electricity or to trade both electricity and heat) based on the economic benefits they would obtain. Those with similar trading preferences will form one coalition, and trade energy within that coalition. More specifically, referred from [21], this study introduces two trading coalitions, i.e., coalition $\mathcal{X}$ for electricity trading only and coalition $\mathcal{Y}$ for electricity and heat trading. The peers choose one of the coalitions since it is beneficial for them to trade with other peers than trading directly with the EUC (see detailed discussion in Section 3.4.1). Furthermore, note that the coalitions are being reformed at each time step and thus at each time step, peers has the option the switch coalitions. The coalitions can be viewed as different sub-markets. Therefore, the market-clearing of the two coalitions is performed separately, resulting in different prices in the two coalitions. Note that, despite the pre-defined coalitions in the proposed market mechanism, it is possible that there are other trading scenarios, such as electricity-only trading and electricity and heat trading without any coalitions. These scenarios will be further explored in Section 4.5 where the advantages of our proposed mechanism with coalitions will also be discussed.

3. System model

This section describes proposed mechanisms in terms of the trading process, the algorithm, and the underlying system model.

It starts with a description of the trading process in Section 3.1. While the mathematical formulations of the trading process are provided later, Section 3.1 aims to give a general picture of the market mechanism. Next, in Section 3.2, the model components are briefly introduced. These components are further elaborated in Sections 3.3 to 3.7.

3.1. Trading process and algorithm

The trading process is illustrated in Fig. 2. The below mentioned terms will be explained and formulated mathematically later in other subsections.

The process starts with the market operator giving the information of the guiding prices to the peers. Based on the guiding prices, the peers first check their own price conditions. The price conditions differ for each peer due to the different parameters. Accordingly, the peers decide on which coalition to join and on their trading volume. After this, the two coalitions are formed and all the peers inform the market operator about their trading volumes.

The market operator then checks the heat balance. Since the detailed clearing process with formulas is explained in detail in Section 3.7, here the process will only be introduced briefly. If the heat is not balanced, the operator will curtail the heat orders and inform the peers accordingly. The peers will consent and make new orders. If the heat is balanced, the operator will clear the heat market and will

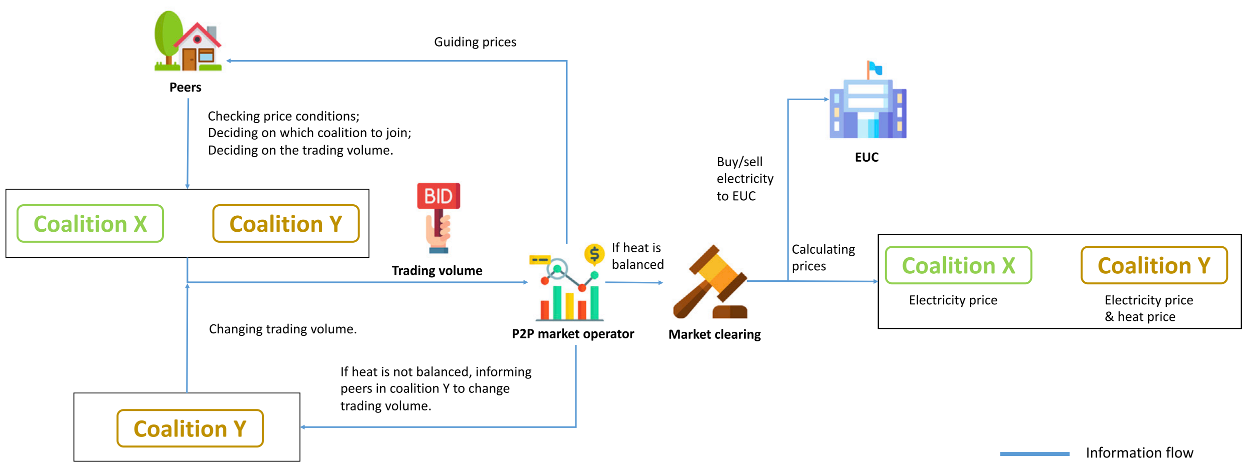


Fig. 2. Schematic for the P2P trading process.

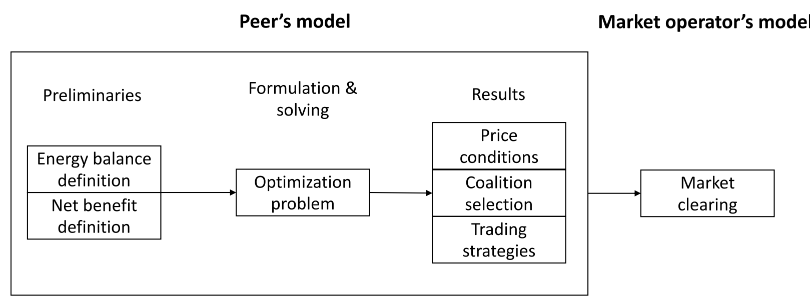


Fig. 3. Different parts of the system model.

then clear the electricity market. After checking the electricity balance for the peers, the imbalance (if any) will be traded with the EUC. As a final step, the electricity prices will be finalized and the market-clearing process ends. Note that since the proposed P2P market is a forward market, the energy will only be produced after the market has been cleared, meaning that no physical imbalance will occur before the market-clearing.

The algorithm which explains and implements the trading process is given in Appendix A. It details the trading strategies from the peers and the heat and the electricity market clearing step by step with pseudo-code.

3.2. Model in a nutshell

Different components of the model are shown in Fig. 3. The trading objective of each peer is to maintain the energy balance and maximize the net benefit. Therefore, the first part of the model describes the energy balance for each peer, where the variables related to generation and trading are introduced. Besides, the net benefit functions are also given. The term net benefit is used here to represent the economic benefits (measured in monetary units such as euros), since there are costs and incomes associated with the trades. Here, the net benefit functions for both electricity and heat are given. Note that the formulations of the net benefit functions are different for different positions in heat trading, i.e., if the peer a seller or a buyer. Then, optimization problems are formulated and solved in order to maximize the net benefit functions. The optimality conditions are derived, based on which various pricing conditions are obtained. The peers will determine the trading strategies, i.e., which coalition to join and what volumes to trade, based on the price conditions. Accordingly, the two coalitions are formed. The last part of the model features the market-clearing process of the heat and the electricity market by the market operator.

Note that the market will be cleared in every time step, e.g., for every hour. Since there are no inter-temporal variables and constraints, we only formulate the system model for one time step in this section. In Appendix A, an algorithm that includes more time steps will be presented.

Lower-case letters and Greek letters represent parameters. Variables are denoted by upper-case letters. Subscripts are variables while superscripts are descriptions. All the defined variables should be non-negative unless specifically mentioned. Let $\mathcal{N}$ denote the set of peers, $\mathcal{HS}$ the set of heat sellers and $\mathcal{HB}$ the set of heat buyers.

3.3. Energy balance

We first introduce the energy balance equations for one peer $n \in \mathcal{N}$. When the peer is trading heat, it can also be a heat seller $hs \in \mathcal{HS}$ or a heat buyer $hb \in \mathcal{HB}$.

The electricity balance equation is given below.

$$e_n^{bas} + E_n^{hp} + E_n^{sel} = e_n^{pv} + e_n^{wt} + E_n^{buy} \tag{1}$$

On the left-hand side of the equation is the total electricity demand and the sold electricity E_n^{sel}. The total electricity demand consists of the base electricity demand e_n^{bas} and the electricity consumption E_n^{hp} of the HP to meet both the base heat demand and the required heat for trading. The electricity generated from solar PV e_n^{pv} and WT e_n^{wt} and the bought electricity E_n^{buy} are on the right-hand side of the equation. Note that at a particular time step, a peer can only be a seller or a buyer, i.e., $E_n^{sel} * E_n^{buy} = 0$.

Similarly, we define Q_n^{sel} and Q_n^{buy} as the heat trades with the constraint $Q_n^{sel} * Q_n^{buy} = 0$. Q_n^{bas} is the elastic base heat demand. When $Q_n^{sel} \geq 0$, the peer will be a heat seller and the heat consumption is Q_{hs}^{bas}. When $Q_n^{buy} \geq 0$, the peer will be a heat buyer and the heat consumption is $Q_{hb}^{bas} + Q_{hb}^{buy}$.

3.4. Net benefit function

In this section, the net benefit functions for peers of different trading positions will be described and formulated. Note that since the peers are assumed to be benefit-driven, the following terms: demand utility, revenue, generation cost, selling benefit, and buying cost are all measured in monetary units (e.g., euros). Hence, the net benefit is measured in monetary units as well.

3.4.1. Electricity trading

The mid-market rate will be used as the guiding pricing scheme for electricity trading. Such a pricing scheme is simple to understand and implement and it has been widely used in the literature on P2P trading such as in [8,15,35]. In this study, the mid-market rate pricing scheme defines the reference prices for peers to form their trading strategies, but the actual prices will be modified in the market-clearing process. The mathematical definition of the mid-market rate will be given and the market-clearing process will be elaborated on in Section 3.7.

Under the mid-market rate pricing scheme, all the peers will participate in the P2P electricity trading. Because it is cheaper to buy electricity in the P2P market than from the EUC, and similarly, it is more profitable to sell electricity in the P2P market than to the EUC. Therefore, by trading in the P2P market, peers will always have fewer costs or obtain more revenues. The net benefit of a peer $n \in \mathcal{N}$ from the electricity trading is defined below.

$$B_n^e = E_n^{sel} p^{e,sel} - E_n^{buy} p^{e,buy} \tag{2}$$

3.4.2. Heat trading

Different from the P2P electricity trading where everyone would participate, whether to participate in the P2P heat trading depends on the trade-offs between the potential benefits and the costs at the two trading positions, i.e., a heat seller $hs \in \mathcal{HS}$ or a heat buyer $hb \in \mathcal{HB}$.

Heat seller. The net benefit function Eq. (3) consists of the heat demand utility U_{hs} of consuming heat Q_{hs}^{bas}, the revenue R_{hs}^{h} of selling heat Q_{hs}^{sel} at the heat selling price $p^{h,sel}$, and the costs C_{hs}^{hp}.

$$B_{hs} = U_{hs} + R_{hs}^{h} - C_{hs}^{hp} \tag{3}$$

The heat demand utility U_{hs} is defined in Eq. (4) as a quadratic utility function of the heat consumption. Quadratic functions are commonly used for utilities in studies on integrated demand response such as [36–38]. v_{hs} and u_{hs} are the parameters of the quadratic function to differentiate the actual heat demand of different peers. q_{hs}^{bas} is the reference base heat demand. Note that Eq. (4) is a concave function, when $Q_{hs}^{bas} = q_{hs}^{bas}/u_{hs}$, it reaches the maximum. This optimal point q_{hs}^{bas}/u_{hs} can also be found in Fig. 4 which will be introduced later in Section 3.5 when the price conditions of the seller are explained.

$$U_{hs} = v_{hs}[q_{hs}^{bas} Q_{hs}^{bas} - \frac{u_{hs}}{2}(Q_{hs}^{bas})^2] \tag{4}$$

In Eq. (5), the revenue R_{hs}^{h} for the seller depends on the sold heat Q_{hs}^{sel} and the price $p^{h,sel}$.

$$R_{hs}^{h} = Q_{hs}^{sel} p^{h,sel} \tag{5}$$

The electricity cost is considered as the fuel cost for the HP, which equals $\frac{Q_{hs}^{bas}+Q_{hs}^{sel}}{cop_{hs}} p^{e,sel}$. This cost can be interpreted as the opportunity cost if the electricity is sold in the P2P market at the price $p^{e,sel}$. Note that this indicates that it is possible for peers to buy electricity to run the HP and sell the generated heat to other peers. Beyond the electricity cost, there is the levelized fixed cost of the HP, represented by Eq. (6) $p_{hs}^{hp,f}$ is defined as the net present value of the capital expenditure ic_{hs}^{hp} and the annual operation and maintenance costs om_{hs}^{hp} over the lifetime l_{hs}^{hp} divided by the net present value of the annual heat generation hg_{hs}^{hp} over l_{hs}^{hp}. Therefore, the costs C_{hs}^{hp} are given in Eq. (7).

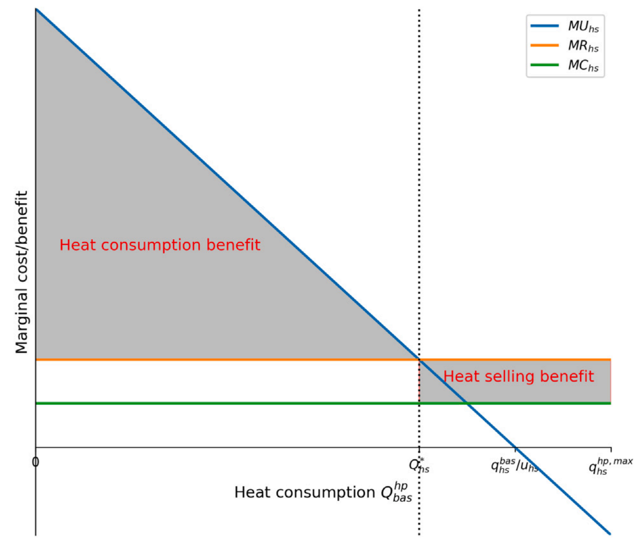


Fig. 4. Illustration of the change of marginal cost/benefit with regard to the heat consumption.

$$p_{hs}^{hp,f} = \frac{ic_{hs}^{hp} + \Sigma_{l=1}^{l_{hs}^{hp}} \frac{om_{hs}^{hp}}{(1+r)^l}}{\Sigma_{l=1}^{l_{hs}^{hp}} \frac{hg_{hs}^{hp}}{(1+r)^y}} = \frac{ic_{hs}^{hp} r + om_{hs}^{hp}[1-(1+r)^{-l_{hs}^{hp}}]}{hg_{hs}^{hp}[1-(1+r)^{-l_{hs}^{hp}}]} \tag{6}$$

$$C_{hs}^{hp} = (Q_{hs}^{bas} + Q_{hs}^{sel})(\frac{p^{e,sel}}{cop_{hs}} + p_{hs}^{hp,f}) \tag{7}$$

Heat buyer. With the change of position in the market, the generic Eq. (3) still applies. Hence, the net benefit function B_{hb} is defined as follows:

$$B_{hb} = v_{hb}[q_{hb}^{bas}(Q_{hb}^{bas} + Q_{hb}^{buy}) - \frac{u_{hb}}{2}(Q_{hb}^{bas} + Q_{hb}^{buy})^2] - Q_{hb}^{buy} p^{h,buy} - Q_{hb}^{bas}(\frac{p^{e,sel}}{cop_{hb}} + p_{hb}^{hp,f}) \tag{8}$$

3.5. Pricing conditions and trading strategies

We first look at the coalition $\mathcal{Y}$, i.e., when peers trade both heat and electricity. Then, the price conditions and trading strategies in the electricity trading only coalition $\mathcal{X}$ are discussed.

Heat seller. To maximize the net benefit, the heat seller has to find the optimal base heat demand Q_{hs}^{bas} and the sold heat Q_{hs}^{sel}. This problem is formulated as an optimization problem as shown below.

$$\begin{aligned} \max\ & v_{hs}[q_{hs}^{bas} Q_{hs}^{bas} - \frac{u_{hs}}{2}(Q_{hs}^{bas})^2] + Q_{hs}^{sel} p^{h,sel} - (Q_{hs}^{bas} + Q_{hs}^{sel})(\frac{p^{e,sel}}{cop_{hs}} + p_{hs}^{hp,f}) \\ \text{s.t. } & Q_{hs}^{bas} + Q_{hs}^{sel} \le q_{hs}^{hp,max} \end{aligned} \tag{9}$$

In order to solve this non-linear optimization problem, we utilize the first derivatives to obtain the marginal utility MU_{hs}, the marginal revenue MR_{hs}, and the marginal cost MC_{hs} as shown in Eq. (10).

$$\begin{aligned} MU_{hs} &= v_{hs}(q_{hs}^{bas} - u_{hs} Q_{hs}^{bas}) \\ MR_{hs} &= p^{h,sel} \\ MC_{hs} &= \frac{p^{e,sel}}{cop_{hs}} + p_{hs}^{hp,f} \end{aligned} \tag{10}$$

To better explain the model, these three marginal costs/benefits are illustrated in Fig. 4. The marginal utility MU_{hs} is a monotonically decreasing function while MR_{hs} and MC_{hs} are constants. To maximize the net benefit, the peer has to choose the optimal consumption. There is essentially a trade-off between consuming and selling heat, which is done by comparing MU_{hs} and MR_{hs}. When $MU_{hs} = MR_{hs}$, i.e., the intersection point in Fig. 4, this gives the threshold value for the optimal consumption, referred to as Q^*_{hs}, see Eq. (11) for its derivation.

$$MU_{hs} = MR_{hs} \Rightarrow Q^*_{hs} = Q^{bas}_{hs} = \frac{q^{bas}_{hs}}{u_{hs}} - \frac{p^{h,sel}}{v_{hs}u_{hs}} \tag{11}$$

In order to be a heat seller, the following two conditions (see Eq. (12)) have to be met: (1) $MR_{hs} \geq MC_{hs}$, i.e., when the peer could increase the net benefit from selling heat. (2) $Q^*_{hs} \leq q^{hp,max}_{hs}$, i.e., when there is remaining HP capacity for trading. Note that from Eq. (12), it is always beneficial for the peer to sell heat within the HP capacity.

$$\begin{aligned} MR_{hs} \geq MC_{hs} &\Rightarrow p^{h,sel} \geq \frac{p^{e,sel}}{cop_{hs}} + p^{hp,f}_{hs} \\ Q^*_{hs} \leq q^{hp,max}_{hs} &\Rightarrow p^{h,sel} \geq v_{hs}(q^{bas}_{hs} - u_{hs}q^{hp,max}_{hs}) \end{aligned} \tag{12}$$

Then the best trading strategy is to sell Q^{sel}_{hs} where $Q^{sel}_{hs} = q^{hp,max}_{hs} - Q^*_{hs}$.

$$Q^{sel}_{hs} = q^{hp,max}_{hs} - \frac{q^{bas}_{hs}}{u_{hs}} + \frac{p^{h,sel}}{v_{hs}u_{hs}} \tag{13}$$

Subsequently, we could decide the peer's position in the P2P electricity trading from Eq. (1), where $E^{hp}_{hs} = \frac{q^{hp,max}_{hs}}{cop_{hs}}$. If $E^{sel}_{hs} \geq 0$, then it means that the peer will be an electricity seller and will sell E^{sel}_{hs}. Otherwise if $E^{buy}_{hs} \geq 0$, the peer will be an electricity buyer and will buy E^{buy}_{hs}.

Heat buyer. Similar to the heat seller's problem, for the heat buyer's problem, we first lay out the optimization problem, then the first-order derivatives are used to obtain optimality conditions and lastly, the position in the P2P electricity trading will be determined.

Eq. (14) details the optimization problem for a heat buyer $hb \in \mathcal{HB}$. The objective is to maximize the net benefit based on Eq. (8) with the two decision variables Q^{bas}_{hb} and Q^{buy}_{hb}.

$$\begin{aligned} \max\ & v_{hb}[q^{bas}_{hb}(Q^{bas}_{hb} + Q^{buy}_{hb}) - \frac{u_{hb}}{2}(Q^{bas}_{hb} + Q^{buy}_{hb})^2] - Q^{buy}_{hb}p^{h,buy} \\ & - Q^{bas}_{hb}(\frac{p^{e,sel}}{cop_{hb}} + p^{hp,f}_{hb}) \end{aligned} \tag{14}$$

There are again three components in this objective function, however, only the first one is the positive net benefit, i.e., the heat demand utility, the other two are costs. The marginal utility MU_{hb} is based on the total consumption $Q^{bas}_{hb} + Q^{buy}_{hb}$. The costs are either incurred from self-generation with the marginal cost MC^1_{hb} or from buying the heat from others with the marginal cost MC^2_{hb}. Note these superscripts are for description only, instead of exponential functions. The marginal utility and costs are shown in Eq. (15).

$$\begin{aligned} MU_{hb} &= v_{hb}[q^{bas}_{hb} - u_{hb}(Q^{bas}_{hb} + Q^{buy}_{hb})] \\ MC^1_{hb} &= \frac{p^{e,sel}}{cop_{hb}} + p^{hp,f}_{hb} \\ MC^2_{hb} &= p^{h,buy} \end{aligned} \tag{15}$$

In order to maximize the net benefit, the peer will always choose the source of heat that has a cost advantage over the other. Therefore, the first condition to be met is that the heat buying price is lower than the self-generation cost. Another condition is when the marginal utility equals $p^{h,buy}$, where the optimal heat consumption Q^*_{hb} could be derived as the buying amount Q^{buy}_{hb}, and it needs to be positive.

$$\begin{aligned} MC^2_{hb} \leq MC^1_{hb} &\Rightarrow p^{h,buy} \leq \frac{p^{e,sel}}{cop_{hb}} + p^{hp,f}_{hb} \\ MU_{hb} = p^{h,buy} &\Rightarrow Q^*_{hb} = \frac{q^{bas}_{hb}}{u_{hb}} - \frac{p^{h,buy}}{v_{hb}u_{hb}} \\ Q^*_{hb} \geq 0 &\Rightarrow p^{h,buy}_t \leq q^{bas}_{hb}v_{hb} \end{aligned} \tag{16}$$

electricity market could be obtained based on Eq. (1). Since there is no heat self-generation, i.e., $E^{hp}_{hs} = 0$, if $E^{sel}_{hb} \geq 0$, the peer would sell electricity E^{sel}_{hb}. Otherwise if $E^{buy}_{hb} \geq 0$, the peer would buy electricity E^{buy}_{hb}.

Only electricity trading. When the price conditions in Eqs. (12) and (16) are not met, peer n will not join the P2P heat trading, but will only participate in the P2P electricity trading, i.e., coalition $\mathcal{X}$. This means that the heat demand is satisfied only by self-generation. The optimization problem is given below in which the heat consumption Q^{con}_n is the only decision variable.

$$\max v_n[q^{bas}_n Q^{con}_n - \frac{u_n}{2}(Q^{con}_n)^2] - Q^{con}_n(\frac{p^{e,sel}}{cop_n} + p^{hp,f}_n) \tag{17}$$

Following the necessary optimality conditions in Eq. (18), and finding that the second derivative is negative, the optimization problem has a maximum.

$$\begin{aligned} \frac{\partial B_n}{\partial Q^{con}_n} &= v_n(q^{bas}_n - u_nQ^{con}_n) - (\frac{p^{e,sel}}{cop_n} + p^{hp,f}_n) = 0 \\ \frac{\partial^2 B_n}{\partial (Q^{con}_n)^2} &= -v_nu_n < 0 \end{aligned} \tag{18}$$

The final optimal heat consumption Q^*_n is determined using Eq. (19). It means that the Q^*_n that is derived from the first equation in Eq. (18) should be smaller than the HP capacity $q^{hp,max}_n$ but also larger than zero.

$$Q^*_n = \max\{\min\{\frac{q^{bas}_n}{u_n} - \frac{\frac{p^{e,sel}}{cop_n} + p^{hp,f}_n}{v_nu_n}, q^{hp,max}_n\}, 0\} \tag{19}$$

According to the electricity balance in Eq. (1), with $E^{hp}_n = \frac{Q^*_n}{cop_n}$, the position of the peer in the P2P electricity trading can be determined. If $E^{sel}_n > 0$, the peer chooses to be an electricity seller and sells E^{sel}_n. Otherwise if $E^{buy}_n > 0$, the peer will be an electricity buyer and buys E^{buy}_n.

3.6. Summary of trading strategies

If at least one of the price conditions which have been derived in Eqs. (12) and (16) are met, the peer will participate in the P2P heat and electricity trading in coalition $\mathcal{Y}$. Otherwise, it would opt for the P2P electricity trading in coalition $\mathcal{X}$. The price conditions for heat trading are summarized using two threshold values as follows, which will be used for the peers to select the coalition.

$$\begin{aligned} p^{h,sel,th}_n &= \max\{\frac{p^{e,sel}}{cop_n} + p^{hp,f}_n, v_n(q^{bas}_n - u_nq^{hp,max}_n)\} \\ p^{h,buy,th}_n &= \min\{\frac{p^{e,sel}}{cop_n} + p^{hp,f}_n, q^{bas}_nv_n\} \end{aligned} \tag{20}$$

In summary, Table 1 demonstrates the price conditions, the corresponding selected coalition, and the trading strategies for one peer. As a matter of fact, since the model discusses one time step, the prices conditions are for one peer at one time step. Each peer (at each time step) would check the 4 cases, and depending on its own condition, choose only one case (and the corresponding coalition and trading volumes) since the price conditions are mutually exclusive. For different peers, all four cases could happen at one time step.

In case 1, case 2 and case 4, the peer joins the coalition $\mathcal{Y}$ to trade electricity and heat. Case 4 is a special case since the position as a buyer or a seller is uncertain based on the price conditions, the peer must compare the net benefits of both positions before making a decision. In case 3, the peer joins the coalition $\mathcal{X}$ to trade only electricity.

Table 1
Summary of the trading strategies based on various price conditions.

Case	Price condition	Coalition	Trading volume
1	$p^{h,sel} > p_n^{h,sel,th}$ and $p^{h,buy} \geq p_n^{h,buy,th}$	$\mathcal{Y}$	Heat: sell Q_n^{sel}; Electricity: sell E_n^{sel} or buy E_n^{buy}
2	$p^{h,sel} \leq p_n^{h,sel,th}$ and $p^{h,buy} < p_n^{h,buy,th}$	$\mathcal{Y}$	Heat: buy Q_n^{buy}; Electricity: sell E_n^{sel} or buy E_n^{buy}
3	$p^{h,sel} \leq p_n^{h,sel,th}$ and $p^{h,buy} \geq p_n^{h,buy,th}$	$\mathcal{X}$	Heat: N/A; Electricity: sell E_n^{sel} or buy E_n^{buy}
4	$p^{h,sel} > p_n^{h,sel,th}$ and $p^{h,buy} < p_n^{h,buy,th}$	$\mathcal{Y}$	Heat: either sell Q_n^{sel} or buy Q_n^{buy} determined by which net benefit is larger; Electricity: sell E_n^{sel} or buy E_n^{buy}

3.7. Heat and electricity market-clearing

The market-clearing process aims to safeguard the heat balance. After receiving all the orders, the market operator will clear the sub-markets, i.e., the heat and the electricity market within each coalition. Unlike electricity where the EUC can be used to deal with the imbalance, the heat balance has to be maintained within the coalition. Hence, the market operator will first clear the heat market in coalition $\mathcal{Y}$ and then clear the electricity markets in both coalitions.

The mean of the electricity buying and selling price with EUC is used as the electricity guiding price $p^{e,mid}$. Moreover, since heat pump is the only option for heat generation, the guiding heat price $p^{h,mid}$ is defined to be directly proportional to $p^{e,mid}$ with the proportionality constant α. Choosing a proper value of α is part of the market design and needs to be checked case by case. Only if α is within a reasonable range, there will be both heat buying and selling to facilitate the heat trading. The chosen value of α in the following case study is elaborated in Appendix B.4.

$$p^{e,mid} = \frac{p^{buy,euc} + p^{sel,euc}}{2} \tag{21}$$

$$p^{h,mid} = \alpha p^{e,mid} \tag{22}$$

To maintain the heat balance, the market operator first receives all the orders in coalition $\mathcal{Y}$ and calculates the heat imbalance $Q^{imb,\mathcal{Y}}$.

$$Q^{imb,\mathcal{Y}} = \Sigma_{y=1}^{|\mathcal{Y}|}(Q_y^{sel} - Q_y^{buy}) \tag{23}$$

Next, depending on whether the imbalance is positive or negative, the operator proportionally curtails the surplus or the deficiency on all the sellers' or the buyers' orders. Eq. (24) shows the amount of curtailment per unit of heat. Note that after the curtailment, the orders will be changed. One peer could change the electricity order to obtain extra electricity for HP generation to get extra heat. Reversely, one peer could also change the electricity order to reduce HP generation. Since the price conditions stay the same, the coalition composition will not change. All the peers will stay in the same coalition and consent to the heat order changes but submit new electricity orders as a result of the changed heat order. Now that heat and electricity are both balanced, the market will be cleared.

$$\begin{aligned} &\text{If } Q^{imb,\mathcal{Y}} \geq 0,\ Q^{cur} = \frac{Q^{imb,\mathcal{Y}}}{\Sigma_{y=1}^{|\mathcal{Y}|} Q_y^{sel}} \text{ for heat sellers.} \\ &\text{If } Q^{imb,\mathcal{Y}} < 0,\ Q^{cur} = -\frac{Q^{imb,\mathcal{Y}}}{\Sigma_{y=1}^{|\mathcal{Y}|} Q_y^{buy}} \text{ for heat buyers.} \end{aligned} \tag{24}$$

Now we look at the clearing process of the electricity markets. When there is an electricity imbalance within the coalition, the market operator will trade with the EUC to maintain the balance. Due to these extra costs or benefits, the electricity guiding price $p^{e,mid}$ will be adjusted to reflect these coalition-level costs or benefits.

We use coalition $\mathcal{X}$ as an example. The electricity imbalance $E^{imb,\mathcal{X}}$ is defined in Eq. (25).

$$E^{imb,\mathcal{X}} = \Sigma_{x=1}^{|\mathcal{X}|}(E_x^{sel} - E_x^{buy}) \tag{25}$$

When the electricity is balanced within the coalition, the guiding prices will remain the same (see Eq. (26)). When there is a surplus, the surplus will be sold to the EUC at a lower price and hence, the selling price will be decreased (see Eq. (27)). When there is a deficit, the operator buys electricity from the EUC at a higher price and the buying price will be increased (see Eq. (28)). These equations are now further explained using Eq. (28) as an example.

Eq. (28) represents the situation when electricity deficiency occurs in coalition $\mathcal{X}$, so the market operator needs to buy electricity from the EUC to maintain the electricity balance within a particular coalition. Note that since the market operator neither earns any income nor pays any costs, the resulted income or cost associated with the EUC trading with has to be reflected in the prices. Here, because the buying is too high, the selling price will be kept unchanged while the buying price needs to be adjusted. Since the EUC buying price is higher than the P2P buying price, the adjusted buying price should cover the extra payments to the EUC.

In Eq. (28), the numerator includes two parts of payments. The first part is the total payments to sellers at the original price within the coalition, while the second part is the payment to the EUC. The denominator indicates the total buying demand. Therefore, the division represents the average cost of unit buying demand. The same logic applies to the electricity surplus situation for Eq. (28).

- When $E^{imb,\mathcal{X}} = 0$

$$p^{e,buy,\mathcal{X}} = p^{e,sel,\mathcal{X}} = p^{e,mid} \tag{26}$$

- When $E^{imb,\mathcal{X}} > 0$

$$p^{e,buy,\mathcal{X}} = p^{e,mid}, \quad p^{e,sel,\mathcal{X}} = \frac{\Sigma_{x=1}^{|\mathcal{X}|} E_x^{buy} p^{e,mid} + E^{imb,\mathcal{X}} p^{sel,euc}}{\Sigma_{x=1}^{|\mathcal{X}|} E_x^{sel}} \tag{27}$$

- When $E^{imb,\mathcal{X}} < 0$

$$p^{e,buy,\mathcal{X}} = \frac{\Sigma_{x=1}^{|\mathcal{X}|} E_x^{sel} p^{e,mid} - E_t^{imb,\mathcal{X}} p^{buy,euc}}{\Sigma_{x=1}^{|\mathcal{X}|} E_x^{buy}}, \quad p^{e,sel,\mathcal{X}} = p^{e,mid} \tag{28}$$

4. Results and discussions

This section showcases the model in a realistic case study. First, Section 4.1 introduces the background of the case study and the relevant data inputs. Next, the results are illustrated using one day of data. Section 4.2 presents the energy prices and the trading volumes and pinpoints the trading positions of the peers. Section 4.3 illustrates the dynamic process of the coalition formation. Then, Section 4.4 discusses the net benefits of the peers. To see the seasonal variations, Section 4.5 shows the results of the simulation for one year and compares the proposed mechanism with other possible ones. In the end, reflections of the approach are given in Section 4.6.

4.1. Case study set-up

The gas-free heat transition in the Netherlands prompts to explore market innovations to accelerate the development of distributed electricity and heat sources [39]. The municipality Apeldoorn aims to be carbon neutral by 2047 and has launched the first pilot project in the Zuidbroek neighborhood [40]. This neighborhood will be used as a case study here to evaluate the proposed P2P multi-energy market.

(a) Six building types.

(b) Clustered 20 energy communities (peers).

Fig. 5. Geospatial information of the case study in the Zuidbroek neighborhood in the municipality of Apeldoorn in the Netherlands.

To determine the generation and demand profiles for each building in the neighborhood, a geographical information system is utilized to access the geospatial data of the buildings. Fig. 5a illustrates the locations and the types of the buildings. There are 1485 buildings in total including 14 apartments, 173 detached houses, 28 offices, 9 retail stores, 3 schools, and 1258 terraced houses. In this case study, we cluster the geographically closed buildings to energy communities, where each energy community is assumed to be a collective peer that submits trading orders together. The 1485 buildings are clustered into 20 energy communities (peers) using the k-means clustering technique [41]. Fig. 5b shows these 20 clustered peers for the P2P energy trading.

The input data including the geospatial information, demand profiles, generation profiles, and prices is summarized in Appendix B. To further increase the transparency and reproducibility, the processed input data will be published online [42] and the model in pseudo-code is provided in Appendix A. The model is run in hourly resolution for the year 2018.

4.2. Trading volumes and energy prices

From Sections 4.2 till 4.4, we will analyze the results for one specific day in order to serve detailed discussions. This case, Thursday, November 22, is just an illustrative example. To focus on the differences of the peers, we only analyze the results of the following six representative peers in this subsection.

- Residential peers
  - Peer 0: mostly terraced houses.
  - Peer 8: mostly apartments and detached houses.
  - Peer 13: mostly detached houses.
- Service-sector peers
  - Peer 6: mostly offices and retailers.
  - Peer 10: mostly offices, retailers and schools.
- Mixed peer
  - Peer 16: a balanced combination of schools and terraced houses.

The stacked plot Fig. 6 shows the electricity and heat demand throughout the day. For service-sector peers 6 and 10, their energy demands, especially their heat demands, are relatively low at night. But their electricity demands are high during the day. Moreover, for all the peers, there are two heat demand peaks in the morning and in the evening, with a valley at noon.

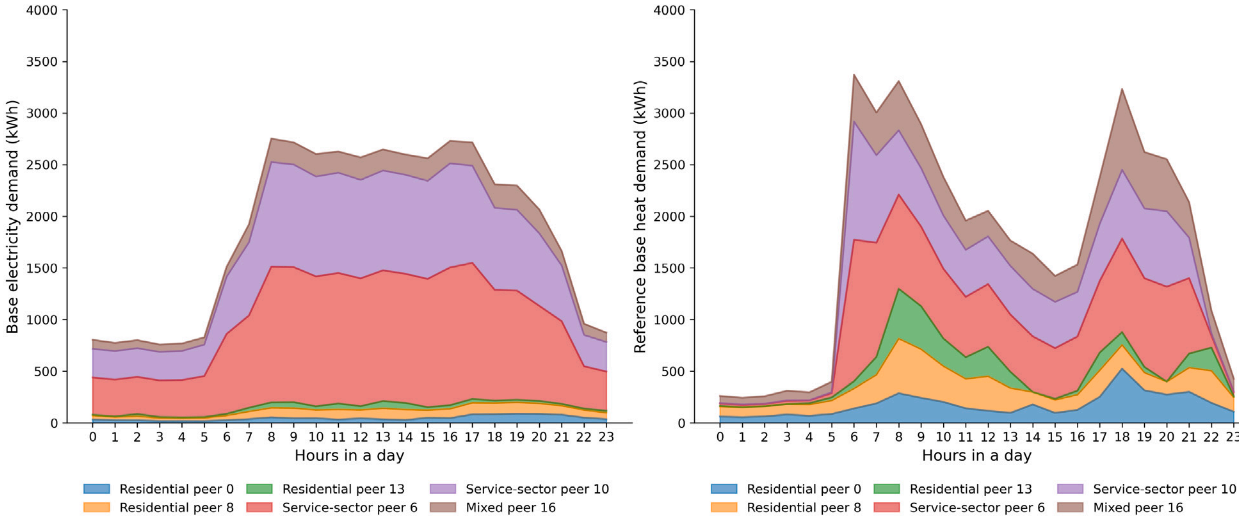
Stacked plots Figs. 7 and 8 demonstrate the electricity and heat trading volumes of each peer as well as the electricity and heat trading prices per time step. In both coalitions, the peak volume of electricity selling occurs at noon (11:00–12:00). This is due to the high generation of solar PV, which also lowers the electricity selling price. In terms of the range of the electricity prices, the price in coalition $\mathcal{X}$ shows a wider swing than that in coalition $\mathcal{Y}$. The reason behind this is that since few peers are willing to join coalition $\mathcal{X}$, the system imbalance in coalition $\mathcal{X}$ is more prone to increasing. There will be more trades with EUC, and thus the deviation from the guiding electricity price will be larger in coalition $\mathcal{X}$. Besides, the peak volume of electricity buying happens in the morning (8:00–9:00) and in the evening (18:00–19:00). The large electricity buying demands drive up the electricity buying prices and from that also the heat trading price. Moreover, the peak volumes of both heat selling and buying occur at 10:00–11:00 and 21:00–22:00, which are driven by the relatively low electricity prices and the high heat demands.

4.3. Dynamic coalition formation

In this section, we focus on the coalition formation of the peers. We start with a general description of the composition of the coalitions for a few hours on Nov. 22. Next, the rationales behind the changes of coalitions will be given not only for these hours but also for other hours across the day. At last, the numbers of peers in each coalition at different hours are shown to give an overall impression.

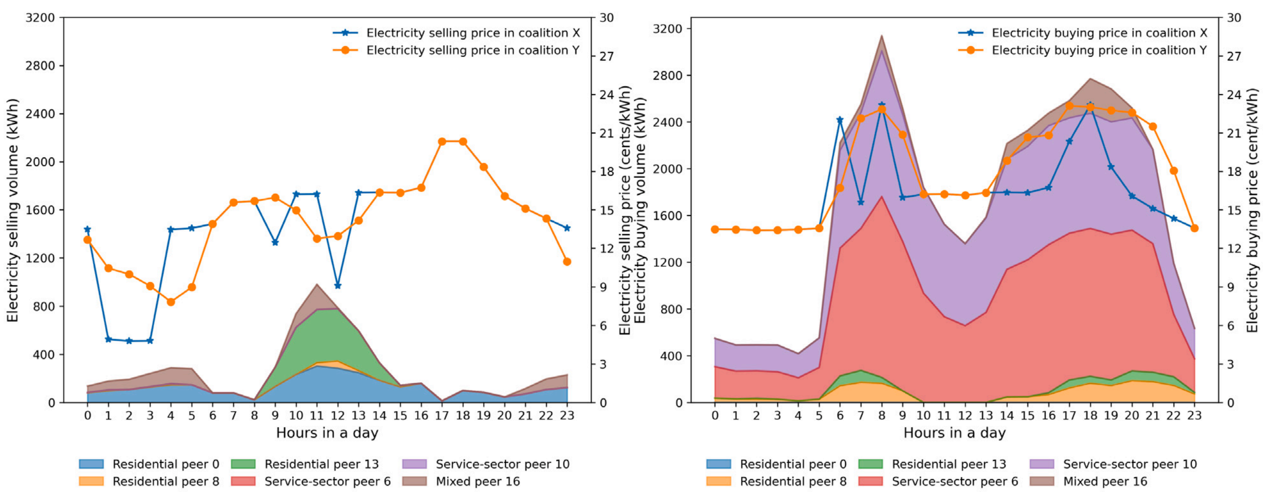
The peers in each coalition change every hour. Fig. 9 illustrates the dynamics of coalition formation from 6:00 to 10:00 on Nov. 22.

- At 7:00, peer 6 and 10 split from the coalition $\mathcal{X}$ and merge into coalition $\mathcal{Y}$. The rest stay in coalition $\mathcal{Y}$ however, peer 3 and 17 change their trading positions from heat buyers to heat sellers. Between 7:00–8:00, all the peers are in coalition $\mathcal{Y}$ to trade both heat and electricity, i.e., a grand coalition is formed for the P2P multi-energy market.
- At 8:00–9:00, peer 3, 8, 13, and 19 split from coalition $\mathcal{Y}$ and form coalition $\mathcal{X}$. The others stay in $\mathcal{Y}$ and keep the same trading positions.



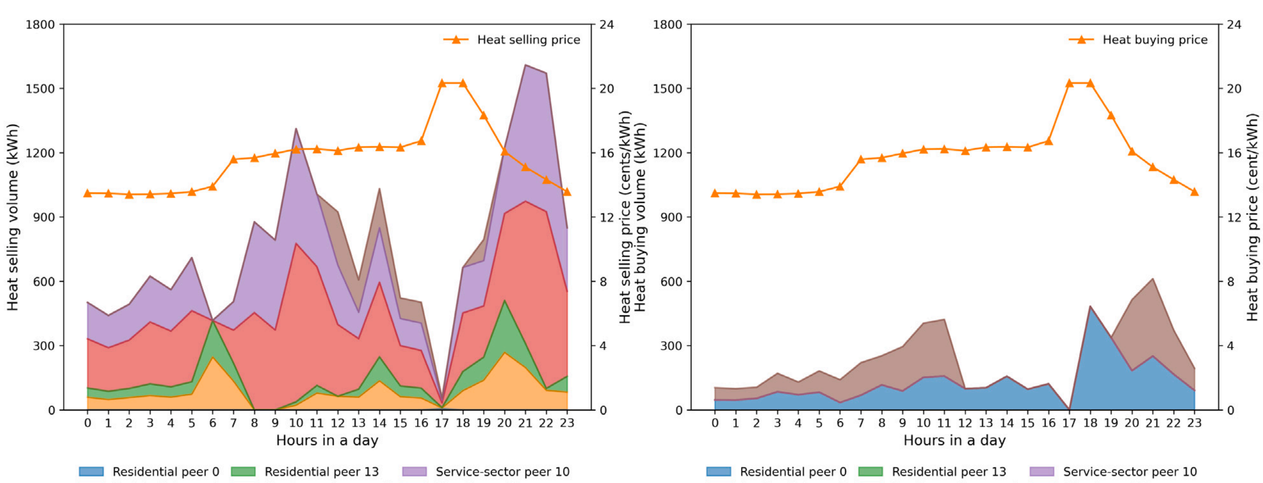
(a) Base electricity demand. (b) Reference base heat demand.

Fig. 6. Energy demands throughout November 22.



(a) Electricity selling price and volume. (b) Electricity buying price and volume.

Fig. 7. Electricity prices and trading volumes in coalition $\mathcal{X}$ and $\mathcal{Y}$ throughout November 22.



(a) Heat selling price and volume. (b) Heat buying price and volume.

Fig. 8. Heat trading prices and volumes in coalition $\mathcal{Y}$ throughout November 22.

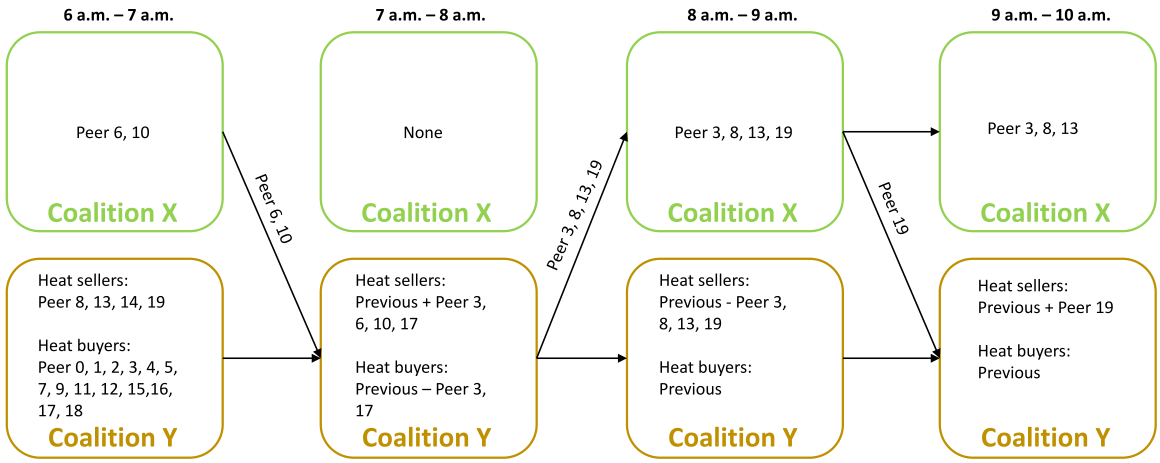


Fig. 9. Exemplary coalition formation process from 6:00 to 10:00 on November 22.

- At 9:00, peer 19 splits from coalition $\mathcal{X}$ and goes into coalition $\mathcal{Y}$ to become a heat seller.

In general, the residential peers 0 and 13 which consist of mostly terraced and detached houses are the major electricity sellers, the service-sector peers 6 and 10 are the major electricity buyers. However, the mixed peer 16 continuously changes its trading position between a seller and a buyer in both electricity and heat trading. Peer 0 and 16 which are mostly comprised of terraced houses are the major heat buyers. Note that in Fig. 6b, there is a large heat demand increase for service-sector peers 6 and 10 at 6:00–7:00, which is prior to that for residential peers 0, 8 and 13 at 8:00–9:00. Therefore, as shown in Fig. 8a, peer 6 and 10, as previous major sellers now use their HP capacity mostly for self-generation. They stop the heat selling from 6:00 to 7:00 and become electricity buyers. Meanwhile, peer 8 and 13 increase their heat selling volumes. Later at 8:00–9:00, they change their trading positions from coalition $\mathcal{Y}$ to coalition $\mathcal{X}$. At the same time, peer 6 and 10 become the major heat sellers. A similar observation is for 20:00 to 23:00, where the peers' heat demands drop while the heat selling volumes increase. We also notice the low heat trading for 17:00–18:00. The heat price is high at this moment, which results in lower heat buying demand. Due to the constraint of heat balance, the actual heat selling is also low. In summary, we found that on the one hand, certain peers are willing to buy extra electricity and use it for heat selling, such as peer 6 and 10. These two peers are major heat sellers, but sometimes (at 6:00 and 17:00) choose to be in coalition $\mathcal{X}$ to only trade electricity. On the other hand, peer 0 is willing to buy heat and sell surplus electricity instead of using the surplus electricity to self-generate heat. This phenomenon verifies the model as P2P heat trading empowers peers to find the most cost-saving way to meet their energy demands.

To fully interpret these results, especially for the results of the peers other than the six representative ones, it would be ideal to show more information about all the 20 peers. However, to give clear illustrations and ease reading burdens, we focus on the peers that change their trading positions in Fig. 9. Besides the six representative peers, the information of peer 3 and 19 is provided to enhance the understanding. Fig. 10 shows the demand profiles of these two peers. The trading prices and volumes are illustrated in Figs. C.17 and C.18 in Appendix C.

At 8:00, peer 3 and 19 reach their peak heat demands of the day. As a result, they stop the heat selling at 8:00 and utilize all the heat pump capacity for self-generation. It means that there is no remaining capacity for heat trading and thereby they change to coalition $\mathcal{X}$. At 9:00, peer 19 has decreased its heat demand but increased its electricity demand. Therefore, peer 19 has the remaining heat pump capacity for heat selling and switches back to coalition $\mathcal{Y}$. Things are the opposite for peer 3 at 9:00 and thus peer 3 stays in coalition $\mathcal{X}$ without changing.

Furthermore, Fig. 11 shows the number of peers in each coalition at different hours of the day. It could be observed that in general, most peers would join coalition $\mathcal{Y}$ to trade both heat and electricity.

4.4. Net benefits

Now we focus on the net benefits of the peers and we would like to see how the P2P multi-energy market changes their net benefits compared to a scenario without P2P trading. To that end, a reference scenario is set where no P2P energy trading takes place. There, the peers consume the electricity and heat that are generated by their own generation portfolios and trade electricity with the EUC. Fig. 12 presents the net benefits for each peer at every hour compared to the reference scenario. There are the following several observations. First, all the peers as a whole can always obtain benefits at any hour. In particular, the total benefit is large between 10:00 to 15:00. Second, there are special instances where certain peers are slightly worse off compared to the reference scenario, such as peer 8 at 7:00–8:00 and peer 16 at 10:00–11:00. In Fig. 12, at hours 7, 10, 11, 19, 20, and 21, there are parts of bars with a negative value, meaning that the relevant peers have negative net benefits at that hour. Despite that the absolute values of the negative net benefits are negligible and hard to distinguish from 0, we would like to draw attention to these instances. The negative net benefits happen because of the post-adjustment of the mid-market rate makes the prices less favorable to conduct heat trading. Nevertheless, the overall benefits throughout the hours overshadow these rare instances.

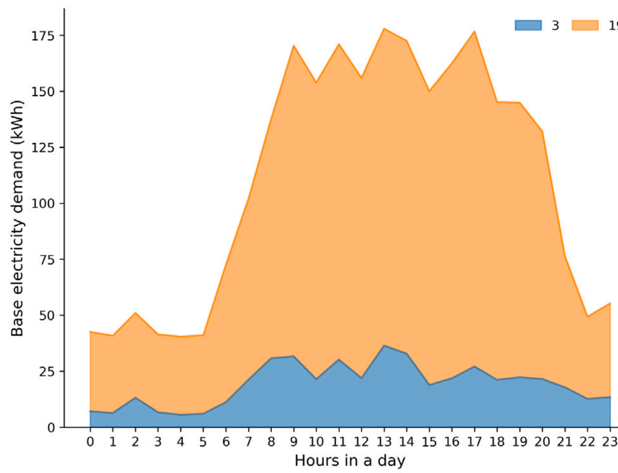
4.5. Discussions of results for one year

In previous sections, we have only discussed the results of one day. Those results help to understand the details, but the mechanism also needs to be examined for a larger period and with other possible market mechanisms. To that end, we will briefly show the results of the whole year for various scenarios.

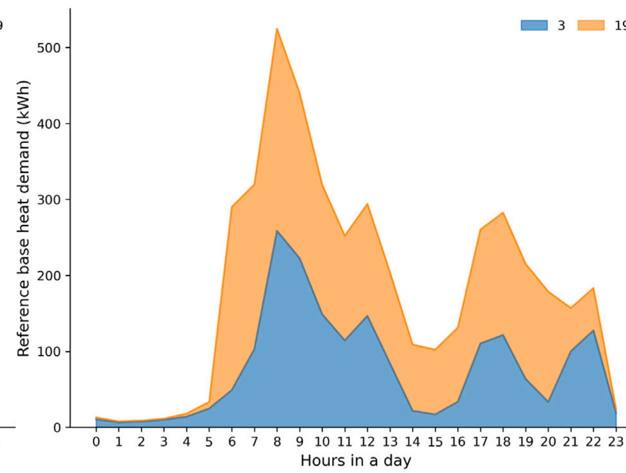
Three scenarios will be discussed. In addition to the heat and electricity coalitional trading, we introduce a scenario for electricity-only trading and one for electricity and heat trading without coalitions.

4.5.1. Influence of fluctuations in demand and generation

Fig. 13 illustrates the seasonality of the net benefits. In summer, all scenarios show similar net benefits due to high electricity surplus and low heat demands. However, in winter, the results of scenarios with P2P heat trading significantly outnumber the other ones. It is worth mentioning here the two main drivers for heat trading. On the one hand, there is a supply–demand mismatch across the peers. At some



(a) Base electricity demand.



(b) Reference base heat demand.

Fig. 10. Energy demands for peer 3 and 19 throughout November 22.

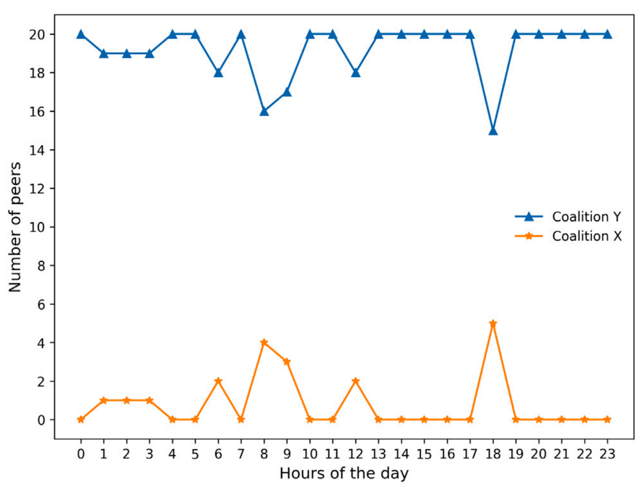


Fig. 11. Number of peers in the coalitions on November 22.

time steps, some peers are not able to meet their own heat demand by self-generation due to HP capacity which is set at 95% confidence level (see Appendix B.2 for details regarding the set-up of the HP capacity), leading to heat buying demand on the market. Meanwhile, some other peers may have remaining heat pump capacity for heat trading. On the other hand, the heat generation costs (the HP levelized fixed costs as detailed in Section 3.4.2) for different peers are different. Therefore, under the same heat price, one peer's generation cost could be higher or lower than the heat price which stimulates the heat buying or selling. In the days where the electricity generation is low for solar PV and WT, there are hardly any P2P electricity tradings. In this situation, the peers will have to trade with the EUC and the P2P market is not utilized.

4.5.2. Net benefits for all the peers in a year

Following from Section 4.4, a question naturally arises: Are there any peers that have no benefits in the current scenario and how often does this phenomenon occur? This section presents results for the different scenarios to answer this question.

Fig. 14 shows the percentage of the hours in a year where the scenario is the best, which is also referred to as participation willingness in this study. At each hour, the peers obtain different benefits for the three scenarios, respectively. If for scenario 3, the peer obtains the most benefit, then it means that this scenario is the best at this hour. In this way, for all the hours, we can obtain the best scenarios for all.

Table 2
Scenario comparison on the overall benefit and the participation willingness for all the peers.

	Overall benefit (€)	Participation willingness
Scenario 1	745 156	0%
Scenario 2	1 125 600	45%
Scenario 3	1 068 350	55%

The differences in prices between scenario 2 and 3 concern the electricity selling and buying prices. In scenario 2, all the peers have the same price adjusted from the system-level imbalance trading with the EUC. In scenario 3, the electricity prices are different in the two coalitions since they are adjusted from the coalition-level imbalance trading with the EUC. Because scenario 2 could decrease the electricity buying from EUC as much as possible, the electricity buying price, in general, will be lower than that in scenario 3. The lower electricity buying prices in scenario 2 bring more arbitrage opportunities for major heat sellers such as heat sellers 6 and 10. For heat buyer 0, the lower electricity buying prices could also lower the heat self-generation cost. However, such conclusions do not apply to all the peers, since the prices in each coalition of scenario 3 are hard to predict and more fluctuated, which results in the reverse observations for heat seller 8 and 13 and heat buyer 16.

In general, while all the peers prefer scenario 2 and scenario 3 most of the time, there are hours where scenario 1 is the best for them. This observation highlights the conclusion that when selecting the best market mechanism, the trade-off emerges between the benefit at a particular time step and the benefit over a period. It aligns with the observation in Section 4.4 that the overall benefits of the current scenario overshadow the rare instances.

4.5.3. Benefit transfer from large peers to small peers

Comparing scenario 2 and scenario 3, we found that the electricity and heat coalitional trading makes the majority of peers better off but the overall benefit slightly worse as shown in Table 2.

First, in scenario 2 in which there is one grand coalition, the overall benefit for all the peers is higher than that for scenario 3. This is because a grand coalition could mitigate the electricity trading with the EUC and hence, the benefit loss is reduced.

Second, the result of participation willingness shows that 55% of the peers obtain their optimal benefit over the year in scenario 3 while the rest prefers scenario 2.

Fig. 15 shows the benefit breakdown per peer. The benefit in scenario 2 or 3 for every peer is higher than that in scenario 1, meaning

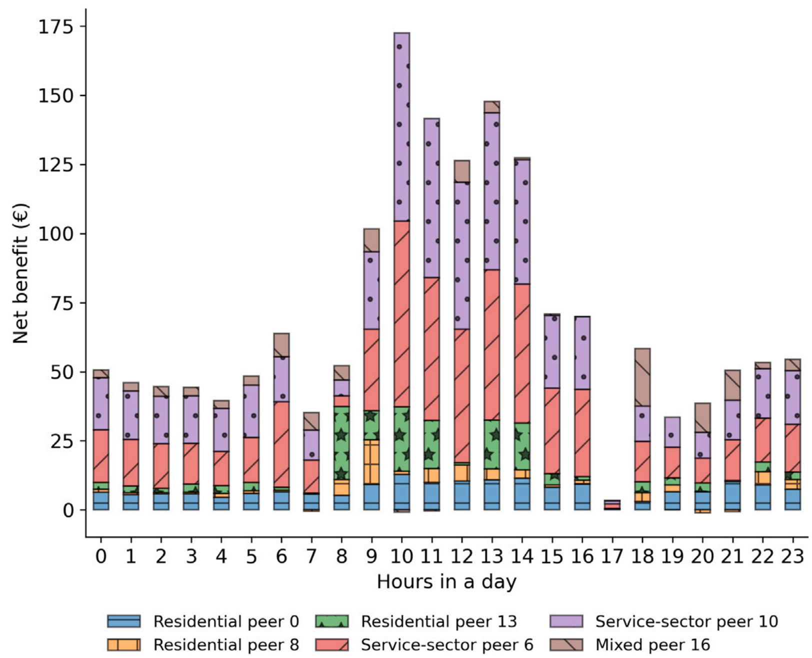


Fig. 12. The hourly net benefits obtained by each peer on November 22.

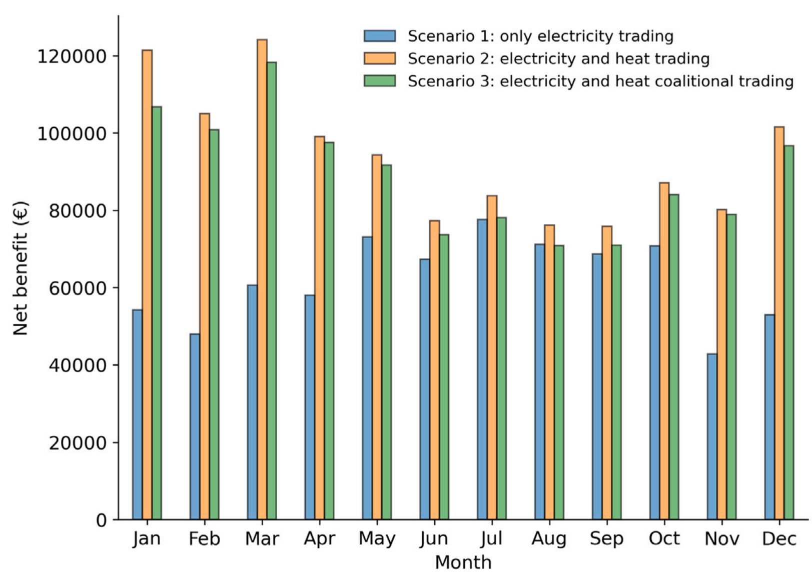


Fig. 13. Scenario comparison on the monthly net benefits.

that both individuals and the system could obtain more benefits compared to the scenario without heat trading. This observation shows the prosumer-centric characteristic of P2P heat trading.

From the geospatial distribution in Fig. 16, the peers mainly comprised of terraced houses prefer scenario 3 while the peers comprised of service-sector buildings prefer scenario 3. Therefore, the introduction of coalitional trading results in a benefit transfer from service-sector peers with larger demands to residential peers with smaller demands.

4.6. Reflections on the approach

The study presents a promising P2P multi-energy market mechanism that covers the electricity and heat demand with three generation technologies. The future improvements of the model lie in the introduction of more energy carriers, like hydrogen and devices, like electric vehicles to fit with future energy scenarios. Besides, apart from the two pre-defined coalitions, the peers can form more coalitions based on e.g., common preferences other than benefit. Future work may explore what and how other coalitions might be formed.

The underlying assumption of this work is that the introduction of heat trading could potentially leverage the time differences of the peak demands between peers and thereby minimize the heat pump investment costs. We use the 95% confidence HP capacity in this case study, which is only a choice to illustrate the model. In future works, it will be interesting to further study the confidence level to reduce the heat pump investment cost as much as possible without sacrificing the heat comfort.

Another relevant future work is to investigate the role of thermal storage. The key characteristic and the motivation of the proposed model is that it attains a balance between computational complexity and autonomy of the trading strategies for the peers, such that the model is simple to understand and implement as well as keeping

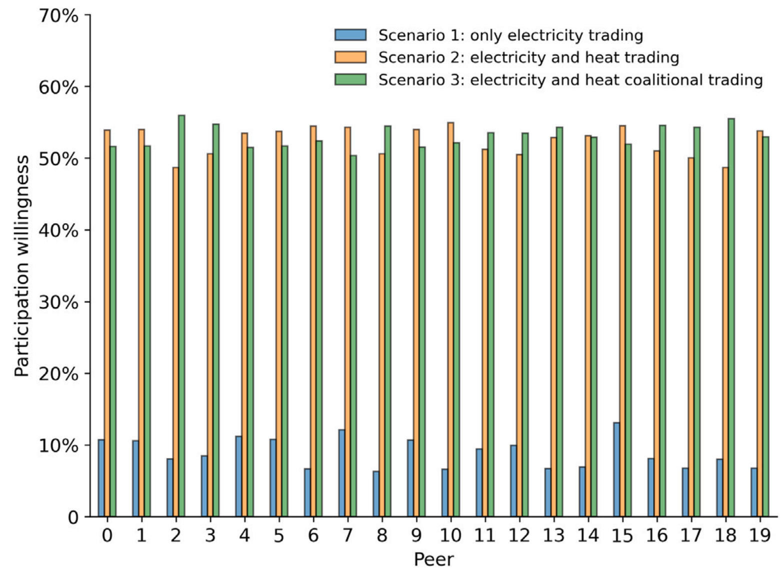


Fig. 14. Participation willingness for the three scenarios for each peer.

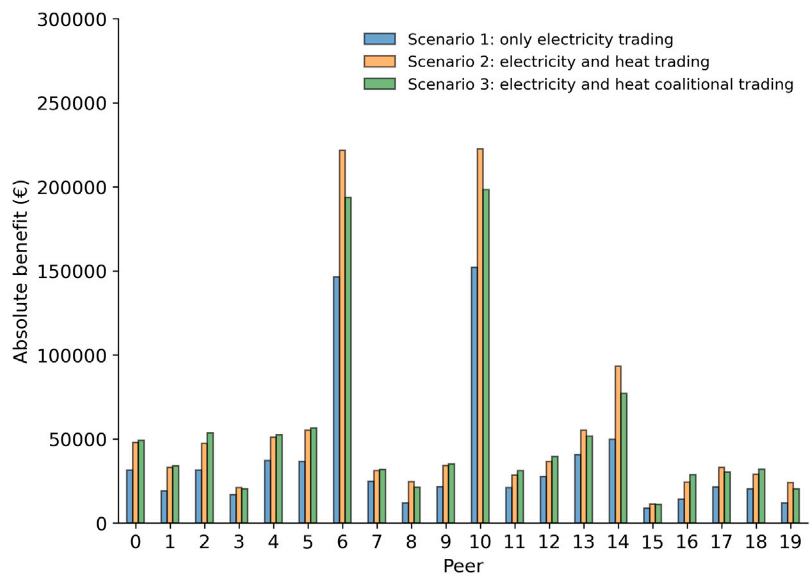


Fig. 15. Benefits for every peer for the three scenarios.

economic incentives for the peers. Considering thermal storage in this model would increase the model complexity since inter-temporal constraints will have to be added. Meanwhile, the increased complexity would require more computational efforts for the energy management system on the prosumer side. But undoubtedly, the business case analysis of thermal storage is a promising research direction. Topics such as comparing the net benefits of the peers when storage is used with our model and/or optimizing the investment portfolio with thermal storage could warrant future research.

In addition, in this study, the market operator is assumed to not extract any benefits from the market. In case the market operator is profit-driven, it will be interesting to see how that materializes compared to the current model. For example, it is possible to introduce a linear parameter between the heat selling price and the heat buying price, indicating a regulated surcharge for the buyer which may represent market operation costs, network tariffs, taxes, etc. The model is ready to be extended in those directions and future research could investigate those particular aspects.

This research proposes a first-of-its-kind mechanism that focuses on the integrated effects of cooperative behaviors and multi-energy coupling on P2P energy trading. Despite this contribution, we are aware that there is no one-fit-all market mechanism since each mechanism has its pros and cons to fit with the specific context. In Section 4.5.3, we argue that one of the main conclusions of the proposed market mechanism is the benefit transfer across peers. In case this is not desirable in a specific application, the following actions could be explored. This paper utilizes a proportional heat price to electricity price where the proportionality constant is assumed to be constant. However, after yearly operations, historical data can be used to design a time-dependent proportionality constant or an independent heat pricing scheme. The new pricing scheme should motivate both heat selling and buying so that the heat balance is maintained and that the system benefits can be distributed in a fairer manner. As a result, more participation willingness can emerge across all the peers.

Besides the insightful case study, the model is ready to be utilized on different administrative levels and locations since the computational complexity will increase only linearly with the number of peers. When

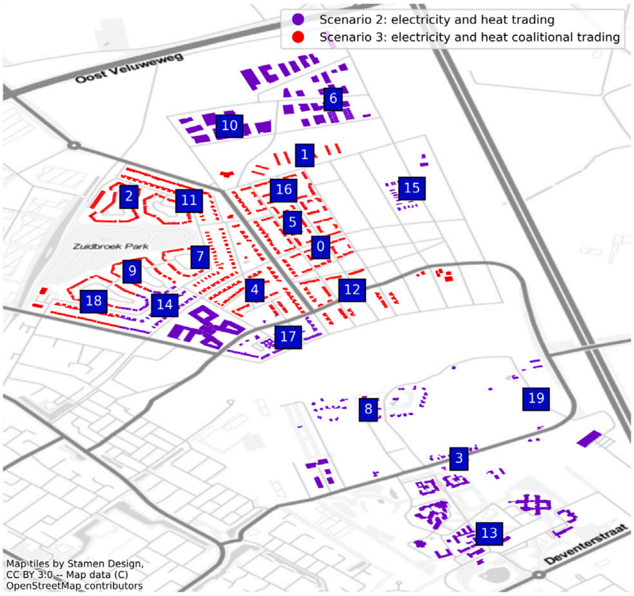


Fig. 16. Spatial distribution of the best scenarios for every peer.

this model will be used in practice, in case the households are clustered into energy communities as in this case study, the following topics might be discussed to complement the case. On the one hand, a proper cost and benefit allocation method could be applied to the households [43]. On the other hand, the orders of the households can be gathered by a community manager who collects and merges the orders and then escalates the single order to the market operator. Future studies could address these coordination issues.

Finally, despite the benefits, the potential roll-out of P2P markets also calls for research attention towards its challenges as discussed in [44]. The resulted decentralization of energy sources may challenge the investment and operation of the transmission grids as well as the design of the wholesale energy markets. The same as numerous existing studies on P2P markets, this paper focuses on the local market design but its amplifying effects are worth investigating in the future.

5. Conclusions

P2P energy trading has attracted attention in recent years, but most existing studies only consider electricity as the single energy carrier, especially within the context that cooperative behaviors may emerge from the interactions of peers. Therefore, this paper proposes a P2P multi-energy market mechanism to conduct both electricity and heat trading and to study the cooperative behaviors between the peers.

In this paper, two coalitions, i.e., an electricity trading coalition and an electricity–heat trading coalition are considered. The peers are given the autonomy to maximize their net benefits by determining which coalition to join, which position to take, i.e., being either a seller or a buyer for heat and electricity, and what quantities to trade with. The heat and electricity markets are cleared separately by a P2P market operator per coalition and the complete trading process has been summarized. The P2P market design has been illustrated using a case study on a neighborhood in the Netherlands with realistic data. In this case study, we have first shown the energy trading prices and volumes across a day. In addition, it is found that by the introduction of the coalitions, the positions of the peers change at different time steps, which indicates that the peers are able to choose the coalition that benefits them the most in a dynamic way. Moreover, compared to the reference case where there is no P2P trading, the P2P multi-energy trading results in higher net benefits for all the peers as a whole and benefits the majority of the individuals. Lastly, we also conclude that the introduction of coalitional trading makes the majority of peers better off but the overall benefit is slightly worse compared to multi-energy trading without coalitions. This demonstrates the benefit transfer from service-sector prosumers with larger demands to residential prosumers with smaller demands. Therefore, on the one hand, depending on the preferred benefit allocation, it is an open question for decision-makers (e.g., collective peers or local market operators if any) on whether to opt for the coalitional trading as defined in this study. On the other hand, through adjusting the electricity–heat pricing scheme, policy interventions could allocate the system benefit more fairly.

CRediT authorship contribution statement

Ni Wang: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Ziyi Liu:** Conceptualization, Methodology, Software, Investigation, Data curation. **Petra Heijnen:** Supervision, Funding acquisition, Writing – review & editing. **Martijn Warnier:** 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.

Acknowledgments

This research received funding from the Netherlands Organisation for Scientific Research (NWO) [project number: 647.002.007]. Icons in Figs. 1 and 2 are made by Freepik from www.flaticon.com. The authors would like to sincerely express the gratitude to the editor and reviewers for their constructive suggestions and valuable observations, which significantly help to improve the manuscript. The authors also thank Samantha Tanzer for her suggestions on writing.

Appendix A. Trading algorithm

In the system model, we only discussed the trading process at one time step. However, in the below algorithm, the system model is expanded to the set $\mathcal{T}$ of all time steps, and therefore $t \in \mathcal{T}$ appears in the subscripts of the variables.

At time step t, the algorithm starts with the price information setting from line 2 to line 3 and the peers' energy profile settings from line 5 to line 7. Next, each peer initially decides its trading strategy including which coalition to join and the trading volumes from line 8 to line 30. After the market operator receives all the trading strategies, line 34 to line 67 showcases the coordination process where certain peers update their heat orders to maintain the heat balance. By far, stable coalitions have been achieved by all the peers and the market operator obtains the market-clearing prices in each coalition. Finally, the algorithm is run for the next time step $t + 1$ until the end.

Appendix B. Data inputs for the case study

This section details the data inputs for the case study. Table B.3 summarizes all the data sources. The demand profiles include electricity and heat demand; the generation profiles include roof-top solar PV, WT, and HP.

Table B.3
Data sources for the case study.

Category	Item	Sources
Geospatial information	Electricity and building quantity, locations, types and projected areas	OpenStreetMap, Python package OSMnx
Demand profiles	Electricity and natural gas: hourly consumption profile of detached and terraced houses	Liander smart meter data in Apeldoorn [45]
	Electricity and heat consumption profile for other four types	PhD thesis: Harnessing Heterogeneity [46]
Generation profiles	Hourly weather availability for solar PV and WT	renewables.ninja [47]
	Solar PV capacity for each building	Proportional to the available roof-top area, the standard product from Dutch PV Portal [48]
	WT capacity for each building	Proportional to the total energy demand, constrained by land use of WT [49]
	HP capacity for each building	Determined by the 95th percentile of the heat demand
	Hourly COP fluctuation for HP	Open power system data [50]
	Initial investment and fixed operation and maintenance costs, equivalent full load hours and lifetime for HP	ECN-TNO [51], Danish Energy Agency [52]
Price profiles	Hourly electricity wholesale price	ENTSOE transparency platform [53]
	Electricity retail peak and offpeak price (time-of-use tariff)	Essent N.V. [54]

Algorithm 1 P2P energy trading algorithm

Require: Set $\mathcal{N}$; Heat and electricity demand profiles $e^{bas}_{n,t}$ and $q^{bas}_{n,t}$; PV, WT and HP generation profiles $e^{pv}_{n,t}$, $e^{wt}_{n,t}$, $q^{hp,max}_{n}$, $cop_{n,t}$ and $p^{hp,f}_{hs}$; Electricity trading price with EUC $p^{buy,euc}_{t}$, $p^{sel,euc}_{t}$; Coefficient υ_n, $u_{n,t}$, α.

Ensure: Set $\mathcal{X}$, $\mathcal{Y}$ for coalitions at each time step; P2P electricity and heat trading price $p^{e,buy,\mathcal{X}}_{t}$, $p^{e,sel,\mathcal{X}}_{t}$, $p^{e,buy,\mathcal{Y}}_{t}$, $p^{e,sel,\mathcal{Y}}_{t}$, $p^{h,buy}_{t}$, $p^{h,sel}_{t}$; P2P electricity and heat trading volume $E^{sel}_{n,t}$, $E^{buy}_{n,t}$, $Q^{sel}_{n,t}$ and $Q^{buy}_{n,t}$.

for time step $t = 1$ **to** $|\mathcal{T}|$ **do**
  Set P2P electricity selling and buying price as $p^{e,mid}_{t} = \frac{p^{buy,euc}_{t} + p^{sel,euc}_{t}}{2}$.
  Set P2P heat selling and buying price as $p^{h,mid}_{t} = \alpha p^{e,mid}_{t}$.
  for Each peer $n \in \mathcal{N}$ **do**
    Set the household electricity and heat demand $e^{bas}_{n,t}$ and $q^{bas}_{n,t}$.
    Set the PV and WT generation $e^{pv}_{n,t}$, $e^{wt}_{n,t}$.
    Set the HP capacity $q^{hp,max}_{n}$, COP $cop_{n,t}$ and the levelized fixed cost $p^{hp,f}_{hs}$.
    if Price condition 1 in Table 1 is TRUE **then**
      Peer n chooses to be in coalition $\mathcal{Y}$ as a heat seller hs.
      Decide to sell $Q^{sel}_{hs,t}$ heat according to Eq. (13).
      Decide to sell $E^{sel}_{hs,t}$ or buy $E^{buy}_{hs,t}$ electricity according to Eq. (1).
    else if Price condition 2 in Table 1 is TRUE **then**
      Peer n chooses to be in coalition $\mathcal{Y}$ as a heat buyer hb.
      Decide to buy heat $Q^{buy}_{hb,t}$ according to Eq. (16).
      Decide to sell $E^{sel}_{hb,t}$ or buy $E^{buy}_{hb,t}$ electricity according to Eq. (1).
    else if Price condition 3 in Table 1 is TRUE **then**
      Peer n chooses to be in coalition $\mathcal{X}$.
      Decide the heat consumption level $Q^{*}_{n,t}$ according to Eq. (19).
      Decide to sell $E^{sel}_{n,t}$ or buy $E^{buy}_{n,t}$ electricity according to Eq. (1).
    else
      Calculate $Q^{sel}_{hs,t}$ and $Q^{buy}_{hb,t}$ according to Eqs. (13) and (16), respectively.
      Calculate $B_{hs,t}$ and $B_{hb,t}$ according to the objective functions in problem (9) and problem (14), respectively.
      if $B_{hs,t} \geq B_{hb,t}$ **then**
        Peer n choose to be in coalition $\mathcal{Y}$ as a heat seller hs.
        Decide to sell $Q^{sel}_{hs,t}$ heat according to Eq. (13).
        Decide to sell $E^{sel}_{hs,t}$ or buy $E^{buy}_{hs,t}$ electricity according to Eq. (1).
      else
        Peer n choose to be in coalition $\mathcal{Y}$ as a heat buyer hb.
        Decide to buy $Q^{buy}_{hb,t}$ heat according to Eq. (16).
        Decide to sell $E^{sel}_{hb,t}$ or buy $E^{buy}_{hb,t}$ electricity according to Eq. (1).
      end if
    end if
  end for
  Market operator calculates the heat imbalance for coalition $\mathcal{Y}$: $Q^{imb,\mathcal{Y}}_{t} = \Sigma^{|\mathcal{Y}|}_{y=1}(Q^{sel,\mathcal{Y}}_{t} - Q^{buy,\mathcal{Y}}_{t})$
  while $Q^{imb,\mathcal{Y}}_{t} \neq 0$ **do**
    if $Q^{imb,\mathcal{Y}}_{t} \geq 0$ **then**
      All the orders from heat buyers are accepted.
      For heat sellers, the required curtailment per volume of heat order is $q^{cur,\mathcal{Y}}_{t} = \frac{Q^{imb,\mathcal{Y}}_{t}}{\Sigma^{|\mathcal{Y}|}_{y=1} Q^{sel}_{y,t}}$.
      for each heat seller $hs \in \mathcal{HS}$ **do**
        if $Q^{sel}_{hs,t} \leq Q^{sel}_{hs,t} q^{cur,\mathcal{Y}}_{t}$ **then**
          The peer hs changes its trading strategy and finally decide to be in coalition $\mathcal{X}$.
          Decide the heat consumption level $Q^{*}_{n,t}$ according to Eq. (19).
          Decide to sell $E^{sel}_{n,t}$ or buy $E^{buy}_{n,t}$ electricity according to Eq. (1).
        else
          peer hs consents the market operator to curtail its heat order $Q^{sel}_{hs,t}$ by $q^{cur,\mathcal{Y}}_{t}$ per volume and decides to continue to be the heat seller in coalition $\mathcal{Y}$.
          Decide the new heat consumption level as the minimum between $q^{hp,max}_{hs} - Q^{sel}_{hs,t}$ and $Q^{*}_{hs,t}$.
          Decide to sell $E^{sel}_{hs,t}$ or buy $E^{buy}_{hs,t}$ electricity according to Eq. (1).
        end if
      end for

50: **else if** $Q_t^{imb,\mathcal{Y}} < 0$ **then**
51: All the orders from heat sellers are accepted.
52: For heat buyers, the required curtailment per volume of heat order is $q_t^{cur,\mathcal{Y}} = \frac{Q_t^{imb,\mathcal{Y}}}{\Sigma_{y=1}^{|\mathcal{Y}|} Q_{y,t}^{buy}}$.
53: **for** Each heat buyer $hb \in \mathcal{HB}$ **do**
54: **if** $Q_{hb,t}^{buy} \leq Q_{hb,t}^{buy} q_t^{cur,\mathcal{Y}}$ **then**
55: Peer hb changes its trading strategy and finally decide to be in coalition $\mathcal{X}$.
56: Decide the heat consumption level $Q_{n,t}^{*}$ according to Eq. (19).
57: Decide to sell $E_{n,t}^{sel}$ or buy $E_{n,t}^{buy}$ electricity according to Eq. (1).
58: **else**
59: Peer hb consents the market operator to curtail its heat order $Q_{hb,t}^{buy}$ by $q_t^{cur,\mathcal{Y}}$ per volume and decides to continue to be the heat buyer in coalition $\mathcal{Y}$.
60: Decide the new heat consumption level as the maximum between $Q_{hb,t}^{buy}$ and $Q_{hb,t}^{*}$.
61: Decide to sell $E_{hb,t}^{sel}$ or buy $E_{hb,t}^{buy}$ electricity according to Eq. (1).
62: **end if**
63: **end for**
64: **end if**
65: Market operator calculates the new heat imbalance for Coalition $\mathcal{Y}$: $Q_t^{imb,\mathcal{Y}} = \Sigma_{y=1}^{|\mathcal{Y}|}(Q_{y,t}^{sel} - Q_{y,t}^{buy})$.
66: **end while**
67: Now the heat balance in coalition $\mathcal{Y}$ is achieved.
68: Stable coalition $\mathcal{X}$ and coalition $\mathcal{Y}$ are formed by all the peers and the final electricity and heat trading orders are accepted by the market operator.
69: Decide the P2P electricity selling and buying price for both coalition $\mathcal{X}$ and $\mathcal{Y}$ according to Eqs. (26)–(28).
70: Decide the P2P heat selling and buying price for coalition $\mathcal{Y}$ according to Eq. (22).
71: Record the market clearing result for each peer at time step t.
72: Move forward to the next time step $t + 1$.
73: **end for**

B.1. Demand profiles

In each building type, we utilize the building with the median area as the benchmark where the profile is considered as standard demand profiles. The energy demand of other buildings in each type is correlated positively with that of the benchmark building by the projected area. Eq. (B.1) shows the relationship mathematically, where 0 represents the benchmark building of the type of n. We introduce a square root function to represent a decreasing marginal demand as the area increases, which to some extent avoids extremely large demand and thereby makes the variations more realistic. In essence, the time-series pattern is the same for all the buildings of one type but the total demand varies.

$$e_{n,t}^{bas} = e_{0,t}^{bas} * \sqrt{\frac{Area_n}{Area_0}} \tag{B.1}$$

$$q_{n,t}^{bas} = q_{0,t}^{bas} * \sqrt{\frac{Area_n}{Area_0}} \tag{B.2}$$

The demand profiles of Table B.3 list the data sources for the standard energy demand profiles for each type. As for the detached and terraced houses, we utilize the actual electricity and natural gas consumption data of 2013 from a smart meter campaign in Apeldoorn. The heat demand (kWh/h) is converted from the natural gas consumption (m^3/h) by multiplying a unit conversion factor of 10.395 and an average heating efficiency of 87%. After examining the missing data, we obtain 26 terraced houses and 5 detached houses with complete energy demand profiles out of 81 households. Therefore, the hourly demand for one year is obtained by calculating the mean value of the selected houses of each type respectively, which serves as the standard energy profiles. As for each of the other four types, the demand profiles from [46] are used as the standard energy profiles. [46] applies a data-driven approach to derive the typical demand profiles for service sectors in the Netherlands, including apartments, offices, retail stores, and schools. For offices, we scale down the demand profiles based on the ratio of the median area of all the offices in this region and the average area of median offices used in [46]. Table B.4 shows the median area and corresponding yearly electricity and heat demand for each building type.

Table B.4
Summary of the standard demand profiles for the six building types.

Building type	Median area (m^2)	Electricity demand (kWh/yr)	Heat demand (kWh/yr)
Apartment	1349	85 134	152 033
Detached house	333	4120	12 500
Office	2844	330 590	90 980
Retail	2049	365 853	230 995
School	4335	1 136 596	597 443
Terraced house	173	3280	8889

Table B.5
Summary of the standard generation profiles for PV and WT.

PV	Median area (m^2)	Capacity (kW)	Yearly generation (kWh)
	182	3.93	4505
WT	Median demand (kWh)	Capacity (kW)	Yearly generation (kWh)
	6446	4.00	10 306

Table B.6
Summary of the PV capacity for six building types.

Building type	Median capacity (kW)	Minimum capacity (kW)	Maximum capacity (kW)
Apartment	29.44	10.47	212.62
Detached house	7.20	2.62	311.74
Office	62.31	15.05	187.43
Retail	44.81	14.07	250.57
School	94.86	50.05	248.60
Terraced house	3.60	2.29	11.12

B.2. Generation profiles

Next, we set the generation profiles including PV, WT and HP for each building. The generation profiles of Table B.3 summarize the sources of weather availability, capacity, COP, and economic parameters for HP.

The PV capacity of each building is calculated by assuming a utilization rate of 0.11 of the projected areas and a required area of 1.64 m^2 for one solar panel (Eq. (B.3)). The area per solar panel is referred from a Monocrystalline-silicon commercial product, which has a nominal power of 299.59 W [48]. The standard capacity of the building with the median area is 3.93 kW with 12 solar panels as shown in Table B.5. The yearly generation is obtained in combination with the weather data from [47]. In addition, Table B.6 summarizes the median, the minimum and the maximum capacity for each building type.

$$e_n^{pv,max} = \frac{Area_n * 0.11}{1.64\,\mathrm{m}^2} * 299.59\,\mathrm{W} \tag{B.3}$$

Similarly to demand profiles, we assign the WT capacity for each building correlated with its total energy demand and the standard capacity of the building with the median energy demand (Eq. (B.4)). The standard capacity $e_0^{wt,max}$ is set as 4 kW and the total energy

Table B.7
Summary of the WT capacity for the six building types.

Building type	Median capacity (kW)	Minimum capacity (kW)	Maximum capacity (kW)
Apartment	18.71	14.27	30.65
Detached house	4.55	3.60	11.64
Office	30.03	21.02	39.56
Retail	33.43	25.08	51.37
School	58.00	49.42	73.76
Terraced house	3.95	3.57	5.20

Table B.8
Summary of the HP capacity for the six building types.

Building type	Median capacity (kW)	Minimum capacity (kW)	Maximum capacity (kW)
Apartment	40.5	24	108
Detached house	6	4	35
Office	43.5	22	75
Retail	99	56	234
School	316	230	511
Terraced house	4	3	6

Table B.9
Summary of two standard profiles for HP.

Profile	I	II
HP capacity (kW)	5	160
Nominal COP	2.95	2.75
Lifetime (years)	16	20
Initial investment (€)	6071	123 489
Fixed operation and maintenance costs (€)	277	2234
Levelized fixed cost (cents/kWh)	9.732	4.314

demand e_n^{tot} refers to the summation of electricity and heat demand. However, since electricity and heat have different energy qualities, we convert the heat demand into electricity demand by dividing the nominal COP of the installed HP (detailed in the next paragraph). Thereby we obtain a total capacity of 7230 kW for all the buildings, equivalent to 3 4 2-MW wind turbines (Vestas V90–2.0 MW used as the standard product [55] for weather data). According to [56], the direct land use per megawatt wind turbine is around 3035 m^2. The wind turbines could be installed in the Zuidbroek park, which has a sufficient area of around 25 000 m^2. In summary, Table B.7 shows the WT capacity for each building type.

$$e_n^{wt,max} = e_0^{wt,max} * \sqrt{\frac{e_n^{tot}}{e_0^{tot}}}, \text{ where } e_n^{tot} = \Sigma_{t=1}^{T} e_{n,t}^{bas} + \frac{\Sigma_{t=1}^{T} q_{n,t}^{bas}}{cop_n} \tag{B.4}$$

In the end, the HP capacity for each building is set at the 95th percentile of the heat demand from the lowest to the highest, which means each building has sufficient capacity to meet its own heat demand during 95% of the time. From practical considerations, all the capacity is rounded up to the next integer and the minimum capacity is set as 3 kW [52]. Table B.8 summarizes the HP capacity for each building type. The COP of HP fluctuates with outdoor temperature and wind speed. The average time series of an air-source heat pump in the Netherlands from 2008 to 2018 is used [50]. Based on [52], two standard profiles with different sizes are introduced as shown in Table B.9. As for nominal COP and lifetime, we set 40 kW as the threshold value, which means the HP with a capacity smaller than 40 kW is set the same as the 5-kW profile and otherwise is the 160-kw profile. For initial investment and fixed operation and maintenance costs, we extrapolate a linear regression with HP capacity as the explanatory variable from two standard profiles. Eq. (B.5) details the functions and coefficients. In addition, the equivalent full load hours for the average climate zone in the Netherlands is 1640 h, which is used to calculate the yearly heat generation hg_n^{hp} [51]. And the discount rate for NPV is set as 4%.

$$ic_n^{hp} = 757.535 * q_n^{hp,max} + 2283.323 \tag{B.5}$$

Table B.10
Overview of the scaling factor υ_n for each peer.

Peer	0	1	2	3	4	5	6	7	8	9
υ_n	1.18	1.98	0.76	3.16	0.98	1.01	0.42	1.45	1.0	1.7
Peer	10	11	12	13	14	15	16	17	18	19
υ_n	0.61	1.12	1.15	2.17	0.45	4.18	0.76	0.78	1.05	2.06

Table B.11
Summary of electricity price profiles.

$p_t^{sel,euc}$	Average value (cents/kWh)	Maximum value (cents/kWh)	Minimum value (cents/kWh)
	5.253	17.500	0.055
$p_t^{buy,euc}$	Value (cents/kWh)	Time-of-use	Period
	23.169	Normal rate	7:00 – 23:00
	22.032	Off-peak rate	23:00 – 7:00; all the weekend and holidays

$$om_n^{hp} = 12.626 * q_n^{hp,max} + 213.871 \tag{B.6}$$

B.3. Heat demand utility coefficients

The heat preference coefficient $u_{n,t}$ is randomized between 0.8 and 1.2 for each hour of each peer. The scaling factor υ_n is set ranging from 0.374 to 3.734 as shown in Table B.10. The υ_n of each peer is calculated based on the reciprocal for the average hourly heat demand times the average hourly heat demand of all the peers (Eq. (B.7)). In this way, if one peer has the average heat demand, its υ is standardized as 1; if the heat demand is larger than the average heat demand, $\upsilon < 1$ and otherwise $\upsilon > 1$. The underlying rationale is to mitigate the influence of the level of heat demand in the decision-making process and to set the marginal heat demand utility of each peer is at a comparable level.

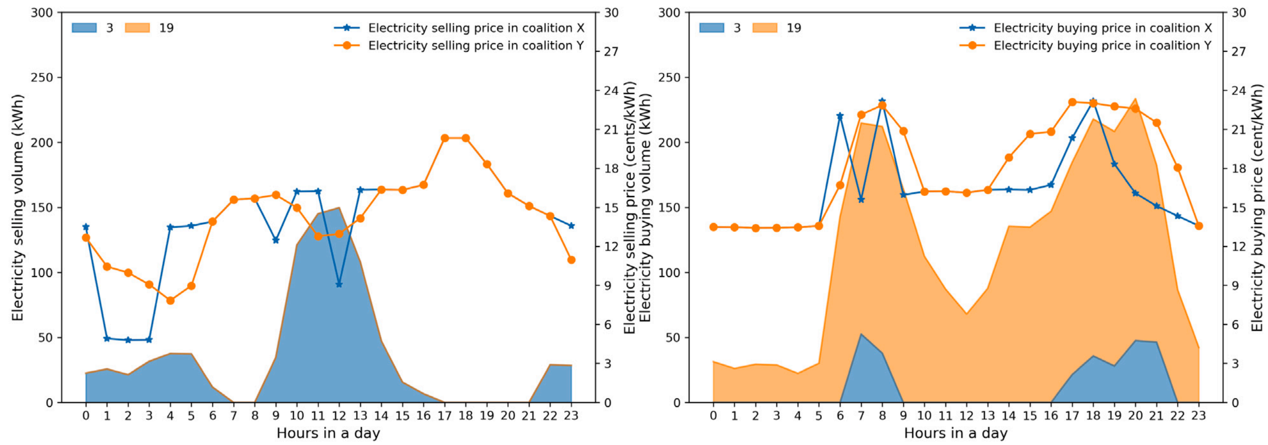
$$\upsilon_n = \frac{T}{\Sigma_{t=1}^{T} q_{n,t}^{bas}} * \frac{\Sigma_{n=1}^{N}\left(\frac{\Sigma_{t=1}^{T} q_{n,t}^{bas}}{T}\right)}{N} = \frac{\Sigma_{n=1}^{N}\Sigma_{t=1}^{T} q_{n,t}^{bas}}{N * \Sigma_{t=1}^{T} q_{n,t}^{bas}} \tag{B.7}$$

B.4. Price profiles

Table B.11 shows the electricity trading prices with EUC. As shown in Table B.3, the electricity selling price to EUC is referred from the day-ahead prices of the electricity wholesale market in the Netherlands in 2018; the electricity buying price from EUC is referred from the time-of-use retail tariff which varies from off-peak hours and normal hours.

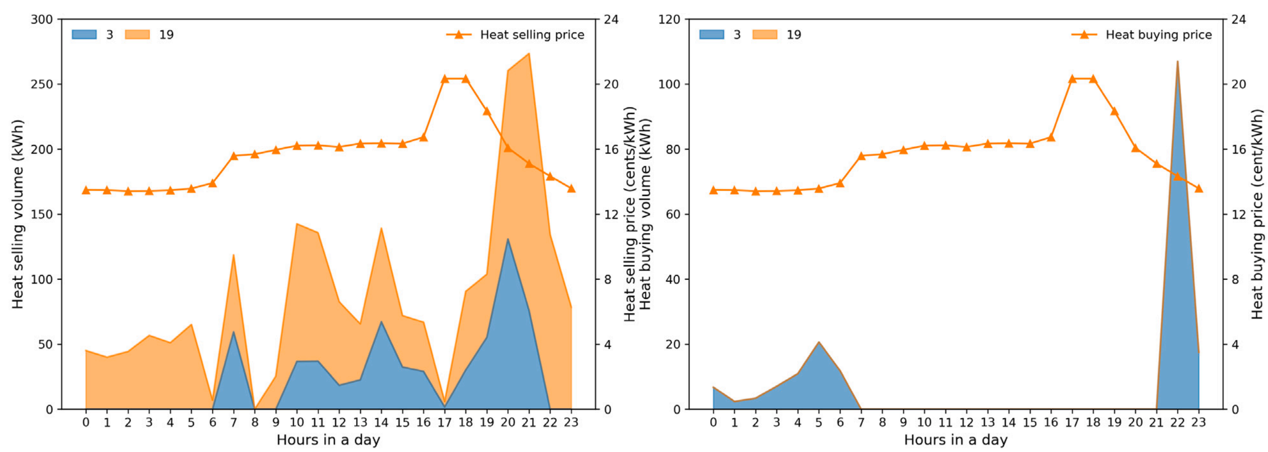
As for the heat price, the proportionality constant α between $p_t^{h,mid}$ and $p_t^{e,mid}$ is set as 1.00. The current average heat price over the year is 13.9 cents/kWh, which is aligned with the realized average price from Heat Company Apeldoorn [57]. This paper constructs a proportional heat price to electricity price and the proportionality constant always keeps as a constant. Such a pricing scheme is easy to implement but to a certain extent, sacrifices the economic benefits and allocation fairness. After the yearly operation, the historical data could be a valuable asset to design a time-dependent proportionality constant or an independent pricing scheme. The new pricing scheme should motivate both heat selling and buying so that it better matches the heat balance and distributes the system benefit in a fairer manner.

Besides, $p_t^{h,mid}$ is assumed to be both the selling and the buying price for heat. By setting the selling and buying prices equal, the benefit spillover by the regulated surcharges (such as network tariffs and taxes) for heat trading scenarios could be avoided and thereby a level playing field is created to compare all the scenarios.



(a) Electricity selling price and volume. (b) Electricity buying price and volume.

Fig. C.17. Electricity prices and trading volumes in coalition $\mathcal{X}$ and $\mathcal{Y}$ throughout November 22.



(a) Heat selling price and volume. (b) Heat buying price and volume.

Fig. C.18. Heat trading prices and volumes in coalition $\mathcal{Y}$ throughout November 22.

Appendix C. Extra results

This appendix shows the electricity and heat prices and the associated trading volumes throughout November 22 for peer 3 & 19, as additional information for Section 4.3.

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