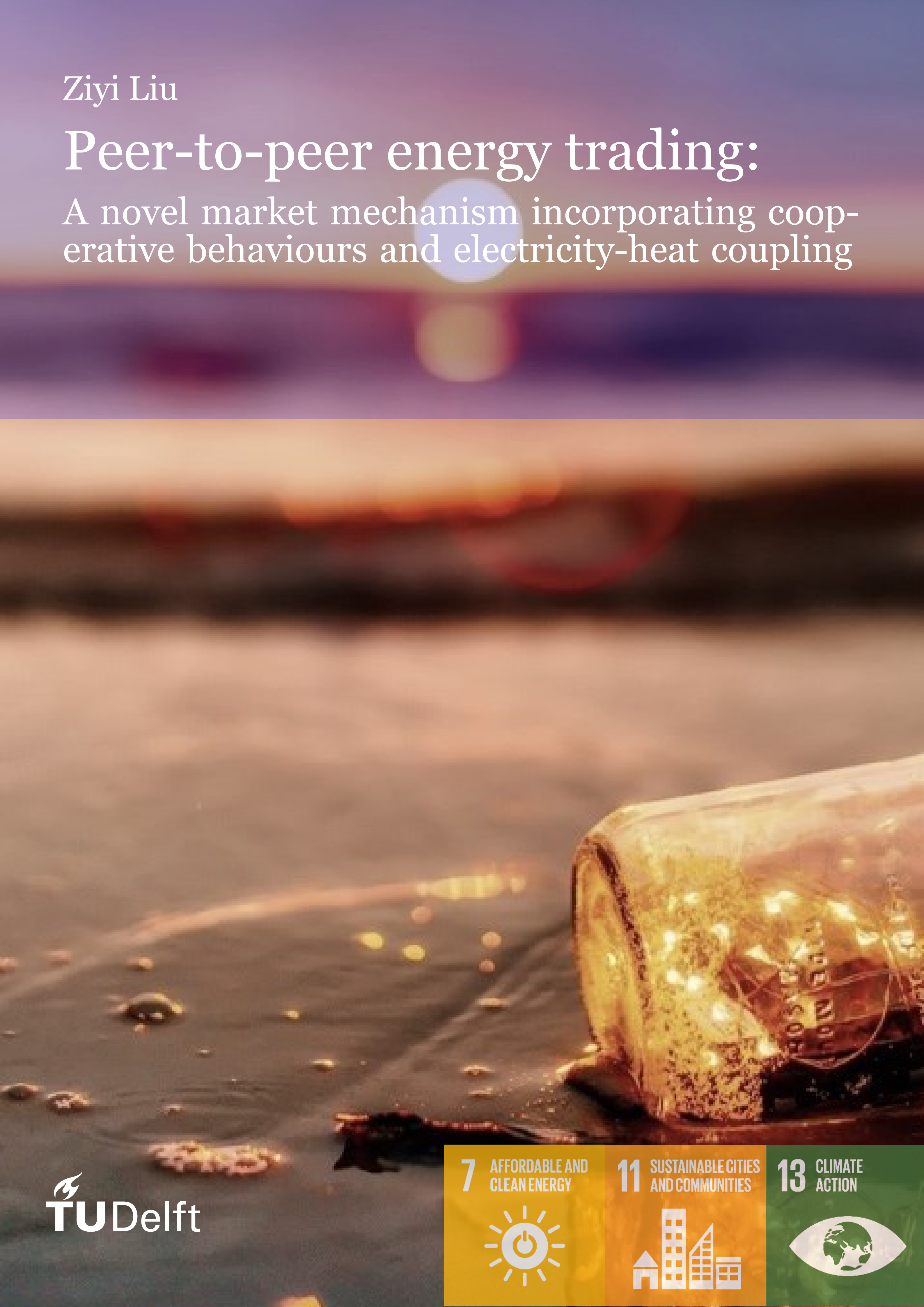

Ziyi Liu

Peer-to-peer energy trading:

A novel market mechanism incorporating cooperative behaviours and electricity-heat coupling

TU Delft

7 AFFORDABLE AND CLEAN ENERGY

11 SUSTAINABLE CITIES AND COMMUNITIES

13 CLIMATE ACTION

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A novel market mechanism incorporating cooperative behaviours and electricity-heat coupling

Master thesis submitted to Delft University of Technology

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Ziyi Liu

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Preface

“Uncertainty is the Only Certainty”

If I wanna conclude my master journey, the first sentence that comes to my mind is above. The uncertainty is carved in the DNA of a CoSEMer, and the uncertainty is what I have been experiencing throughout the past two years.

Born in a small town in northeast China, I always dream to go out and to see the world. The milestone happened in 2014, when a new adult chooses to leave home 2000+ km away and to study in the most modern city in China. In 2016, I got the opportunity to go abroad in New Zealand for the first time; in 2017, I was selected to exchange in Denmark and had my first footprint in Europe. Until now, the one-year exchange is like a daydream for me, cherishing the places I visited, the people I met and the culture I experienced.

In 2019, I came back to Europe again, but the destination is the Netherlands. I am surrounded with brilliant teachers and fellow students, overthrown by the worldview of complexity, and of course, immersed in the ocean of arts and innovations. I enjoy the multi-disciplinary and multi-nation collaboration, apply systematic thinking to solve real cases and enhance my skill sets in energy technologies, market design and policy analysis. Beyond the academic achievements, I am more critical about the phenomena and opinions to ask why and more open to the diversity of people and objects to ask why not.

What’s more, it is impossible to ignore the special 2020 out of control. When I was enjoying the spring break in Iberia, I never expected that was my last travel till now. All the plans were interrupted, e.g. withdrawn internship offer, cancelled study abroad in the UK and blocked way back to home. I feel myself besieged by the online meetings, by a small bedroom and by the uncertain future. Fortunately, I confirmed my company by the Douro River and she shines my stay-at-home period. Besides, all the love I received from my parents, brothers, relatives and friends helps me go through the difficulties and embrace the uncertainty.

Thankfully, I never walk alone along the journey. First of all, I would like to thank the Sino-Dutch Scholarship, funded by Dutch Ministry of Education, Culture and Science and China Scholarship Council, which greatly eases the financial burden on my family. Secondly, I am grateful to all the lecturers, teammates, teaching assistants and supporting staff in TU Delft, who contribute to a solid foundation for my study. Last but not the least, I am so lucky to have an enlightening and caring graduation committee to facilitate the master thesis. I appreciate the patient and helpful daily supervision from Ni and the constructive suggestions from Petra and Martijn. With all of you, I cannot make it so far.

When looking back, I found out I always unintentionally choose the road less travelled. I am an outlier to be away from the hometown, to take one gap year, to pursue a master in Europe, and to select the programme "no none" understands its name:) But I am also stubborn to explore the world with curiosity, to continue the adventure of energy transition and to do something good for all.

“Challenge the Future”

Ziyi Liu
Delft, June 2021

Executive Summary

Background and motivation

Nowadays, the energy sector is undergoing an accelerating transformation of decarbonisation and decentralisation. Meanwhile, the multi-energy system (MES) attracts increasing attention to explore the synergies of sector coupling. Within the MES, the penetration of distributed energy resources contributes to the emergence of prosumers who can both generate and consume energy. Therefore, the direct energy exchange between prosumers becomes a feasible and promising way to harmonise the transformation above, which is peer-to-peer (P2P) energy trading. P2P energy trading has a close connection with the concept of sharing economy, which could potentially bring benefits to all the participants and the external environment. This decentralised energy management paradigm contributes to the reorganization of energy markets into a prosumer-centric and bottom-up manner.

The market mechanism is the core of a P2P energy market, which regulates the peers' trading behaviours and decides the market-clearing results. In this multi-actor environment, a well-designed market mechanism needs to be compatible with strategic behaviours resulting from peers' diverse preferences. Besides competitions, cooperative behaviours could also emerge among peers with common preferences or geographical proximity. Furthermore, electricity and heat are the dominant energy carriers at the end consumers, but the existing research mainly focuses on the electricity sector while how to integrate other energy carriers in a multi-energy system is lack of attention. Therefore, a knowledge gap exists in the integrated effect of cooperative behaviours and electricity-heat coupling. It is unknown how peers form trading coalitions in the multi-energy context, how peers change their trading strategies due to the additional energy carrier trading and how the coalitional electricity-heat trading influences the individual and system benefits. Thereby the following research question is formulated:

What is the economic and social performance of a novel peer-to-peer energy trading market that incorporates cooperative behaviours and electricity-heat coupling?

This research answers the research question by designing and evaluating a novel market mechanism that integrates coalitional and electricity-heat trading. We firstly design the market operation process to address coordination issues between coalition formation and electricity-heat orders. Then we simulate peers' trading activities based on a coalition formation game. Besides, a case study in the Netherlands is conducted to showcase the performance of the proposed market mechanism with the comparison against non-coalitional and electricity-only trading scenarios.

Market design and system model

A design process is conducted to identify stakeholder needs & requirements, integrate system requirements & functions and obtain the design results. The design results for the market mechanism consist of four first-level functions, namely Market information sharing, Trading strategy processing, Market clearing and Market settlement. The market operator firstly publishes previous market operation results and shares with peers the weather availability prediction for renewables and guiding electricity & heat price in the upcoming time step. Then peers determine the trading strategies including trading coalition and electricity & heat trading volume. And all the orders are received and processed by the market operator. In the end, all the executed orders are settled in terms of energy delivery and payment.

As shown in Figure 1, the system model including 7 modules is developed to simulate the P2P trading activities in the proposed market mechanism. Above all, two trading coalitions, namely

Electricity-only trading Coalition $\mathbb{X}$ and Electricity-heat trading Coalition $\mathbb{Y}$ are formed for peers to choose from. The trading objective of each peer is to maintain the energy balance and maximise the net benefit. The expected energy surplus or deficiency influences the peer's trading position in the P2P energy market. Furthermore, the peer's decision-making process is modelled by defining and optimising the net benefit functions for each of four trading positions, e.g. electricity seller or buyer and heat seller or buyer. And the heat demand utility is quantified and active heat demand response is considered. Both heat consumption level and heat trading volume are the decision variables in the optimisation, which influences the electricity demand. So the electricity trading volume is obtained in the end based on the electricity balance equation.

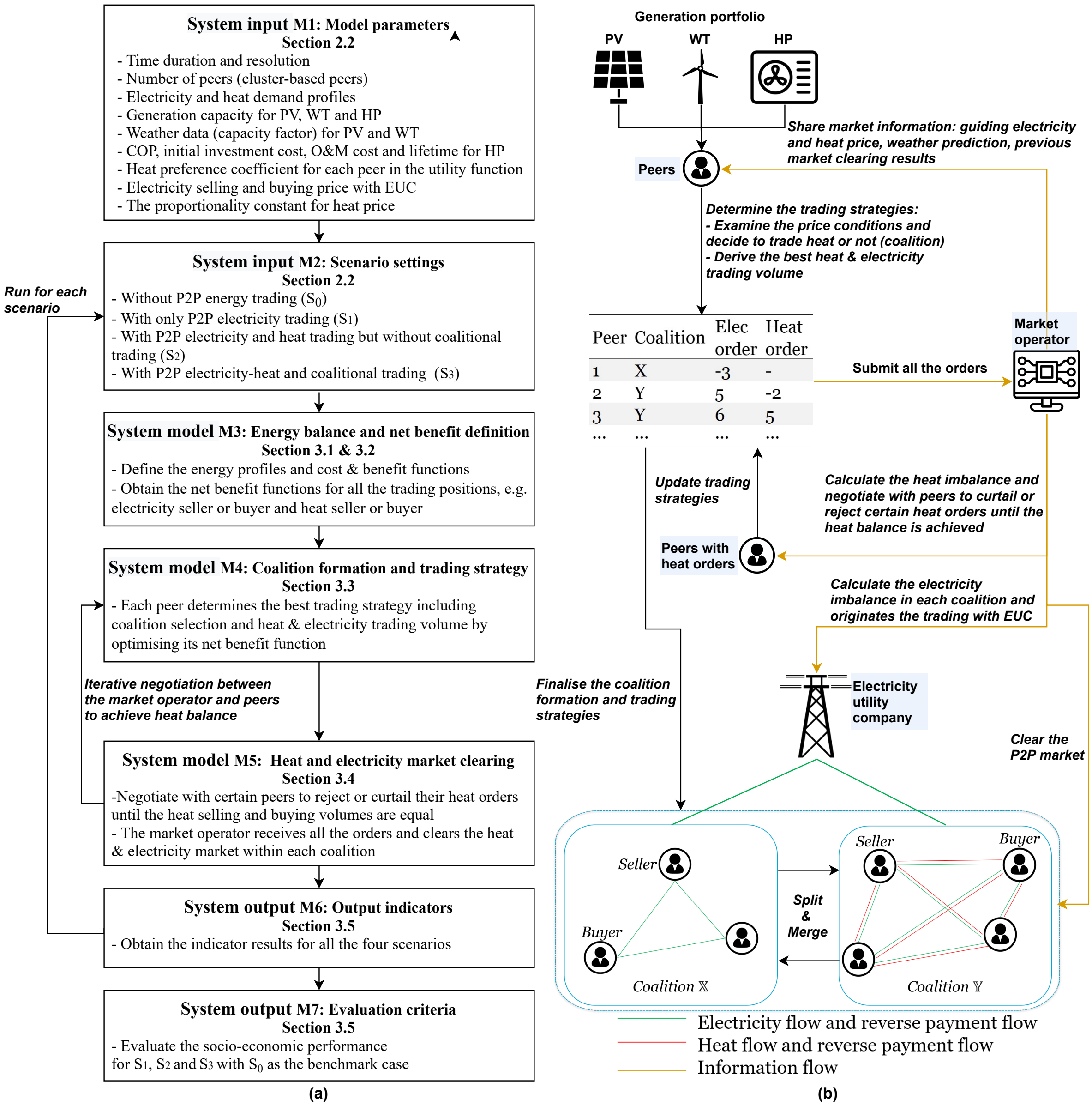
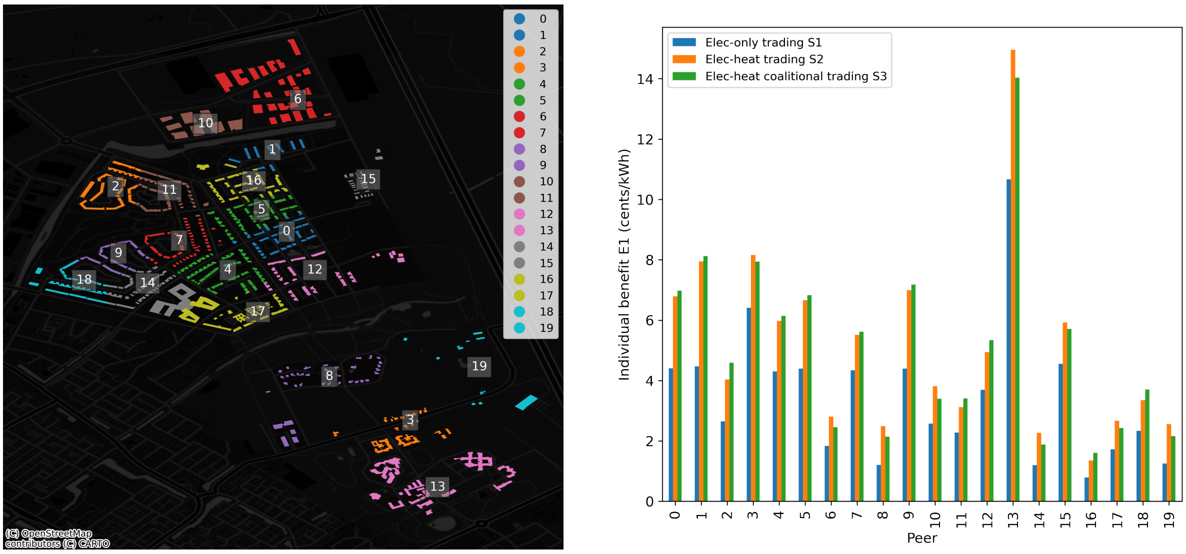


Figure 1: (a) Flow chart for the system model including 7 modules; (b) Graphical illustration of the P2P energy trading in a multi-energy system

After receiving all the trading strategies from the peers, the market operator clears the heat & electricity market within each coalition. The market operator firstly clears the heat market in Coalition $\mathbb{Y}$ by iteratively negotiating with certain peers to reject or curtail their heat orders until the heat selling and buying volumes are equal. After the coalition formation is finalised, the market operator clears the electricity market in Coalition $\mathbb{X}$ & $\mathbb{Y}$ separately by trading electricity imbalance with the electricity utility company and determining the P2P electricity price.

Evaluation results

A case study is formulated based on the Zuidbroek neighbourhood in Apeldoorn, the Netherlands. There are 1485 buildings in this neighbourhood, including 3 types of service-sector buildings and 3 types of residential buildings. The temporal and geospatial information are combined to set up demand & generation profiles for each building. Furthermore, to mitigate the computational burden, 20 geographically-closed energy communities are formulated using the k-means clustering (Figure 2a). Each energy community serves as a collective peer to participate in the P2P energy trading. According to the composition of building types, 20 peers are classified as residential (peer 0-5, 7-9, 12-13, 15, 17-18), service-sector (peer 6, 10) and mixed types (peer 11, 14, 16, 19).



(a)

(b)

Figure 2: (a) 20 energy communities by clustering in the Zuidbroek neighbourhood; (b) Scenario comparison on the individual benefit of unit energy consumption for each peer

The research evaluates the proposed market mechanism across 4 scenarios, namely No P2P energy trading (S_0), P2P electricity-only trading (S_1), P2P electricity-heat trading (S_2) and P2P electricity-heat coalitional trading (S_3). With S_0 as the benchmark scenario, Figure 2b showcases the scenario comparison on the individual benefit of unit energy consumption for each peer.

Overall, the proposed market mechanism could bring positive benefits to each peer during one year, which indicates the prosumer-centric characteristic. Compared to S_0, either any peer or the system could obtain benefit by introducing the P2P energy trading. Moreover, the introduction of heat trading increases economic incentives to the peers in S_2 and S_3. The P2P heat trading enables peers to leverage the mismatch of individual demand profiles and the difference between heat pump degradation cost, so that to lower the heat generation cost. On average, one peer in S_2 and S_3 obtains a 50% higher individual benefit of unit energy consumption after participating in the P2P electricity-heat trading compared to the electricity-only trading. And the cost-saving does not sacrifice the heat comfort, since peers only consume an average of 2.47 % less heat than that in S_0.

However, the introduction of the separate electricity and electricity-heat coalition in S_3 makes the majority of peers better off but the system benefit slightly worse compared to that in S_2. The system benefit of S_2 and S_3 is respectively 51.06% and 43.37% higher than that of S_1. Essentially, S_2 represents a grand coalition for all the peers where a unified electricity market is obtained rather than two sub-markets in S_3. A grand coalition could mitigate, to the greatest extent possible, electricity trading with the electricity utility company so that to reduce the benefit loss. Therefore, S_2 is superior to S_3 in terms of system benefit. However, 55% of peers obtain the optimal benefit in S_3 throughout the year while the rest prefer S_2. Based on the spatial distribution, it is concluded that the introduction of coalitional trading results in benefit transfer from service-sector peers with larger demand to residential peers with smaller demand. But the service-sector peers could still obtain higher benefits in terms of absolute value.

When zooming into the evaluation results from the temporal dimension, special patterns are observed in terms of seasonality and normal-off-peak comparison. Based on the monthly absolute benefit, the P2P heat trading drives the dramatic increase of benefit in winter to surpass the benefit in summer. Meanwhile, the benefit of S_2 and S_3 in summer does not decrease compared to that of S_1. Therefore, a reserve seasonality is observed for S_1 compared to S_2 and S_3. Moreover, the peers characterised by numerous service-sector building obtains higher benefit in the off-peak period, which indicates a low energy consumption but high energy selling. In contrast, the peers dominated by residential building performs better in the normal period. Therefore, the energy profiles of residential and service-sector peers are temporally complementary to facilitate reciprocally beneficial P2P energy trading.

Conclusion

In conclusion, a novel market mechanism incorporating P2P electricity-heat coalitional trading is superior on both economic and social performance in comparison with no P2P trading and electricity-only trading scenarios. Specifically, the key findings are:

- The P2P heat trading showcases the prosumer-centric property, which on average improves each peer's benefit of unit energy consumption by over 50% compared to electricity-only trading.
- The introduction of coalitional trading makes the majority of peers better off but the system benefit slightly worse compared to P2P electricity-heat trading. This indicates the benefit transfer from large prosumers to small prosumers.
- The complementary characteristic is demonstrated between the energy profiles of residential and service-sector peers to facilitate the reciprocally beneficial P2P energy trading

Keyword: Peer-to-peer energy trading, Local energy market, Game theory, Multi-energy system, Energy community, Distributed energy sources

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Nomenclature

Abbreviation

DERs	Distributed energy resources
EUC	Electricity utility company
HP	Heat pump
MES	Multi-energy system
P2P	Peer-to-peer
PV	Photovoltaic modules
WT	Wind turbine

Set

$\mathbb{HB}$	Set of heat buyer hb; EB elements in total
$\mathbb{HS}$	Set of heat seller hs; HS elements in total
$\mathbb{N}$	Set of peer n; N elements in total
$\mathbb{X}$	Set of peer x in Coalition $\mathbb{X}$; X elements in total
$\mathbb{Y}$	Set of peer y in Coalition $\mathbb{Y}$; Y elements in total

Subscript & Superscript

$e, h, \mathbb{X}, \mathbb{Y}$	Superscripts to represent the P2P trading market: electricity market, heat market, market in Coalition $\mathbb{X}$, market in Coalition $\mathbb{Y}$; following is taking e as an example if coalition superscripts co-exist for one variable
n, hs, hb, x, y	Subscripts to represent the index of peer category: any peer, heat seller, heat buyer, peer in Coalition $\mathbb{X}$, peer in Coalition $\mathbb{Y}$; following is taking n as an example if multiple peer subscripts co-exist for one variable

Variable (V) & Parameter (P)

α	P: proportionality constant between P2P heat and electricity price
β	P: proportionality constant between P2P heat buying and selling price
$B_{n,t}$	V: Net benefit in the P2P market for n at t
$C_{n,t}^{hp,e}$	V: HP variable electricity cost for n at t
$C_{n,t}^{hp,f}$	V: HP levelised fixed cost for n at t
$C_{n,t}^{hp}$	V: HP generation cost for n at t

$cop_{n,t}$	P: HP coefficient of performance for n at t
cop_n	P: HP nominal coefficient of performance for n
$e^{bas}_{n,t}$	P: Base electricity demand for n at t
$E^{buy}_{n,t}$	V: Electricity buying volume for n at t
$E^{dem}_{n,t}$	V: Total electricity demand for n at t
$e^{gen}_{n,t}$	P: Total electricity generation for n at t
$E^{hp,bas}_{n,t}$	V: HP electricity consumption on base heat demand for n at t
$E^{hp,tra}_{n,t}$	V: HP electricity consumption on trading for n at t
$e^{pv}_{n,t}$	P: Electricity generation from PV for n at t
$E^{sel}_{n,t}$	V: Electricity selling volume for n at t
$e^{wt}_{n,t}$	P: Electricity generation from WT for n at t
$e^{pv,max}_{n}$	P: Nominal capacity of PV for n
e^{tot}_{n}	P: Sum up of yearly electricity and heat base demand for n
$e^{wt,max}_{n}$	P: Nominal capacity of WT for n
$E^{imb,\mathbb{X}}_{t}$	V: Electricity imbalance in Coalition $\mathbb{X}$ at t
hg^{hp}_{n}	P: HP yearly heat generation for n
ic^{hp}_{n}	P: HP initial investment cost for n
l^{hp}_{n}	P: HP lifetime (years) for n
om^{hp}_{n}	P: HP yearly Operation&Maintenance cost for n
$p^{h,buy,th}_{n,t}$	V: Threshold price to sell heat for n at t
$p^{h,sel,th}_{n,t}$	V: Threshold price to buy heat for n at t
$p^{hp,f}_{n}$	P: HP degradation cost of unit generation for n
$p^{buy,euc}_{t}$	P: Electricity buying price from EUC at t
$p^{e,buy}_{t}$	V: P2P electricity buying price at t
$p^{e,mid}_{t}$	P: Electricity mid-market rate as the guiding price
$p^{e,sel}_{t}$	V: P2P electricity selling price at t
$p^{h,buy}_{t}$	V: P2P heat buying price at t
$p^{h,mid}_{t}$	P: Heat mid-market rate as the guiding price
$p^{h,sel}_{t}$	V: P2P heat selling price at t

$p_t^{sel,euc}$	P: Electricity selling price to EUC at t
$q_{n,t}^{bas}$	P: Base heat demand for n at t
$Q_{n,t}^{buy}$	V: Heat buying volume for n at t
$Q_{n,t}^{con*}$	V: Best heat consumption level for n at t
$Q_{n,t}^{con}$	V: Heat consumption level for n at t
$Q_{n,t}^{dem}$	V: Total heat demand for n at t
$Q_{n,t}^{gen}$	V: Total heat generation for n at t
$Q_{n,t}^{hp,bas}$	V: HP heat generation on base demand for n at t
$Q_{n,t}^{hp,tra}$	V: HP heat generation on trading for n at t
$Q_{n,t}^{sel}$	V: Heat selling volume for n at t
$q_n^{hp,max}$	P: HP capacity/maximal-generation for n at t
Q_t^{cur}	Q: The curtailment per volume of heat selling or buying order
$Q_t^{imb,\mathbb{Y}}$	V: Heat imbalance in Coalition $\mathbb{Y}$ at t
r	P: Discount rate for net present value
$R_{n,t}^{e}$	V: Revenue of electricity trading for n at t
$R_{n,t}^{h}$	V: Revenue of heat trading for n at t
T	P: Total time steps
t	V: At time step t
$u_{n,t}$	P: Preference coefficient of heat demand utility for n at t
$U_{n,t}$	V: Heat demand utility for n at t
v_n	P: Scaling factor of heat demand utility for n

1

Introduction

1.1. Background on peer-to-peer energy trading

Nowadays, the energy sector is undergoing an accelerating transformation of decarbonisation and decentralisation [1]. Meanwhile, the multi-energy system (MES) attracts increasing attention, because the sector coupling between electricity, heat, gas and transport showcases its superiority on technical, economic and environmental performance [2]. Within the MES, the penetration of distributed energy resources (DERs) contributes to the emergence of prosumers who can both generate and consume energy [3]. Therefore, the direct energy exchange between prosumers becomes a feasible and promising way to harmonise the transformation above, which is peer-to-peer (P2P) energy trading.

P2P energy trading has a close connection with the concept of sharing economy, which could potentially bring benefits to all the participants and the external environment. On the one aspect, compared to existing DERs support mechanisms, P2P energy trading gives each peer the autonomy to make trading decisions based on their diverse demand profiles, generation portfolios and preferences. Each peer is able to maximise its own benefits and behave more actively in the energy markets [4]. On another aspect, P2P energy trading could stimulate the DERs investments and exhibit positive externality to the large-scale energy market such as peak shaving and reduced network investment [5], [6]. This decentralised energy management paradigm contributes to the reorganization of energy markets into a prosumer-centric and bottom-up manner [7]. Overall, peer-to-peer (P2P) energy trading is a promising solution in the future energy systems, which contributes to the fulfilment of the United Nations Sustainable Development Goal 7&11&13 [8]

The market mechanism is the core of a P2P energy market, which regulates the peers' trading behaviours and decides the market-clearing results [9]. Specifically, a market mechanism matches the selling & buying demand and settles the trading time, price & volume to complete the bidirectional energy exchange and financial transaction. However, there is no one-fit-all mechanism considering diverse peers preferences and complex trading strategies, so research efforts are needed in the market design and modelling. In this multi-actor environment, a well-designed market mechanism needs to be compatible with self-interested behaviours and dynamic interactions among peers [10]. Furthermore, advanced techniques are required to model peers' decision-making process and simulate the market operation [11]. Besides, the research on P2P energy trading starts from the electricity sector, while how to integrate other energy carriers is lack of attention. Therefore, we review the existing market mechanisms in the field of P2P energy trading with a focus on both multi-actor interaction and multi-energy coupling.

1.2. Literature review on market mechanisms of peer-to-peer energy trading

1.2.1. Review method

In recent years, P2P energy trading has received more and more attention in the academic field. Figure 1.1 shows the publication trend in Scopus [1] by searching peer-to-peer energy trading in article titles, abstracts and keywords, which showcases an exponential growth after 2015. The following literature review emphasises the market design within the field of P2P energy trading.

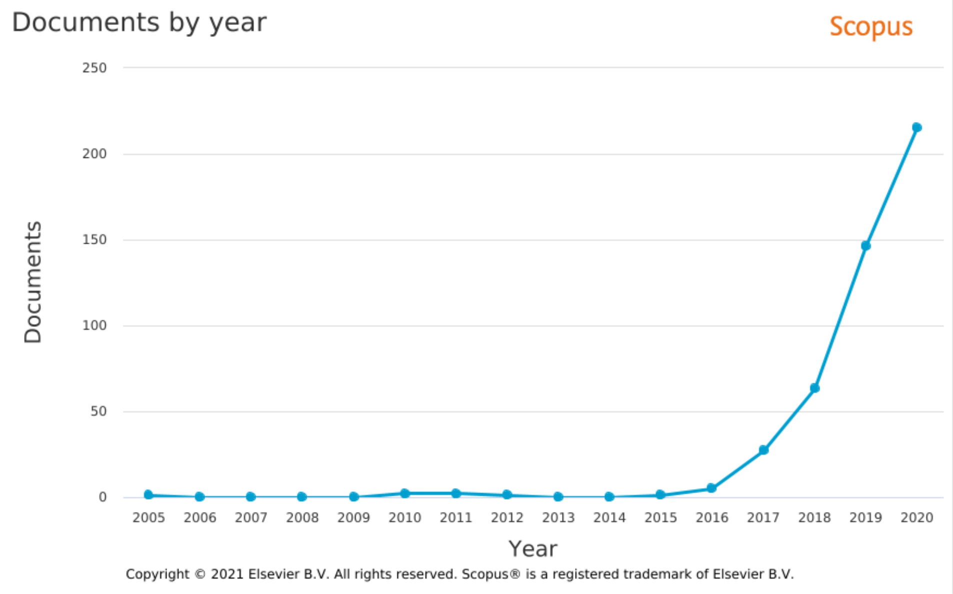

Figure 1.1: Publication of P2P energy trading trend by year, retrieved from Scopus

The reviewed literature is obtained by searching keywords and using snowballing in Scopus. Figure 1.2 illustrates the scoping down of the searching process. The used search strings are ((TITLE-ABS-KEY (peer-to-peer AND energy AND trading)) AND (optimization OR market AND design)) based on the emphasised research area. The preliminary search results in 196 articles. Firstly, the 10 most cited articles are moved into the final selection stage; secondly, since this research area is fast-evolving, more criteria about publication year and subject area are added to find the 5 most cited and relevant articles after 2019. Besides, the forward snowballing is targeted at the article [11] recommended by the thesis advisor, and the same criteria with the second step above are applied to select the top 5 articles. Therefore, 20 articles in total are selected for the final step. By reading the abstract, 7 articles are excluded mostly due to a lack of relevance to the energy community and market design. While studying the remaining 13 articles, 10 articles of interest are added by backward snowballing. In addition, along with the research process, 4 latest articles are added by screening the results from Search Alert.

In summary, Table 1.1 gives an overview of the 28 studies in terms of the author(s) & year, Market mechanism (Game types), energy trading commodity and main findings. It could be observed that game theory is widely used to model the market mechanism for P2P energy trading, along with certain pricing schemes or auction mechanisms. And most of the literature focuses on P2P electricity trading while the other three studies cover electricity and heat as two trading commodities. In the next section, we will zoom into the types of mechanisms, different games and the coupling of multi-energy commodities.

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[1] Scopus is a source-neutral abstract and citation database with abundant peer-reviewed literature as well as powerful discovery and analytics tools

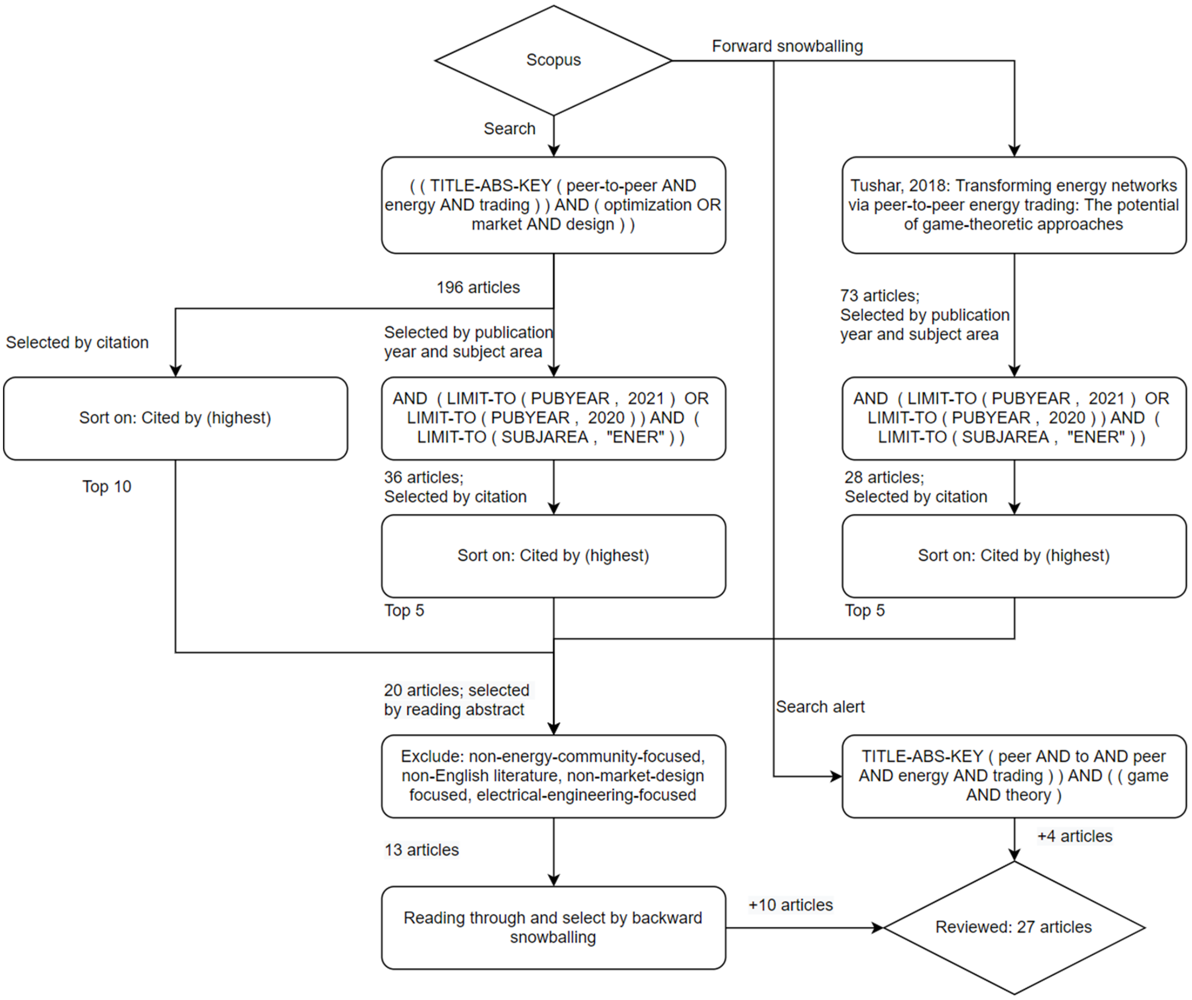

Figure 1.2: Searching strategy for literature review about P2P energy trading

Table 1.1: Overview of reviewed literature about P2P energy trading

Reference	Market mechanism (Game types)	Trading commodity	Main findings
Amin et al., 2020 [12]	Two-step game: non-cooperative and a grand coalition game	Electricity	Two-step market mechanism with a non-cooperative game and a grand coalition game
Andoni et al., 2019 [13]	N/A	N/A	A systematic review on the application of blockchain technology on P2P energy trading
Azim et al., 2019 [14]	N/A	Electricity	Comparison on the network loss between various degree of P2P penetration
Chen et al., 2020 [15]	A non-cooperative bi-level game with a benevolent	Electricity	Comparison between four market mechanisms, e.g. cooperative bargaining/coalition game, non-cooperative bi-level game with a selfish/benevolent leader

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Reference	Market mechanism (Game types)	Trading commodity	Main findings
Fan et al., 2018 [16]	A non-cooperative bargaining game	Electricity & Heat	A bargaining game between energy hubs to improve electricity-natural gas-heat scheduling
Guerrero et al., 2020 [10]	N/A	N/A	Classification and review of three kinds of DERs integration approaches: home energy management systems, virtual power plant and peer-to-peer trading
Hahnel et al., 2020 [17]	N/A	Electricity	Four target groups based on peers trading preferences and decision strategies
Hayes et al., 2020 [18]	Blockchain-based double auction mechanisms	Electricity	The impact on distribution networks by P2P energy trading through python-based blockchain co-simulation
Jiang et al., 2020 [19]	Stackelberg game and non-cooperative static game	Electricity	A game theory-based pricing model for interaction between sellers and buyers and between sellers
Jing et al., 2020 [3]	Non-cooperative Nash game	Electricity & Heat	Determine the optimal multi-energy trading price (electricity & heat)
Lee et al., 2014 [20]	A coalitional game	Electricity	A coalitional game based mechanism and a pricing scheme with Shapley value
Li et al., 2018 [21]	Bilateral contracts and continuous double auction	Electricity	Simulation of two trading strategies under different supply-demand ratio
Mei et al., 2019 [22]	A coalitional game	Electricity	A multi-agent model to derive the best trading coalition based on auction-theory-based utility
Mengelkamp et al., 2018 [9]	Double auction mechanism	Electricity	Seven components for the efcient design and operation of a blockchain-based microgrid energy markets
Morstyn et al., 2018 [23]	N/A	N/A	A new concept: Federated power plant: a combination of virtual power plants and P2P energy trading
Morstyn et al., 2018 [24]	A centralised price-setting mechanism	Electricity	Incorporate energy classes that represent individual preference to conduct system optimization
Soursa et al., 2019 [7]	Full, community-based and hybrid market	Electricity	Three kinds of P2P market structure and their simulation comparison & potential future development
Tushar et al., 2018 [11]	Double auction mechanism	Electricity	The potential of game-theoretic approaches for energy management in P2P networks
Tushar et al., 2018 [25]	A canonical coalition game		A coalitional P2P market with the property of stability and prosumer-centre using the mid-market rate
Tushar et al., 2020 [26]	A cooperative coalition formation game	Electricity	Design and evaluation of a prosumer-centric coalitional-game-based framework

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Reference	Market mechanism (Game types)	Trading commodity	Main findings
Tushar et al., 2020 [27]	N/A	N/A	6 & 3 research challenges in the virtual and physical layer respectively as well as 4 common research approaches
Wang et al., 2020 [28]	A multi-leader multi-follower (MLMF) Stackelberg game	Electricity & Heat	A novel market mechanism with power-heat coupling and discriminate pricing
Wang et al., 2020 [29]	N/A	N/A	Review of the trading mechanism into three categories: cost-sharing, auction-based and bilateral contracts
Yang et al., 2015 [30]	N/A	N/A	Three consumer segments in electricity retail market based on heterogeneous preferences
Zhang et al., 2018 [31]	A non-cooperative game	Electricity	Four-layer and three-dimension system architecture of Peer-to-Peer energy trading; simulation using non-cooperative games
Zhou et al., 2018 [32]	Bill sharing, mid-market rate and auction-based pricing schemes	Electricity	A general multiagent-based simulation framework with two heuristic techniques for simulation convergence with a last-defence mechanism
Zhou et al., 2020 [33]	Continuous double auction mechanism	Electricity	An integrated framework for P2P energy trading, residual balancing and ancillary service
Zhu et al., 2020 [34]	Double-auction mechanism	Electricity	A multi-energy management framework for scheduling and trading

1.2.2. State-of-the-art literature on market mechanisms

This section starts from the classification of existing market mechanisms in the P2P energy trading, and then reviews the methods used in the literature to deal with the multi-actor interaction and multi-energy coupling.

Classification of market mechanisms

A P2P energy market mechanism regulates the peers' trading behaviours and decides the market clearing process [9]. It matches energy demand with supply, and settles the time, price and volume of the trades. [29] reviewed the mechanisms and classified them into cost-sharing mechanism, auction-based mechanism and bilateral contracts. Cost-sharing mechanism refers to cost & benefit allocation after a system-level market clearing, for example, shapley-value distribution in cooperative games [12], [15], [20] and pricing schemes such as mid-market rate [4], [32], supply-demand ratio [32], [35] and discriminate pricing [28]. In the auction-based mechanism, peers bid price-volume orders and then a (virtual) market operator facilitates the transactions, where double auction mechanism and its variation are mostly used [18], [33]. The bilateral contract indicates the over-the-counter (OTC) and long-term agreement through direct negotiation to satisfy the special preferences of involving prosumers [21]. In comparison to the cost-sharing mechanism, the auction-based mechanism gives the peers full autonomy to conduct trading strategies, but indicates a heavier computational burden for peers to speculate others' behaviours and cope with incomplete information. From the systematic perspective, the unpredictable trading strategies of peers expose radical uncertainty on energy balance and profit allocation fairness. In the research, the auction-based mechanism requires the simulation of peers' trading strategies, where several methods are proposed to mimic a self-interested rational peer such as zero intelligence (ZI) & its variations (e.g. ZI-P and ZI-C), eye on the best price (EOB) [21], [36]. However, such methods neglect the complexity of strategic behaviours in the reality such as trading coalition formation. In contrast, a well-designed cost-sharing mechanism could mitigate the trading complexity and selfish behaviours, but still construct enough incentives for all the peers to participate. Meanwhile, the bilateral contract could serve as a complement to the former two mechanisms, but this is not considered in this study. Thereby this study aims to design a novel market mechanism to combine the advantages of cost-sharing mechanism and auction-based mechanism, which is explained in section 4.1. In addition, three types of P2P market structures have been proposed in the literature, namely full P2P market, community-based P2P market and hybrid P2P market[7]. A full P2P market represents the direct negotiation and transaction between each other, which gives peers the full autonomy to trade based on individual preferences. However, computational burdens and lengthy negotiation will emerge as the number of participants increases. In the second structure, peers with geographical proximity or common interests form a community and agree the (virtual) market operator to handle the trades between peers and the import/export with other communities or main grid. In comparison, the community-based P2P market structure mitigates the negotiation complexity and enables the peers as a whole to provide ancillary services to the main grid. The existing literature mainly concerns these two structures, addressing peers trading strategies [11], [12], [15], [19], [21], [31], [32], trading preferences [17], [24], [30], multi-energy coupling [16], [28], [34], interaction with distribution networks [14], [18], [33] as well as security & privacy issues [6], [9], [13]. The hybrid P2P market integrates the former two into a hierarchical structure and [7] argues it is the most inclusive and scalable to integrate other market innovations.

Market mechanisms on the multi-actor interaction

In order to simulate the operation of market mechanisms, it is necessary to study the individuals trading behaviours in a multi-actor interactive context, which falls into the scope of game theory. As an integrated part of the local energy community, the performance of a market mechanism is highly influenced by the peers behaviours and their interactions. The numerous decision-makers are self-interested but their utility is inter-dependent with each others trading decisions [10]. Therefore, the game-theoretic approaches are widely applied to design and analyze various P2P market mechanisms considering heterogeneous human factors and interactions [11]. Game theory can be classified as non-cooperative games (e.g. Nash games, Stackelberg) and cooperative games (e.g. canonical coalitional, coalition formation and coalitional graph games) [37]. We review the related literature using these two types of games respectively. [31] utilises a non-cooperative Nash game to simulate multiple time-period bidding and similarly, [32] assumes a non-cooperative game between peers to simulate complete competition in a multiagent-based framework. [19] segments the P2P trading between prosumers into the interaction between sellers & buyers as a hierarchical Stackelberg game and interaction between sellers as a non-cooperative game. [16] explores the benefits of energy trading between multiple energy hubs and utilises a bargaining game to achieve a fair and incentive benefit allocation scheme.

In comparison, cooperative games attract less attention than non-cooperative game, but cooperative behaviours could emerge among peers with common preferences or geographical proximity. Several studies summarised peers' trading preference from the economic, psychological and social perspectives [17], [24], [30]. In a German market research, three types of prosumers are identified, namely price-focused, autarky-focused and heuristic prosumers [17]. Moreover, [24] proposed three energy classes based on preferences of low-income consumers, philanthropic prosumer and green prosumer. Therefore, it is possible for peers to form a coalition and conduct cooperative trading instead of non-cooperative trading. [20] applies a canonical coalitional game to explore the cooperation between prosumers and proposes a pricing scheme with Shapley value for a fair revenue allocation. [12] sets 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 from the first step. But a grand coalition game only provides two options to the peers, i.e. leave or join the coalition, which could become disincentives for participation in the long run. Furthermore, [26] proposes a trading scheme based on a coalition formation game to explore the social cooperation between prosumers on electric vehicle usage. The simulation results show an increase in individual benefits and indicate the prosumer-centric characteristic. However, the related literature is constrained into the electricity-only trading, which is not applicable for a multi-energy context.

Market mechanisms on the multi-energy coupling

Electricity and heat are two major energy consumption segments especially in the residential sector, therefore, it is important to expand P2P electricity trading into P2P electricity-heat trading. Around the world, heating takes up a dominant 69% of the residential final energy consumption, with the remaining 25% for electric lighting & appliance [38]. Thereby electricity and heat nearly complete the energy profiles for a peer. Furthermore in the MES, the interconnected physical infrastructure for multiple energy carriers makes it feasible to implement the P2P multi-energy trading [16], [39]. Reversely, the P2P multi-energy trading indicates a virtual interconnection to facilitate the interaction between different energy sectors. Therefore, as the dominant energy carriers at the end consumers, electricity and heat are two promising energy commodities in the P2P energy trading.

However, from the TransActive Grid in the USA to SonnenCommunity in Germany, the existing pilot projects only focus on P2P electricity trading with a single commodity [7], [9]. Even in the literature, few literature considers the coupling of P2P electricity and heat trading. Although [34] couples the electricity, heat and hydrogen demand to investigate synergies among them, the trading commodity is constrained to electricity. In a further step, [28] proposes a bi-commodity electricity & heat market mechanism with a multi-leader multi-follower Stackelberg game and motivates the participants with a discriminatory pricing scheme. [3] couples the electricity and heat trading between a residential community and a commercial community, and reaches out a fair pricing strategy using a non-cooperative Nash game. However, the study only considers two peers and emergent cooperation between multi-peers is neglected.

1.3. Research question and research contribution

Based on the literature review, both the cooperative behaviours and multi-energy coupling require research attention in the field of P2P energy trading. An inclusive market mechanism that allows cooperative behaviours could satisfy the peers preferences, stimulate proactive participation and safeguard the long-term market reliability. Meanwhile, electricity-heat trading is promising in the MES setting to exploit the synergies of energy coupling. Although some studies explore one of the two topics, a knowledge gap exists in the integrated effect. Under the context of sector coupling in the energy transition and the emerging P2P markets where peers could make decisions autonomously, their synergies are crucial to study. It is unknown how peers form trading coalitions in the multi-energy context, how peers change their trading strategies due to the additional energy carrier trading and how the coalitional electricity-heat trading influences the individual and system benefits.

The study aims to fill the knowledge gap by designing and evaluating a novel market mechanism that integrates coalitional trading and electricity-heat coupling. We firstly design the market operation process to address coordination issues between electricity-heat coupling and coalitions. Then we simulate peers' trading activities based on a coalition formation game. Besides, a case study in the Netherlands is conducted to showcase the performance of the proposed market mechanism with the comparison against non-coalitional and electricity-only trading scenarios.

Thereby the following research question is formulated:

What is the economic and social performance of a novel peer-to-peer energy trading market that incorporates cooperative behaviours and electricity-heat coupling?

The thesis is structured as follows. Chapter 2 defines the research scope and derives the research framework including research approach, research sub-questions and research flow diagram. Five stages are envisaged to instruct the following research. Then chapter 3 designs the novel market mechanism that incorporates cooperative behaviours and multi-energy coupling. The design process starts from stakeholder needs & requirements to system requirement to design result to evaluation criteria. Therefore, based on the proposed market mechanism, chapter 4 delineates the system model mathematically to simulate the trading activities. The algorithm decides the trading coalition, position and volume for each peer at each time step. Furthermore, chapter 5 introduces a case study to evaluate the market design, where the setting of peer, demand, generation and price profiles is detailed. Subsequently, chapter 6 demonstrates and discusses the modelling results from the case study. The socio-economic performance of the market mechanism is compared across four scenarios from both individual and system level and from both spatial and temporal perspective. In the end, chapter 7 concludes the main findings from the research. The research question is answered and the research limitation is discussed for potential future improvement.

2

Research Scope

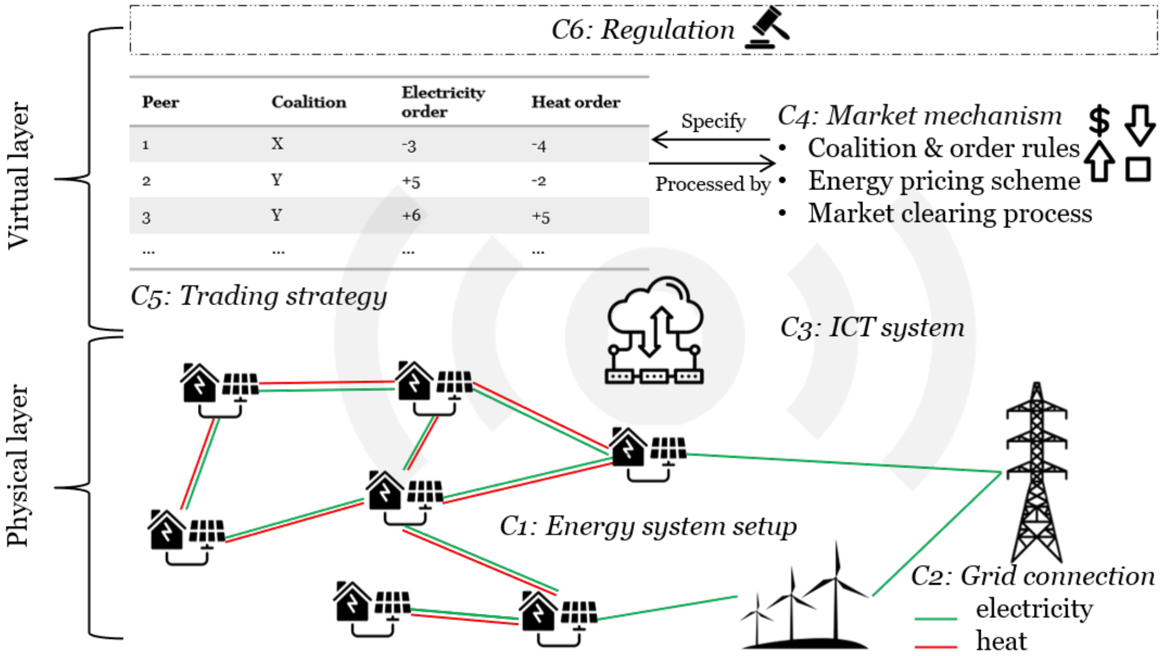
This chapter firstly defines threes terms in the research question in order to draw a clear boundary for the research in section 2.1, and then section 2.2 derives the research framework including research approach, research sub-questions and research flow diagram.

2.1. Scope definition of the research question

The key terms in the research question define the research scope, namely peer-to-peer energy trading market, cooperative behaviours and electricity-heat coupling. Following is the detailed definition of each term.

2.1.1. Peer-to-peer energy trading market: six key components

As introduced in chapter 1, a P2P energy trading network is characterised as a complex socio-technical system. Adapted from [9], six key components are derived to complete the P2P energy trading as illustrated in Fig. 2.1. Following is the detailed explanation of each component.



Peer	Coalition	Electricity order	Heat order
1	X	-3	-4
2	Y	+5	-2
3	Y	+6	+5
...	...	...	...

Figure 2.1: Key components of P2P energy trading (Adapted from [9])

1. *Energy system setup (C1)* covers system objective, market participants (peers) and energy trading commodity. In this research, we do not conduct system-level objective optimisation but empower each peer to optimise his own objective. The market participants refer to all the peers within the energy system of interest, i.e. all the prosumers, consumers and producers with distinct energy demand & generation profiles. And the energy trading commodities include electricity and heat detailed in 2.1.3
2. *Grid connection (C2)* refers to both network connections among the peers as a local microgrid and connections between the local microgrid and the main grid. This research assumes that sufficiently connected grid infrastructure has been constructed for the energy system and the P2P energy trading would not violate the network constraints.
3. *ICT system (C3)* supports the trading platform and ensures all the peers to access and share trading information in an efficient and secure manner. Besides, the energy management system (EMS) should be widely deployed to record, predict and control the generation or demand of each energy device. Similarly to C2, this research assumes the existence of reliable ICT infrastructure.
4. *Market mechanism (C4)* matches peers' selling & buying demand and settles the trading time, price and volume so that to facilitate the bidirectional energy exchange and financial transaction. The study aims to design a novel market mechanism to combine the advantages of cost-sharing and auction-based mechanisms, which is explained in chapter 3 including the coalition, pricing and market clearing rules.
5. *Trading strategy (C5)* concerns peers' strategic decision-making in trading to maximise their own benefits. In reality, peers could set their preferences in the EMS that could conduct trading strategies automatically to ease the human burden. In this research, the peers' trading strategies include coalition selections, electricity orders and heat orders (detailed in section 4.4).
6. *Regulation (C6)* sets the institutional context to implement the P2P energy trading including market participant requirements, tax, surcharge, subsidy. This research assumes a friendly regulatory context to support the proposed market mechanism and qualifies all the peers within the energy system as market participants.

As a result, *Market mechanism (C4)* and *Trading strategy (C5)* are the focus of this research, which should align with the cooperative behaviours and electricity-heat coupling in the following discussion. Besides, other components are treated as the existing and supporting environment.

2.1.2. Cooperative behaviours: a pre-defined set of trading coalitions

The cooperative behaviours are represented by emerging trading coalitions in the P2P energy trading market. Two different types of coalitions could be envisaged:

1. Type 1: Several peers form a coalition and agree to participate in the market as one collective peer. This indicates that a virtual system operator coordinates the demand and generation profiles of all the peers in this coalition and thereby conduct the trading strategy for the interest of the coalition. The trading counterparties are other coalitions or peers outside the coalition. In addition, this type of coalition requires a predefined cost/benefit allocation mechanism in order to distribute the coalition cost/benefit over individual peer in a fair way. Examples: predefined energy hubs in [16], predefined microgrids in [26].
2. Type 2: several peers form a coalition based on their similar preferences and thereby conduct P2P energy trading within the coalition. In contrast to type 1, a virtual market operator is

required to clear the market based on peers' trading strategies within the coalition. Without any constraint, the numerous kinds of coalitions for n peers indicates a huge computational complexity to find the best coalition. Another way to approach the problem is to pre-define a set of coalitions for peers to choose from. For example, concerning the EVs use, there could be an active EVs trading coalition where to charge or discharge EVs for P2P trading and by contrast, passive EVs trading coalition; in a electricity-heat coupling setting, there could be an electricity-only trading coalition, electricity-heat trading coalition. Examples: [22], [26]

It is also possible to combine the Type 1 and Type 2 coalition, e.g. the type 1 coalition will be used to trade surplus/deficient energy after the P2P trading within the Type 2 coalition. But to limit the research scope, Type 2 with a pre-defined set of coalitions is the focus of the research and the surplus/deficient energy after P2P trading will be traded with the utility company only. In this way, we constraint the possibility of coalition formation and make a trade-off between peers' freedom and computational complexity. Essentially, peers will compare different trading coalitions and choose one to join. And there is no upper-level game for the trading coalitions, so the trading coalitions are price takers to deal with electricity imbalance.

2.1.3. Electricity-heat coupling: a fully electrified and distributed scenario with two trading commodities

Electricity takes up 19.3% of final energy consumption globally in 2018, which represents the second-largest source after oil products and indicates an increasing trend under electrification [38]. In 2040, the global electricity demand is expected to increase by over 50% from 2018, taking up 31% of final energy consumption [1]. Although the heat segment is only 3.0% of total final energy consumption, space and water heating takes up a dominant 68% (resp. 53% and 16%) of the residential final energy consumption [38]. Especially in EU-27, heating represents as high as 78.4% with the remaining 14.1% for electric lighting & appliance and 6.1% for cooking [40]. Therefore, it is important to cover both electricity and heat demand to complete the peers' energy profiles.

As for electricity generation, the study considers two forms of DERs: roof-top photovoltaic modules (PV) and wind turbines (WT). Peers install the PV on the roof of their houses and own the electricity generation from PV. As for the WT, it is assumed that all the peers collectively invest the WT and each peer own a portion of the WT, i.e. certain WT generation capacity. The WT could be installed out of the residential areas to avoid the NIMBY, i.e. not in my back yard.

There are various future scenarios towards meeting heat demand. In terms of network diagrams, there are central district heating, distributed heat generation and hybrid forms of the former two; in terms of generation portfolios, there are electricity-driven, hydrogen-driven and biomass-driven [41]. Considering huge uncertainty around the cost and distribution safety of the hydrogen and harmful impact on air quality from individual biomass heating, we limit the heating option to electric heating using the heat pump (HP). As a commercially mature technology, HP represents a feasible option to decarbonise the heat sector in both a large-scale and distributed manner [41], [42]. Although HP has a higher capital cost than the gas boiler and direct electric heater, the approx. 300% heating efficiency makes HP a cost-efficient option, especially in thermally-efficient buildings.

To sum up, the research considers a fully electrified and distributed scenario with PV, WT and HP owned by each peer. As for the P2P energy trading, there are two directions to investigate the coupling effect of electricity and heat demand:

1. One direction is to explore the effect of heat demand on the P2P electricity trading as studies in [34], which requires the investment of electric or thermal storage. Otherwise, the heat generation portfolio would become passive electricity consumption devices and cannot optimise the heat generation according to the market information.

2. Another direction is to expand the trading commodities from single electricity to electricity and heat (in the form of hot water). Then even without the existence of energy storage, the peers could proactively increase or decrease their heat generation levels as well as heat trading levels to optimise their benefits.

This second direction is chosen as the focus of the study. This direction could avoid the high investment cost of energy storage at the consumer side but require a local district heating network for hot-water exchange. No centralised heat plant and higher-level network are considered due to the long-distance transmission loss, which means the household HP is the only mean to generate heat. What's more, we assume that the peers are willing to make a trade-off between heat comfort by consuming heat and economic benefit by trading heat. Note that the heat demand is assumed to be elastic while the electricity demand is assumed to be inelastic to limit the scope. The detailed mathematical formulation is given in section 4.3 and section 4.4.

In summary, there are bi-directional electricity & heat flow between peers and bi-directional electricity flow between peers and electricity utility company (EUC), as shown in Fig. 2.2. Meanwhile, the payment flow occurs in the reverse direction of the commodity flow. The EUC hereby refers to a new role with a combination of retailers and wholesalers in the future energy systems to make bi-directional transactions with distributed prosumers. Besides the P2P electricity market, EUC is the backup option for peers to sell surplus electricity or buy deficient electricity. But in the current setting, the surplus heat could only be sold to other peers within the region; and the deficient heat could be bought from other peers or be met from self-generation by buying extra electricity. Therefore, the heat supply and demand must be balanced within the community, as heat grids are mostly more local than electricity grids. In the future, if there are inter-connected heat networks between different regions, there will be a possibility for peers to trade with so-called "heat utility company" and essentially with other regions, where the network investment cost and heat transmission loss should be considered to decide the financial feasibility. However, this is out of the current research scope.

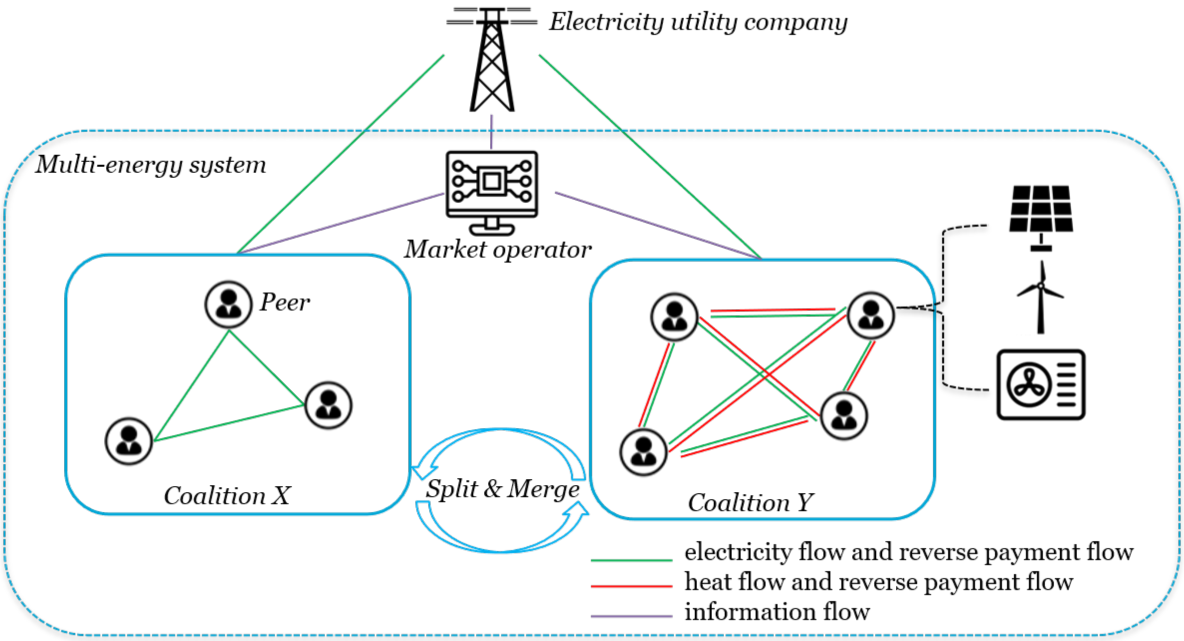


Figure 2.2: Overview of the system scope (coalitions detailed in Chapter 4)

2.2. Research framework towards answering the research question

2.2.1. Research approach: modelling

The proposed research question indicates a modelling research approach so that to explore the influence of cooperative behaviours and electricity-heat coupling in P2P energy trading. In modern science, modelling is recognised as a ubiquitous approach to understand complex socio-technical systems [43]. Modelling represents the process to obtain a portion of the real world", which is usually followed by the simulation to conduct experiments over time with the model [44]. Modelling and simulation provide a way to evaluate the novel market mechanism under various operation scenarios and overcome the barriers of time and costs for implementation [43]. However, the modelling approach does have the limitation that the simulation results are highly dependent on the quality of model and data, and thereby it requires high expertise of the modeller and indicates a time-consuming process of data collection [43].

The modelling approach in this research is firmly backed by the theory of systems engineering and game-theoretic approaches. System engineering incorporates multi-disciplinary knowledge and constructs a holistic framework to study complex socio-technical systems [45]. Specifically, the P2P energy network is not solely regarded as a technical system, but a constellation of technical, economic and social systems. Therefore, a design alternative of market mechanism should consider various aspects to improve the market performance, including institutional coordination of multiple energy carriers and social integration of peers' strategic behaviours. [46] suggest five stages in a design process, namely problem definition, conceptual design, preliminary design, detailed design and design communication. The focus of this research is to find a feasible solution for specific requirements but not to find the best alternative, so the design process is more straightforward rather than interactive. In a further step, the modelling method is implemented to evaluate the proposed design alternative quantitatively. As emphasised in [45], the method of modelling and simulations take a prominent role in system engineering to analyse the alternative and facilitate the consensus.

Within the modelling, another complementary theory is game theory to address human factors. As defined by [37], Game theory is a bag of analytical tools designed to help us understand the phenomena that we observe when decision-makers interact. The fundamental assumption behind the theory is that the decision-makers are rational and reason strategically. Considering proactive and self-interested participants in the market, different trading behaviours could emerge based on peers demand, generation and preferences. This research attaches importance on the coalitional behaviours of peers using cooperative games.

2.2.2. Five research sub-questions

There are two major steps towards the research outcome: firstly, design a novel market mechanism for P2P energy trading to accommodate peers cooperative behaviours and facilitate multi-commodity trading; secondly, simulate P2P energy trading in the novel market mechanism and evaluate the socio-economic performance. Furthermore, five sub-questions (SQ) are identified as follows:

SQ1: What are the necessary components to implement P2P energy trading?

It is a prerequisite to identify key elements in the P2P energy market and narrow down the scope of the research. The starting point to answer the question is the existing mechanisms in the large-scale energy market as well as the common-used mechanisms in the literature of the local energy community. This SQ serves as a foundation for any adaptions in SQ2 and also set a boundary for the following market design. This question has been answered in section 2.1 and 2 out of 6 components are derived as the research focus, namely market mechanism and trading strategy.

SQ2: How should the market mechanism incorporate cooperative behaviours and electricity-heat coupling?

Besides the literature review, design-related approaches could be implemented to find coordination issues and derive the solution so that to enable coalitional trading and integrate electricity & heat trading. The design method is derived from the engineering design to define the problem, identify requirements and generate alternatives [46]. In addition, a set of structured criteria is derived from the design process to evaluate the market mechanism in the following modelling & simulation. The existing criteria in the literature could be adapted based on the particularities of the market mechanism. The evaluation criteria should exhibit systematic properties including economic and social aspects.

SQ3: How does the model simulate the trading activities in the proposed market mechanism?

Based on the novel market mechanism in SQ2, this section starts from the analytical formulation of the whole trading process from energy profile initialisation to coalition formulation to trading strategies to market clearing. The coalition formation method could be referred to and adapted from [26]. Next, such mathematical formulas are converted into computer programs to construct the simulation model. Meanwhile, the pseudocode is written to showcase the core algorithm for coalition formation.

SQ4: What is a suitable case study to evaluate the proposed market mechanism?

A selected case study needs to be introduced to simulate the proposed market mechanism in a real-life setting. Based on the targeted case study, the simulation model should be set up according to specific demographic & geospatial characteristic, generation & demand profiles, price information, etc. Such a case study could evaluate the market mechanism against other scenarios, and also create a testbed for the real implementation.

SQ5: Why does the novel market mechanism for P2P energy trading outperform/underperform other mechanisms from the socio-economic perspective?

According to the simulation results from SQ4, this SQ discusses the P2P market performance using the evaluation criteria from SQ2. Furthermore, the results are compared against various scenarios such as non-cooperative trading and single-commodity trading. In conclusion, the insights retrieved from the evaluation contribute to the key findings of the research.

Table 2.1 provides an overview of methods & tools, input and output for each sub-question. The literature review serves as the research method to answer SQ1,2&4 with the help of the online database and search engine, e.g. Scopus and Google. The existing market mechanisms in the energy markets and proposed designs in the literature are the main input to derive the design alternative to coordinate cooperative trading and electricity-heat trading. Besides, design-related tools are used to facilitate the design process for SQ2 such as requirement breakdown structure. Next, the P2P trading process in the designed market mechanism is firstly formulated analytically based on game theory, and then the mathematical formulation is transformed into a simulation model with Python for SQ3. Since P2P energy trading is still in the conceptual phase and far from the real implementation, a case study is selected based on data availability and implementation feasibility of the target region – that is to say, the relevant stakeholder should be positive towards energy transition in terms of DERs investment, infrastructure construction and P2P trading participation. In order to set up the case study for SQ4, multiple quantitative data sets are needed as the model input including the demand profiles, technical and economic parameters of generation portfolios, weather-dependent renewable energy availability, energy tariffs, etc. In the end, scenario analysis is conducted to evaluate the design alternative against other market mechanisms and to extract key insights from the comparison results (SQ5).

2.2.3. Five-phase research flow diagram

Based on the discussion above, Figure 2.3 illustrates the five-phase research flow, namely Introduction, Design, Modelling, Evaluation and Conclusion. The Introduction phase conveys the societal and scientific relevance of the research, conducts a structured literature review and thereby derives

Table 2.1: Research methods & tools, input and output for each research sub-question

SQ	Methods & Tools	Input	Output
SQ1	Literature review: Scopus, Google	Existing literature about both P2P and large-scale energy trading market	Key physical and virtual elements of P2P energy trading market and the focus of the research with system scope.
SQ2	Literature review: Scopus; design method: requirement breakdown structure, etc	Existing electricity & heat market mechanism; system objective of the P2P energy market	A novel market operation process to facilitate the coalitional formation and electricity-heat trading as well as a set of evaluation criteria
SQ3	Modelling: mathematical optimisation, game theory, Python packages	Designed Market mechanism and system scope	Mathematical formulation and computer program to simulate the whole trading process
SQ4	Literature review: Scopus, policy documents, online open database	Peer setting; demand & generation profiles; electricity tariffs; time horizons; simulation model	Simulation results of the proposed market mechanism in the target case
SQ5	Scenario analysis & system evaluation	Scenario settings; evaluation criteria	Evaluation results for all the scenarios; key findings from the comparison

the research question, research scope and research framework. Starting from the scope definition of the market design in the first phase, the Design phase clarifies the system requirements, identifies the coordination issues and generates design alternatives for a novel market mechanism. Subsequently, the Modelling phase formulates the P2P trading process mathematically and sets up the simulation program under the given market mechanism. Furthermore, the Evaluation phase includes a case study to analyse the simulation results and compare different market mechanisms quantitatively. Finally, the main insights and suggestions from the research are synthesised in the Conclusion phase.

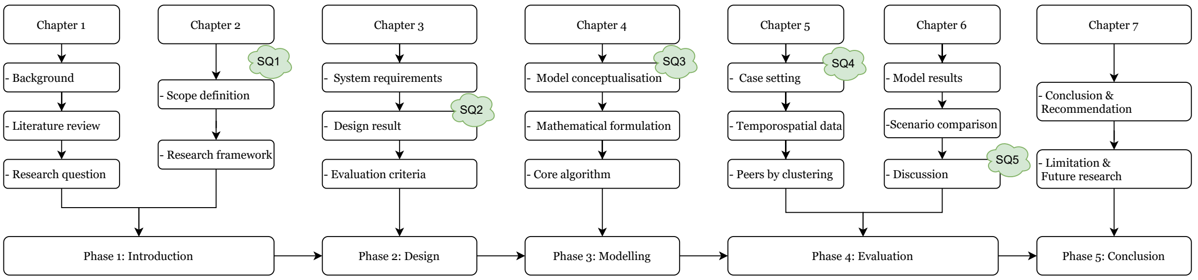


Figure 2.3: Research flow diagram

3

Market design

Based on the research question and scope definition, the system goal is to enable the formation of trading coalitions and integrate electricity & heat trading in the P2P energy market. The following sections will delineate the design process to fulfil the system goal from stakeholder needs & requirements in section 3.1 to system requirement in section 3.2 to design result in section 3.3 to evaluation criteria in section 3.4.

3.1. Stakeholder needs & requirements for peers, market operator and electricity utility company

In the P2P energy trading, the involved stakeholders are three types:

1. *Peers* are the market participators who sell or buy energy in the market to optimise their benefits and meet their energy balance;

2. *Market operator* is a virtual role to conduct the market clearing by deciding the trading price and quantity for each peer and the market settlements for maintaining the system energy balance;

3. *Electricity utility company (EUC)* is the intermediary between the P2P market and the large-scale electricity market by trading electricity with the P2P market operator.

Based on the definition above, we could derive the needs and requirements for each stakeholder detailed in Table 3.1-3.3. A reasonable interval for P2P energy trading is required for the peers to conduct trading strategy based on the market information and for the market operator to conduct the market clearing and settlement (R1&R2). Therefore, the market mechanism should avoid huge computational complexity, which will not only lower the threshold for market participants but also increase the practicality from the system perspective (R9). The trading process for peers starts from coalition formation to trading strategy submission and the peers should have the freedom to decide their trading coalition and strategy every interval (R3&R4&R5). Furthermore, energy balance is a key requirement at both the individual level and system level. Since peers will submit their trading strategy based on their own energy balance, the market needs to execute one peer' trading orders by contracting the peer with market participants (R6). However, there is no other stakeholder in the heat trading besides peers and thereby heat balance must be maintained between the peers. Therefore, the market operator should be able to further coordinate (curtail or reject) certain heat orders, before which the relevant peers should be fully informed and allowed to re-decide their trading strategies (R10). This particularity indicates that the heat market should be cleared before the electricity market since EUC serves as the last resort to deal with any surplus or deficiency. After the market clearing, the market operator should guarantee the financial and physical settlements between market participants to fulfil their trades (R6 & R11). To achieve long-term stable operation, the market participants should have economic incentives to conduct P2P energy trading rather than become independent or trade with other parties. Therefore, the pricing scheme is crucial to bring benefits to all the peers and EUC (R7&R12). Last but not the least, transparency, equality and privacy should be safeguarded during the whole market operation (R8).

Table 3.1: Stakeholder needs and requirements: peers

Peers’ needs	Requirements
Enough market information to decide the trading strategy	R1: The market information should be shared in a timely manner to each market participator
Enough time to decide trading strategy	R2: The market should be cleared at every reasonable interval
Cooperate with certain peers to conduct energy trading among them	R3: The market should allow peers to form trading coalitions and the market is cleared in each coalition individually
Change the trading coalitions freely	R4: The market should allow peers to form a new coalition every interval
Submit the trading strategy for both electricity and heat trading	R5: The market operator should receive all the orders from each peer and register them in an order book
Maintain electricity and heat balance for themselves	R6: The market is obligatory to execute the submitted order and get the traded energy delivered to or dispatched from peers
Obtain benefits from participating in the P2P market	R7: The energy price should be attractive to both sellers and buyers
Monitor the market operation and maintain an equal position to other peers	R8: The market should be operated in a transparent and privacy-secure manner and without discrimination during market clearing & settlement

Table 3.2: Stakeholder needs and requirements: market operator

Market operator’ needs	Requirements
Clear the market timely and efficiently every certain interval	R9: The market mechanism should implicate durable computational complexity
Maintain the system electricity and heat balance	R10: The market operator should have the right to curtail or reject certain orders to maintain the system balance
Ensure both financial and physical settlements of each trade	R11: According to the executed orders, the sellers are obligatory to deliver the energy and the buyers are obligatory to pay the costs at the market clearing price

3.2. Integration of stakeholders’ requirements into system requirements

Requirement breakdown structures (RBS) is a widely-used system engineering tool to decompose the requirements with a hierarchical tree structure [47]. The following RBS synthesises the require-

Table 3.3: Stakeholder needs and requirements: electricity utility company

EUC' needs	Requirements
Sell and buy electricity at a favourable price	R12: The selling and buying price with EUC should be aligned with that in the large-scale electricity market

ments from each stakeholder and showcases the system requirements (Figure 3.1). There are 4 top-level system requirements with 12 second-level requirements. The market should facilitate the peer to decide trading strategy via efficient information sharing (R1.1), reasonable trading interval (R1.2) and less-complex mechanism (R1.4). Furthermore, the market should support the cooperative behaviours by clearing the market within each trading coalition (R1.3). As for heat balance at both individual and system level, there could be a conflict between peers and market operator by observing R6 and R10 in the last section. Therefore, the heat market should be cleared before the electricity market, so that the market operator coordinates order changes with certain peers to maintain heat balance (R2.1 & R2.2). Then, the electricity surplus or deficiency should be traded with EUC followed by the electricity market clearing (R2.3). Next, the market should guarantee the sellers and buyers to fulfil their obligation leading to the successful market settlement (R3.1 & R3.2). R4.1 and R4.2 concerns a beneficial and non-discriminated energy price to sustain peers' willingness to stay in the P2P market. Besides economic incentive and fairness, transparency and privacy security are key principles for the market operation (R4.3).

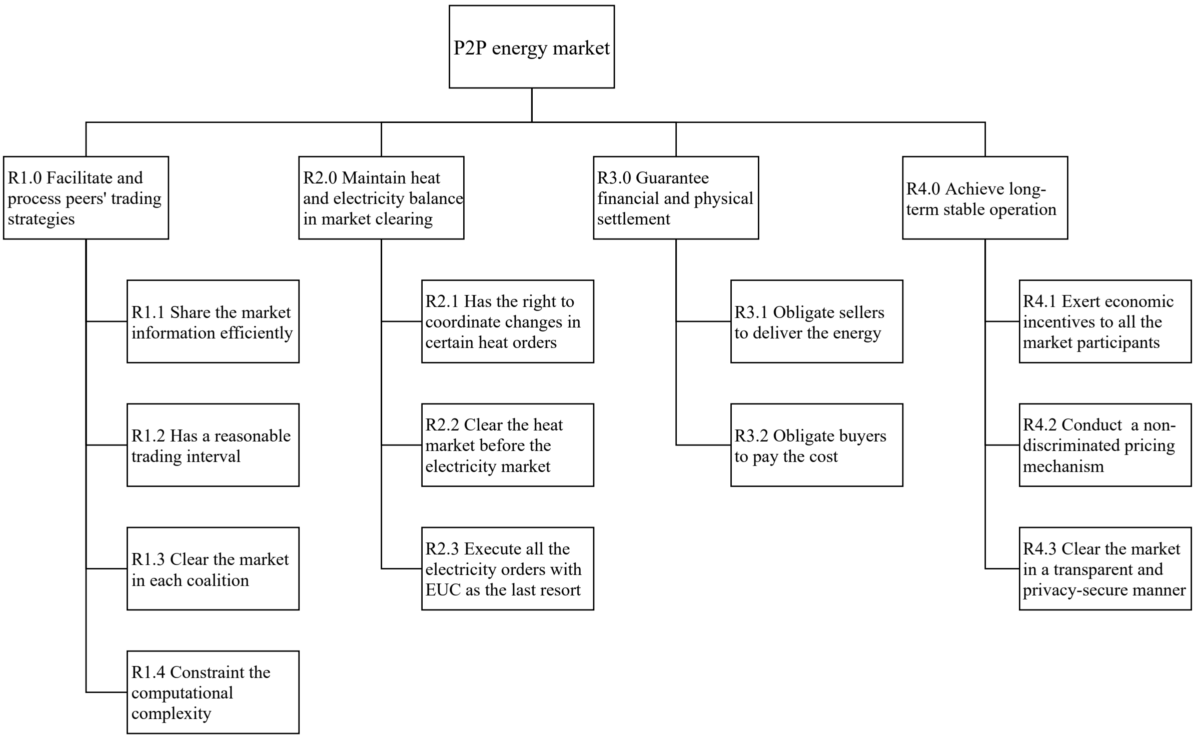


Figure 3.1: System requirement breakdown structures

In addition, we deploy another system engineering tool – Functional flow block diagrams (FFBD) to illustrate the complete market functioning process. FFBD, as a useful complement to RBS, could demonstrate the interrelationship of the system functions to accomplish the system goal, for example, performed in sequence, parallel or under certain conditions [47]. Figure 3.2 shows four sequential top-level functions to complete the P2P energy trading including market information sharing, trading strategy processing, market clearing and market settlement.

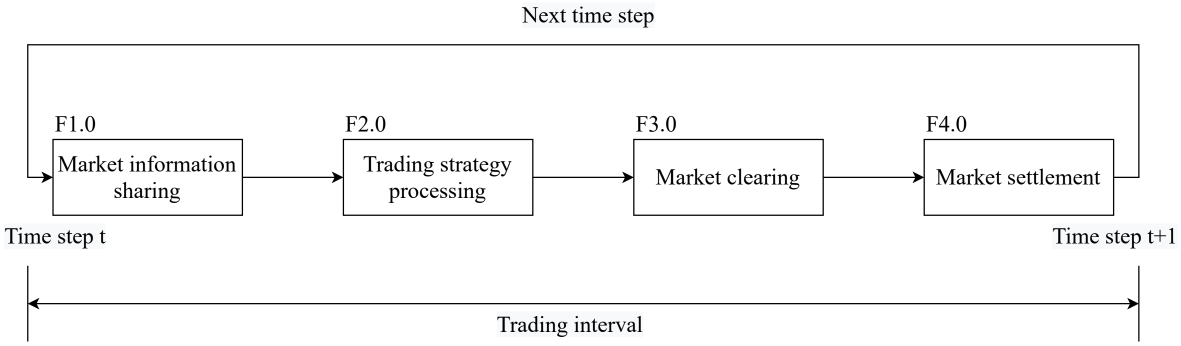


Figure 3.2: Functional flow block diagram (top-level)

3.3. Design result to meet system requirements

As mentioned in section 2.2, the design objective is to find a feasible alternative rather than the best/perfect one to achieve the desired P2P energy market. Therefore, we will derive means for four system function based on system RBS and illustrate the design alternative in the form of lower-level FFBD.

1. *Market information sharing*: Market operation activities from the last time step should be published including the submitted order book, coordination process and final execution; but peers' anonymity should be kept. Thereby the market participants could supervise the market operation in terms of transparency and equality. Besides, the market operator could share the weather condition prediction for renewables and price information in the large-scale electricity market. Now, the peers are ready to determine trading strategies towards the next function F2.0. (Align with R1.1 & R4.3)

2. *Trading strategy processing*: The market operator receives all the trading strategies and coordinates with certain peers to change their orders for the sake of heat balance. Figure 3.3 showcases five sub-functions to fulfil this function. After obtaining the system-level heat surplus/deficiency in F2.2, the market operator determines to proportionally curtail heat selling or buying order in F2.3. Then the market operator informs the relevant peers about the potential order changes in F2.4. Next, the peers could choose to submit the new coalition selections and electricity-heat orders in F2.5 or consent to the changes. The market will move forward to market clearing only if all the peers consent to the potential order changes, which indicates an iterative negotiation between peers and the market operator. (Align with R2.1 & R2.3)

3. *Market clearing*: Subsequently, the market operator will clear the heat and electricity marker through four sequential sub-functions as illustrated in Figure 3.4. Based on the latest orders, the market operator will clear the heat market first and decide the heat price for both sellers and buyers in F3.1. Secondly, before clearing the electricity market in F2.4, the market operator will trade the electricity surplus or deficiency at the coalition level with the EUC to maintain the electricity balance (F2.2&2.3). (Align with R1.3 & R2.2)

4. *Market settlement*: At the end, all the executed orders should be fulfilled. Relevant regulations should be established to obligate the market participants about the energy delivery and payment, such as imposing a penalty to the defaulter. (Align with R3.1 & R3.2)

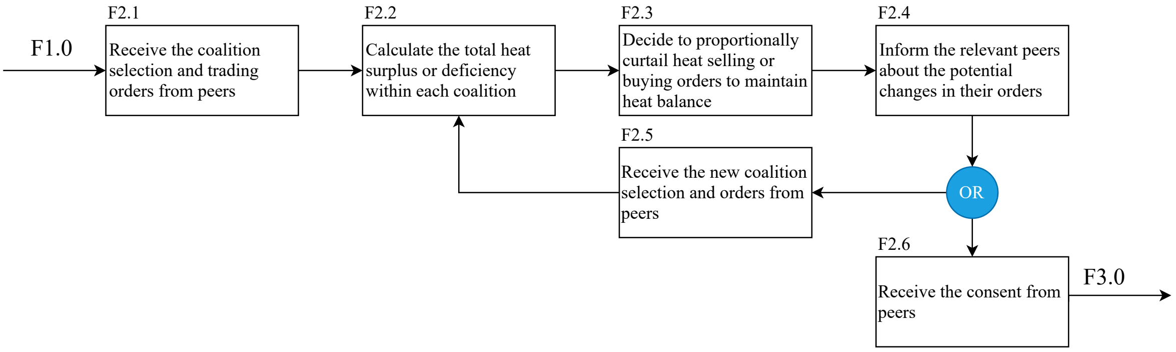


Figure 3.3: Functional flow block diagram of trading strategy processing (second-level)

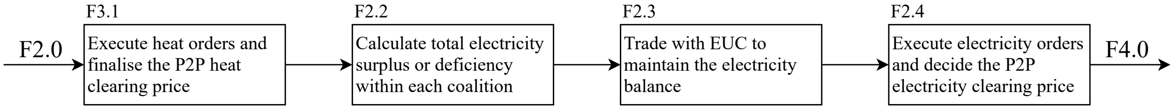


Figure 3.4: Functional flow block diagram of market clearing (second-level)

One core issue emerges as the pricing scheme, which directly connects to the remaining R1.4, R4.1 and R4.2. We aim to attain a balance between cost-sharing mechanism and auction-based mechanism, that is to say, combining the advantages of the former's lower computational complexity and the latter's trading strategy autonomy. Specifically, we adapt the mid-market rate as the pre-defined pricing scheme but empower the peers to conduct their own strategies about trading coalitions and quantity. The mid-market rate refers to the mid-value between the wholesale and retail price in the large-scale electricity market, which is widely used in the literature to determine the P2P electricity selling and buying price [4], [25], [32]. Such a pricing mechanism is simple to understand and implement. And compared to trading with the EUC, the mid-market rate still keeps the economic incentives of the P2P market at any time step for both electricity sellers and buyers. Furthermore, since the only option to generation heat is heat pump in the system, the heat generation cost is dependent on the electricity price. Therefore, the guiding heat price is defined to be directly proportional to the mid-market rate and the proportionality constant is adjustable. Overall, the mid-market rate serves as a guiding price for peers to decide their best trading strategies, but the final clearing price will be slightly adjusted according to the system energy balance (detailed in section 4.5).

As for R1.2, the trading interval should be aligned with the large-scale electricity market. In the current spot market of the European Power Exchange, the day-ahead auction has the resolution of one hour and the intraday market execute orders into hourly, half-hourly or quarter-hourly contracts [48]. In this research, we choose one hour as the trading interval, which has the potential to decrease with the improvement of the energy management system and advanced meter infrastructure. A higher granularity indicates a high level of flexibility for peers to adjust their trading positions closer to real-time [48].

By far, a market design alternative is obtained meeting all the system requirements

3.4. Socio-economic evaluation criteria for the proposed market mechanism

To examine the economic and social performance of the market design, a structured set of criteria could be adapted from [32]. The system evaluation will be conducted through the comparison between various scenarios (detailed in section 4.1). Following is the explanation of five evaluation criteria and the explicit mathematical formulation is derived in section 4.7.

Considering no P2P energy trading as the benchmark case, the evaluation criteria $E1$ & $E2$ address the economic perspective to determine the energy cost-saving either at the individual or the system level. The use of unit energy consumption in $E1$ is due to the divergent demand and cost level across peers so that the absolute value of benefits would distort the comparison to favour peers with larger energy demand. Moreover, in terms of social performance, $E3$ & $E4$ measures the key principle of economic incentives and fairness respectively; $E3$ compares the individual benefit to that in other scenarios and $E4$ compares the individual benefit across peers within one scenario.

- Economic performance
  - *Individual benefit of unit energy consumption (E1)*: the average cost-saving per energy consumption for the individual peer compared to the case without P2P energy trading
  - *System benefit (E2)*: the energy cost-saving for all the peers compared to the case without P2P energy trading
- Social performance
  - *Participation willingness (E3)*: the ratio of peers who obtain the maximum benefits compared to all the other scenarios
  - *Benefit allocation equality (E4)*: the measure of benefit dispersion between peers to reflect the system fairness

In the next chapter, we model the trading activities in the proposed market mechanism and evaluate the market performance based on the four criteria.

4

System model

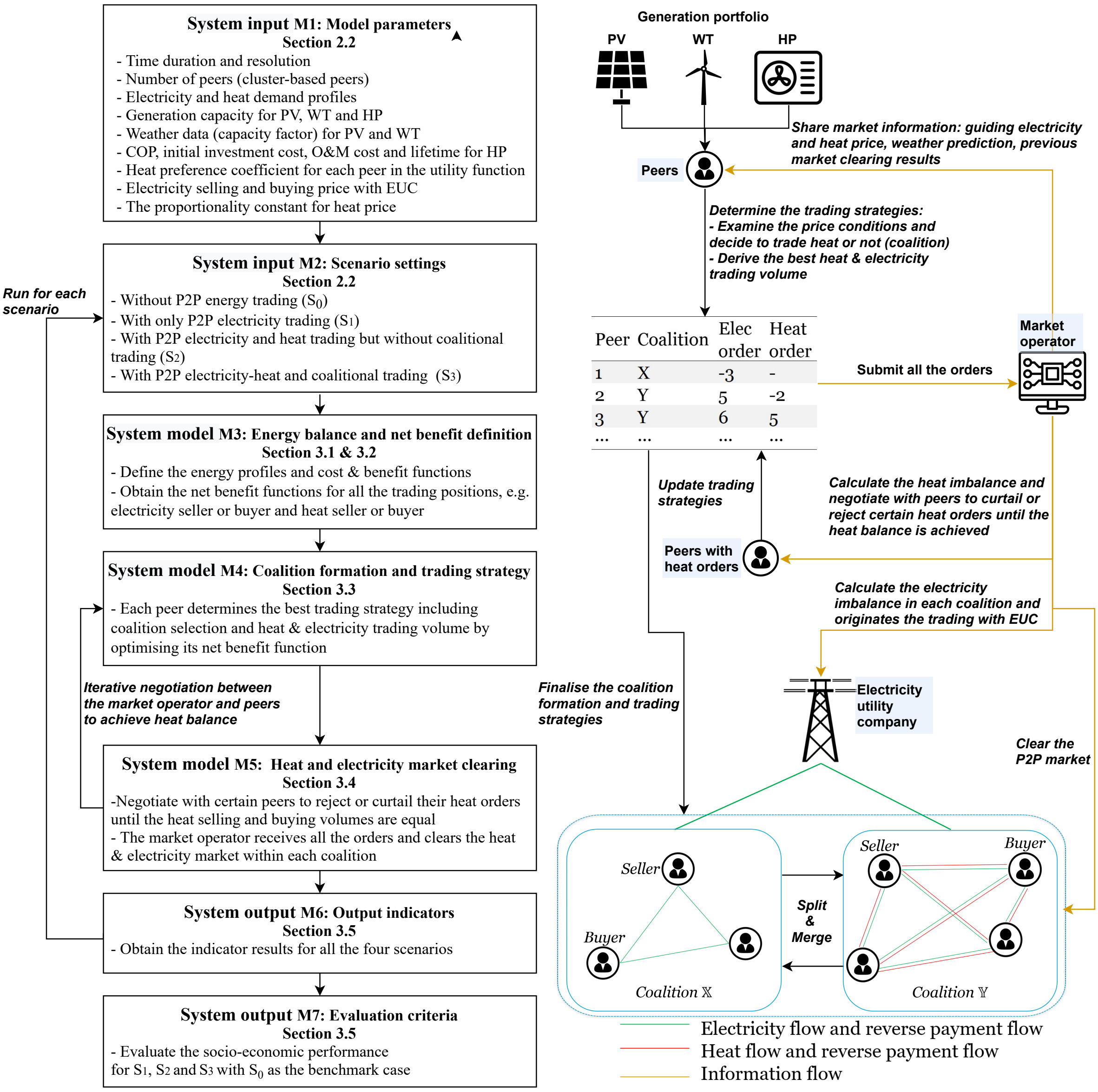
This chapter will delineate the modelling process for the proposed market design from model conceptualisation & system input (section 4.1) to system model (section 4.2-4.5) to system output (section 4.7). Besides the mathematical formulation, section 4.6 showcases the core algorithm for the system model. In the following formulation, symbols with the lower-case letter or Greek letter are parameters while symbols with the upper-case letter are variables; the symbol subscripts are independent variables while the symbol superscripts are for description.

4.1. Model conceptualisation and system input

The research aims to model the proposed market design in a multi-energy system (MES) as illustrated in Figure 4.1(b). The MES introduces both electricity and heat (in the form of hot water) as two energy trading commodities. Besides, there are three types of actors, namely peers, (virtual) market operator, and electricity utility company (EUC). The EUC hereby refers to a new role with a combination of retailers and wholesalers in the future energy systems to make bi-directional transactions with distributed prosumers. As for network connections, there are local electricity distribution network between peers and grid connection with the EUC; and the local district heating network exists between peers. The generation portfolios include photovoltaic modules (PV), wind turbines (WT) and heat pumps (HP), where peers own diverse capacity of these three based on the roof-top area and demand level.

In P2P energy trading, all the actors have their own needs and thereby interacts with each other. The peers need to meet their electricity and heat demand through self-generation or trading in the P2P energy market. Therefore, there are electricity and heat flow between peers with the accompanying reverse payment flow. The market operator shares market information with peers and processes trading orders from peers. During the P2P market clearing, the market operator needs to monitor the system-level electricity imbalance and originates the electricity trading with EUC to maintain demand-supply balance. But the market operator only serves as an information hub to control the trading among peers and facilitate the electricity & payment flow between peers and EUC. In the current setting, the surplus heat could only be sold to other peers within the region; and the deficient heat could be bought from other peers or be met from self-generation by buying extra electricity. Therefore, the heat demand-supply balance must be maintained within the MES.

Moreover, the proposed market mechanism empowers certain peers to form coalitions based on their similar preferences and to conduct P2P energy trading within each coalition. Without any constraint, there will be 2^n kinds of coalitions for n peers, which indicates a huge computational complexity to find the best coalition. Referred from [26], the research introduces two pre-defined trading coalitions, namely Electricity-only trading Coalition $\mathbb{X}$ and Electricity-heat trading Coalition



(a) (b)

Figure 4.1: (a) Flow chart for the system model including 7 modules; (b) Graphical illustration of the P2P energy trading in a multi-energy system

𝕐, to explore the integrated effect of coalition formation and electricity-heat coupling. Each peer could choose one trading coalition at each time step, which means each peer could stay in the previous coalition or split from the previous coalition & merge into another coalition. Essentially, there will be two sub-markets at each time step and the market operator will clear each sub-market. And the surplus/deficient electricity of each coalition will be traded with the EUC.

To simulate the P2P energy trading, Figure 4.1(a) conceptualise the system model including 2 input modules, 3 model modules and 2 output modules. And Figure 4.1(b) graphically illustrates the whole process of P2P energy trading at one time step. Following is the explanation of each model module and the mathematical formulation is detailed in the following sections.

4.1.1. Input modules: Model parameters & Scenario setting

The Model parameters (M1) and Scenario setting (M2) specifies the target case with input parameters and preset a certain scenario to the system model. The model parameters cover the time duration & resolution, energy profiles for peers and price information in the market, which are detailed in the System input M1 of Figure 4.1(a).

Another system input is the Scenario setting for comparative evaluation of the proposed market mechanism across scenarios. For this research, four scenarios are formulated about the P2P energy trading market :

1. No P2P energy trading (S_0)
   The benchmark scenario is without the P2P energy trading, where the peers only consume the electricity & heat generated by their own portfolio, sell surplus electricity to the EUC and buy deficient electricity from the EUC.

2. P2P electricity-only trading (S_1)
   Compared to the scenario S_0, peers could exchange electricity directly with each other to deal with the surplus/deficient electricity.

3. P2P electricity-heat trading (S_2)
   Added on scenario S_1, peer could exchange heat directly with each other but without coalitional trading. Therefore, the HP becomes an active generation device, where peers could decide whether to activate or withhold their HP capacity to sell or buy heat through P2P trading.

4. P2P electricity-heat coalitional trading (S_3)
   Based on scenario S_2, coalition formulation is enabled for peers to choose between electricity-only and electricity-heat trading coalition. This scenario enables social cooperation between peers and explores the multi-energy synergies at the same time.

4.1.2. Model modules: Energy balance and net benefit definition, Coalition formation and trading strategy & Heat and electricity market clearing

Subsequently, for the model modules, Energy balance and net benefit definition (M3), Coalition formation and trading strategy (M4) and Heat and electricity market clearing (M5) have a sequential order to simulate the P2P energy market operation with iterations between M5 and M4.

M3: The trading objective of each peer is to maintain the energy balance and maximise the net benefit. Therefore, to simulate each peer's decision-making process, it is important to define the energy profiles and cost & benefit functions for each peer in the first place (detailed in section 4.2). The expected energy surplus or deficiency influences the peer's trading position in the P2P energy market. Under the current pricing scheme, the peer will balance between the expected cost & benefit from trading based on the guiding P2P electricity & heat price. The benefit includes the demand utility of heat consumption, selling revenue of electricity & heat, and the cost includes HP generation cost and purchase cost of electricity & heat. Then the net benefit functions are obtained for all the trading positions, e.g. electricity seller or buyer and heat seller or buyer.

M4: Next, each peer determines the best trading strategy including coalition selection and heat & electricity trading volume by optimising its net benefit function (detailed in section 4.4). Specifically, one peer will only select Coalition $\mathbb{Y}$ to participate in the P2P heat trading when it could obtain a positive benefit. Thereby certain price conditions are derived for being a heat seller and buyer respectively; under other price conditions, the peer will quit the heat trading and select Coalition $\mathbb{X}$. Both heat consumption level and heat trading volume are the decision variables in the optimisation that influence the electricity demand. Then the electricity trading volume is obtained based on the electricity balance equation, which determines to be an electricity seller or buyer.

M5: After receiving all the trading strategies from the peers, the market operator clears the heat & electricity market within each coalition (detailed in section 4.5). No "heat utility company" exists as a backup option to maintain the system-level heat balance. Therefore, the market operator firstly clears the heat market in Coalition 𝕐 by negotiating with certain peers to reject or curtail their heat orders until the heat selling and buying volumes are equal. Therefore, there are iterations between M4 and M5 to update trading strategies and finalise the coalition formation. Then the market operator clears the electricity market in Coalition 𝕏 & 𝕐 separately by trading electricity imbalance with EUC and determining the P2P electricity price.

4.1.3. Output modules: Output indicators & Evaluation criteria

Finally, the output modules include Output indicators (M6) and Evaluation criteria (M7) to obtain the model results. The arrow from M5 to M2 explains that the system model is run for each scenario, from which the result is stored in the M6 of the specific scenario. Furthermore, the M7 compares and synthesises the indicator results across scenarios into a structured set of evaluation criteria adapted from [32], which showcases the economic and social performance of the proposed market mechanism. The mathematical formulation of 3 indicators and 4 evaluation criteria is detailed in section 4.7.

Next, we analytically formulate the model modules. Section 4.2 & 4.3 firstly defines the energy balance and net benefit functions for peers and thereby section 4.4 derives their trading strategies under different price conditions. Next, section 4.5 showcases the market clearing by determining the P2P electricity and heat price in each coalition. And the core algorithm for coalition formation is shown in section 4.6. In the end, section 4.7 defines the indicators and criteria for comparative evaluation.

4.2. Definition of peers' energy demand and generation profile

Firstly, we define the electricity and heat balance equations and delineate each element in this section. Secondly in section 4.3, we define the benefit and cost function for all the trading positions, i.e. electricity seller or buyer, heat seller or buyer. These two steps complete the module M3 to serve as the basis to decide the best trading strategies in section 4.4Let ℕ denotes the set of N peers. We firstly delineate the energy profiles for peer n ($n \in \mathbb{N}$) at time step t ($t \leq T$, T is the total time steps) including electricity & heat demand and generation. All the defined variables should be non-negative unless specifically mentioned.

For electricity demand profiles, we split up the total electricity demand $E^{dem}_{n,t}$ into non-trading base demand including base electricity demand $e^{bas}_{n,t}$ and electricity consumption $E^{hp,bas}_{n,t}$ to drive the HP to meet the base heat demand, and HP electricity consumption $E^{hp,tra}_{n,t}$ to generate extra heat for P2P trading (Eq.4.1). For electricity generation profiles, as shown in Eq.4.2, the total generation $e^{gen}_{n,t}$ consists of electricity generation from PV $e^{pv}_{n,t}$ and WT $e^{wt}_{n,t}$

$$E^{dem}_{n,t} = e^{bas}_{n,t} + E^{hp,bas}_{n,t} + E^{hp,tra}_{n,t} \tag{4.1}$$

$$e^{gen}_{n,t} = e^{pv}_{n,t} + e^{wt}_{n,t} \tag{4.2}$$

For heat demand profile, the base heat demand is defined as $q^{bas}_{n,t}$, but due to elastic heat demand, the real heat consumption is defined as $Q^{bas}_{n,t} \leq q^{bas}_{n,t}$ (Eq.4.3). Since HP is the only heat generation device, correspondingly, the heat generation profile $Q^{gen}_{n,t}$ includes heat generation from HP for base demand $Q^{hp,bas}_{n,t}$ and for trading $Q^{hp,tra}_{n,t}$ (Eq.4.4). In contrast to weather-dependent PV and WT, the heat generation from HP is controllable by electricity consumption $E^{hp,bas}_{n,t}$ & $E^{hp,tra}_{n,t}$ and constrained by the HP capacity $q^{hp,max}_{n}$ as shown in Eq.4.5-4.7. $cop_{n,t}$, short for coefficient of performance, is an efficiency indicator for HP that differs from working fluid and fluctuates with temperature difference between hot & cold sources [49].

$$Q_{n,t}^{dem} = Q_{n,t}^{bas} \tag{4.3}$$

$$Q_{n,t}^{gen} = Q_{n,t}^{hp,bas} + Q_{n,t}^{hp,tra}, \text{ where } Q_{n,t}^{hp,bas} \leq q_{n,t}^{bas} \tag{4.4}$$

$$Q_{n,t}^{hp,bas} = cop_{n,t} \cdot E_{n,t}^{hp,bas} \tag{4.5}$$

$$Q_{n,t}^{hp,tra} = cop_{n,t} \cdot E_{n,t}^{hp,tra} \tag{4.6}$$

$$Q_{n,t}^{hp,bas} + Q_{n,t}^{hp,tra} \leq q_{n}^{hp,max} \tag{4.7}$$

Furthermore, the expected difference between energy demand and generation at t is linked with peer n's trading strategy and eventually leads to the energy exchanges between peer n and other peers & EUC. We define $E_{n,t}^{sel}$ and $E_{n,t}^{buy}$ as the electricity sold and bought in the P2P electricity market (including the transaction with the EUC). But at one time step, one peer could only take one position between seller and buyer, i.e. $E_{n,t}^{sel} \cdot E_{n,t}^{buy} = 0$. Similarly, $Q_{n,t}^{sel}$ and $Q_{n,t}^{buy}$ are defined for the P2P heat market and $Q_{n,t}^{sel} \cdot Q_{n,t}^{buy} = 0$. Thereby the electricity and heat balance equations are formulated as Eq.4.8-4.9, where $e_{n,t}^{bas}$, $e_{n,t}^{pv}$ and $e_{n,t}^{wt}$ are parameters and others are variables.

$$e_{n,t}^{bas} + E_{n,t}^{hp,bas} + E_{n,t}^{hp,tra} + E_{n,t}^{sel} = e_{n,t}^{pv} + e_{n,t}^{wt} + E_{n,t}^{buy} \tag{4.8}$$

$$Q_{n,t}^{bas} + Q_{n,t}^{sel} = Q_{n,t}^{hp,bas} + Q_{n,t}^{hp,tra} + Q_{n,t}^{buy} \tag{4.9}$$

4.3. Definition of benefits and costs in the P2P energy trading

4.3.1. Benefits and costs in the electricity trading

We assume all the peers will participate in the P2P electricity trading. The motivation is that under the mid-market rate pricing scheme, either the P2P electricity selling price $p_t^{e,sel}$ or buying price $p_t^{e,buy}$ will lie between buying price $p_t^{buy,euc}$ from EUC and selling price $p_t^{sel,euc}$ to EUC as shown in Eq.4.10. Thereby as either sellers or buyers, peers could obtain more benefits to participate in the P2P electricity trading compared to the trading with EUC.

$$p_t^{sel,euc} \leq p_t^{e,sel} \leq p_t^{e,buy} \leq p_t^{buy,euc} \tag{4.10}$$

So the benefit (revenue) $R_{n,t}^{e}$ for electricity trading is defined as Eq.4.11. Such formulations include the transaction costs/benefits both with other peers and EUC as the P2P electricity trading price is adjusted to reflect the whole system cost/benefit based on the system-level imbalance (details in section 4.5).

$$R_{n,t}^{e} = E_{n,t}^{sel} \cdot p_t^{e,sel} - E_{n,t}^{buy} \cdot p_t^{e,buy} \tag{4.11}$$

4.3.2. Benefits and costs in the heat trading

In contrast, the rationale to choose in or out of the P2P heat trading depends on the trade-off between the potential benefits and costs for either heat seller hs or for heat buyer hb. Let $\mathbb{HS}$ and $\mathbb{HB}$ denotes the set of heat sellers and heat buyers respectively, where $hs \in \mathbb{HS}$ and $hb \in \mathbb{HB}$.

From the heat seller's perspective, the benefits includes heat demand utility $U_{hs,t}$ of consuming heat $Q_{hs}^{hp,bas}$ and revenue $R_{hs,t}^{h}$ of selling heat $Q_{hs,t}^{hp,tra}$ at P2P heat selling price $p_t^{h,sel}$; the costs includes HP generation cost $C_{hs,t}^{hp}$ of heat $(Q_{hs}^{hp,bas}+Q_{hs,t}^{hp,tra})$. Therefore, the net benefit $B_{hs,t}$ is formulated as the different between benefits and costs (Eq.4.12).

$$B_{hs,t}=U_{hs,t}+R_{hs,t}^{h}-C_{hs,t}^{hp} \tag{4.12}$$

We firstly define $U_{hs,t}$ as a quadratic utility function of heat consumption (Eq.4.13) that is widely-used especially in the studies of integrated demand response [50]–[52]. v_{hs} is the scaling factor and $u_{hs,t}$ is the heat preference coefficient for peer hs, representing various satisfaction levels across peers from consuming heat. The rationale behind the different v_{hs} and $u_{hs,t}$ could be the sensitivity to heat comfort and urgency for heat consumption. But we do not consider the inter-temporal connection of the heat demand since heat demand is usually less shiftable than electricity demand. Essentially, v_{hs} and $u_{hs,t}$ are the parameters of the quadratic function to differentiate the actual heat demand of different peers across different time steps. This concave function indicates a decreasing marginal utility as the heat consumption approaches the saturation level of q_{hs}^{bas}/u_{hs}. Secondly, Eq.4.14 defines the sales revenue $R_{hs,t}^{h}$ for the seller,

$$U_{hs,t}=v_{hs}\cdot(q_{hs,t}^{bas}\cdot Q_{hs,t}^{hp,bas}-\frac{u_{hs}}{2}\cdot(Q_{hs,t}^{hp,bas})^2) \tag{4.13}$$

$$R_{hs,t}^{h}=Q_{hs}^{hp,tra}\cdot p_{t}^{h,sel} \tag{4.14}$$

Thirdly, there are two parts for generation cost $C_{hs,t}^{hp}$ including variable fuel (electricity) cost $C_{hs,t}^{hp,e}$ and levelised fixed cost $C_{hs}^{hp,f}$ of HP (Eq.4.15). The electricity used by HP implicates an opportunity cost of $p_{t}^{e,sel}$ if selling in the P2P market, so $C_{hs,t}^{hp,e}$ is defined as Eq.4.16. $p_{hs}^{hp,f}$ is introduced to represent the degradation cost of unit generation for HP, which is a constant for all the time steps. $p_{hs}^{hp,f}$ is defined as the net present value (NPV) of initial investment cost ic_{hs}^{hp} and yearly Operation&Maintenance cost om_{hs}^{hp} over the lifetime l_{hs}^{hp} divided by the NPV of yearly heat generation hg_{hs}^{hp} over l_{hs}^{hp}. Assuming om_{hs}^{hp} and hg_{hs}^{hp} keep the same for each year, Eq.4.17 demonstrates the calculation method with a discount rate of r. Thereby $C_{hs}^{hp,f}$ is derived as Eq.4.18.

$$C_{hs,t}^{hp}=C_{hs,t}^{hp,e}+C_{hs,t}^{hp,f} \tag{4.15}$$

$$C_{hs,t}^{hp,e}=\frac{Q_{hs,t}^{hp,bas}+Q_{hs,t}^{hp,tra}}{cop_{hs,t}}\cdot p_{t}^{e,sel} \tag{4.16}$$

$$p_{hs}^{hp,f}=\frac{ic_{hs}^{hp}+\Sigma_{l=1}^{l_{hs}^{hp}}\frac{om_{hs}^{hp}}{(1+r)^{l}}}{\Sigma_{l=1}^{l_{hs}^{hp}}\frac{hg_{hs}^{hp}}{(1+r)^{y}}}=\frac{ic_{hs}^{hp}\cdot r+om_{hs}^{hp}\cdot(1-(1+r)^{-l_{hs}^{hp}})}{hg_{hs}^{hp}\cdot(1-(1+r)^{-l_{hs}^{hp}})} \tag{4.17}$$

$$C_{hs,t}^{hp,f}=(Q_{hs,t}^{hp,bas}+Q_{hs,t}^{hp,tra})\cdot p_{hs}^{hp,f} \tag{4.18}$$

Next, from the heat buyer's perspective, the benefits includes heat demand utility $U_{hb,t}$ to consume heat $(Q_{hb,t}^{hp,bas}+Q_{hb,t}^{buy})$; the costs includes HP generation cost $C_{hb,t}^{hp}$ of heat $Q_{hb,t}^{hp,bas}$ and heat purchase cost (equal to minus revenue) $-R_{hb,t}^{h}$ of heat $Q_{hb,t}^{buy}$ at P2P buying price $p_{t}^{h,buy}$. Similarly, the net benefit for the heat buyer $B_{hb,t}$ is defined as Eq.4.19-4.22.

$$U_{hb,t}=v_{hb}\cdot(q_{hb,t}^{bas}\cdot(Q_{hb,t}^{hp,bas}+Q_{hb,t}^{buy})-\frac{u_{hb,t}}{2}\cdot(Q_{hb,t}^{hp,bas}+Q_{hb,t}^{buy})^2) \tag{4.19}$$

$$C^{hp}_{hb,t} = Q^{hp,bas}_{hb,t} \cdot (\frac{p^{e,sel}_{t}}{cop_{hb,t}} + p^{hp,f}_{hb}) \tag{4.20}$$

$$R^{h}_{hb,t} = -Q^{buy}_{hb,t} \cdot p^{h,buy}_{t} \tag{4.21}$$

$$B_{hb,t} = U_{hb,t} - C^{hp}_{hb,t} + R^{h}_{hb,t} \tag{4.22}$$

4.4. Formulation of peers' coalition formation and trading strategy

Based on the net benefit functions, this section models the peers' decision-making on the coalition formation and trading volume, which aligns with module M4. Since a peer's decision in the P2P heat trading influences its electricity balance for electricity trading, we start the formulation from the heat seller's and buyer's perspective in section 4.4.1&4.4.2 to no-heat trading's perspective in section 4.4.3. And section 4.4.4 summarises the trading strategies according to different price conditions.

4.4.1. Trading strategy from the heat seller's perspective

Eq.4.23 details the optimisation problem for seller hs. The objective function is to maximise the net benefit based on Eq.4.12 with two variables $Q^{hp,bas}_{hs,t}$ & $Q^{hp,tra}_{hs,t}$ and one constraint.

$$\begin{aligned} \text{Maximise: } B_{hs,t} =& v_{hs} \cdot (q^{bas}_{hs,t} \cdot Q^{hp,bas}_{hs,t} - \frac{u_{hs,t}}{2} \cdot (Q^{hp,bas}_{hs,t})^2) + Q^{hp,tra}_{hs,t} \cdot p^{h,sel}_{t} \\ & - (Q^{hp,bas}_{hs,t} + Q^{hp,tra}_{hs,t}) \cdot (\frac{p^{e,sel}_{t}}{cop_{hs,t}} + p^{hp,f}_{hs}) \\ \text{Subject to: } & Q^{hp,bas}_{hs,t} + Q^{hp,tra}_{hs,t} \leq q^{hp,max}_{hs} \end{aligned} \tag{4.23}$$

In the objective function, there are two benefit components including heat demand utility and selling revenue and only one cost component from HP generation. We obtained the marginal benefit/cost of each component based on the first-derivative function. $MB_{hs,1}$ is a decreasing function and $MB_{hs,2}$ & MC_{hs} are constant. To maximise the net benefit, the peer hs chooses to consume or sell heat by comparing the $MB_{hs,1}$ and $MB_{hs,2}$. There is a threshold value of $Q^{hp,bas}_{hs,t}$ when $MB_{hs,1} = MB_{hs,2}$ as the best heat consumption level $Q^{con*}_{hs,t}$ (Eq.4.25).

$$\begin{aligned} &\text{Marginal cost/benefit:} \\ &MB_{hs,1} = \frac{\partial U_{hs,t}}{\partial Q^{hp,bas}_{hs,t}} = v_{hs} \cdot (q^{bas}_{hs,t} - u_{hs,t} \cdot Q^{hp,bas}_{hs,t}) \\ &MB_{hs,2} = \frac{\partial R^{h}_{hs,t}}{\partial Q^{hp,tra}_{hs,t}} = p^{h,sel}_{t} \\ &MC_{hs} = \frac{\partial C^{hp}_{hs,t}}{\partial Q^{hp,\cdot}_{hs,t}} = \frac{p^{e,sel}_{t}}{cop_{hs,t}} + p^{hp,f}_{hs} \end{aligned} \tag{4.24}$$

$$MB_{hs,1} = MB_{hs,2} \Rightarrow Q^{con*}_{hs,t} = Q^{hp,bas}_{hs,t} = \frac{q^{bas}_{hs,t}}{u_{hs,t}} - \frac{p^{h,sel}_{t}}{v_{hs} \cdot u_{hs,t}} \tag{4.25}$$

Therefore, the condition to be a heat seller is that (1) $MB_{hs,2} > MC_{hs}$ when peer hs could increase the net benefit from selling heat and (2) $Q^{con*}_{hs,t} < q^{hp,max}_{hs}$ when there is remaining HP capacity for trading as derived in Eq.4.26. If the two conditions are met, the best trading strategy is to sell

$Q^{sel}_{hs,t} = q^{hp,max}_{hs} - Q^{con*}_{hs,t}$ (Eq.4.27).

$$\begin{aligned} MB_{hs,2} > MC_{hs} &\Rightarrow p^{h,sel}_t > \frac{p^{e,sel}_t}{cop_{hs,t}} + p^{hp,f}_{hs} \\ Q^{con*}_{hs,t} < q^{hp,max}_{hs} &\Rightarrow p^{h,sel}_t > v_{hs} \cdot (q^{bas}_{hs,t} - u_{hs,t} \cdot q^{hp,max}_{hs}) \end{aligned} \tag{4.26}$$

$$Q^{sel}_{hs,t} = q^{hp,max}_{hs} - \frac{q^{bas}_{hs,t}}{u_{hs,t}} + \frac{p^{h,sel}_t}{v_{hs} \cdot u_{hs,t}} \tag{4.27}$$

Subsequently, we could decide the peer's position in the P2P electricity trading referred to Eq.4.8, where $E^{hp,bas}_{hs,t} + E^{hp,tra}_{hs,t} = \frac{q^{hp,max}_{hs}}{cop_{hs,t}}$. The electricity balance is obtained as follows:

$$e^{bas}_{hs,t} + \frac{q^{hp,max}_{hs}}{cop_{hs,t}} + E^{sel}_{hs,t} = e^{pv}_{hs,t} + e^{wt}_{hs,t} + E^{buy}_{hs,t} \tag{4.28}$$

So if $E^{sel}_{hs,t} > 0$, the strategy taken by peer hs is to sell electricity $E^{sel}_{hs,t}$; otherwise if $E^{buy}_{hs,t} > 0$, the strategy is to buy $E^{buy}_{hs,t}$.

4.4.2. Trading strategy from the heat buyer's perspective

Eq.4.29 details the optimisation problem for buyer hb. The objective function is to maximise the net benefit based on Eq.4.22 with two variables $Q^{hp,bas}_{hb,t}$ & $Q^{buy}_{hb,t}$ and no constraint.

$$\begin{aligned} \text{Maximise: } B_{hb,t} = & v_{hb} \cdot (q^{bas}_{hb,t} \cdot (Q^{hp,bas}_{hb,t} + Q^{buy}_{hb,t}) - \frac{u_{hb,t}}{2} \cdot (Q^{hp,bas}_{hb,t} + Q^{buy}_{hb,t})^2) \\ & - Q^{hp,bas}_{hb,t} \cdot (\frac{p^{e,sel}_t}{cop_{hb,t}} + p^{hp,f}_{hb}) - Q^{buy}_{hb,t}) \cdot p^{h,buy}_t \end{aligned} \tag{4.29}$$

In the objective function, the only benefit for peer nb is the demand utility of actual base heat consumption $Q^{con}_{hb} = Q^{hp,bas}_{hb,t} + Q^{buy}_{hb,t}$, and the marginal benefit MB_{hb} is decreasing; there are two ways to meet the heat demand: either self-generation at the cost $MC_{hb,1}$ of or buying heat at the cost of $MC_{hb,2}$ as shown in Eq.4.30. It could be observed that each of the two marginal cost is a constant at the time step t.

$$\begin{aligned} &\text{Marginal cost/benefit:} \\ &MB_{hb} = \frac{\partial U_{hb,t}}{\partial Q^{con}_{hb,t}} = v_{hb} \cdot (q^{bas}_{hb,t} - u_{hb,t} \cdot Q^{con}_{hb,t}) \\ &MC_{hb,1} = \frac{p^{e,sel}_t}{cop_{hb,t}} + p^{hp,f}_{hb} \\ &MC_{hb,2} = p^{h,buy}_t \end{aligned} \tag{4.30}$$

Consequently, to maximise its benefit, the peer hb will always choose one way that has a cost advantage over the other to meet the heat demand. To become a heat buyer, the first condition in Eq.4.31 should be met that the heat buying price is lower than the self-generation cost. Then we could derive the best heat consumption level $Q^{con*}_{hb,t}$ when the marginal benefit is equal to $p^{h,buy}_t$ as shown in Eq.4.32. The $Q^{con*}_{hb,t}$ needs to be larger than 0, so we obtain the second condition in Eq.4.31.

If the two conditions are met, the best trading strategy is to buy $Q^{buy}_{hb,t} = Q^{con*}_{hb,t}$.

$$\begin{aligned} MC_{hb,2} < MC_{hb,1} &\Rightarrow p^{h,buy}_t < \frac{p^{e,sel}_t}{cop_{hb,t}} + p^{hp,f}_{hb} \\ Q^{con*}_{hb,t} > 0 &\Rightarrow p^{h,buy}_t < q^{bas}_{hb,t} \cdot v_{hb} \end{aligned} \tag{4.31}$$

$$\frac{\partial U_{hb,t}}{\partial Q^{con}_{hb,t}} = p^{h,buy}_t \Rightarrow Q^{con*}_{hb,t} = \frac{q^{bas}_{hb,t}}{u_{hb,t}} - \frac{p^{h,buy}_t}{v_{hb} \cdot u_{hb,t}} \tag{4.32}$$

Subsequently, because there is no heat self-generation, namely $E^{hp,bas}_{hb,t} + E^{hp,tra}_{hb,t} = 0$, the electricity balance is obtained based on Eq.4.8:

$$e^{bas}_{hb,t} + E^{sel}_{hb,t} = e^{pv}_{hb,t} + e^{wt}_{hb,t} + E^{buy}_{hb,t} \tag{4.33}$$

So if $E^{sel}_{hb,t} > 0$, the strategy taken by peer hb is to sell electricity $E^{sel}_{hb,t}$; otherwise if $E^{buy}_{hb,t} > 0$, the strategy is to buy $E^{buy}_{hb,t}$.

4.4.3. Trading strategy from the electricity-only trader's perspective

When the price conditions in Eq.4.26 and Eq.4.31 are not met, peer n will choose to only participate in the P2P electricity trading instead of the P2P heat trading. In this case, the heat demand is met from self-generation only, therefore, the net benefit $B_{n,t}$ from heat consumption $Q^{con}_{n,t}$ (equal to $Q^{con}_{n,t}$) is defined as the different between the demand utility $U_{n,t}$ and generation cost $C^{hp}_{n,t}$ (Eq.4.34). The optimisation problem is to maximise the $B_{n,t}$ with one variable $Q^{con}_{n,t}$.

$$\begin{aligned} \text{Maximise: } B_{n,t} &= U_{n,t} - C^{hp}_{n,t} \\ &= v_n \cdot (q^{bas}_{n,t} \cdot Q^{con}_{n,t} - \frac{u_{n,t}}{2} \cdot (Q^{con}_{n,t})^2) - Q^{con}_{n,t} \cdot (\frac{p^{e,sel}_t}{cop_{n,t}} + p^{hp,f}_n) \end{aligned} \tag{4.34}$$

The necessary optimality condition is derived as Eq.4.35, and the second derivative is negative. In addition, the heat consumption should be smaller than the HP capacity. Therefore, we obtain the maximum point $Q^{con*}_{n,t}$ from the optimality condition as shown in Eq.4.36, which indicates that the peer n is willing to conduct heat demand response at this level. And $Q^{con*}_{n,t}$ should be larged than 0 and smaller than the HP capacity.

$$\begin{aligned} &\text{The necessary optimality conditions:} \\ &\frac{\partial B_{n,t}}{\partial Q^{con}_{n,t}} = v_n \cdot (q^{bas}_{n,t} - u_{n,t} \cdot Q^{con}_{n,t}) - (\frac{p^{e,sel}_t}{cop_{n,t}} + p^{hp,f}_n) = 0 \\ &\text{The second derivative:} \\ &\frac{\partial^2 B_{n,t}}{\partial (Q^{con}_{n,t})^2} = -\, v_n \cdot u_{n,t} < 0 \end{aligned} \tag{4.35}$$

$$Q^{con*}_{n,t} = \max\{\min\{\frac{q^{bas}_{n,t}}{u_{n,t}} - \frac{\frac{p^{e,sel}_t}{cop_{n,t}} + p^{hp,f}_n}{v_n \cdot u_{n,t}}, q^{hp,max}_n\}, 0\} \tag{4.36}$$

Subsequently, according to the electricity balance Eq.4.8, where $E_{n,t}^{hp,bas} = \frac{Q_{n,t}^{con*}}{cop_{n,t}}$ and $E_{n,t}^{hp,tra} = 0$, the $E_{n,t}^{sel}$ and $E_{n,t}^{buy}$ could be calculated as shown in Eq.4.37.

$$e_{n,t}^{bas} + \frac{Q_{n,t}^{con*}}{cop_{n,t}} + E_{n,t}^{sel} = e_{n,t}^{pv} + e_{n,t}^{wt} + E_{n,t}^{buy} \tag{4.37}$$

So if $E_{n,t}^{sel} > 0$, the peer chooses to be a electricity seller and conducts the trading strategy to sell $E_{n,t}^{sel}$; otherwise if $E_{n,t}^{buy} > 0$, the peer chooses to be a electricity buyer with the trading volume $E_{n,t}^{buy}$.

4.4.4. Trading strategy summary based on four price conditions

Based on the discussion above, any peer n's willing to participate in the P2P heat trading is dependent on the dynamic price conditions as shown in Eq.4.26 and Eq.4.31. Therefore, at each time step t, we introduce two coalitions $\mathbb{X}$ and $\mathbb{Y}$ for peers to choose:

1. Electricity-only trading Coalition $\mathbb{X}$: peer $x \in \mathbb{X}$ only participates in the P2P electricity trading as either a seller or buyer. Peer x's HP supplies its own base heat demand as a passive electricity consumption device
2. Electricity-heat trading Coalition $\mathbb{Y}$: peers $y \in \mathbb{Y}$ participate in both P2P electricity and heat trading. Peer y utilises HP as an active generation device and decides whether to generate surplus heat for selling or to buy heat in the P2P market instead of generating at the maximum level.

In summary, Table 4.1 demonstrates the peers' trading strategies according to the P2P trading price conditions. Based on condition Eq.4.26 and Eq.4.31, Eq.4.38 introduces two price thresholds for the coalition selection. In case 1, peer n is willing to join the Coalition $\mathbb{Y}$ as a heat seller and the best trading strategy is to sell $Q_{n,t}^{sel}$ heat; its real-time electricity generation and demand (including usage for heat generation) will decide peer n's position in the electricity trading. In contrast, in case 2, peer n is willing to join the Coalition $\mathbb{Y}$ as a heat buyer to buy $Q_{n,t}^{buy}$. A special case 4 motivates the peer n to join the Coalition $\mathbb{Y}$ either as a buyer or seller; then peer n will compare the net benefit of the two positions and choose the better one. As for case 3, peer n is willing to join the Coalition $\mathbb{X}$ excluding the P2P heat trading, and its trading strategy is dependent on the electricity surplus or deficiency to sell $E_{n,t}^{sel}$ or buy $E_{n,t}^{buy}$.

$$\begin{aligned} p_{n,t}^{h,sel,th} &= \max\{\frac{p_t^{e,sel}}{cop_{n,t}} + p_n^{hp,f}, v_n \cdot (q_{n,t}^{bas} - u_{n,t} \cdot q_n^{hp,max})\} \\ p_{n,t}^{h,buy,th} &= \min\{\frac{p_t^{e,sel}}{cop_{n,t}} + p_n^{hp,f}, v_n \cdot q_{n,t}^{bas}\} \end{aligned} \tag{4.38}$$

4.5. Formulation of P2P heat and electricity market clearing

Finally, this section showcases the market clearing by determining the P2P electricity and heat price in each coalition (module M5). The market operator will clear the heat market and then electricity market in Coalition $\mathbb{Y}$ before the electricity market in Coalition $\mathbb{Y}$

Above all, the mid-value $p_t^{e,mid}$ between electricity buying and selling price with EUC is utilised as the electricity guiding price (Eq.4.39). As for Coalition $\mathbb{Y}$, the guiding heat price $p_t^{h,mid}$ is defined to be directly proportional to $p_t^{e,mid}$ with the proportionality constant α (Eq.4.40). In addition, we assume a linear relationship between $p_t^{h,sel}$ and $p_t^{h,buy}$ as shown in Eq.4.41, where β implicates the

Table 4.1: Summary of the peer's trading strategy based on various price conditions

Case	Price condition	Coalition	Trading strategy
1	$p_t^{h,sel} > p_{n,t}^{h,sel,th}$ and $p_t^{h,buy} \geq p_{n,t}^{h,buy,th}$	$\mathbb{Y}$	Heat: sell $Q_{n,t}^{sel}$; Electricity: sell $E_{n,t}^{sel}$ or buy $E_{n,t}^{buy}$
2	$p_t^{h,sel} \leq p_{n,t}^{h,sel,th}$ and $p_t^{h,buy} < p_{n,t}^{h,buy,th}$	$\mathbb{Y}$	Heat: buy $Q_{n,t}^{buy}$; Electricity: sell $E_{n,t}^{sel}$ or buy $E_{n,t}^{buy}$
3	$p_t^{h,sel} \leq p_{n,t}^{h,sel,th}$ and $p_t^{h,buy} \geq p_{n,t}^{h,buy,th}$	$\mathbb{X}$	Heat: N/A; Electricity: sell $E_{n,t}^{sel}$ or buy $E_{n,t}^{buy}$
4	$p_t^{h,sel} > p_{n,t}^{h,sel,th}$ and $p_t^{h,buy} < p_{n,t}^{h,buy,th}$	$\mathbb{Y}$	Heat: either sell $Q_{n,t}^{sel}$ or buy $Q_{n,t}^{buy}$ determined by which net benefit is larger; Electricity: sell $E_{n,t}^{sel}$ or buy $E_{n,t}^{buy}$

regulated surcharge for the buyer such as network subscription fee and tax. Specifically, the guiding heat price $p_t^{h,mid}$ is used as $p_t^{h,sel}$ and thus $p_t^{h,buy} = (1+\beta)\cdot p_t^{h,mid}$.

$$p_t^{e,mid} = \frac{p_t^{buy,euc} + p_t^{sel,euc}}{2} \tag{4.39}$$

$$p_t^{h,mid} = \alpha \cdot p_t^{e,mid} \tag{4.40}$$

$$p_t^{h,buy} = (1+\beta)\cdot p_t^{h,sel} \tag{4.41}$$

The market clearing process should aim to safeguard the principle of heat balance. Therefore, the market operator receives all the orders in Coalition $\mathbb{Y}$ and calculates the system-level heat imbalance $Q_t^{imb,\mathbb{Y}}$ (Eq.4.42). Then the market operator decides to proportionally curtail the heat surplus or deficiency on all the sellers' or buyers' orders. The curtailment per volume of heat order Q_t^{cur} is calculated as Eq.4.43. After informing the relevant peers, the peers with negative orders after curtailment will decide to leave the Coalition $\mathbb{Y}$ and instead join the Coalition $\mathbb{X}$; the peers with positive orders after curtailment will still stay in the Coalition $\mathbb{Y}$ but changes their electricity orders based on the new heat orders. Specifically, if $Q_t^{imb,\mathbb{Y}} > 0$, the heat sellers have to curtail heat orders and thereby reduce the electricity demand originally for generating the curtailed heat volume; if $Q_t^{imb,\mathbb{Y}} < 0$, the heat buyers have to curtail heat orders and thereby demand extra electricity to self-generate the curtailed heat volume with HP. In reality, due to the implementation of proportional curtailment and mid-market rate, the negative orders would not happen and the price conditions stay the same. Therefore, all the peers will give consents to the heat order changes and submit new electricity orders. The coalition composition will not change and then the markets will be cleared.

And the detailed formulation is available in line 35-68 of algorithm 1.

$$Q_t^{imb,\mathbb{Y}} = \Sigma_{y=1}^{Y}(Q_{y,t}^{sel} - Q_{y,t}^{buy}) \tag{4.42}$$

$$\begin{aligned} &\text{If } Q_t^{imb,\mathbb{Y}} > 0,\ Q_t^{cur} = \frac{Q_t^{imb,\mathbb{Y}}}{\Sigma_{y=1}^{Y} Q_{y,t}^{sel}} \text{ for heat sellers} \\ &\text{If } Q_t^{imb,\mathbb{Y}} < 0,\ Q_t^{cur} = -\frac{Q_t^{imb,\mathbb{Y}}}{\Sigma_{y=1}^{Y} Q_{y,t}^{buy}} \text{ for heat buyers} \end{aligned} \tag{4.43}$$

By far, the coalition formation between $\mathbb{X}$ and $\mathbb{Y}$ is finalised. There will be different P2P electricity prices in the two coalition. So we introduce $p_t^{e,sel,\mathbb{X}}$ & $p_t^{e,buy,\mathbb{X}}$ to represent the Coalition $\mathbb{X}$ and $p_t^{e,sel,\mathbb{Y}}$ & $p_t^{e,buy,\mathbb{Y}}$ to represent the Coalition $\mathbb{Y}$. The electricity market clearing process in each coalition is defined as a canonical coalition game between all the electricity buyers and sellers as defined in [25]. Due to the system-level electricity imbalance and thereby trading with EUC, the electricity guiding price $p_t^{e,mid}$ should be adjusted accordingly to reflect the system-level cost. Taking Coalition $\mathbb{X}$ as an example, the electricity imbalance $E_t^{imb,\mathbb{X}}$ is defined as Eq.4.44 with positive value for surplus and negative value for deficiency. When the electricity is balanced within the coalition, the guiding prices will remain the same (see Eq.(4.45)). When there is a surplus, the surplus will be sold to the EUC with a lower price, and hence, the selling price will be decreased (see Eq.(4.47)). When there is a deficit, the operator buys electricity from the EUC at a higher price, then the buying price will be increased (see Eq.(4.48)).

$$E_t^{imb,\mathbb{X}} = \Sigma_{x=1}^{X}(E_{x,t}^{sel} - E_{x,t}^{buy}) \tag{4.44}$$

- Case 1: system balance when $E_t^{imb,\mathbb{X}} = 0$

$$p_t^{e,buy,\mathbb{X}} = p_t^{e,sel,\mathbb{X}} = p_t^{e,mid} \tag{4.45}$$

- Case 2: system surplus when $E_t^{imb,\mathbb{X}} > 0$

$$p_t^{e,buy,\mathbb{X}} = p_t^{e,mid} \tag{4.46}$$

$$p_t^{e,sel,\mathbb{X}} = \frac{\Sigma_{x=1}^{X} E_{x,t}^{buy} \cdot p_t^{e,mid} + E_t^{imb,\mathbb{X}} \cdot p_t^{sel,euc}}{\Sigma_{x=1}^{X} E_{x,t}^{sel}} \tag{4.47}$$

- Case 3: system deficiency when $E_t^{imb,\mathbb{X}} < 0$

$$p_t^{e,buy,\mathbb{X}} = \frac{\Sigma_{x=1}^{X} E_{x,t}^{sel} \cdot p_t^{e,mid} - E_t^{imb,\mathbb{X}} \cdot p_t^{buy,euc}}{\Sigma_{x=1}^{X} E_{x,t}^{buy}} \tag{4.48}$$

$$p_t^{e,sel,\mathbb{X}} = p_t^{e,mid} \tag{4.49}$$

This pricing scheme has the main advantage of lower computational complexity, thereby indicating higher practicality in reality. Moreover, as proved in [25], the canonical coalition game with mid-market rate has a superadditive value function with a non-empty core. Therefore, the Coalition $\mathbb{X}$ is stable - that is to say, no peer x or a subset of the $\mathbb{X}$ could benefit more by leaving the coalition or forming a new coalition. Similarly, the P2P electricity market in Coalition $\mathbb{Y}$ is cleared by determining $p_t^{e,sel,\mathbb{Y}}$ and $p_t^{e,buy,\mathbb{Y}}$.

4.6. Pseudocode for the model algorithm

Overall, Figure 4.2 gives an overview of the trading process. 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 their trading volume. After this, the two coalitions have been formed and all the peers inform the market operator about their trading volumes. The market operator then checks the heat balance. If the heat is not balanced, the operator will curtail the heat orders and inform the peers the order changes. The peers will consent the heat order changes and submit new electricity orders. If the heat is balanced, the operator will clear the heat market and then the electricity market. After checking the electricity balance from the peers, the imbalance (if any) will be traded with the EUC. At last, the electricity prices will be finalised and the market-clearing process ends.

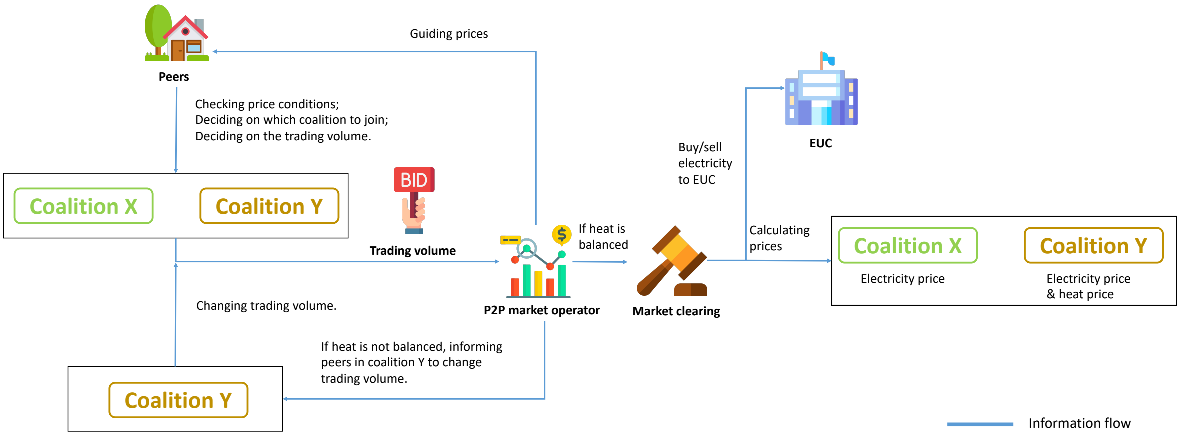


Figure 4.2: Schematic illustration for the P2P trading process

Accordingly, algorithm 1 details the model algorithm for coalition formation & trading strategy and heat & electricity market clearing step by step with pseudocode. At time step t, the algorithm starts from price information setting starts from line 2 to line 4 and peers' energy profile setting from line 6 to line 8. Next, each peer initially decides its trading strategy including trading coalition and trading quantity from line 9 to line 31. After the market operator receives all the trading strategies, line 35-68 showcases the coordination process where certain peers updates their coalition selections and orders to maintain the heat balance. By far, a stable coalition pattern has been achieved by all the peers and the market operator obtains the energy clearing price in each coalition (line 70-72). Finally, the algorithm is run for the next time step $t+1$ until the end time T.

4.7. Formulation of system output: three indicators and four evaluation criteria

The final system output is based on the set of evaluation criteria from section 4.1.3. According to the system model, 3 indicators are formulated for the Output indicators (M6), which will contribute to the calculation in Evaluation criteria (M7). When some variables do not exist in certain scenarios (e.g. no heat trading volume and price in S_0 and S_1), the relevant variables should be treated as 0.

1. *Individual energy cost (I1)* is equal to the sum of purchase cost minus revenue in both P2P electricity and heat market minus saving HP levelised cost from time step 1 to T (Eq.4.50). The subscript "·" refers to the trading coalition for peer n at t. The saving HP levelised cost actually includes two parts, i.e the cost-saving when buying heat minus the extra cost when selling heat.

$$I1_n^{S_i} = \Sigma_{t=1}^{T}(p_t^{e,\cdot,buy}\cdot E_{n,t}^{buy} + p_t^{h,buy}\cdot Q_{n,t}^{buy} - p_t^{e,\cdot,sel}\cdot E_{n,t}^{sel} - p_t^{h,sel}\cdot Q_{n,t}^{sel} - (Q_{n,t}^{buy} - Q_{n,t}^{sel})\cdot p_n^{hp,f}) \quad (4.50)$$

2. *System energy cost (I2)* is the sum of the individual energy cost of n peers (Eq.4.51).

$$I2_n^{S_i} = \Sigma_{n=1}^{N} I1_n^{S_i} \quad (4.51)$$

Algorithm 1 P2P energy trading modelling including trading strategy formulation, coalition formation and market clearing prmaintain energy balance, finalise trading coalitions and ocess to determine trading price & volume

```
Require: Set $\mathbb{N}$; Heat & electricity demand profiles $e_{n,t}^{bas}$ and $q_{n,t}^{bas}$; PV, WT and HP generation profiles $e_{n,t}^{pv}$, $e_{n,t}^{wt}$, $q_n^{hp,max}$, $cop_{n,t}$ and $p_n^{hp,f}$; Electricity trading price with electricity utility company $p_t^{buy,euc}$, $p_t^{sel,euc}$; Coefficient $\upsilon_n$, $u_{n,t}$, $\alpha$, $\beta$
Ensure: Set $\mathbb{X}$, $\mathbb{Y}$ for coalitions at each time step; P2P electricity and heat trading price $p_t^{e,buy,\mathbb{X}}$, $p_t^{e,sel,\mathbb{X}}$, $p_t^{e,buy,\mathbb{Y}}$, $p_t^{e,sel,\mathbb{Y}}$, $p_t^{h,buy}$, $p_t^{h,sel}$; P2P electricity and heat trading volume $E_{n,t}^{sel}$, $E_{n,t}^{buy}$, $Q_{n,t}^{sel}$ and $Q_{n,t}^{buy}$

for Time step $t \leftarrow 1$ to $T$ do
    Set P2P electricity selling and buying price as $p_t^{e,mid} = \frac{p_t^{buy,euc}+p_t^{sel,euc}}{2}$
    Set P2P heat selling price as $p_t^{h,sel} = \alpha \cdot p_t^{e,mid}$
    Set P2P heat buying price as $p_t^{h,buy} = (1+\beta) \cdot p_t^{h,sel}$
    for Each peer $n \in \mathbb{N}$ do
        Set the household electricity and heat demand $e_{n,t}^{bas}$ and $q_{n,t}^{bas}$
        Set the PV and WT generation $e_{n,t}^{pv}$, $e_{n,t}^{wt}$
        Set the HP capacity, COP and levelised fixed cost $q_n^{hp,max}$, $cop_{n,t}$, $p_n^{hp,f}$
        if Price condition 1 is TRUE (According to Table 4.1) then
            Peer n chooses to be in Coalition $\mathbb{Y}$ as a heat seller hs
            Decide to sell $Q_{hs,t}^{sel}$ heat according to Eq.4.27
            Decide to sell $E_{hs,t}^{sel}$ or buy $E_{hs,t}^{buy}$ electricity according to Eq.4.28
        else if Price condition 2 is TRUE then
            Peer n chooses to be in Coalition $\mathbb{Y}$ as a heat buyer hb
            Decide to buy $Q_{hb,t}^{buy}$ heat according to Eq.4.32
            Decide to sell $E_{hb,t}^{sel}$ or buy $E_{hb,t}^{buy}$ electricity according to Eq.4.33
        else if Price condition 3 is TRUE then
            Peer n chooses to be in Coalition $\mathbb{X}$
            Decide the heat consumption level $Q_{n,t}^{con*}$ according to Eq.4.36
            Decide to sell $E_{n,t}^{sel}$ or buy $E_{n,t}^{buy}$ electricity according to Eq.4.37
        else
            Calculate $Q_{hs,t}^{sel}$ and $Q_{hb,t}^{buy}$ according to Eq.4.27 and Eq.4.32 respectively
            Calculate $B_{hs,t}$ to sell $Q_{hs,t}^{sel}$ or $B_{hb,t}$ to buy $Q_{hb,t}^{buy}$ according to Eq.4.12 and Eq.4.22 respectively
            if $B_{hs,t} \geq B_{hb,t}$ then
                Peer n choose to be in Coalition $\mathbb{Y}$ as a heat seller hs
                Decide to sell $Q_{hs,t}^{sel}$ heat
                Decide to sell $E_{hs,t}^{sel}$ or buy $E_{hs,t}^{buy}$ electricity according to Eq.4.28
            else
                Peer n choose to be in Coalition $\mathbb{Y}$ as a heat buyer hb
                Decide to buy $Q_{hb,t}^{buy}$ heat
                Decide to sell $E_{hb,t}^{sel}$ or buy $E_{hb,t}^{buy}$ electricity according to Eq.4.33
            end if
        end if
    end for
    Market operator calculates the heat imbalance for Coalition $\mathbb{Y}$ $Q_t^{imb,\mathbb{Y}} = \Sigma_{y=1}^{Y}((Q_{y,t}^{sel} - (Q_{y,t}^{buy})$
```

```
    while $Q_t^{imb,\mathbb{Y}} \neq 0$ do
        if $Q_t^{imb,\mathbb{Y}} > 0$ then
            All the orders from heat buyers are accepted
            For heat sellers, the required curtailment per volume of heat order is $Q_t^{cur} = \frac{Q_t^{imb,\mathbb{Y}}}{\Sigma_{y=1}^{Y} Q_{y,t}^{sel}}$
            for Each heat seller $hs \in \mathbb{HS}$ do
                if $Q_{hs,t}^{sel} \leq Q_{hs,t}^{sel} \cdot Q_t^{cur}$ then
                    The peer hs changes its trading strategy and finally decide to be in Coalition $\mathbb{X}$
                    Decide the heat consumption level $Q_{n,t}^{con*}$ according to Eq.4.36
                    Decide to sell $E_{n,t}^{sel}$ or buy $E_{n,t}^{buy}$ electricity according to Eq.4.37
                else
                    The peer hs consents the market operator to curtail its heat order $Q_{hs,t}^{sel}$ by $Q_{hs,t}^{sel} \cdot Q_t^{cur}$ and decides to continue to be the heat seller in Coalition $\mathbb{Y}$
                    Decide the new heat consumption level (equivalent to $Q_{hs,t}^{hp,bas}$) as the minimum between $q_{hs}^{hp,max} - Q_{hs,t}^{sel}$ (available HP capacity after curtailment) and $Q_{hs,t}^{con*}$ (self-generation optimum according to Eq.4.36)
                    Decide to sell $E_{hs,t}^{sel}$ or buy $E_{hs,t}^{buy}$ electricity according to Eq.4.8
                end if
            end for
        else if $Q_t^{imb,\mathbb{Y}} < 0$ then
            All the orders from heat sellers are accepted
            For heat buyers, the required curtailment per volume of heat order is $Q_t^{cur} = -\frac{Q_t^{imb,\mathbb{Y}}}{\Sigma_{y=1}^{Y} Q_{y,t}^{buy}}$
            for Each heat buyer $hb \in \mathbb{HB}$ do
                if $Q_{hb,t}^{buy} \leq Q_{hb,t}^{buy} \cdot Q_t^{cur}$ then
                    The peer hb changes its trading strategy and finally decide to be in Coalition $\mathbb{X}$
                    Decide the heat consumption level $Q_{n,t}^{con*}$ according to Eq.4.36
                    Decide to sell $E_{n,t}^{sel}$ or buy $E_{n,t}^{buy}$ electricity according to Eq.4.37
                else
                    The peer hb consents the market operator to curtail its heat order $Q_{hb,t}^{buy}$ by $Q_{hb,t}^{buy} \cdot Q_t^{cur}$ and decides to continue to be the heat buyer in Coalition $\mathbb{Y}$
                    Decide the new heat consumption level (equivalent to $Q_{hb,t}^{hp,bas}$) as the maximum between $Q_{hb,t}^{buy}$ (buying volume after curtailment) and $Q_{hb,t}^{con*}$ (self-generation optimum according to Eq.4.36)
                    Decide to sell $E_{hb,t}^{sel}$ or buy $E_{hb,t}^{buy}$ electricity according to Eq.4.8
                end if
            end for
        end if
        Market operator calculates the new heat imbalance for Coalition $\mathbb{Y}$ $Q_t^{imb,\mathbb{Y}} = \Sigma_{y=1}^{Y}(Q_{y,t}^{sel} - Q_{y,t}^{buy})$
    end while
    Now the heat balance in Coalition $\mathbb{Y}$ is achieved
    Stable Coalition $\mathbb{X}$ and $\mathbb{Y}$ are formed by all the peers and the final electricity & heat trading orders are accepted by the market operator
    Decide the P2P electricity selling and buying price for both Coalition $\mathbb{X}$ and $\mathbb{Y}$ according to Eq.4.45-4.49
    Decide the P2P heat selling and buying price for Coalition $\mathbb{Y}$ according to Eq. 4.40 and Eq.4.41
    Record the market clearing result for each peer at time step t
    Move forward to the next time step $t+1$
end for
```

3. *Individual energy consumption (I3)* is each peer's electricity and heat consumption over T (Eq.4.52). The electricity consumption is fixed as $e_{n,t}^{bas}$; the heat consumption level $Q_{n,t}^{con}$ is recorded at each time step. However, since electricity and heat have different energy quality, we convert the heat consumption into electricity consumption by dividing the nominal COP of the installed HP cop_n.

$$I3_n^{S_i} = \Sigma_{t=1}^{T}(e_{n,t}^{bas} + \frac{Q_{n,t}^{con}}{cop_n}) \tag{4.52}$$

These indicators are applicable to all four scenarios in the system evaluation. It is assumed $S_i \in \{S_1, S_2, S_3\}$ and S_0 is the benchmark scenario for others to compare against. Hence we derive the mathematical formulation of four evaluation criteria as follows.

1. *Individual benefit of unit energy consumption (E1)* is the difference of individual energy cost $I1$ in scenario S_0 and S_i over energy consumption $I3$ in S_i.

$$E1_n^{S_i} = \frac{I1_n^{S_0} - I1_n^{S_i}}{I3_n^{S_i}} \quad S_i \in \{S_1, S_2, S_3\} \tag{4.53}$$

2. *System benefit (E2)* is the difference of system energy cost $I2$ in scenario S_0 and S_i.

$$E2^{S_i} = I2^{S_0} - I2^{S_i} \quad S_i \in \{S_1, S_2, S_3\} \tag{4.54}$$

3. *Participation willingness (E3)* is the ratio of the number of peers who have the maximum individual benefit $E1$ at scenario S_i over the total number of peers. $E3$ ranges from zero to one and $E3 = 1$ represents the highest willingness.

$$E3^{S_i} = \frac{N_{E1_n^{S_i} \geq E1_n^{S_j} \ \forall j,n}}{N} \quad S_i \in \{S_1, S_2, S_3\} \tag{4.55}$$

4. *Benefit allocation equality (E4)* is equal to 1 minus the relative mean absolute difference of individual benefit $E1$, which is referred from the definition of the Gini coefficient in economics. $E4$ ranges from zero to one and $E4 = 1$ represents perfect equality.

$$E4^{S_i} = 1 - \frac{\Sigma_{n=1}^{N}\Sigma_{m=1}^{N}|E1_n^{S_i} - E1_m^{S_i}|}{2 \cdot N * \Sigma_{n=1}^{N} E1_n^{S_i}} \quad S_i \in \{S_1, S_2, S_3\} \tag{4.56}$$

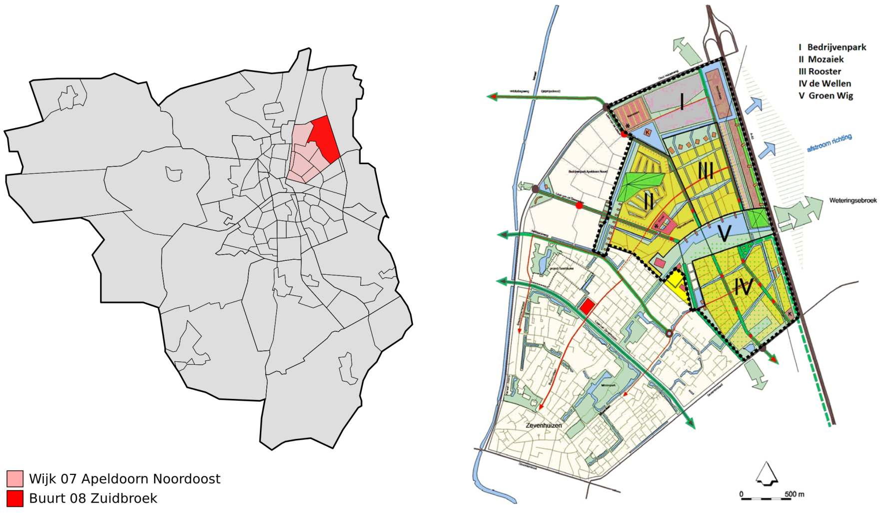
5

Case study

In this chapter, a case study is introduced to simulate the proposed market mechanism. We first introduce the basic information about the target neighbourhood (section 5.1). Then in section 5.2, the data preprocessing for each building's energy profiles are detailed, which is correlated to the geospatial information. Furthermore in section 5.3, we cluster the building into 20 upper-level energy communities for further P2P energy trading. Besides, the electricity and heat price profiles are introduced at the end (section 5.4).

5.1. Basics of Zuidbroek neighbourhood

To evaluation the proposal market mechanism, a case study is formulated based on the Zuidbroek neighbourhood in Apeldoorn, the Netherlands 5.1. As shown in Figure 5.1a, the Zuidbroek neighbourhood is located on the northeast side of Apeldoorn. And this neighbourhood consists of one business area (I), three newly-developed residential areas (II, III & IV) and one park (V) (Figure 5.1b), with around 5800 inhabitants in total [53], [54].



(a)

(b)

Figure 5.1: (a) Location of Zuidbroek in Apeldoorn, the Netherlands (Retrieved from [55]); (b) Overview map of Zuidbroek neighbourhood (Retrieved from [54])

The gas-free heat transition in the Netherlands indicates the importance to explore the market innovations to accelerate distributed electricity and heat sources [56]. Furthermore, Apeldoorn aims to be carbon neutral by 2047 and has launched the first pilot project in Zuidbroek [57]. Several energy-saving measures have been implemented including building insulation and district heating network. Therefore, there is an existing network infrastructure for electricity and heat trading and the energy-efficient buildings favour the deployment of heat pumps. Moreover, the institutional environment is friendly to set up a test bed for this P2P energy market innovation.

5.2. Energy profile setting of each building

Next, we set and differentiate the demand & generation profiles for each building combining the temporal and geospatial information. Table 5.1 summarises all the data sources.

The Geographic Information Systems (GIS) is utilised to access the geospatial data of each building in this neighbourhood [58]. There are 1485 buildings in total and six building types are identified including 14 apartments, 173 detached houses, 28 offices, 9 retails, 3 schools and 1258 terraced houses (Figure 5.2). Among them, offices, retails, schools are characterised as service-sector buildings while apartments, detached houses and terraced houses are residential buildings. In addition, we obtain the projected area of each building, ranging from 115 m^2 to 14221 m^2. The building types and projected area are two key factors to assume the energy profiles. Following are the detailed process to set the demand and generation profiles.

Category	Item	Sources
Geospatial information	Electricity & building quantity, locations, types and projected area	OpenStreetMap, OSMnx Python package
Demand profiles	Electricity & Natural gas hourly consumption profile for detached and terraced houses	Liander smart meter data in Apeldoorn
	Electricity & Heat consumption profile for other four types	PhD thesis: Harnessing Heterogeneity
Generation profiles	Hourly weather availability for PV and WT	renewables.ninja
	PV capacity for each building	Proportional to the available roof-top area, the standard product from Dutch PV Portal
	WT capacity for each building	Proportional to the total energy demand, the land use constraint from NREL
	HP capacity for each building	Determined by the 95th percentile of the heat demand
	Hourly COP fluctuation for HP	Open power system data
	Initial investment and fixed O&M cost, equivalent full load hours and life time for HP	ECN-TNO, Danish Energy Agency
Price profiles	Hourly electricity wholesale price	ENTSOE transparency platform
	Electricity retail peak and offpeak price (time-of-use tariff)	Essent N.V.

Table 5.1: Data sources for the case study setting

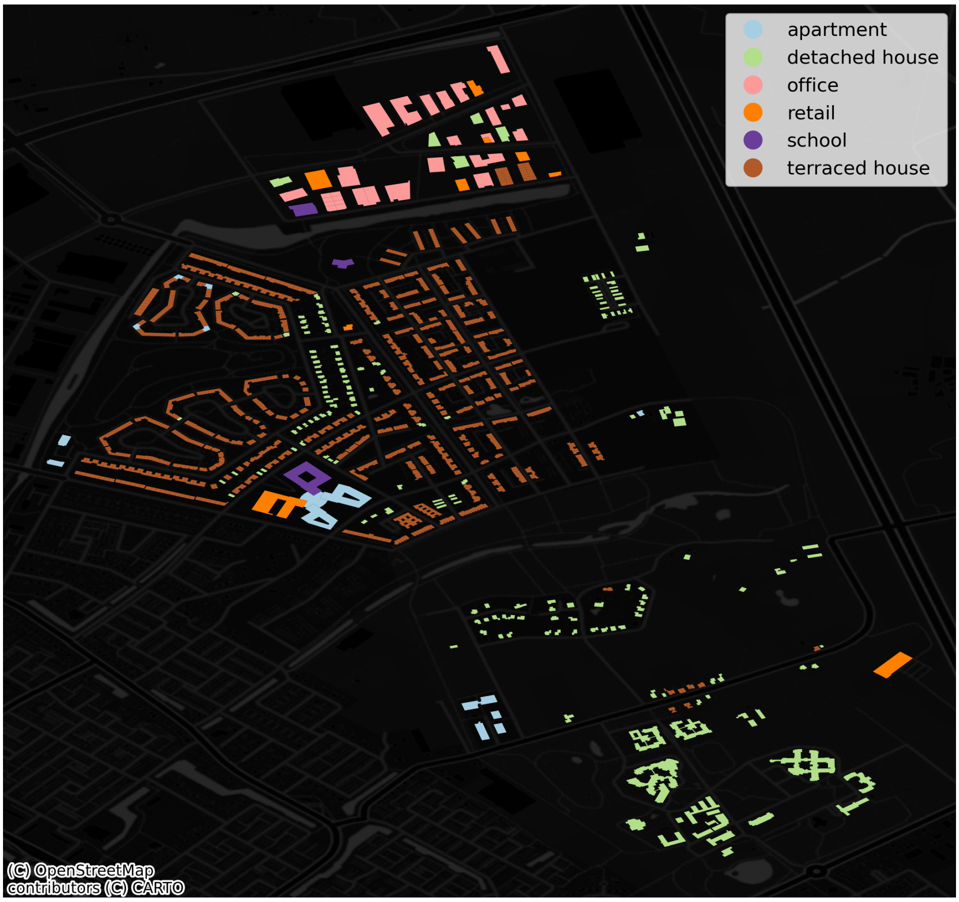


Figure 5.2: Six building types of Zuidbroek neighbourhood

5.2.1. Electricity & heat demand profile setting

In each building type, we utilise the building with the median area as the benchmark that has the standard demand profiles. And the energy demand of other buildings in each type is correlated positively with that of the benchmark building by the projected area. Eq.5.1 shows the relationship mathematically, where 0 represents the benchmark building of the type of building n. We introduce a square root function to represent a decreasing marginal demand as area increases, which to some extent avoids extreme large demand and thereby makes the variations more realistic. Essentially, the time-series pattern is the same for all the buildings of one type but the total demand varies.

$$e_{n,t}^{bas} = e_{0,t}^{bas} \cdot \sqrt{\frac{Area_n}{Area_0}} \tag{5.1}$$

$$q_{n,t}^{bas} = q_{0,t}^{bas} \cdot \sqrt{\frac{Area_n}{Area_0}} \tag{5.2}$$

Specifically, the demand profiles of Table 5.1 lists the data sources for the standard energy demand profiles for each type. As for the detached and terraced houses, we utilises the actual electricity and natural gas consumption data in 2013 from a smart meter campaign in Apeldoorn. The heat demand (kwh/hr) is converted from the natural gas consumption (m3/hr) by multiplying a unit conversion factor of 10.395 and a 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

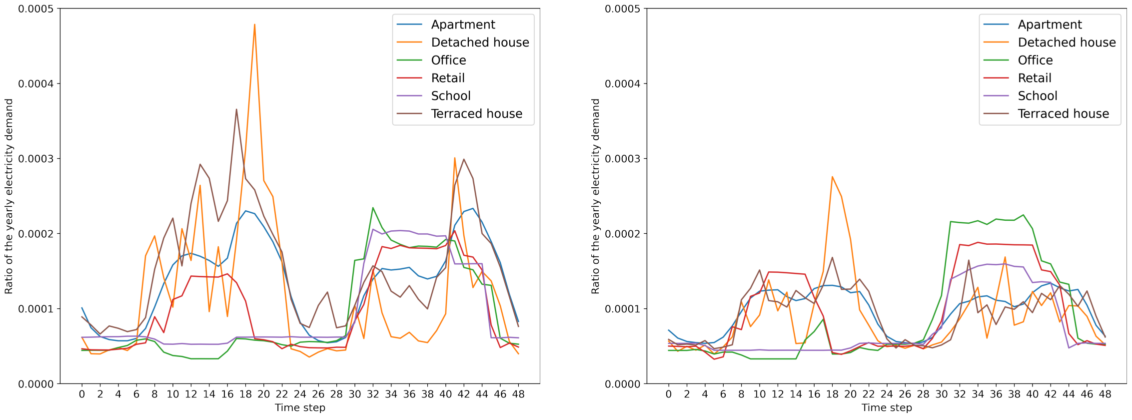
81 households. Therefore, the hourly demand for one year is obtained by calculate the mean value of the selected houses of each type respectively, which serves as the standard energy profiles. As for each of the other four types, the demand profiles from [59] is used as the the standard energy profiles. [59] applies a data-driven approaches to derive the typical demand profiles for service sectors in the Netherlands, including apartments, office, retail and school. Particularly for office, we firstly exclude the 20% of electricity demand profiles that is used for electric heating [59]. Then we scale down the electricity & heat demand based on the ratio of the median area 2843m^2 of all the offices in this region and the average area 4982m^2 of median offices used in [59].

In summary, Table 5.2 shows the median area and corresponding yearly electricity & heat demand for each building type. It could be observed that one service-sector building has a extremely larger demand profiles than that of one residential building, where the maximum difference is over 200 times between the energy demand of school and terraced house. As for residential buildings, the heat demand is considerably larger than the electricity demand while the opposite relationship is observed for service sectors. In the service sectors, lighting, ventilation systems, refrigeration and IT equipment and appliances contribute to the larger electricity consumption [60], [61].

Building type	Median area (m^2)	Electricity demand (kWh/y)	Heat demand (kWh/y)
Apartment	1349	85134	152033
Detached house	333	4120	12500
Office	2844	330590	90980
Retail	2049	365853	230995
School	4335	1136596	597443
Terraced house	173	3280	8889

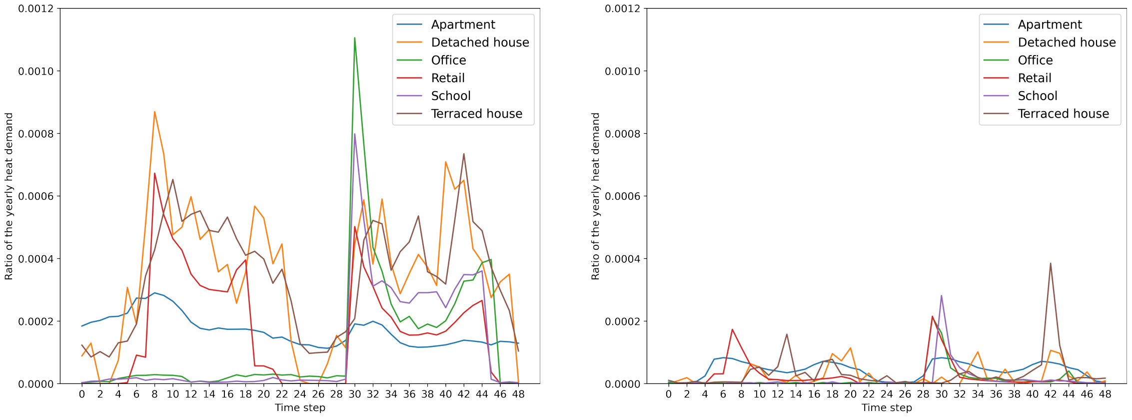
Table 5.2: Overview of the standard demand profiles for six building types

Figure 5.3 demonstrates the electricity demand pattern for a typical day of weekend and weekday in the winter and summer respectively. The y-axis represents the hourly contribution of the yearly electricity demand. There is higher electricity demand in winter than summer for residential buildings. But no obvious seasonality on the electricity demand is observed for the service-buildings. Similarly, Figure 5.4 represents the heat demand pattern. It is obvious that there is a higher heat demand in the winter for all six building types while the heat demand in the summer keeps at a low level. Furthermore, there is nearly no electricity and heat demand for office and school on weekends. And the retail has a lower electricity demand on weekends than weekdays, but the heat demand in winter is higher on weekends while the opposite relation exists in summer. In contrast, residential buildings have the same or even higher level of electricity & heat demand on weekends than weekdays. Within one day, two peak demand periods are observed in the morning and evening respectively. And service-sector buildings tend to have a considerable higher electricity & heat demand in the morning peak, especially in the winter. In general, the major differences of demand profiles lie between the 3 residential building types and 3 service-sector building types.



(a) (b)

Figure 5.3: Overview of electricity demand distribution for a typical weekend on Sunday to a typical weekday on Monday: (a) Jan. 21 - 22 in the winter and (b) Jul. 22- 23 in the summer



(a) (b)

Figure 5.4: Overview of heat demand distribution for a typical weekend on Sunday to a typical weekday on Monday: (a) Jan. 21 - 22 in the winter and (b) Jul. 22- 23 in the summer

5.2.2. Generation profile setting for roof-top PV, wind turbines and heat pumps

Next, we set the generation profiles including PV, WT and HP for each building. The generation profiles of Table 5.1 summarise the sources of weather availability, capacity and COP & economic parameters for HP. Actually, such a generation setting is a projection to fit with the distributed energy scenario in the future.

The PV capacity $e_n^{pv,max}$ of each building is calculated by assuming a utilisation rate 0.11 of the projected area and a required area 1.64 m^2 for one solar panel (Eq.5.3). The utilisation rate reflects the mismatch between the projected area and available area for PV installation due to numerous factors, including roof title & orientation and row space to avoid shadows. And the area per solar panel is referred from a Monocrystalline-silicon commercial product, which has a nominal power of 299.59W [62]. Then the standard capacity of the building with median area is 3.93 kw with 12 solar panels as shown in Table 5.3. The yearly generation is obtained combining with the weather data from [63]. In addition, Table 5.4 summarises the median, minimum and maximum capacity for each building type.

$$e_n^{pv,max} = \frac{0.11 \cdot Area_n}{1.64} \cdot 299.59 \tag{5.3}$$

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	10306

Table 5.3: Overview of the standard generation profiles for PV and WT

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

Table 5.4: Overview of the PV capacity for six building types

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 median energy demand (Eq.5.4). The standard capacity $e_0^{wt,max}$ is set as 4 kW and the total energy demand e_n^{tot} refers to the sum up of yearly electricity and heat base demand (Table 5.3). However, since electricity and heat have different energy quality, we convert the heat demand into electricity demand by dividing the nominal COP cop_n 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 [64] for weather data). According to [65], the direct land use per megawatt wind turbine is around 3035 m^2. To avoid NIMBY, the wind turbines could be installed in the park (area V in Figure 5.1b), which has a sufficient area of around 25000 $m2$. In summary, Table 5.5 shows the WT capacity for each building type.

$$e_n^{wt,max} = e_0^{wt,max} \cdot \sqrt{\frac{e_n^{tot}}{e_0^{tot}}}, \text{ where } e_n^{tot} = \Sigma_{t=1}^{T} e_{n,t}^{bas} + \frac{\Sigma_{t=1}^{T} q_{n,t}^{bas}}{cop_n} \tag{5.4}$$

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 5.5: Overview of the WT capacity for six building types

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 [66]. Table 5.6 summarise the HP capacity for each building type. The COP of HP fluctuates with the outdoor temperature and wind speed, and the average time series of an air-source heat pump in the Netherlands from 2008 to 2018 is used [67].

Based on [66], two standard profiles with different sizes are introduced as shown in Table 5.7. As for nominal COP and life time, we set 40 kW as the threshold value, which means the HP with smaller capacity than 40 kw is set the same as 5-kw profile and otherwise 160-kw profile is used. As for initial investment (ic_n^{hp}) and fixed O&M cost (om_n^{hp}), we extrapolate a simple linear regression with HP capacity as the explanatory variable from two standard profiles. Eq.5.5-5.6 details the functions and coefficients. Therefore, different degradation costs of unit generation emerge across the diverse capacity, and the rationale behind that is the principle of economies of scale [66]. In addition, the equivalent full load hours for average climate zone in the Netherlands is 1640 hours, which is used as the yearly heat generation hg_n^{hp} [68]. And the discount rate r for NPV is set as 4%, which is commonly used in the energy projects according to [69].

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 5.6: Overview of the HP capacity for six building types

HP capacity (kW)	Nominal COP	Life time (years)	Initial investment (€)	Fixed O&M cost (€)	Levelised fixed cost (cents/kWh)
5	2.95	16	6071	277	9.732
160	2.75	20	123489	2234	4.314

Table 5.7: Overview of two standard profiles for HP (5kw and 160kw)

$$ic_n^{hp} = 757.535 \cdot q_n^{hp,max} + 2283.323 \tag{5.5}$$

$$om_n^{hp} = 12.626 \cdot q_n^{hp,max} + 213.871 \tag{5.6}$$

5.3. Introduction of twenty energy communities as peers

5.3.1. Formulation of energy communities by distant-based clustering

By far, the energy profiles are obtained for all 1485 buildings. If each building is a peer in the P2P energy trading, it indicates a huge computational burden and a long duration of iterative negotiation during the market clearing. Therefore, we choose to formulate geographically closed energy communities by distant-based clustering, where each of the energy communities is a collective peer to submit trading orders together. In the current setting, each energy community itself is a Type 1 coalition of involved buildings, but in the P2P energy trading, the energy communities could form Type 2 coalitions (defined in section 2.1.2). Essentially, we could leverage this clustering technique from the household level to the city level and construct a bottom-up hierarchical P2P market structure. Therefore, a limited number of peers exist at each level of the P2P market, which showcases a durable computational complexity and a scalable characteristic for real implementation. Moreover, the formulation of energy communities could connect the households both physically and spiritually through regular catch-ups, such as on trading strategies and collective investment. Such mechanisms contribute to the social cohesion of local neighbourhoods.

In this case, the commonly-used K-Means clustering is chosen to segment the buildings into 20 clusters based on the spatial distance [70]. Firstly, we obtain the centroid of each building to represent the location. Then together with the number of clusters 20, the longitude and latitude of 1485 centroids are utilised as the input of the K-Means algorithm. Next, the algorithm (1) initialises 20 cluster centroids, and then iteratively (2) assigns each building to its nearest centroid to form a cluster and (3) updates each cluster centroid into the centroid (mean value) of the buildings in each cluster. The last two steps are iterated until the threshold condition is met. Now the threshold conditions are 10 attempts at maximum with different initial centroids and 300 iterations at maximum between step (2) and (3) in each attempt. The final result is the output of one attempt with the minimum inertia, i.e. within-cluster sum-of-squares criterion, as defined in Eq.5.7. C represents the set of cluster c_j with the centroid μ_j and x_i represents the location of the building i. Finally, Figure 5.5 showcases the final 20 peers for the P2P energy trading. Such energy communities represent an upper-level management structure from the household level. But We do not consider the cost/benefit distribution within each energy community in this study.

$$\text{inertia} = \Sigma_{i=0}^{1485} \min_{\mu_j \in C}(||x_i - \mu_j||^2) \tag{5.7}$$

Figure 5.5: 20 energy communities by clustering in the Zuidbroek neighbourhood

More specifically, Table 5.8 details the composition of building types in each peer. As mentioned in last sector, the major differences of demand profiles lie between the residential buildings and service-sector buildings. Thereby based on the yearly energy demand (combining electricity and heat), Table 5.9 demonstrations the proportion of residential and service-sector demand over total demand , which classifies each peer as residential (R), service-sector (S) and mixed (M) types.

Peer	0	1	2	3	4	5	6	7	8	9
Apartment	-	-	4	-	-	-	-	-	4	-
Detached house	1	-	-	12	6	2	4	31	32	1
Office	-	-	-	-	-	-	15	-	-	-
Retail	-	-	-	-	-	-	5	-	-	-
School	-	-	-	-	-	-	-	-	-	-
Terraced house	114	73	128	12	120	130	32	53	2	80
Peer	10	11	12	13	14	15	16	17	18	19
Apartment	-	-	1	-	1	-	-	2	2	-
Detached house	1	13	4	15	6	24	1	11	-	9
Office	13	-	-	-	-	-	-	-	-	-
Retail	1	1	-	-	1	-	-	-	-	1
School	1	-	-	-	1	-	1	-	-	-
Terraced house	-	77	89	-	77	-	130	57	82	2

Table 5.8: The composition of building types in each peer

Peer	0	1	2	3	4	5	6	7	8	9
Residential demand ratio	1.0	1.0	1.0	1.0	1.0	1.0	0.04	1.0	1.0	1.0
Service-sector demand ratio	0.0	0.0	0.0	0.0	0.0	0.0	0.96	0.0	0.0	0.0
Type	R	R	R	R	R	R	S	R	R	R
Peer	10	11	12	13	14	15	16	17	18	19
Residential demand ratio	0.0	0.71	1.0	1.0	0.21	1.0	0.45	1.0	1.0	0.11
Service-sector demand ratio	1.0	0.29	0.0	0.0	0.79	0.0	0.55	0.0	0.0	0.89
Type	S	M	R	R	M	R	M	R	R	M

Table 5.9: The composition of residential and service-sector demand in each peer

To achieve better illustrations and ease reading burdens, following is a shortlist of peers that will be used later to represent the whole group.

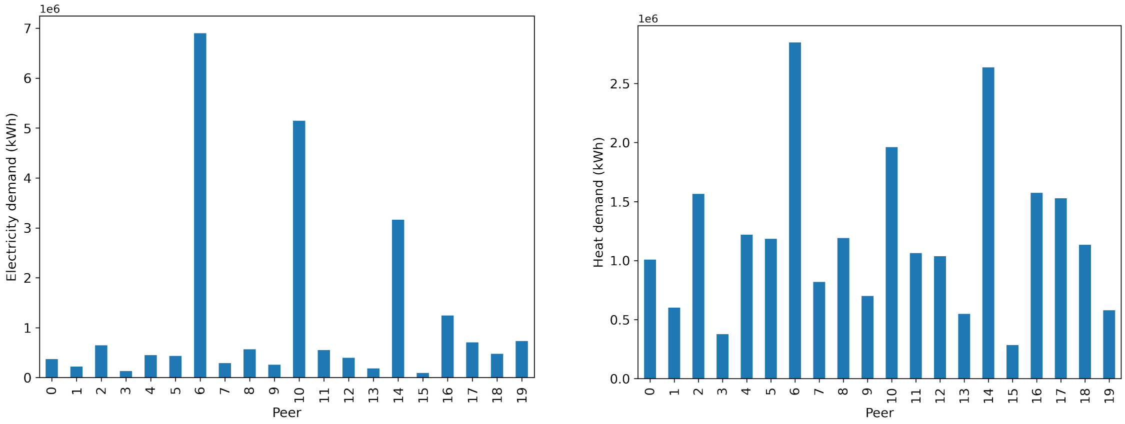
- Residential peers
  - Peer 0: dominated by terraced houses in terms of quantity and energy demand
  - Peer 8: dominated by apartments and detached houses in terms of energy demand (1 apartment ≈ 20 detached houses according to Table 5.2)
  - Peer 13: dominated by detached houses in terms of quantity and energy demand
- Service-sector peers
  - Peer 6: dominated by the offices and retails in terms of quantity and energy demand (1 retail ≈ 1.25 offices ≈ 70 terraced houses according to Table 5.2)
  - Peer 10: dominated by the offices, retails and schools in terms of quantity and energy demand

- Mixed peers
    - Peer 16: a balanced combination of service-sector demand from the school and residential demand from terraced houses (1 school ≈ 200 terraced houses according to Table 5.2)

5.3.2. Aggregation of demand and generation profiles in each energy community

The corresponding energy profiles for each peer are aggregated based on the individual profiles from the last section. Specifically, the demand and generation of all the building in one cluster are summed up into one; the nominal COP and levelised fixed cost is set as the weighted mean of that of all the building with HP capacity as the weight.

Figure 5.6 illustrates the yearly electricity and heat demand for each peer. We could observe that Peer 6, 10, 14 own extremely larger energy demand than others, especially for the electricity demand. As for the heat demand, the peers with large quantities of residential buildings close the gap with the service-sector buildings, such as peer 2, 16, 17. Referred from Figure 5.5 and Table 5.9, peer 6 and 10 are service-sector peers located at the business area (I); peer 14 is a mixed peer but with 79% of service-sector demand. This phenomenon reflects the fact that the service-sector building has a higher energy density (energy consumption per area) than the residential building.

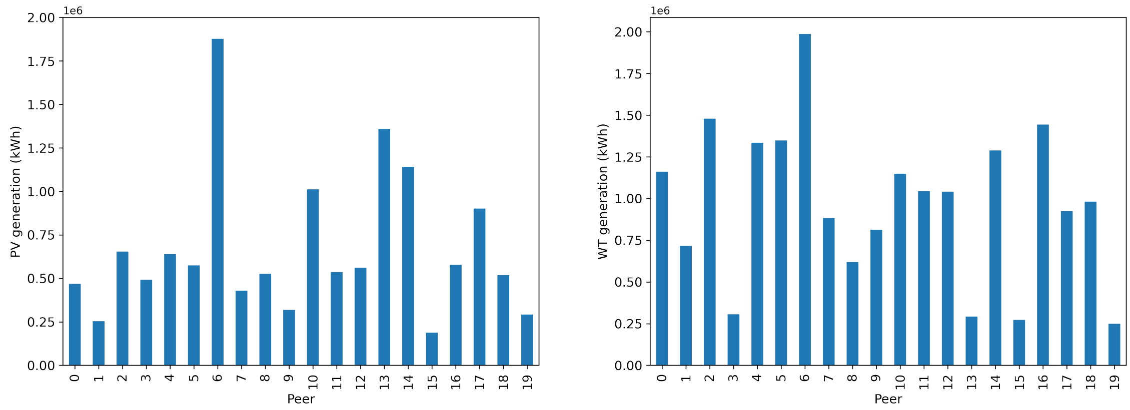


(a) (b)

Figure 5.6: (a) Yearly electricity demand and (b) heat demand for each peer

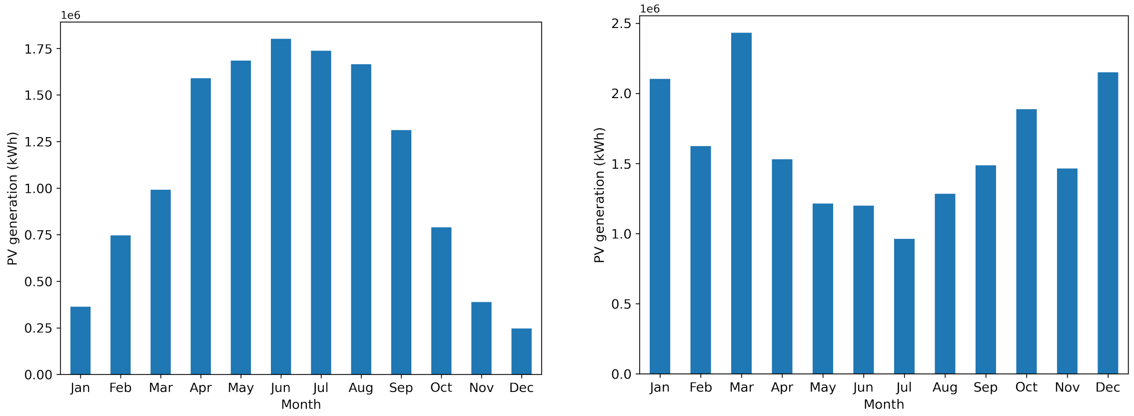
In general, the peers with higher energy demand also have a larger generation capacity of PV, WT and HP. Accordingly, Figure 5.7 shows the yearly electricity generation from PV and WT respectively. The generation of peer 6, 10, 14 is at a higher level but the advantage is not as distinct as that in demand. Because the variation in project area across peers is larger than that in total energy demand, the generation variation in PV across peers is larger than that in WT. Based on the monthly generation in Figure 5.8, the PV generation is obviously larger in the summer period than the winter period while the opposite holds true for the WT generation. The complementary characteristic of PV and WT contributes to a reliable electricity supply at the distributed level.

In the end, Figure 5.9 shows the installed HP capacity, average COP value of one-year operation and the levelised fixed cost. Peer 6, 10, 14 also have an extremely larger HP capacity. Although the average COP falls as the capacity increases, a large investment capacity of certain buildings contributes a lower levelised fixed cost owing to the economies of scale. For example, peer 6, 10, 13, 14, 19.



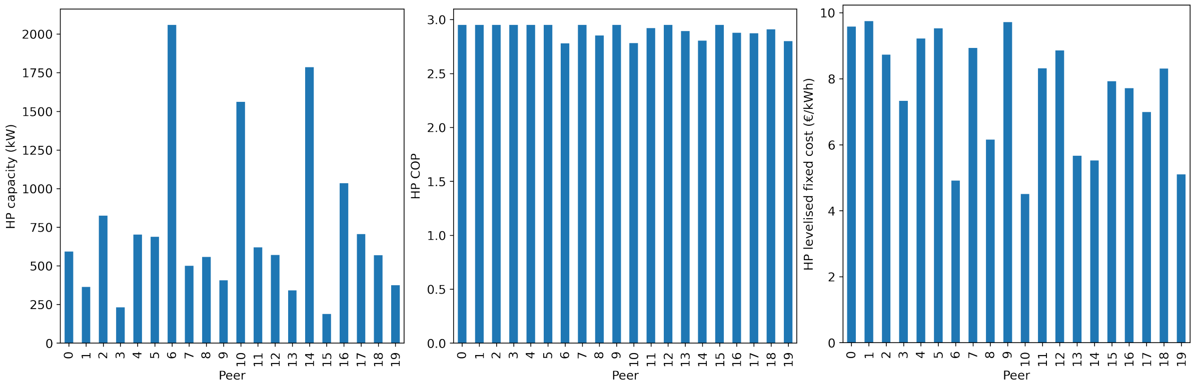
(a) (b)

Figure 5.7: Yearly electricity generation (a) from PV and (b) from WT for each peer



(a) (b)

Figure 5.8: Monthly electricity generation for one year (a) from PV and (b) from WT



(a) (b) (c)

Figure 5.9: (a) The installed HP capacity, (b) average COP of the year and (c) levelised fixed cost for each peer

5.3.3. Heat demand utility coefficient of each energy community

As for the heat demand utility, the heat preference coefficient $u_{n,t}$ is randomised between 0.8 and 1.2 for each hour of each peer. When $u_{n,t} \in (1, 1, 2]$, it means the peer n has a lower urgency to the heat demand and is less sensitive to the heat comfort; and vice versa. The introduction of $u_{n,t}$ essentially differentiates the time-series pattern of the actual heat demand of buildings in the same type.

The scaling factor v_n is set ranging from 0.374 to 3.734 as shown in Table 5.10. The v_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.5.8). In this way, if one peer has the average heat demand, its v is standardised as 1; if the heat demand is larger than the average heat demand, $v < 1$ and otherwise $v > 1$. The underlying rationale is to mitigate the influence of the level of heat demand in the decision-making process. In this way, the marginal heat demand utility of each peer is at a comparable level.

Peer	0	1	2	3	4	5	6	7	8	9
v_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
v_n	0.61	1.12	1.15	2.17	0.45	4.18	0.76	0.78	1.05	2.06

Table 5.10: Overview of the scaling factor v_n for each peer

$$v_n = \frac{T}{\Sigma_{t=1}^{T} q_{n,t}^{bas}} \cdot \frac{\Sigma_{n=1}^{N}\left(\frac{\Sigma_{t=1}^{T} q_{n,t}^{bas}}{T}\right)}{N} = \frac{\Sigma_{n=1}^{N}\Sigma_{t=1}^{T} q_{n,t}^{bas}}{N \cdot \Sigma_{t=1}^{T} q_{n,t}^{bas}} \tag{5.8}$$

5.4. Electricity and heat price profile setting

As shown in the price profiles of Table 5.1, 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. Table 5.11 shows the statistic of electricity price profiles. One special line to mentions is that there is a calendar mismatch between the original demand profiles and price profiles. The demand profiles for detached and terraced houses are obtained in the year 2013 starting from Tuesday and demand profiles for others is based on the year 2014 starting from Wednesday; in contrast, the price profiles is in 2018 starting from Monday. Therefore, we adjust the original detached & terraced (others') profiles to fit with the year 2018 by duplicating Jan 3 (& Jan 2) series and deleting Dec 23 (& Dec 22) series, to make sure the weekends and weekends consistent with the year 2018. However, the mismatch between movable public holidays (other than New Year's Day, Christmas Day and 2nd Day of Christmas) is ignored.

$p_{e,t}^{sel,euc}$	Average value (cents/kWh)	Maximum value (cents/kWh)	Minimum value (cents/kWh)
	5.253	17.500	0.055
$p_{e,t}^{buy,euc}$	Value (cents/kWh)	Time-of-use	Period
	23.169 22.032	Normal rate Off-peak rate	7:00 am - 11:00 pm 11 pm - 7 am; all the weekend and holidays [1]

Table 5.11: Overview of electricity price profiles

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[1] The public holidays of the Netherlands in 2018 include New Year's Day 1 Jan, Good Friday 30 Mar, Easter Sunday 1 Apr, Easter Monday 2 Apr, King's Day 27 Apr, Ascension Day 10 May, Whitsun 20 May, Whit Monday 21 May, Christmas Day 25 Dec, 2nd Day of Christmas 26 Dec

As for the heat price, the proportionality constant α between $p_t^{h,mid}$ and $p_t^{e,mid}$ is set as 1.00. Besides, the regulated surcharge ratio for the heat buyer is set as $\beta = 0$, i.e. $p_t^{h,buy} = p_t^{h,sel} = p_t^{h,mid}$. This could avoid benefit spillover by the regulated surcharges for heat trading scenarios and thereby create a level playing field to compare all the scenarios. By far, we have set up a uniform electricity and heat guiding pricing scheme. Figure 5.10 gives an overview of average, minimum and maximum guiding energy (electricity/heat) price by month. In general, the average guiding energy price fluctuates slightly within a 1.22-cent range, but the price jumps do occur in March and November of the winter period.

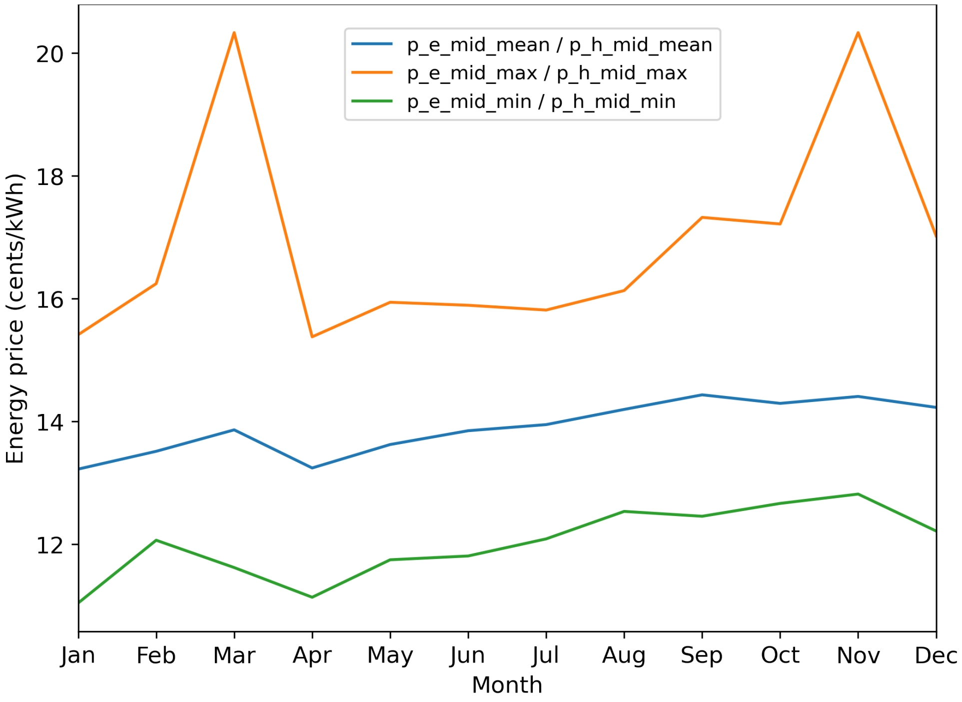


Figure 5.10: Overview of guiding electricity and heat price profiles

6

Results & Discussion

This chapter demonstrates, validates and discusses the modelling results for the case study. Section 6.1 gives an overview of the P2P market clearing results under the proposed market mechanism with P2P electricity-heat and coalitional trading. Specifically to validate the results, section 6.1.1 summarises the trading price & volume, section 6.1.2 summarises the trading coalition & position, and section 6.1.3 takes a weekday of November 22 as an example to demonstrate the results. Furthermore, section 6.2 showcases the evaluation results comparing the different scenarios. Section 6.2.1 delineates the results of four criteria and compares the results between peers from the spatial perspective; section 6.2.2 zooms into more detailed temporal dimension including seasonality, normal-off-peak comparison and hourly participation willingness.

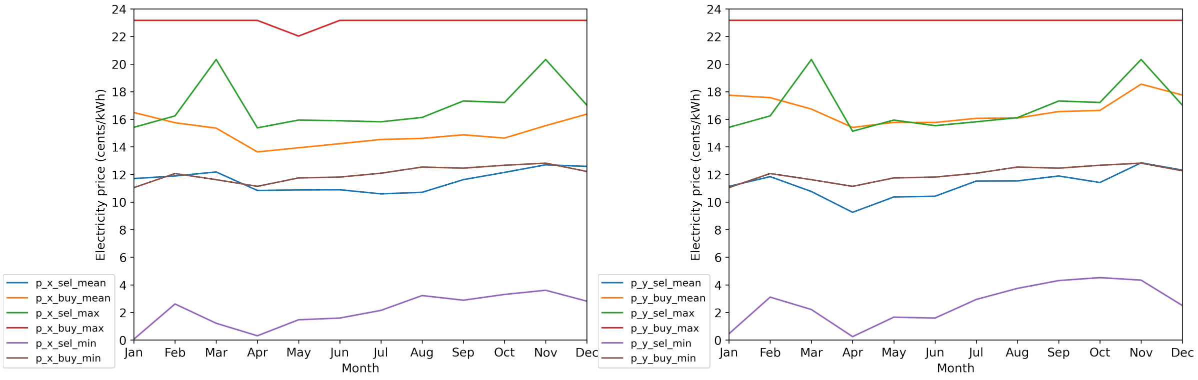
6.1. Model output and validation

The section illustrates the market clearing results in the coalitional electricity-heat trading S_3 including the electricity & heat trading price and volume in section 6.1.1, coalition formation and trading position in section 6.1.2. The underlying rationale is explained to validate the system model.

6.1.1. Overview of trading price and volume

Figure 6.1 demonstrates the average, minimum and maximum electricity selling & buying price by the month in Coalition $\mathbb{X}$ and Coalition $\mathbb{Y}$ respectively. Compared to the summer period, either electricity buying or selling price is higher in the winter period, which is driven by higher heat demand and thereby higher electricity demand by HP. The maximum buying price (red line) is capped at 23.169, which is the normal rate of the retail tariff; that means no peers are willing to sell electricity at those time steps. In both coalitions, the minimum buying price (brown line) fluctuates with the mid-market value between 11.044 and 12.818; similarly, the maximum selling price (green line) fluctuates with the mid-market rate between 15.380 and 20.335. And the minimum selling price drops as low as 0.055 for Coalition $\mathbb{X}$ and 0.242 for Coalition $\mathbb{Y}$. Specifically, Figure 6.2a illustrates the comparison on electricity selling & buying price between the two coalitions. In most of the time, the electricity selling price is quite close between the two coalitions, but the electricity selling price in Coalition $\mathbb{Y}$ is more fluctuated. However, the electricity buying price is higher in Coalition $\mathbb{Y}$ than that in Coalition $\mathbb{X}$. Because the existence of heat trading could motivate certain peers to buy extra electricity to drive HP for heat selling, this could result in system-level deficiency and thereby trading with EUC to drive up the P2P electricity buying price.

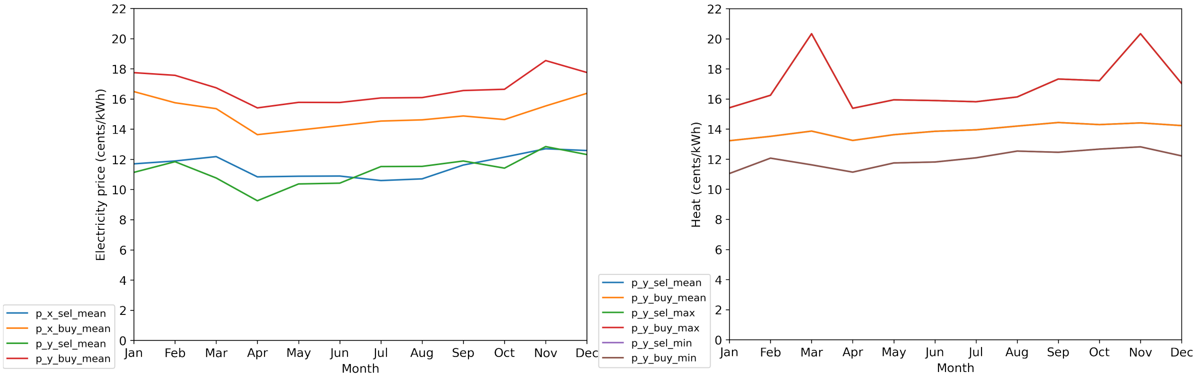
Similarly, Figure 6.2b summarises the heat selling and buying price by the month in Coalition $\mathbb{Y}$. Indeed, each line is overlapped by two lines for heat selling and buying respectively. It is obvious that the average heat price decreases from February and reaches the lowest level in April, then gradually



(a) (b)

Figure 6.1: The P2P electricity price (a) in Coalition 𝕏 and (b) in Coalition 𝕐

increases and peaks in November, and keeps at a relatively high level afterwards. The trend of heat price aligns with the fluctuations of electricity price in Figure 6.2a.



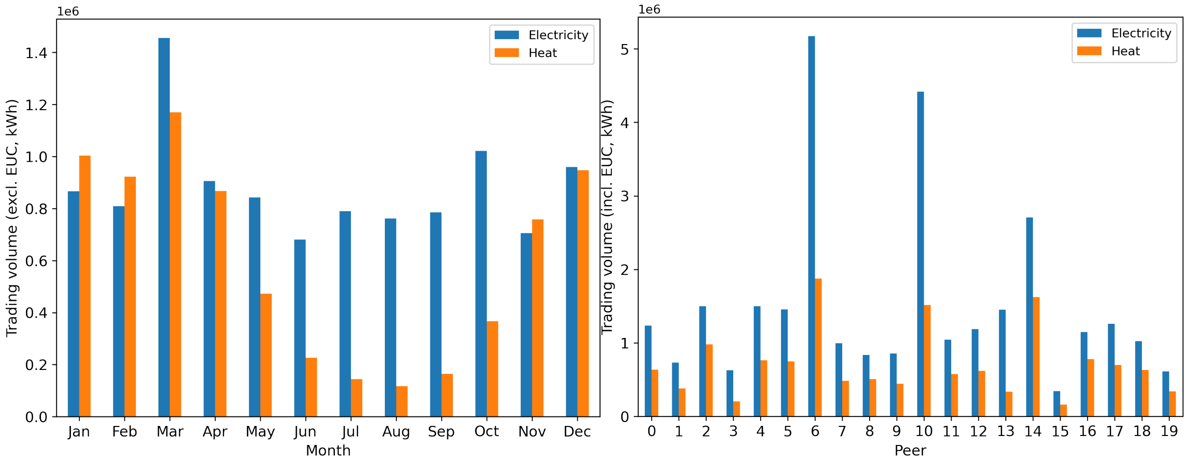
(a) (b)

Figure 6.2: (a) The P2P electricity price of Coalition 𝕏 & 𝕐 in comparison; (b) The P2P heat price in Coalition 𝕐

Accordingly, Figure 6.3a illustrates the electricity & heat trading volume per month. And the P2P electricity trading volume excludes trading with EUC. It is obvious that the heat trading volume is extremely lower between June and September due to the low heat demand in the summer period; in contrast, the heat trading is more active from December to March in the winter period. The electricity trading volume does not show seasonality and is relatively stable throughout the year. Furthermore, Figure 6.3b demonstrates the trading volume for each peer, where the electricity trading volume includes the trading with EUC. Overall, the electricity trading volume is larger than heat trading volume for each peer; peer 6, 10, 14 are taking the leading position in terms of trading volume across peers, which is due to the existence of service-sector buildings with large energy demand and generation capacity.

6.1.2. Overview of trading coalition and position

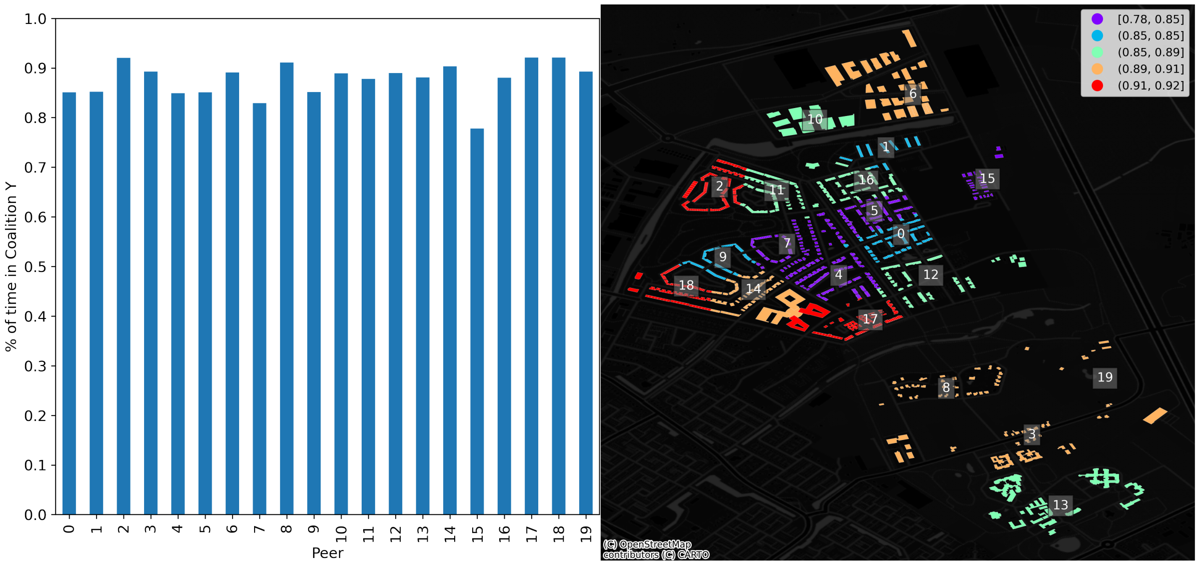
Figure 6.4a showcases the ratio of time steps when one peer chooses to be in Coalition 𝕐 for P2P heat trading. All the peers are willing to participate in the heat trading most of the time. However, as shown in Figure 6.4b, the peers mainly comprised of service-sector buildings and apartments are inclined to have a higher participation willingness for Coalition 𝕐, such as service-sector peer 6 & 10, residential peer 2, 17 & 18 with apartments according to Table 5.8. This could be explained by the lower HP generation cost of them due to the economics of scale for the large-capacity heat pump, so that they are more willing to activate the HP for heat trading.



(a)

(b)

Figure 6.3: (a) The electricity & heat trading volume per month (excluding trading with EUC); (b) The electricity & heat trading volume per peer (including trading with EUC)

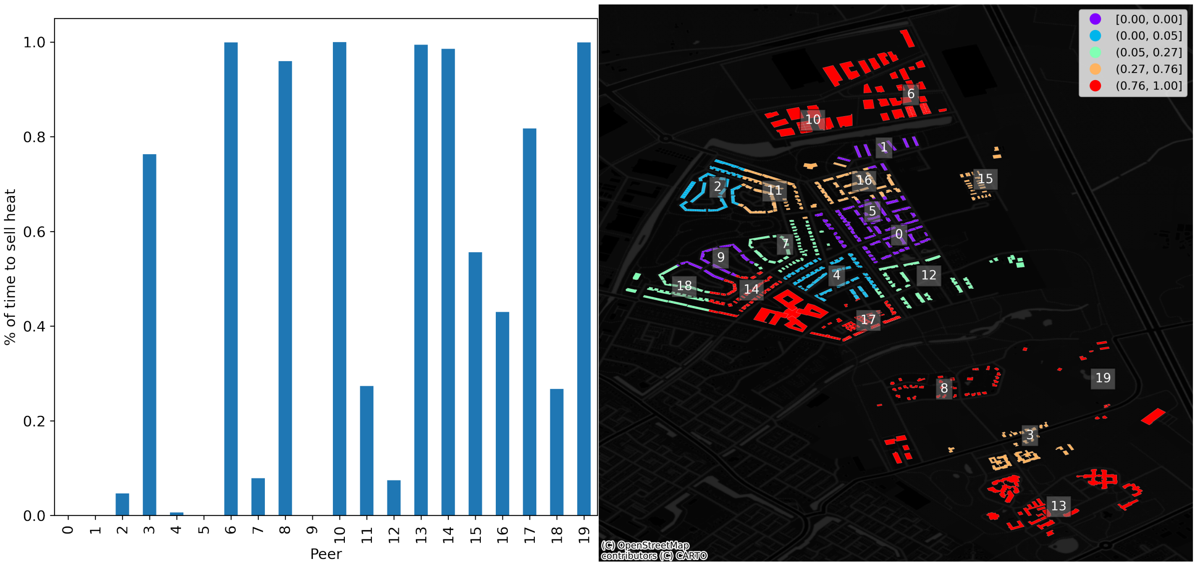


(a)

(b)

Figure 6.4: (a) The participation willingness for Coalition 𝕐 for each peer; (b) Geospatial representation of the participation willingness for Coalition 𝕐

When trading in Coalition 𝕐, Figure 6.5a reflects the trading position selections for each peer using the ratio of time steps to sell heat over total time steps in Coalition 𝕐. Peer 3, 6, 8, 10, 13, 14, 17 & 19 take the position of heat sellers for most of their time in Coalition 𝕐; in contrast, peer 0, 1, 4, 5 & 9 hardly sell any heat but are mainly as heat buyers. From Figure 6.5b, it could be observed that the peers comprised of service-sector buildings or apartments are major heat selling contributors while peers mainly comprised of terraced houses usually participate in Coalition 𝕐 out of heat buying demand. This implicates the complementary characteristic of demand and generation profiles between service-sector and residential buildings, which facilitates the heat exchange between them.



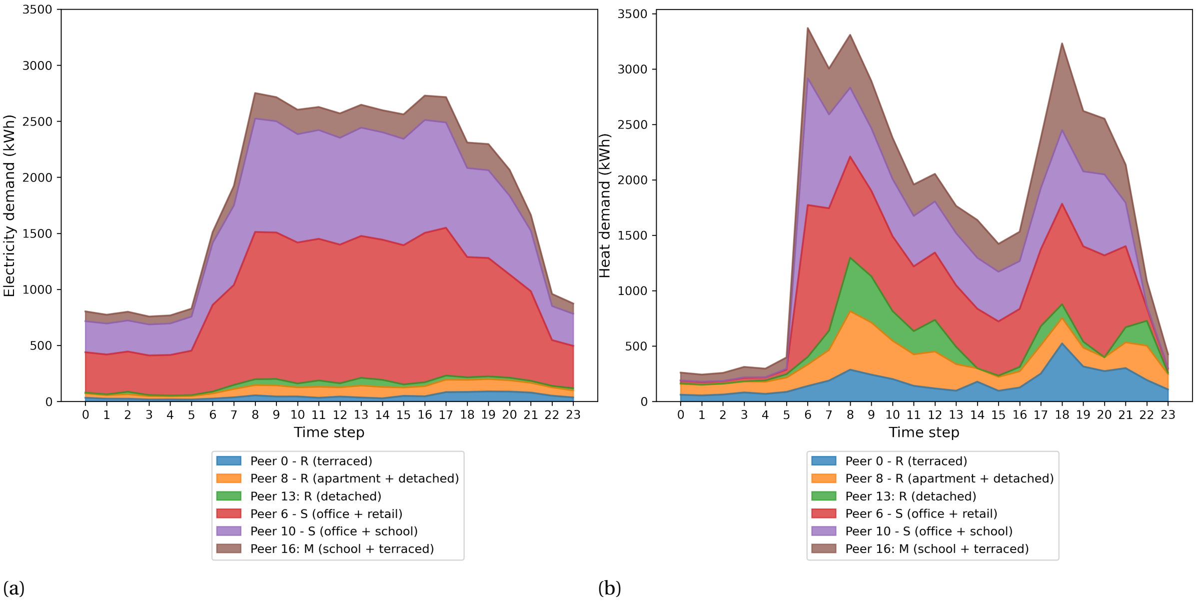
(a) (b)

Figure 6.5: (a) The willingness to sell heat in Coalition 𝕐 for each peer; (b) Geospatial representation of the willingness to sell heat in Coalition 𝕐

6.1.3. Example of a specific day on November 22

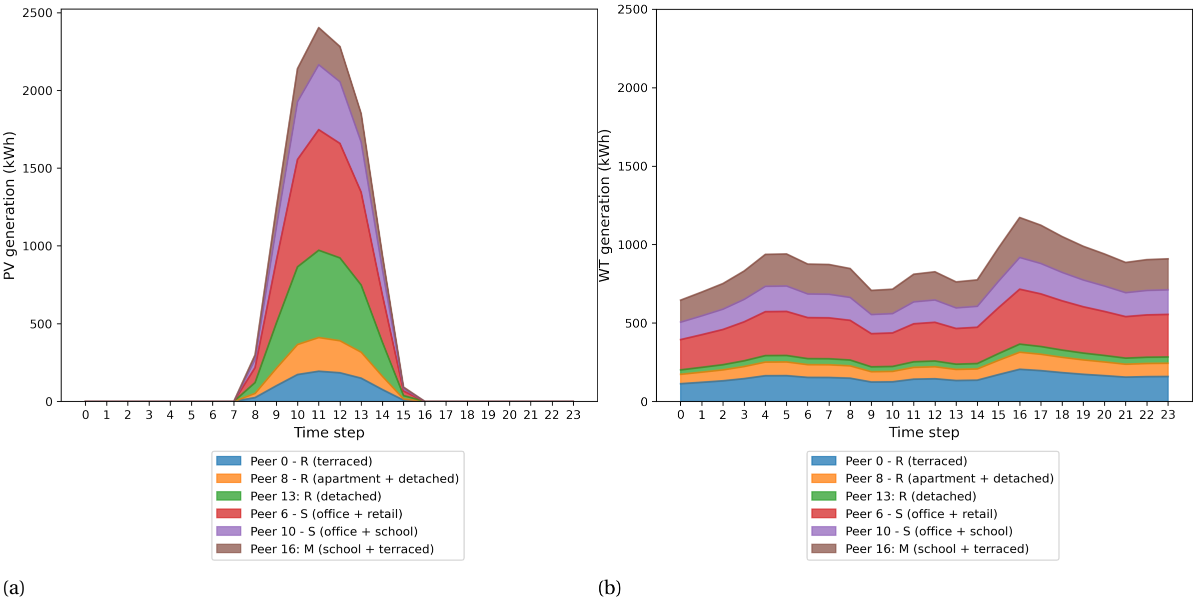
Taking Thursday November 22 as an example, we zoom into a specific day for more detailed observation. The following illustrations focus on the shortlist of 6 peers proposed in section 5.3 to avoid the ambiguity of too many peers (colours) in one figure. Meanwhile, the corresponding illustrations with complete peers will be available in the Appendix A.

Figure 6.6 gives an overview of electricity and heat demand respectively throughout Nov.22. Such a figures is the stacked area plot, which adds on the demand of peer 0 to 16 one by one from bottom to top. So the stacked area plot showcases the composition of total demand with one colour area representing the value of one peer. At night, the energy demand of service-sector peer 6 & 10 keeps at a lower level, especially for heat demand. The electricity demand keeps at a relatively high level throughout the day. In contrast, the heat demand has two peaks in the morning and in the evening respectively with a volley at noon. Besides, Figure 6.7 shows the generation profiles of PV and WT. PV generation starts from 7-8 a.m, peaks at 11 a.m.-12 p.m. and then gradually decreases to zero at 4-5 p.m.. However, the WT generation is relatively stable throughout the 24 hours.



(a) (b)

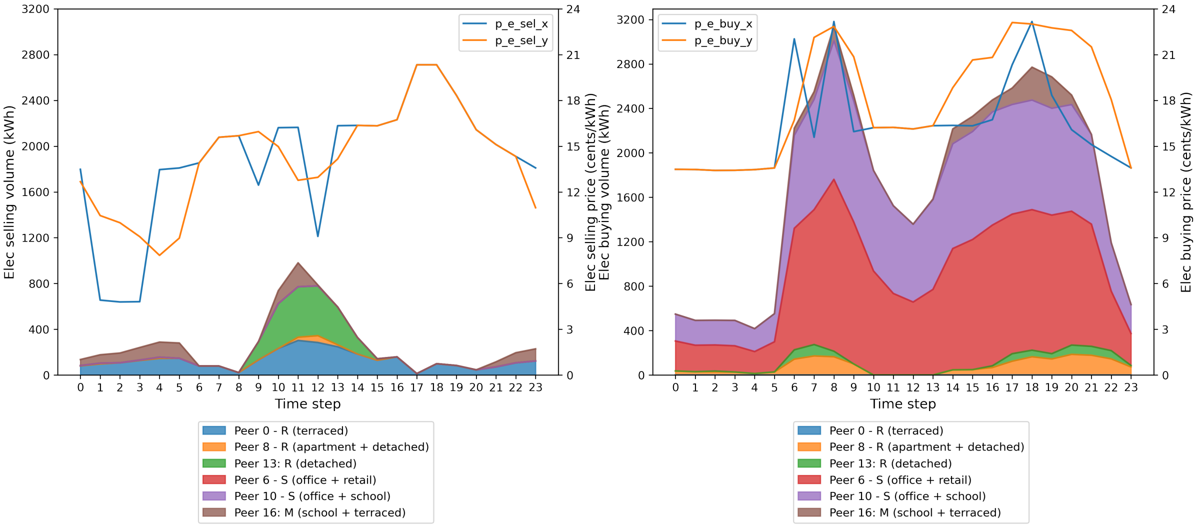
Figure 6.6: (a) The electricity demand and (b) the heat demand throughout Nov. 22



(a) (b)

Figure 6.7: (a) The PV generation and (b) the WT generation throughout Nov. 22

Next, we move to the trading results. Figure 6.8 & 6.9 demonstrates the electricity and heat trading volume of each peer at each time step, accompanied with the electricity & heat trading price. The peak volume of electricity selling occurs at noon (11-12 p.m.) driven by high PV generation, which contributes to the electricity price valley. And the electricity selling price has a wider price swing in Coalition $\mathbb{X}$ than that in Coalition $\mathbb{Y}$. Because few peers are willing to join the Coalition $\mathbb{X}$, system-level imbalance as well as trading with EUC is prone to be larger. Therefore, the deviation from the guiding electricity price is prone to be larger in Coalition $\mathbb{X}$. Besides, the peak volume of electricity buying occurs in the morning (8-9 a.m.) and evening (6-7 p.m). The large electricity buying demand lifts up the electricity trading price as well as the heat trading price. In general, the residential peer 0 & 13 mainly with terraced and detached houses are major electricity sellers and the service-sector peer 6 & 10 are major electricity buyers. However, the mixed peer 16 continuously changes its trading position between seller and buyer for both electricity and heat trading. Moreover, the peak volume of either heat selling or heat buying occurs at 10-11 a.m. and 21-22 p.m, which is driven by relatively low electricity price and high heat demand. And peer 0 & 16 mainly with terraced houses are major heat buyers.



(a) (b)

Figure 6.8: (a) The electricity selling price & volume and (b) the electricity buying price & volume throughout Nov. 22

More specifically, there is an obvious heat demand jump for service-sector peer 6 & 10 at 6-7 a.m., which is prior to that for residential peer 0, 8 & 13 at 8-9 a.m. as shown in Figure 6.6b. Therefore, peer 6 & 10 gives up the heat selling from 6 to 7 a.m (Figure 6.9a) and conducts the electricity-only trading as buyers. At the same time, peer 8 & 13 increases the heat selling volume. But later at 8-9 a.m, peer 8 & 13 change the trading position from Coalition $\mathbb{Y}$ to Coalition $\mathbb{X}$ to buy extra electricity and drive HP to meet the heat demand jump. Meanwhile, peer 6 & 10 becomes the major heat sellers. A similar mismatch of peers' demand drop also occurs in the evening between 20 to 23 p.m.. Combining Figure 6.8 and 6.9, it could be observed that certain peers are willing to buy extra electricity used for heat selling, such as peer 6 & 10; on the contrary, peer 0 is willing to buy heat and sell surplus electricity instead of using the surplus electricity to self-generate heat. This phenomenon reflects that P2P heat trading empowers peers to leverage the differences between the generation profiles and find the most cost-saving way to meet the energy demand.

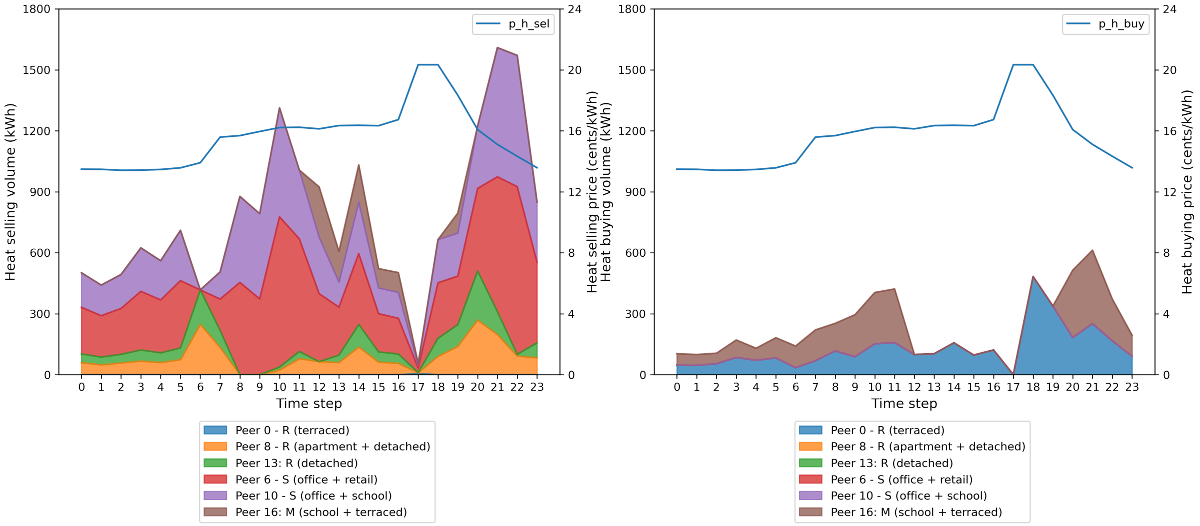
As for coalition formation, there is changing composition in each coalition from time to time. Figure 6.10 illustrates the dynamics of coalition formation from 6 a.m to 10 a.m.in Nov. 22.

- At 7 a.m., peer 6 & 10 split from the Coalition $\mathbb{X}$ and merge into Coalition $\mathbb{Y}$; all the other peers stay in Coalition $\mathbb{Y}$ but peer 3 & 17 changes their trading position from heat buyer to heat seller. Therefore, a grand coalition is formed between 7-8 a.m. for the P2P market.

- In the next time step 8-9 a.m., peer 3, 8, 13 & 19 split from Coalition $\mathbb{Y}$ and form a new Coalition $\mathbb{X}$. Other peers stay in the Coalition $\mathbb{Y}$ as well as keep the same trading positions.

- Reversely at 9 a.m., peer 19 split from Coalition $\mathbb{X}$ and merge into Coalition $\mathbb{Y}$ as a heat seller. Other peers stay the same.

In the end, Figure 6.11 showcases the net benefits obtained by each peer at each time step compared to S_0 without P2P energy trading. It is obvious that the system, i.e. all the peers as a whole, could always obtain benefits at any time step and the system benefit is significant between 10 a.m.



(a) (b)

Figure 6.9: (a) The heat selling price & volume and (b) the heat buying price & volume throughout Nov. 22

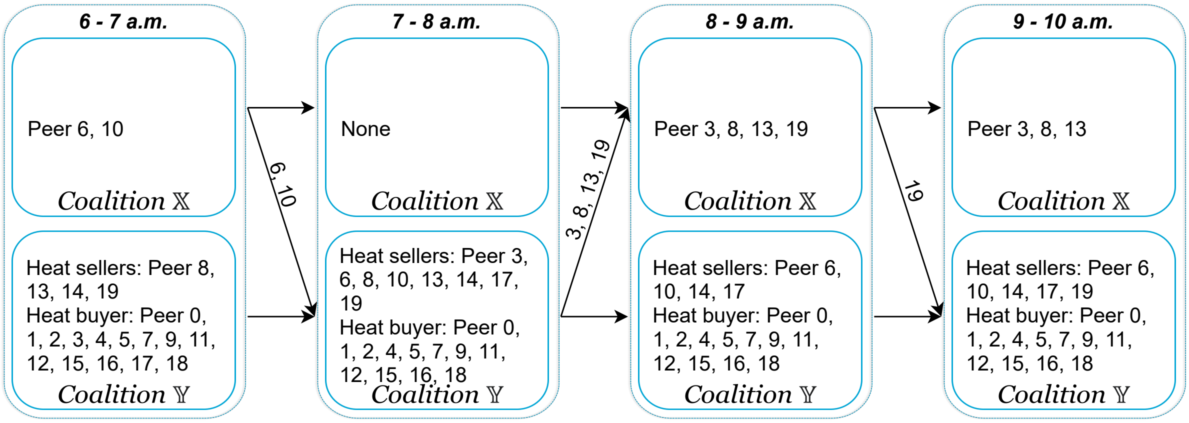


Figure 6.10: Example of coalition formation process from 6 a.m to 10 a.m. in Nov. 22

to 3 p.m. However, there are special instances when certain peers are worse off compared to S_0, such as peer 8 at 7-8 a.m. and peer 16 at 10 a.m.. The reason behind that is the post-adjustment of the mid-market rate that made the electricity selling or buying price less favourable to conduct heat trading. But the overall benefits throughout the time steps overshadow the rare instances. This phenomenon also implicates the trade-off between the implementation simplicity and benefit optimality by using such a predefined pricing scheme.

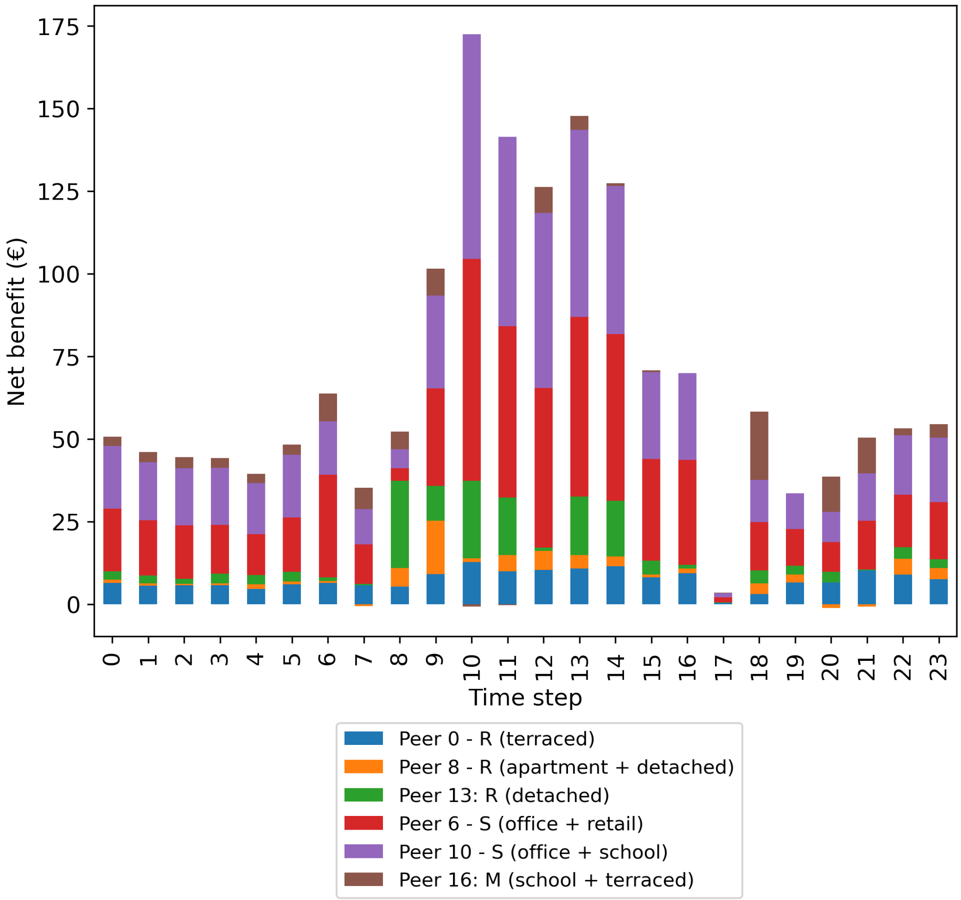


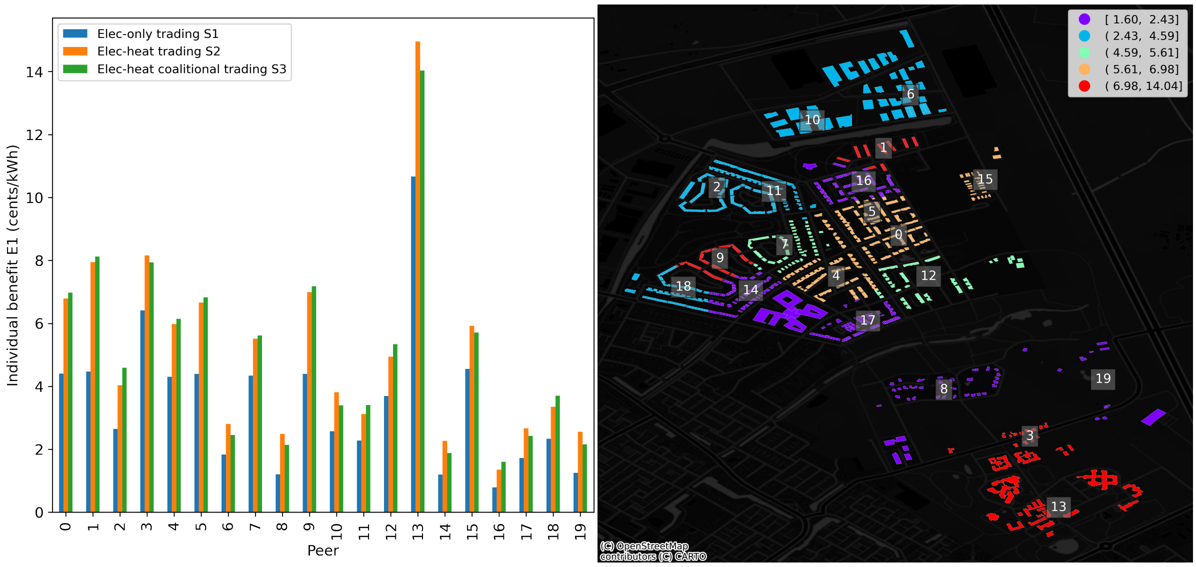
Figure 6.11: The hourly net benefits obtained by each peer in Nov. 22

6.2. Evaluation results across four scenarios

This section utilises the set of evaluation criteria to compare the different scenarios for the proposed market mechanism. The results cover the economic performance in terms of individual and system benefit and the social performance in terms of participation willingness and benefit allocation equality. Section 6.2.1 discusses the evaluation results from the spatial perspective; section 6.2.2 delineates the results into a more detailed temporal level including the monthly comparison and normal & off-peak comparison.

6.2.1. Scenario comparison and spatial analysis between residential and service-sector peers

Figure 6.12a demonstrates the positive individual benefit of unit energy consumption $E1$ for each peer across three scenarios. It is obvious that either any peer or the system could obtain benefit compared to the scenario without P2P energy trading S_0. Moreover, the introduction of heat trading in S_2 and S_3 brings more economic incentives to the peers, which indicates the prosumer-centric characteristic. The P2P heat trading enables peers to leverage the mismatch of individual demand profiles and difference between HP levelised fixed cost, so that to lower the heat generation cost. On average, the extra heat trading increases the individual benefit $E1$ by over 50% with the minimum value at 21.71% and the maximum value at 105.14%. And the cost-saving does not sacrifice the heat comfort, since peers still keep a high level of heat consumption in S_2 and S_3 (an average 2.47 % less than that in S_0). Besides, Figure 6.12b illustrates the geospatial distribution of individual benefit in Electricity-heat coalitional trading S_3. The peer mainly comprised of detached houses tends to have a higher benefit of unit energy consumption. For detached houses, the large roof-top area for PV installation contributes to a high electricity surplus for trading so that more benefits are obtained. On the contrary, the peers comprised of service-sector buildings tend to have a lower benefit of unit energy consumption, however, such peers have a high absolute benefit due to the large trading volume.



(a) (b)

Figure 6.12: (a) Scenario comparison on the individual benefit of unit energy consumption $E1$ for each peer; (b) Geospatial distribution of individual benefit of unit energy consumption $E1$ in Electricity-heat and coalitional trading S_3

Comparing S_2 and S_3, the introduction of the separate electricity and electricity-heat coalition makes the majority of peers better off but the system benefit slightly worse. As shown in Table 6.1, the system benefit $E2$ of Electricity-heat trading S_2 and Electricity-heat coalitional trading S_3 is respectively 51.06% and 43.37% higher than that of Electricity-only trading S_1. Essentially, S_2 represents a grand coalition for all the peers where a unified electricity market is obtained rather than two sub-markets in S_3. A grand coalition could mitigate, to the greatest extent possible, the electricity trading with EUC so that to reduce the benefit loss. Therefore, S_2 is superior to S_3 in terms of system benefit. However, the result of participation willingness $E3$ showcases that 55% of peers obtain the optimal benefit throughout the year in S_3 while the rest prefer S_2. From the spatial distribution in Figure 6.13, the peers mainly comprised of terraced houses prefer S_3 while the peer comprised of service-sector buildings prefer S_2. Therefore, the introduction of coalitional trading results in benefit transfer from service-sector peers with larger demand to residential peers with smaller demand. But the service-sector peers could still obtain higher benefits in terms of absolute value. In the end, the benefit allocation equality $E4$ is improved slightly in S_2 and S_3.

	System benefit E2 (€/kWh)	Participation willingness E3	Benefit allocation equality E4
Elec-only trading S1	745156	0.00	0.675
Elec-heat trading S2	1125600	0.45	0.698
Elec-heat coalitional trading S3	1068350	0.55	0.694

Table 6.1: Scenario comparison on the system benefit $E2$, participation willing $E3$ and benefit allocation equality $E4$

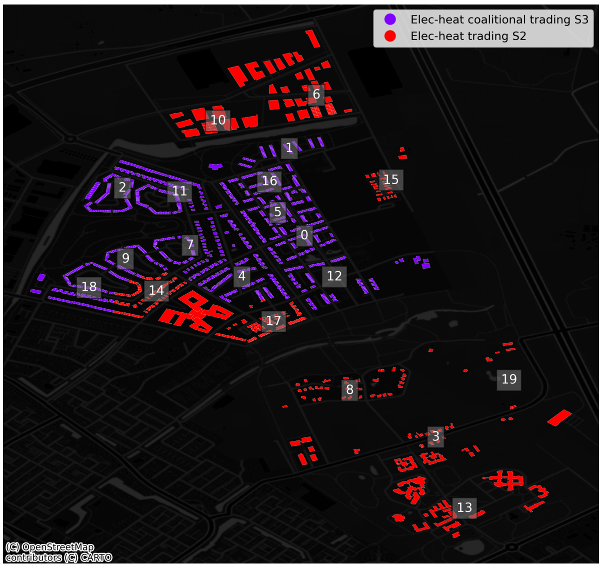
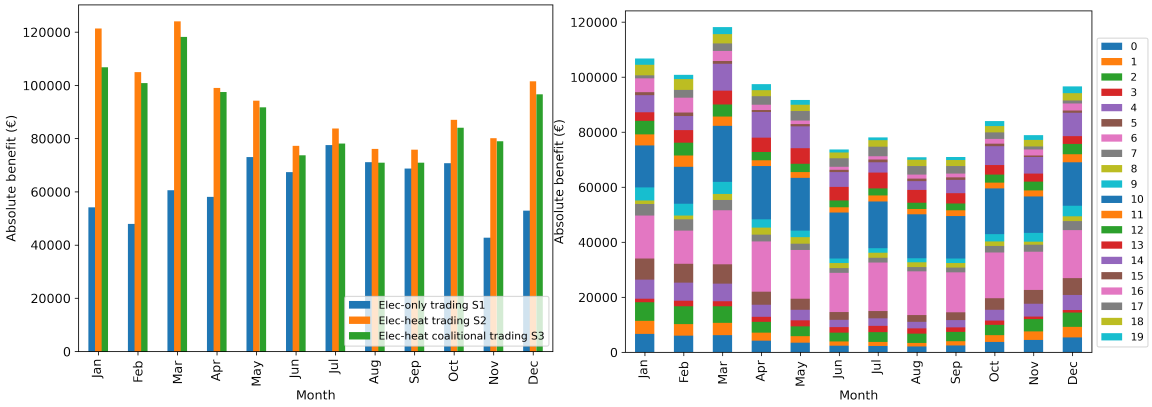


Figure 6.13: Geospatial distribution of partipation willingness S_3, i.e. best scenario for each peer

6.2.2. Temporal analysis of seasonality, normal-off-peak periods and hourly participation willingness

This section continues to explore the evaluation results from the temporal dimensions including seasonality, normal-off-peak comparison and hourly participation willingness.

Figure 6.14a illustrates the seasonality of the absolute benefit by month. For S_1, more benefits are obtained in summer driven by a high electricity surplus for trading. However, S_2 and S_3 have a reverse seasonality. The P2P heat trading drives the dramatic increase of benefits in winter to surpass the benefit in summer. It is worth mentioning that the benefit of S_2 and S_3 in summer does not decrease compared to that of S_1. Specifically, Figure 6.14b decomposes the monthly absolute benefit in S_3 by peers. Similar seasonality could be observed for each peer. In the days where the solar and wind is scarcely available, there will be hardly any P2P electricity tradings. In this situation, the peers will have to trade with the EUC (just like S_0) and the P2P market will not function.

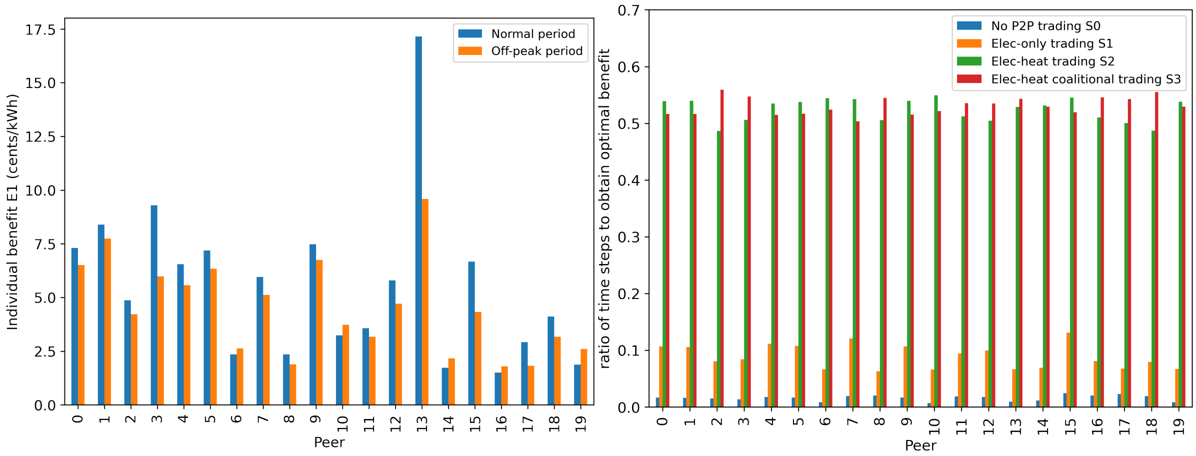


(a) (b)

Figure 6.14: (a) Scenario comparison on the monthly absolute benefit; (b) The composition of monthly absolute benefit in S_3 by peers

Moreover, Figure 6.15a segments the individual benefit of unit energy consumption in S_3 into normal and off-peak time periods. Different from others, peer 6, 10, 14, 16 & 19 obtain a higher benefit in the off-peak period, which indicates a low energy consumption but high energy selling.

Referred from Figure 5.5, these peers are characterised by numerous service-sector building. In contrast, the peers dominated by residential building performs better in the normal period. Therefore, it is safe to conclude that the energy profiles of residential and service-sector peers are temporally complementary to facilitate the reciprocally beneficial P2P energy trading, even without the investment of energy storage.



(a) (b)

Figure 6.15: (a) Comparison on the individual benefit of unit energy consumption in normal and off-peak time periods of S_3; (b) The participation willingness towards four scenarios at the hourly resolution, i.e. the percentage of time steps over a year as the best scenario for one peer

In the end, Figure 6.15b examines the participation willingness at the hourly resolution instead of throughout the year. The y axis is the percentage of time steps over a year when one peer could obtain the best benefit at the specific scenario compared to other scenarios. The sum-up of y-axis values of four scenarios may be over 1 due to the equal benefits for multiple scenarios at certain time steps. The average y-axis values across peers in four scenarios are 1.60%, 8.89%, 52.41%, 53.07% respectively. While all the peers prefer S_2 and S_3 during most of time, special instances do exist when S_0 or S_1 are superior. The results align with the proposition in the Nov. 22 example in section 6.1.2. When selecting the best market scenario, the trade-off emerges between the one-time-step benefit and the overall benefit. The proposed market mechanism is not always the best, but attains a balance between economic benefit and implementation complexity. And the overall benefits throughout a long time duration would triumph in the end.

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7

Conclusion

In this chapter, the main findings from the research are presented by answering the research questions & sub-questions and summarising the main contributions in section 7.1. Besides, the research limitation and potential future improvement are discussed in section 7.2.

7.1. Answers to the research question

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 behaviours may emerge from the interactions of the peers. Therefore, the main research question is defined as:

What is the economic and social performance of a novel peer-to-peer energy trading market that incorporates cooperative behaviours and electricity-heat coupling?

To answer the research question, the research designs a novel market mechanism for P2P energy trading to facilitate electricity-heat coalitional trading and then evaluates the market performance from the socio-economic perspective by modelling a case study. The answer to the main research question is segmented into five sub-answers (SA) to the sub-questions so that to derive the final conclusions.

7.1.1. SA1 to *What are the necessary components to implement P2P energy trading?*

Six key components are identified to complete the P2P energy trading including Energy system setup (C1), Grid connection (C2), ICT system (C3), Market mechanism (C4) and Trading strategy (C5) as illustrated in Fig. 2.1.

C1, C2 & C3 are assumed as the existing environment in this research. A multi-energy system is set up to couple the electricity and heat demand of peers. The energy generation concerns a fully electrified and distributed scenario including photovoltaic modules, wind turbines and heat pump. And there are sufficient capacity for electricity & heat network as well as ICT connections. Three types of actors are involved to complete the P2P energy trading, i.e. peers as the market participants, market operator to coordinate energy trading and electricity utility company to deal with surplus/deficient electricity.

C4 and C5 are the focus of this research. The trading strategy concerns peers' strategic decision-making in trading to maximise their own benefits. Afterwards, the market mechanism matches peers' selling & buying demand and settles the trading time, price and volume so that to facilitate the bidirectional energy exchange and financial transaction. Specifically, the research defines the coalition & order rules, energy pricing scheme and market clearing process for the proposed market mechanism in the next sub-question.

7.1.2. SA2 to *How should the market mechanism incorporate cooperative behaviours and electricity-heat coupling?*

The research constrains the research scope into 2 predefined trading coalitions, i.e. electricity-only trading coalition & electricity-heat trading coalition and 2 energy trading commodities, i.e. electricity & heat. Then a design process is conducted to identify stakeholder needs & requirements, integrate system requirements & functions, obtain the design results.

The design results for the market mechanism consist of four first-level functions, namely Market information sharing, Trading strategy processing, Market clearing and Market settlement as shown in Figure 3.2. The market operator firstly public market operation results from the last time step and share with peers the weather availability prediction for renewables and guiding electricity & heat price in the upcoming time step. Then peers determine the trading strategies including trading coalition and electricity & heat trading volume. And all the orders are received and processed by the market operator following the process in Figure 3.3 and 3.4. Two key coordination issues are solved:

- Maintain heat balance: the market operator negotiates with peers to proportionally curtail heat selling or buying order according to the system-level heat surplus/deficiency. There is an iterative process for peers to update coalition selections and electricity-heat trading volume (F2.5) and for the market operator to facilitate heat balance (F2.2-2.4). The market will move forward to market clearing only if all the peers consent to the potential order changes.

- Trade-off between computational complexity and trading strategy autonomy: the market mechanism adapts the mid-market rate as the pre-defined pricing scheme but empowers the peers to conduct their own strategies about trading coalitions and quantity. Such a pricing scheme is simple to understand and implement but keeps economic incentives for both electricity sellers and buyers. Besides, the heat price is regulated to be directly proportional to the mid-market rate. Therefore, a uniform electricity-heat price scheme is constructed to guide peers to decide their best trading strategies.

It the end, all the executed orders are settled in terms of energy delivery and payment. By far, the market operation for one trading interval is complete. And the same process is iterated for all the time steps.

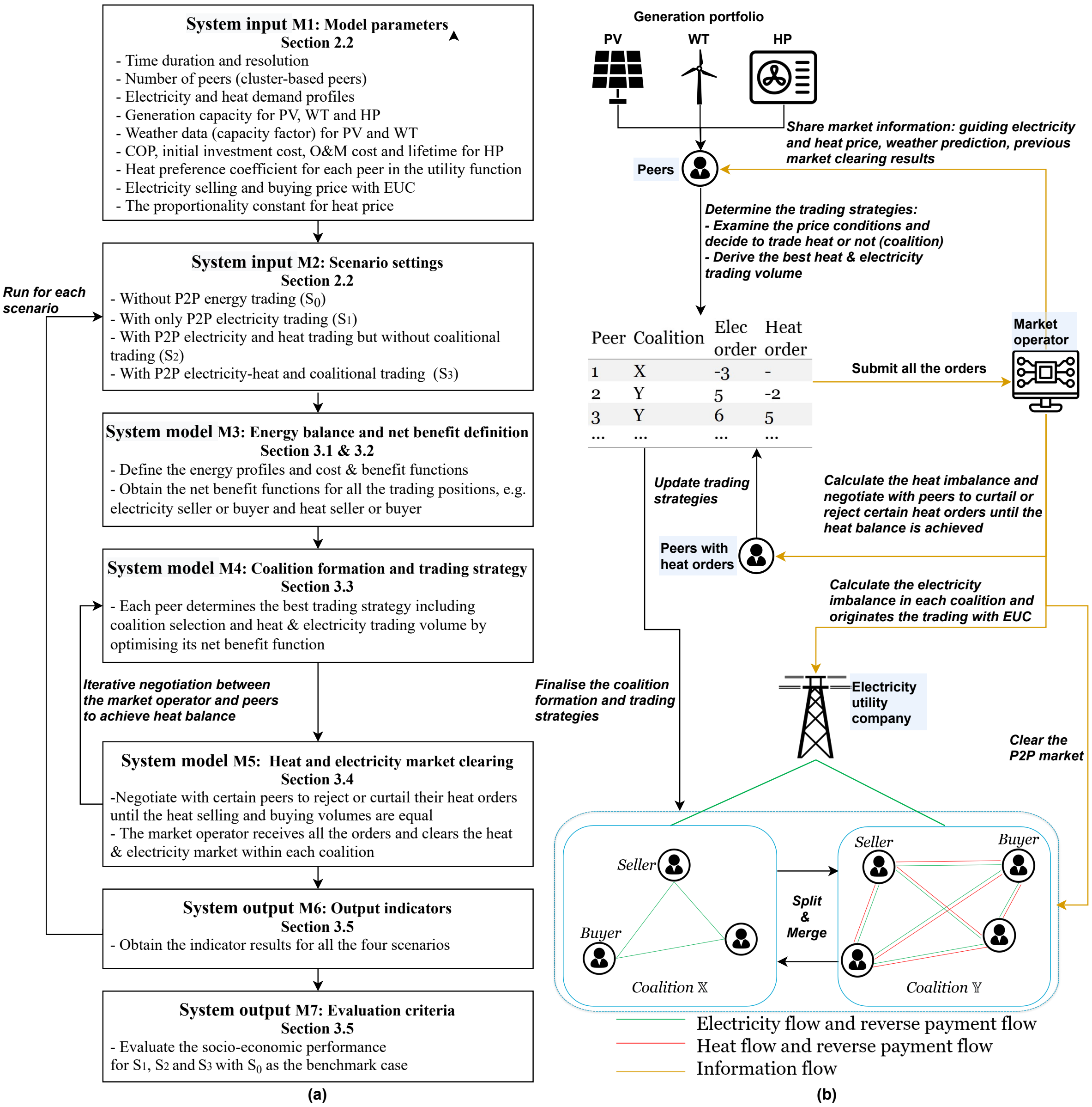
7.1.3. SA3 to *How does the model simulate the trading activities in the proposed market mechanism?*

Based on the market design result in SQ2, the system model includes 2 input modules, 3 model modules and 2 output modules as shown in Figure 7.1. The model modules simulated the trading activities in the proposed market mechanism. Above all, two coalitions $\mathbb{X}$ and $\mathbb{Y}$ are formed for peers to choose:

1. Electricity-only trading Coalition $\mathbb{X}$: peer $x \in \mathbb{X}$ only participates in the P2P electricity trading as either a seller or buyer. Peer x's HP supplies its own base heat demand as a passive electricity consumption device.

2. Electricity-heat trading Coalition $\mathbb{Y}$: peers $y \in \mathbb{Y}$ participate in both P2P electricity and heat trading. Peer y utilises HP as an active generation device and decides whether to generate surplus heat for selling or to buy heat in the P2P market instead of generating at the maximum level.

The trading objective of each peer is to maintain the energy balance and maximise the net benefit. The expected energy surplus or deficiency influences the peer's trading position in the P2P energy market. Furthermore, the peer's decision-making process is modelled by defining and optimising the net benefit functions for each of four trading positions, e.g. electricity seller or buyer and heat seller or buyer. And the heat demand utility is quantified and active heat demand response is considered. Both heat consumption level and heat trading volume are the decision variables in the optimisation, which influences the electricity demand. So the electricity trading volume is obtained in the end based on the electricity balance equation. Thereby, the trading strategies are categorised according to four price conditions as shown in Table 4.1.



Peer	Coalition	Elec order	Heat order
1	X	-3	-
2	Y	5	-2
3	Y	6	5
...	...	...	...

Figure 7.1: (a) Flow chart for the system model including 7 modules; (b) Graphical illustration of the P2P energy trading in a multi-energy system

After receiving all the trading strategies from the peers, the market operator clears the heat & electricity market within each coalition. The arrow from M5 to M4 align with the iterative negotiation process in Figure 3.3 of the last sub-question. The market operator firstly clears the heat market in Coalition 𝕐 by negotiating with certain peers to reject or curtail their heat orders until the heat selling and buying volumes are equal. After the coalition formation is finalised, the market operator clears the electricity market in Coalition 𝕏 & 𝕐 separately by trading electricity imbalance with EUC and determining the P2P electricity price.

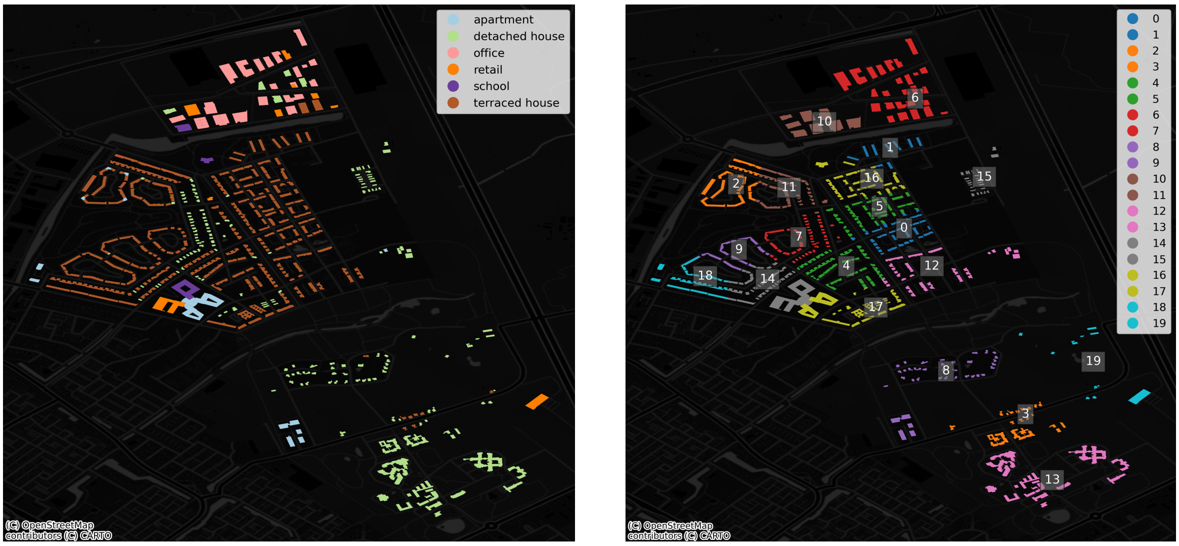
Finally, the mathematical formulation is converted into Python programs to construct the simulation model.

7.1.4. SA4 to *What is a suitable case study to evaluate the proposed market mechanism?*

A case study is formulated based on the Zuidbroek neighbourhood in Apeldoorn, the Netherlands. One reason is the openly available household smart meter data in Apeldoorn mitigates the data collection workload and makes the case study more realistic. Another reason is that the municipality of Apeldoorn has launched the first pilot project for carbon neutrality in Zuidbroek to implement building insulation and build district heating networks. Therefore, there is an existing network infrastructure for electricity and heat trading and the energy-efficient buildings favour the deployment of the heat pump. Last but not the least, the institutional environment is friendly to set up a testbed for this P2P energy market innovation.

First of all, the temporal and geospatial information are combined to set up unique demand & generation profiles for each building. From the Geographic Information Systems, 1485 buildings in total are retrieved in the neighbourhood with six building types including apartments, detached houses, offices, retails, schools and terraced houses (Figure 7.2a). And the building types and projected area are two key factors to differentiate the energy profiles.

Furthermore, to mitigate the computational burden, 20 geographically-closed energy communities are formulated using the k-means clustering (Figure 7.2b). Each energy community serves as a collective peer to participate in the P2P energy trading. Essentially, this clustering technique could be leveraged from household level to city level so that to construct a bottom-up hierarchical P2P market structure. Therefore, a limited number of peers exist at each level of the P2P market, which showcases a durable computational complexity and a scalable characteristic for real implementation.



(a) (b)

Figure 7.2: (a) Six building types in the Zuidbroek neighbourhood; (b) 20 energy communities by clustering in the Zuidbroek neighbourhood

7.1.5. SA5 to *Why does the novel market mechanism for P2P energy trading outperform/underperform other mechanisms from the socio-economic perspective?*

The research evaluates the proposed market mechanism across 4 scenarios based on 2 economic criteria and 2 social criteria. The scenarios include No P2P energy trading (S_0), P2P electricity-only trading (S_1), P2P electricity-heat trading (S_2) and P2P electricity-heat coalitional trading (S_3).

Overall, the proposed market mechanism could bring positive benefits to each peer during one year, which indicates the prosumer-centric characteristic. Compared to S_0, either any peer or the system could obtain benefit by introducing the P2P energy trading. Moreover, the introduction of heat trading increases economic incentives to the peers in S_2 and S_3. The P2P heat trading enables peers to leverage the mismatch of individual demand profiles and difference between HP degradation cost, so that to lower the heat generation cost. On average, one peer in S_2 and S_3 obtains 50% higher individual benefit of unit energy consumption after participating in the P2P electricity-heat trading compared to the electricity-only trading. And the cost-saving does not sacrifice the heat comfort, since peers only consume an average 2.47 % less heat than that in S_0. In S_3, all the peers are willing to participate in the heat trading for over 45% of the time. However, the peers mainly comprised of service-sector buildings or apartments are inclined to have a higher participation willingness for the heat trading. This could be explained by the lower HP generation cost of them due to the economies of scale for the large-capacity heat pump. Therefore, the peers comprised of service-sector buildings or apartments are major heat selling contributors while peers mainly comprised of terraced houses usually participate in heat trading out of heat buying demand. This implicates the complementary characteristic of demand and generation profiles between service-sector and residential buildings.

However, the introduction of the separate electricity and electricity-heat coalition in S_3 makes the majority of peers better off but the system benefit slightly worse compared to that in S_2. The system benefit of S_2 and S_3 is respectively 51.06% and 43.37% higher than that of Electricity-only trading S_1. Essentially, S_2 represents a grand coalition for all the peers where a unified electricity market is obtained rather than two sub-markets in S_3. A grand coalition could mitigate, to the greatest extent possible, the electricity trading with EUC so that to reduce the benefit loss. Therefore, S_2 is superior to S_3 in terms of system benefit. However, 55% of peers obtain the optimal benefit in S_3 throughout the year while the rest prefer S_2. Based on the spatial distribution, it is concluded that the introduction of coalitional trading results in benefit transfer from service-sector peers to residential peers. But the service-sector peers could still obtain higher benefits in terms of absolute value. In the end, the benefit allocation equality is improved slightly in S_2 and S_3.

When zooming into the evaluation results from the temporal dimension, special patterns are observed in terms of seasonality, normal-off-peak comparison and hourly participation willingness. Based on the monthly absolute benefit, the P2P heat trading drives the dramatic increase of benefit in winter to surpass the benefit in summer. Meanwhile, the benefit of S_2 and S_3 in summer does not decrease compared to that of S_1. Therefore, a reserve seasonality is observed for S_1 compared to S_2 and S_3. Moreover, the peers characterised by numerous service-sector buildings obtains higher benefit in the off-peak period, which indicates a low energy consumption but high energy selling of service-sector buildings in the off-peak period. In contrast, the peers dominated by residential building performs better in the normal period. Therefore, the energy profiles of residential and service-sector peers are temporally complementary to facilitate the reciprocally beneficial P2P energy trading, even without the investment of energy storage. In the end, special instances are observed when peers are better off in S_0 and S_1 during 1.60% and 8.89% of the time respectively. The reason behind that is the post-adjustment of the mid-market rate that made the electricity selling or buying price less favourable to conduct heat trading. But the overall benefit throughout a long time duration overshadows the rare instances, which implicates the trade-off between the implementation simplicity and benefit optimality.

7.1.6. Main research contributions

The main contributions of the research concern five aspects:

- The research proposes a market mechanism for P2P energy trading to facilitate electricity-heat coalitional trading. To the best of our knowledge, the market mechanism is a first-of-its-kind that explores the synergies of multiple energy trading commodities in an MES and the cooperative behaviours among the peers.

- The research applies a systematic design process to identify and address all the needs & requirements from relevant stakeholders. A complete market operation process is proposed to solve coordination issues between electricity-heat and coalitional trading including maintaining heat balance.

- The research presents a trading process where the decision-making of each peer and the market operator is simulated and the corresponding algorithm is developed. Each peer is able to optimise their net benefit by autonomously selecting their trading strategies. The strategies include which trading coalition to join, the heat consumption level and the trading of both electricity and heat.

- The research conducts a case study using realistic data from the Netherlands. Geographic Information System (GIS) has been used to obtain the locations, areas and the types of the buildings. We leverage both temporal and spatial information to set the energy profiles and cluster the buildings into geographically closed energy communities.

- The case study compares the economic and social performance across 4 scenarios, i.e. no P2P energy trading, P2P electricity-only trading, P2P electricity-heat trading and P2P electricity-heat coalitional trading. And the results showcase prosumer-centric property by introducing heat trading. However, the introduction of coalitional trading indicates benefit transfer from service-sector peers to residential peers.

7.2. Research limitation and future improvement

Due to the time and capacity limit, the current research scope is constrained and model simplification is assumed. Therefore, three future research directions are proposed to address the limitations.

7.2.1. Limitation on the multi-energy system set-up

The research covers the electricity & heat demand with three distributed generation technologies including roof-top photovoltaic modules, wind turbines and heat pump. However, it is possible to expand the energy forms and devices to fit with future energy scenarios.

The transport demand could be considered in the form of electric vehicles. The electric vehicles are not only electricity consumption devices but also serve as energy storage. So there should be optimisation on the charging and discharging pattern of electric vehicles. This also indicates active electricity demand response to consider flexible demand and inter-temporal constraints.

Besides electric storage, thermal storage could be included to serve as active devices in the heat trading. The current research does not include any energy storage out of the concerns on high investment costs. However, it is possible to introduce electric & thermal storage and evaluate the financial feasibility by comparing the extra benefits and investment & operation costs. The existence of thermal storage also provides a feasible way to couple electricity & heat demand but constrain the trading commodity into electricity, which could be compared against the multi-energy trading. Moreover, inter-temporal constraints have to be considered for storage in the optimisation problems, which imposes concerns on the computational complexity.

Moreover, hydrogen could play a role in the future energy system either to replace natural gas for heat demand or to drive fuel cell electric vehicles. As technologies advance, there is potential to mitigate the uncertainty around the cost and distribution safety of hydrogen. If distributed through the centralised network, hydrogen could serve as a "green" gas source to replace the role of natural gas. Moreover, the development of electrolysis using distributed electricity generation could enable hydrogen to be a new P2P energy trading commodity.

7.2.2. Limitation on the market mechanism

The research proposes a market mechanism to facilitate electricity-heat coalitional trading, however, there are simplifications on trading coalitions and pricing scheme.

As for the coalition formation, the research introduces two coalitions from the perspective of energy trading commodities and the main objective is to maximise economic benefits. However, it is possible for peers to form more coalitions based on common preferences, for example, the autarky-focused coalition to maximum energy self-sufficiency, the sustainability-focused coalition to maximum green-energy sources. So more research efforts are needed to provide more freedom for peers to form coalitions out of diverse preferences.

Besides, the research constructs a proportional heat price to electricity price and the proportionality constant always keeps as constant. Such a pricing scheme is easy to implement but to a certain extent, sacrifices the economic benefit 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 to better match the heat balance and distribute the system benefit in a fairer manner.

7.2.3. Limitation on the case study

The research evaluates the proposed market mechanism based on one case study at the neighbourhood level in the Netherlands. The data accuracy for the case study setting could be improved and more case studies could be conducted to examine the generality.

During the case study setting, numerous assumptions are made to cope with data incompleteness. The demand profiles of each building are correlated with building types and projected area, but other factors are ignored such as inhabitant composition, building height and construction year. It will be higher accuracy to record the real electricity & heat for each building with the smart meter. Besides, the generation profiles are essentially a projection for a future distributed scenario. The real generation data from actual energy communities will be more realistic.

Moreover, the system model is generic to be utilised for different administrative levels and locations. The current case study treats one energy community with several buildings as a peer to participate in the energy trading. It is feasible to zoom into the energy community and treat the individual building as a peer or zoom out to the city-level and treat each neighbourhood as a peer. Thereby a bottom-up hierarchical P2P market structure could be established but the coordination between different layers requires research attention. In addition, it is necessary to evaluate the market mechanism in different locations, which differs from the weather conditions and building type composition that influence the demand & generation to peers' preferences and energy prices.

Last but not the least, a real pilot project could be established apart from the computational simulation. The potential roll-out of P2P markets also calls for research attention towards its externalities. The resulted decentralisation of energy sources may challenge the investment and operation of the transmission grids as well as the design of the wholesale energy markets. Therefore, the regulators should cooperate with the market designers to construct correct incentives for peers to invest DERs for self-interest but responsibly utilise DERs to maintain the grid stability, such as obligation to ancillary services. 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.

7.3. Highlights

In conclusion, a novel market mechanism incorporating P2P electricity-heat coalitional trading is superior on both economic and social performance in comparison with no P2P trading and electricity-only trading scenarios. Specifically, the key findings are:

- The introduction of P2P heat trading showcases the prosumer-centric property, which on average improves each peer's benefit of unit energy consumption by over 50% compared to electricity-only trading.
- The introduction of coalitional trading makes a majority of peers better off but the system benefit slightly worse compared to P2P electricity-heat trading. This indicates the benefit transfer from large prosumers to small prosumers.
- The complementary characteristic is demonstrated between the energy profiles of residential and service-sector peers to facilitate the reciprocally beneficial P2P energy trading

All in all, there is no one-fit-all market mechanism and each mechanism has its pros and cons to fit with specific energy systems. This research contributes a small step to unlock the integration of cooperative behaviours and multi-energy coupling in P2P energy trading. The proposed market mechanism facilitates and regulates one of the strategic behaviours from peers, namely coalition formation. The coalitional trading empowers the self-interested peers to leverage the mismatch of demand and generation profiles across peers, which results in the cooperation between energy-surplus peers and energy-deficient peers in one trading coalition. Furthermore, the introduction of multiple trading commodities frees more energy devices to actively involved in the P2P energy market and stimulates integrated demand response from the prosumer side. Essentially, the novel P2P energy trading market serves as an invisible hand to convert and allocate the limited energy resources to the most needed energy carriers and peers, when utilising the most cost-saving generation options and obtaining the largest demand utility.

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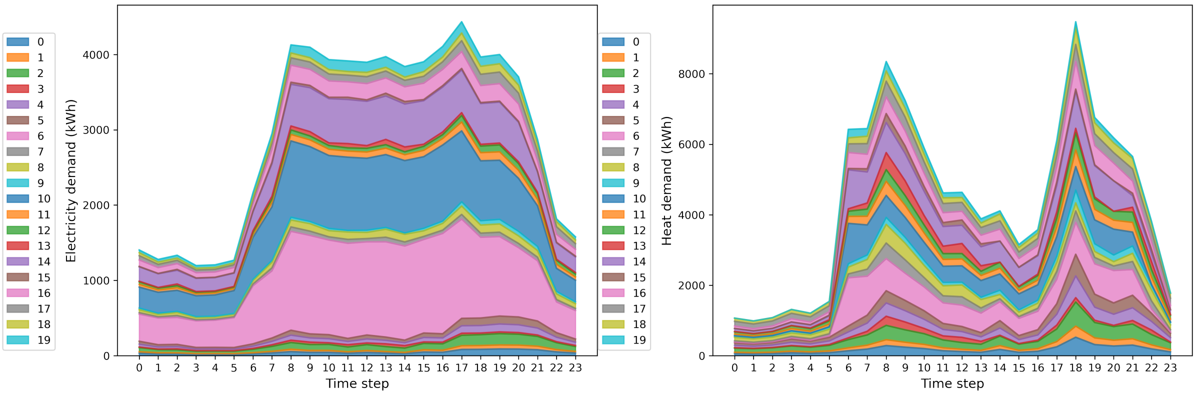
A

Appendix A: Supplement case study result

A.1. Example of November 22 with all the peers

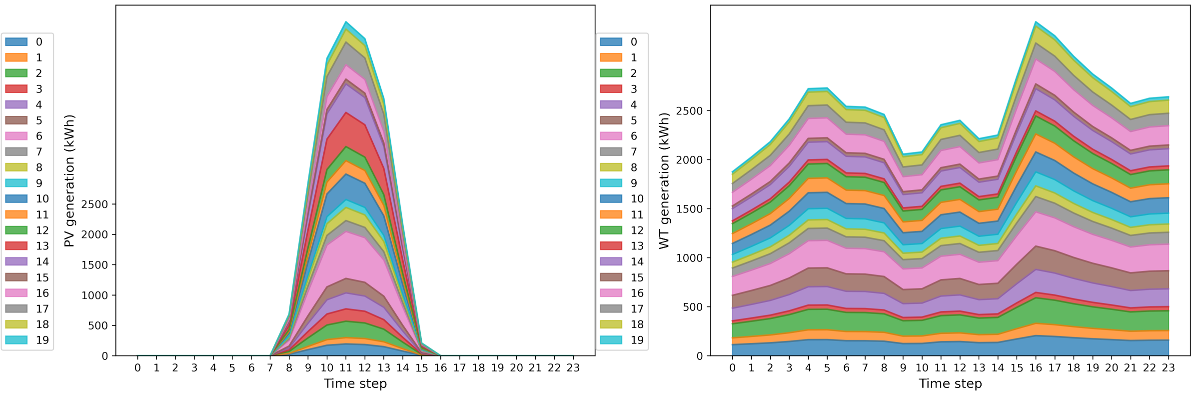
Following is complete illustrations of November 22 example with all the 20 peers. Figure A.1a & A.1b show the electricity and heat demand throughout the day respectively, while Figure A.2a & A.2b shows the PV and WT generation profiles. Figure A.3a & A.3b and A.4a & A.4b demonstrates the electricity and heat selling & buying trading volume of each peer at each time step, accompanied with the trading price. The peak volume of electricity selling occurs at noon (11-12 p.m.) driven by high PV generation, which contributes to the electricity price valley. And the electricity selling price has a wider price swing in Coalition $\mathbb{X}$ than that in Coalition $\mathbb{Y}$. In contrast, the peak volume of electricity buying occurs in the morning (8-9 a.m.) and evening (6-7 p.m). The large electricity buying demand lifts up the electricity trading price as well as the heat trading price. The peak volume of heat trading occurs at 10-11 a.m. and 21-22 p.m, which is driven by relatively low electricity price and high heat demand.



(a)

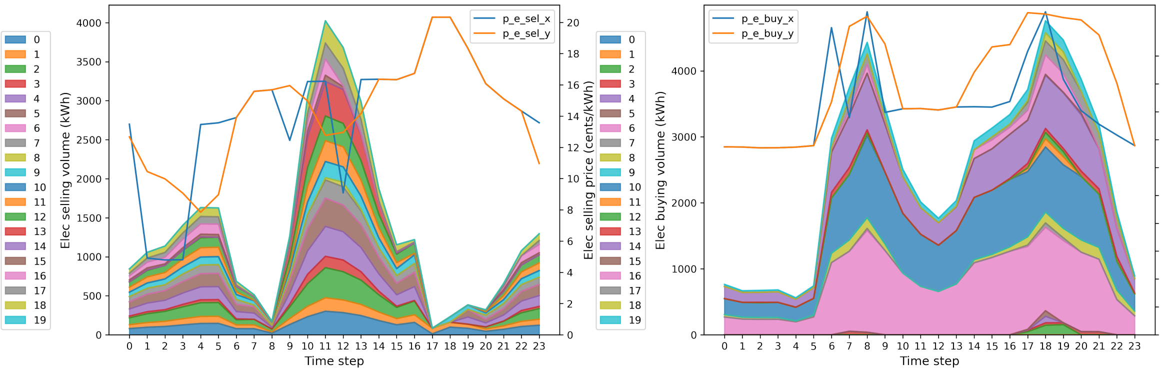
(b)

Figure A.1: (a) The electricity demand and (b) the heat demand throughout Nov. 22



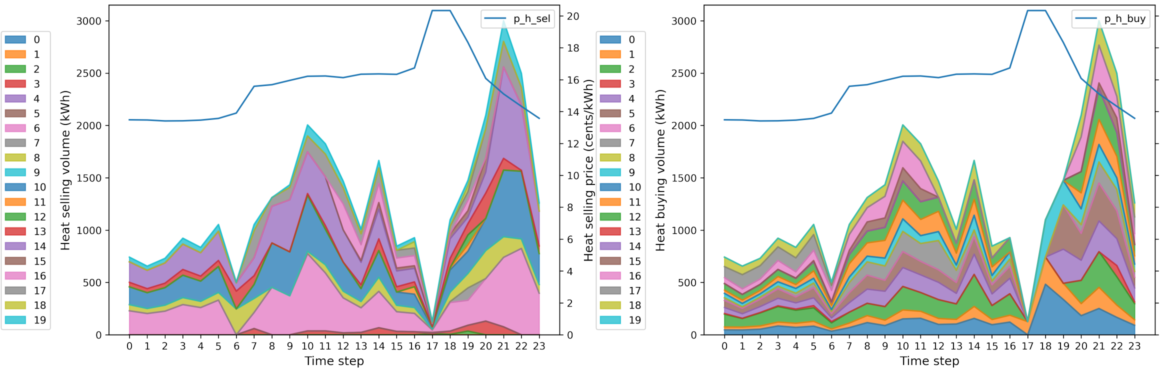
(a) (b)

Figure A.2: (a) The PV generation and (b) the WT generation throughout Nov. 22



(a) (b)

Figure A.3: (a) The electricity selling price & volume and (b) the electricity buying price & volume throughout Nov. 22



(a) (b)

Figure A.4: (a) The heat selling price & volume and (b) the heat buying price & volume throughout Nov. 22

In the end, Figure A.5 showcases the net benefits obtained by each peer at each time step compared to S_0 without P2P energy trading. Similar observations to 6 peers could be derived. It is obvious that the whole system could always obtain benefits at any time step and the system benefit is significant between 10 a.m. to 3 p.m. However, there is special instances when certain peers are worse off compared to S_0.

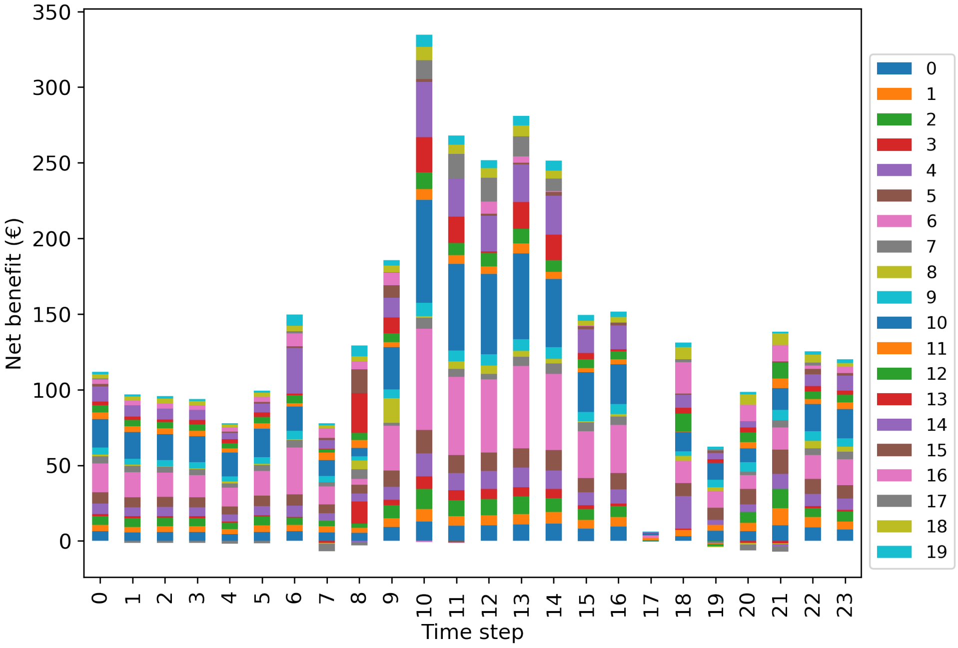


Figure A.5: The hourly net benefits obtained by each peer in Nov. 22

The cover photos are retrieved from the website of Sustainable Development Goals, United Nations. URL: https://sdgs.un.org/goals