Blockchain Enabled Decentralized Local Electricity Markets With Flexibility From Heating Sources

Weiqi Hua, *Student Member, IEEE*, Yue Zhou, *Member, IEEE*, Meysam Qadrdan, *Senior Member, IEEE*, Jianzhong Wu, *Senior Member, IEEE*, and Nick Jenkins, *Fellow, IEEE*

***Abstract*—Electric power systems are transitioning towards a decentralized paradigm with the engagement of active prosumers (both producers and consumers) through using distributed multi-energy sources. This paper proposes a novel Blockchain based peer-to-peer trading architecture which integrates negotiation-based auction and pricing mechanisms in local electricity markets, through automating, standardizing, and self-enforcing trading procedures using smart contracts. The negotiation of the volume and price of the peer-to-peer electricity trading among prosumers is modeled as a cooperative game, and the interaction between a retailer and its ensemble of prosumers is modeled as a Stackelberg game. The flexibility provision from residential heating systems is incorporated into the energy scheduling of prosumers. Case studies demonstrate that the proposed architecture in local electricity markets helps improve local energy balance. Flexibility from the residential heating systems enables prosumers to be more responsive to the variation of retail electricity prices. The proposed model reduces 41.24% of average daily electricity costs for individual prosumers or consumers compared to the case without the peer-to-peer electricity trading.**

***Index Terms*—Blockchain, electrification of heat, local electricity market, prosumer, renewable energy, smart contract.**

Nomenclature

Functions

f_n^{tradeoff}	Function of the tradeoff of the prosumer n.
f^{profit}	Function of the profits of a retailer.

Parameters

Δt	Scheduling interval (0.5 h).
ϵ_n^{hp}	Coefficient of performance of the air-source heat pump of the prosumer n.
$\pi_t^{\text{rt,max}}$	Maximum retail electricity price at the scheduling time t (GBP/kWh).
$\pi_t^{\text{rt,min}}$	Minimum retail electricity price at the scheduling time t (GBP/kWh).
π_t^{wh}	Wholesale electricity price at the scheduling time t (GBP/kWh).
τ_t^{a}	Temperature of the ambient air at the scheduling time t (K).
τ_n^{max}	Maximum temperature boundary to maintain the comfort of the prosumer n (K).
τ_n^{min}	Minimum temperature boundary to maintain the comfort of the prosumer n (K).
ξ_n^{b}	Price elasticity of the prosumer n as an electricity buyer.
ξ_n^{s}	Price elasticity of the prosumer n as an electricity seller.
c_n	Thermal capacitance of the prosumer n's household (J/kgK).
$d_{n,t}^{\text{e}}$	Electricity consumption of appliances of the prosumer n at the scheduling time t (kW).
$d_n^{\text{ts, max}}$	Maximum charging rate of the thermal energy storage of the prosumer n (kW).
$p_{n,t}^{\text{pv}}$	Electricity produced by the roof-top solar panel of the prosumer n at the scheduling time t (kW).
$q_n^{\text{hp,max}}$	Nominal maximum heating power of the air-source heat pump of the prosumer n (kW).
$q_n^{\text{ts, max}}$	Maximum discharging rate of the thermal energy storage of the prosumer n (kW).
$s_n^{\text{ts, max}}$	Thermal energy storage capacity of the prosumer n (kWh).
u_n	Thermal transmittance of the prosumer n's household (W/K).

Sets

$\mathcal{C}_i$	Set of the smart contracts deployed by the seller i.
$\mathcal{C}_j$	Set of the smart contracts deployed by the buyer j.
$\mathcal{N}$	Index set of prosumers.
$\mathcal{S}_{F,n}$	Decision space of the follower n.
$\mathcal{S}_L$	Decision space of the leader.
$\mathcal{T}$	Index set of the scheduling time.

Variables

ϕ_i	Network serial number of the seller i.

Manuscript received 15 September 2021; revised 3 February 2022; accepted 22 February 2022. Date of publication 11 March 2022; date of current version 20 February 2023. This work was supported in part by the EPSRC through the Project "Maximizing Flexibility Through Multi-Scale Integration of Energy System (MISSION)" under Grant EP/S001492/1, and in part by the Project "Integrated Heating and Cooling Networks With Heat-Sharing-Enabled Smart Prosumers" under Grant EP/T022795/1. Paper no. TSG-01499-2021. *(Corresponding author: Meysam Qadrdan.)*

Weiqi Hua was with the School of Engineering, Cardiff University, Cardiff CF24 3AA, U.K. He is now with the Department of Engineering Science, University of Oxford, Oxford OX1 3QG, U.K. (e-mail: weiqi.hua@eng.ox.ac.uk).

Yue Zhou, Meysam Qadrdan, Jianzhong Wu, and Nick Jenkins are with the School of Engineering, Cardiff University, Cardiff CF24 3AA, U.K. (e-mail: zhouy68@cardiff.ac.uk; qadrdanm@cardiff.ac.uk; wuj5@cardiff.ac.uk; jenkinsn6@cardiff.ac.uk).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TSG.2022.3158732.

Digital Object Identifier 10.1109/TSG.2022.3158732

ϕ_j Network serial number of the buyer j.
$\pi_i^{\min}$ Minimum accepted buying price of the seller i (GBP/kWh).
$\pi_j^{\max}$ Maximum accepted selling price of the buyer j (GBP/kWh).
$\pi_{n,m,t}^{\text{p2p}}$ Agreed selling/buying price between the prosumer n and prosumer m at the scheduling time t (GBP/kWh).
π_t^{rt} Retail electricity price at the scheduling time t (GBP/kWh).
$\tau_{n,t}$ Indoor temperature of the prosumer n's household at the scheduling time t (K).
θ_i Auction end time of the seller i.
θ_j Auction end time of the buyer j.
ϑ Binary variable indicating the charging (if $\vartheta = 1$) or discharging (if $\vartheta = 0$) of the thermal energy storage.
$d_{n,t}^{\text{hp}}$ Electricity used to run the air-source heat pump of the prosumer n at the scheduling time t (kW).
$d_{n,t}^{\text{h}}$ Heating power supplied to the household of the prosumer n at the scheduling time t (kW).
$d_{n,t}^{\text{matched}}$ Matched electricity demand of the prosumer n at the scheduling time t (kW).
$d_{n,t}^{\text{ts}}$ Heating power charged to the thermal energy storage of the prosumer n at the scheduling time t (kW).
$d_{n,t}^{\text{unmatched}}$ Unmatched electricity demand of the prosumer n at the scheduling time t (kW).
id_i Address of the account of the seller i.
id_j Address of the account of the buyer j.
p_i Amount of the supplied electricity of the seller i (kW).
p_j Amount of the electricity demand of the buyer j (kW).
$p_{n,m,t}^{\text{p2p}}$ power exchange between the prosumer n and prosumer m at the scheduling time t (kW).
$p_{n,t}^{\text{matched}}$ Matched electricity supply of the prosumer n at the scheduling time t (kW).
$p_{n,t}^{\text{p2r}}$ Power export from the prosumer n to a retailer at the scheduling time t (kW).
$p_{n,t}^{\text{r2p}}$ Power import from a retailer to the prosumer n at the scheduling time t (kW).
$p_{n,t}^{\text{unmatched}}$ Unmatched electricity supply of the prosumer n at the scheduling time t (kW).
$q_{n,t}^{\text{hp}}$ Heating power supplied by the heat pump of the prosumer n at the scheduling time t (kW).
$q_{n,t}^{\text{ts}}$ Heating power discharged from the thermal energy storage of the prosumer n at the scheduling time t (kW).
$s_{n,t}^{\text{ts}}$ Stored thermal energy of the prosumer n at the scheduling time t (kWh).
t_i Start time of the supplied electricity of the seller i.
t_j Start time of the electricity demand of the buyer j.

I. Introduction

In efforts to achieve the goals of clean energy supply and zero carbon emissions, electric power systems are transitioning to a decentralized paradigm with the integration of distributed energy sources (DERs), e.g., roof-top solar panels [21]. Increasing numbers of consumers in distribution networks are able to produce energy on-site and actively participate in local electricity markets using DERs, which gives them a new role of prosumers [22]. Decarbonization of heat through electrification [23], e.g., using air-source heat pumps, provides great flexibility for prosumers to strategically store energy, shift or curtail demand, and exchange electricity with retailers or neighboring prosumers in responding to dynamic electricity pricing signals.

Accommodating the new role of prosumers requires a flexible structure of local electricity markets. The innovation of peer-to-peer electricity trading enables prosumers to directly exchange electricity in local markets for regional energy balance. The peer-to-peer electricity trading has been well documented in terms of the architecture design [1]–[3], pricing design [4], [5], auction mechanisms [6], [7], and regulations [24], for which the game-theoretic approaches have been widely applied to analyze the decision making and interactions among stakeholders. In [1], the key elements and technologies of the peer-to-peer electricity trading were identified and categorized into a hierarchical system architecture, in which the trading behaviors were modeled through using the game theory. Reference [2] designed a peer-to-peer architecture based on the coalition formation game, under which prosumers were incentivized to form social coalition groups and benefited from their groups. Yan *et al.* [3] studied an innovative architecture of joint energy and carbon markets, through which the impacts of network constraints on the carbon prices and carbon footprint among energy networks were investigated. In [4], a pricing mechanism of the peer-to-peer energy trading was designed based on the coalition game to construct a stable grand coalition for prosumers and facilitate the local energy balance. Tushar *et al.* [5] designed a pricing scheme to incentivize prosumers to participate in the peer-to-peer electricity trading during the peak demand period through forming coalitions based on the cooperative Stackelberg game. Haggi and Sun [6] developed a multi-round double auction mechanism with matching algorithm to facilitate the peer-to-peer energy exchange in distribution networks. Reference [7] designed a uniform-price auction mechanism for peer-to-peer energy trading in both sellers and buyers' markets for an efficient energy allocation. Schneiders *et al.* [24] investigated practical regulations and regulatory trails for implementing the peer-to-peer electricity trading, and identified the policy barriers for policy makers in order to reap the social benefits while avoid risks on power system infrastructures and prosumers.

Recent research has recognized the importance of the electrification of heat in terms of the power system decarbonization and energy market decentralization. Nematkhah *et al.* [8] designed a peer-to-peer trading framework for residential prosumers with heating, ventilation, and air conditioning systems,

TABLE I
COMPARISON BETWEEN THE EXISTING STUDIES AND OUR PROPOSED RESEARCH

Reference	Blockchain or Smart Contracts	Game Method	Multi-Energy Systems
Zhang *et al.* [1]	×	Non-Cooperative Game	Heating and Electricity
Tushar *et al.* [2]	×	Coalition Formation Game	×
Yan *et al.* [3]	Ethereum for Transaction Settlement and Market Clearing	Cooperative Game	×
Li *et al.* [4]	×	Cooperative Game	×
Tushar *et al.* [5]	Blockchain Based Trading Platform	Cooperative Stackelberg Game	×
Haggi and Sun [6]	×	×	×
Grubler *et al.* [7]	×	Non-Cooperative Game	×
Nematkhah *et al.* [8]	×	Non-Cooperative Game	Heating, Cooling, and Electricity
Liu *et al.* [9]	×	×	Heating, Cooling and Electricity
Jing *et al.* [10]	×	Non-Cooperative Game	Heating, Cooling, and Electricity
Langer [11]	×	×	Heating and Electricity
Chen *et al.* [12]	×	×	Heating and Electricity
Zhang *et al.* [13]	×	×	Heating and Electricity
Danzi *et al.* [14]	Blockchain Smart Contracts for Enforcing Proportional Fairness		
Thomas *et al.* [15]	Ethereum Smart Contracts for Negotiation of Control Rulesets	×	×
Brandstätt *et al.* [16]	Smart Contracts for Implementing Signals in Distribution Networks	×	×
The Sun Exchange [17]	Blockchain for Providing Crowdsale of Solar Panels	×	×
Liu *et al.* [18]	Ethereum Smart Contracts for Managing Charging/Discharging of Electric Vehicles	×	×
Han *et al.* [19]	Ethereum Smart Contracts for Executing Trading and Payment Rules	×	×
Abdella *et al.* [20]	Smart Contracts for Settlement and Authentication of Multiple Markets	×	×
Proposed Research	Ethereum Smart Contracts for Enforcing Negotiation-Based Pricing and Clearing Mechanism	Cooperative Game for Prosumers Themselves and Stackelberg Game between Retailers and Prosumers	Flexibility Provision from Heating System to Electricity Consumption and Exchange

in which an online scheduling for individual prosumers was developed along with the energy sharing among prosumers in achieving the local energy balance. Analogously, Liu *et al.* [9] incorporated the heat pump, refrigeration devices, and energy storage units into a designed peer-to-peer energy trading platform, and proposed a double-auction mechanism to promote the collaboration among prosumers. Researchers in [10] developed a Nash-type non-cooperative game model to feature the peer-to-peer trading among multi-energy prosumers, in which fair pricing strategies for the trading of both electricity and heat were yielded through minimizing the energy costs of prosumers. In [11], residential prosumers with heat pumps, solar panels, and electrical and thermal storage systems were modeled under various pricing regimes of the peer-to-peer energy trading. Chen *et al.* [12] investigated the peer-to-peer energy trading by considering the energy conversion of multi-energy microgrids. Zhang *et al.* [13] analyzed the impacts of multi-energy systems on the peer-to-peer energy trading, and demonstrated that the multi-energy coupling could reduce the electricity import from the utility grid.

Nonetheless, the large numbers of transactions and negotiations in the peer-to-peer electricity trading amplify the volumes of the information flows. The emergence of smart contracts [25], based on Blockchain technologies, has the potential to reduce the burdens of information flows through supporting a secure, automatic, and trusted electricity trading platform. On this platform, standardized procedures of the peer-to-peer electricity trading are set out by programmable functions of smart contracts which are replicable for all prosumers. The execution of smart contracts and settlement of electricity trading are self-enforced and collectively verified by every node in Blockchain networks. Implementing the Blockchain smart contracts into the operation [14], [15], planning [16], [17], and trading [18]–[20] in power systems has been focused in the literature. Danzi *et al.* [14] designed a smart contact to enforce the control strategy for the operation of DERs, so that the voltage of power systems was maintained below the recommended limits. Thomas *et al.* [15] incorporated instructions for the shared control of separated distribution networks into a general form of smart contracts, and demonstrated the advantages of the reduced transaction cost and computational requirements. In [16], a smart contract was designed for power system operators to improve the investment coordination in electricity networks. As an industrial practice, the Sun Exchange [17] partnered with local solar constructors to provide a crowdsale of solar panels to customers through Blockchain smart contracts, so as to encourage customers for investing in clean energy generation and earning incomes from selling surplus electricity. To manage increasing volumes of charging or discharging requests from electric vehicle owners, a peer-to-peer electricity trading system was proposed by [18], in which the trading procedures were standardized as smart contracts executed on the Ethereum platform. Han *et al.* [19] designed a smart contract to enforce the predefined rules of the trading and payment for enhancing the security and fairness. Abdella *et al.* [20] designed multiple smart contracts for the payment settlement and authentication of balancing markets, pool markets, and bilateral markets, and demonstrated the improvements on the throughput, scalability, and success rate.

The differences between the existing studies and our proposed research are presented in Table I. Compared to the existing studies, the key research questions to be addressed by this paper are:

- How to design the architecture of local electricity markets to accommodate prosumers and support the peer-to-peer electricity trading? What energy scheduling and trading decisions should prosumers make and what electricity pricing strategy should retailers/aggregators formulate to maximize their benefits?

• How to tailor smart contracts to the auction and pricing mechanisms of the peer-to-peer electricity trading, in order to enhance the automation, standardization, and self-enforcement?

• How will heating sources affect the flexibility of electricity consumption and exchange, and benefit for both prosumers and retailers in local electricity markets?

Overall, by addressing the aforementioned research questions, this paper has made following key contributions:

• The flexibility and benefits of heating sources in decentralized local electricity markets were investigated, along with scheduling and trading decisions of multi-energy prosumers.

• A novel negotiation-based pricing and clearing mechanism for peer-to-peer electricity trading was designed in the form of standardized smart contracts, supported by a Blockchain based platform to guarantee the verifiability, information efficiency, and tamper-resistance.

• The interactions between retailers and prosumers were modeled as a Stackelberg game, and iterative negotiations among prosumers were modeled as a cooperative game to yield optimal decisions which maximize the profits for retailers and maximize the tradeoff for individual prosumers. The proposed model can reduce 41.24% of average daily electricity costs for individual prosumers or consumers compared to the case without the peer-to-peer electricity trading.

The rest of this paper is organized as follows. Section II introduces the framework and problem formulations of local electricity markets to analyze the decision making and interactions of retailers and prosumers through using the cooperative Stackelberg game. Section III discusses the architecture of Blockchain networks and two standardized forms of smart contracts for the peer-to-peer electricity trading among prosumers. Case studies are provided in Section IV. Section V concludes this paper and identifies the future works.

II. Framework of Peer-to-Peer Trading

This research investigates the architecture of local electricity markets in supporting peer-to-peer electricity trading, by analyzing the roles of prosumers and electricity retailers. The objectives of this research include *1)* helping individual prosumers strategically schedule electrical and heating energy sources and loads, and make trading decisions in the day-ahead market, so as to save their electricity costs. *2)* helping retailers determine the day-ahead half-hourly electricity prices considering effects of peer-to-peer electricity trading and flexibility provision from heating sources, so as to maximize their profits. Considering the increasing deployment of roof-top solar panels and electrified heating sources [7], the intended application scale of the proposed research is on residential neighboring prosumers with both the roof-top solar panel and air-source heat pump.

A schematic illustration of the peer-to-peer electricity trading between multi-energy prosumers is presented in Fig. 1. These prosumers are able to exchange electricity with retailers or other neighboring prosumers. This research assumes that a retailer provides the day-ahead half-hourly electricity prices for its prosumers. Each household is equipped with an

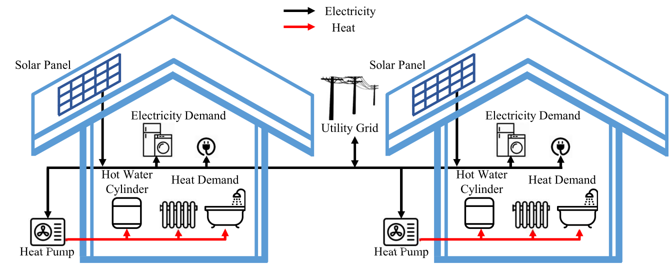


Fig. 1. Schematic illustration of the peer-to-peer electricity trading between multi-energy prosumers. Each prosumer is equipped with a roof-top solar panel, air-source heat pump, and hot water cylinder, along with other electrical and heating loads. Prosumers are able to exchange electricity with other neighboring prosumers or the retailer.

air-source heat pump and a hot water cylinder to meet its heating demand and provide flexibility for its electricity consumption and exchange. The thermal inertia of a household is modeled by a simple (1R1C [26]) thermal model and the indoor temperature is controlled within the comfort range of residents. A prosumer has three options to meet its electricity demand: *1)* buying electricity from its retailer at retail electricity prices, *2)* generating electricity using its roof-top solar panels, and *3)* buying electricity from other neighboring prosumers through the designed peer-to-peer trading platform at agreed prices. Meanwhile, a prosumer has two options to sell the extra electricity for earning revenues: *1)* selling electricity to its retailer at wholesale electricity prices, and *2)* selling electricity to other neighboring prosumers through the designed peer-to-peer trading platform at agreed prices.

A. The Role of Prosumers

Individual prosumers aim to maximize their own tradeoff by strategically deciding the generation, consumption, and power exchange with its retailer or other neighboring prosumers, and selling/buying prices agreed with other neighboring prosumers. The tradeoff of a prosumer can be described as the revenues of selling electricity to retailers or neighboring prosumers, subtracting the payments of buying electricity from retailers or neighboring prosumers as

$$f_n^{\text{tradeoff}} := \sum_{t\in\mathcal{T}} \left(p_{n,t}^{\text{p2r}} \cdot \pi_t^{\text{wh}} + \sum_{m\in\mathcal{N}, m\neq n} p_{n,m,t}^{\text{p2p}} \cdot \pi_{n,m,t}^{\text{p2p}} - p_{n,t}^{\text{r2p}} \cdot \pi_t^{\text{rt}} \right) \times \Delta t, \tag{1}$$

where f_n^{tradeoff} is the function of the tradeoff of the prosumer n, $\mathcal{T}$ is the index set of the scheduling time, $p_{n,t}^{\text{p2r}}$ is the power export from the prosumer n to a retailer at the scheduling time t, π_t^{wh} is the wholesale electricity price at the scheduling time t, $\mathcal{N}$ is the index set of prosumers, $p_{n,m,t}^{\text{p2p}}$ is the power exchange between the prosumer n and prosumer m ($m \in \mathcal{N}$, $m \neq n$) at the scheduling time t, $\pi_{n,m,t}^{\text{p2p}}$ is the agreed selling/buying price between the prosumer n and prosumer m at the scheduling time t, $p_{n,t}^{\text{r2p}}$ is the power import from a retailer to the prosumer n at the scheduling time t, π_t^{rt} is the retail electricity price at the scheduling time t, and Δt is the scheduling interval. When the prosumer n sells electricity to the prosumer m, $p_{n,m,t}^{\text{p2p}}$ becomes positive, $\pi^{\text{p2p}}_{n,m,t}$ indicates the agreed selling price, and the term $(p^{\text{p2p}}_{n,m,t} \cdot \pi^{\text{p2p}}_{n,m,t} \cdot \Delta t)$ indicates the revenues of the prosumer n at the scheduling time t; When the prosumer n buys electricity from the prosumer m, $p^{\text{p2p}}_{n,m,t}$ becomes negative, $\pi^{\text{p2p}}_{n,m,t}$ indicates the agreed buying price, and the term $(p^{\text{p2p}}_{n,m,t} \cdot \pi^{\text{p2p}}_{n,m,t} \cdot \Delta t)$ indicates the costs of the prosumer n at the scheduling time t.

When a prosumer imports/exports electricity from/to a retailer, this prosumer is a price taker which accepts the retail prices (π^{rt}_t)/wholesale prices (π^{wh}_t) determined by centralized energy markets, considering the small market share of individual prosumers compared to retailers or generation companies; When a prosumer trades electricity with neighboring prosumers, this prosumer becomes a price maker which determines its own buying/selling prices $(p^{\text{p2p}}_{n,m,t})$ through the negotiation. This decentralized pricing scheme incentivizes prosumers to strategically schedule their multi-energy sources and participate in the peer-to-peer electricity trading. In addition, since our research focuses on the operation of residential prosumers, for which the operational costs of the roof-top solar panel, air-source heat pump, and thermal energy storage is extremely low, compared to the installation costs, it is assumed that the operational costs of the roof-top solar panel, air-source heat pump, and thermal energy storage of a prosumer are zero.

When a prosumer schedules its multi-energy generation and consumption, the following operational constraints need to be considered:

- Electricity balance constraint:

$$p^{\text{r2p}}_{n,t} + p^{\text{pv}}_{n,t} = p^{\text{p2r}}_{n,t} + \sum_{m \in \mathcal{N}} p^{\text{p2p}}_{n,m,t} + d^{\text{hp}}_{n,t} + d^{\text{e}}_{n,t}, \forall n \in \mathcal{N}, t \in \mathcal{T}, \tag{2}$$

where $p^{\text{pv}}_{n,t}$ is the electricity produced by the roof-top solar panel of the prosumer n at the scheduling time t, $d^{\text{hp}}_{n,t}$ is the electricity used to run the air-source heat pump of the prosumer n at the scheduling time t, and $d^{\text{e}}_{n,t}$ is the electricity consumption of appliances of the prosumer n at the scheduling time t.

- Available heating power constraint:

$$q^{\text{ts}}_{n,t} + q^{\text{hp}}_{n,t} \geq d^{\text{ts}}_{n,t} + d^{\text{h}}_{n,t}, \forall n \in \mathcal{N}, t \in \mathcal{T}, \tag{3}$$

where $q^{\text{ts}}_{n,t}$ is the heating power discharged from the thermal energy storage of the prosumer n at the scheduling time t, $q^{\text{hp}}_{n,t}$ is the heating power supplied by the heat pump of the prosumer n at the scheduling time t, $d^{\text{ts}}_{n,t}$ is the heating power charged to the thermal energy storage of the prosumer n at the scheduling time t, and $d^{\text{h}}_{n,t}$ is the heating power supplied to the household, e.g., for space heating, of the prosumer n at the scheduling time t.

- Air-source heat pump constraints: Eq. (4) describes the capacity constraint of the air-source heat pump, and Eq. (5) describes the performance of the air-source heat pump for using electricity to pump heat from a cold place to a warm place.

$$0 \leq q^{\text{hp}}_{n,t} \leq q^{\text{hp,max}}_{n}, \forall n \in \mathcal{N}, t \in \mathcal{T}, \tag{4}$$

$$q^{\text{hp}}_{n,t} = \epsilon^{\text{hp}}_{n} \cdot d^{\text{hp}}_{n,t}, \forall n \in \mathcal{N}, t \in \mathcal{T}, \tag{5}$$

where $q^{\text{hp,max}}_{n}$ is the nominal maximum heating power of the air-source heat pump of the prosumer n, and ϵ^{hp}_{n} is the coefficient of performance of the air-source heat pump of the prosumer n.

- Thermal energy storage constraints: Eqs. (6) and (7) describe the constraints of charging and discharging rates of the thermal energy storage, respectively, Eq. (8) describes the energy dynamics of the thermal energy storage, and Eq. (9) describes the capacity constraint of the thermal energy storage.

$$0 \leq d^{\text{ts}}_{n,t} \leq d^{\text{ts, max}}_{n}, \forall n \in \mathcal{N}, t \in \mathcal{T}, \tag{6}$$

$$0 \leq q^{\text{ts}}_{n,t} \leq q^{\text{ts, max}}_{n}, \forall n \in \mathcal{N}, t \in \mathcal{T}, \tag{7}$$

$$s^{\text{ts}}_{n,t} = s^{\text{ts}}_{n,t-1} + \left[\vartheta \cdot d^{\text{ts}}_{n,t} - (1-\vartheta) \cdot q^{\text{ts}}_{n,t}\right] \cdot \Delta t, \forall n \in \mathcal{N}, t \in \mathcal{T}, \tag{8}$$

$$0 \leq s^{\text{ts}}_{n,t} \leq s^{\text{ts, max}}_{n}, \forall n \in \mathcal{N}, t \in \mathcal{T}, \tag{9}$$

where $d^{\text{ts, max}}_{n}$ and $q^{\text{ts, max}}_{n}$ are the maximum charging and discharging rates of the thermal energy storage of the prosumer n, respectively, $s^{\text{ts}}_{n,t}$ is the stored thermal energy of the prosumer n at the scheduling time t, $\vartheta \in \{0, 1\}$ is a binary variable indicating the charging (if $\vartheta = 1$) or discharging (if $\vartheta = 0$) of the thermal energy storage, and $s^{\text{ts, max}}_{n}$ is the thermal energy storage capacity of the prosumer n.

- Buildings' thermal inertia constraints: Eqs. (10) - (12) describe the building thermal inertia by using the 1R1C model [26], where Eq. (10) describes the dynamics of the indoor temperature of a household, Eq. (11) describes the temperature boundaries to maintain a prosumer's comfort, and Eq. (12) describes that the temperature at the end of the scheduling horizon needs to be greater than or equal to the temperature at the start of the scheduling horizon.

$$\begin{aligned}\tau_{n,t} = {} & \exp\left(\frac{-\Delta t \cdot u_n}{c_n}\right) \cdot \tau_{n,t-1} + \left[1 - \exp\left(\frac{-\Delta t \cdot u_n}{c_n}\right)\right] \cdot \tau^{\text{a}}_t \\ & + \frac{1}{u_n} \cdot \left[1 - \exp\left(\frac{-\Delta t \cdot u_n}{c_n}\right)\right] \cdot d^{\text{h}}_{n,t}, \forall n \in \mathcal{N}, t \in \mathcal{T},\end{aligned} \tag{10}$$

$$\tau^{\min}_{n} \leq \tau_{n,t} \leq \tau^{\max}_{n}, \forall n \in \mathcal{N}, t \in \mathcal{T}, \tag{11}$$

$$\tau_{n,|\mathcal{T}|} \geq \tau_{n,1}, \forall n \in \mathcal{N}, \tag{12}$$

where $\tau_{n,t}$ is the indoor temperature of the prosumer n's household at the scheduling time t with the unit of K, u_n is the thermal transmittance of the prosumer n's household with the unit of W/K, c_n is the thermal capacitance of the prosumer n's household with the unit of J/kgK, τ^{a}_t is the temperature of the ambient air at the scheduling time t, and $\tau^{\min}_{n}$ and $\tau^{\max}_{n}$ are the minimum and maximum temperature boundaries to maintain the comfort of the prosumer n.

Therefore, the tradeoff maximization problem of the prosumer n can be described as

$$\max_{\substack{p^{\text{p2r}}_{n,t}, p^{\text{p2p}}_{n,m,t}, \pi^{\text{p2p}}_{n,m,t}, p^{\text{r2p}}_{n,t}, d^{\text{hp}}_{n,t}, \\ q^{\text{ts}}_{n,t}, q^{\text{hp}}_{n,t}, d^{\text{ts}}_{n,t}, d^{\text{h}}_{n,t}, s^{\text{ts}}_{n,t}, \tau_{n,t}}} : f^{\text{tradeoff}}_{n}, \forall n \in \mathcal{N}, t \in \mathcal{T}, \tag{13}$$

$$\text{s.t. Eqs. (2)} - \text{(12)}.$$

B. The Role of Retailers

Individual retailers aim to maximize their profits by strategically determining the retail electricity prices. The profits of a retailer can be described as the revenues of selling electricity to its prosumers, subtracting the costs of buying the electricity in wholesale markets ($\sum_{n\in\mathcal{N}} p^{\text{r2p}}_{n,t} \cdot \pi^{\text{wh}}_t \cdot \Delta t$) and buying the electricity from its prosumers at the wholesale electricity prices ($\sum_{n\in\mathcal{N}} p^{\text{p2r}}_{n,t} \cdot \pi^{\text{wh}}_t \cdot \Delta t$). Since the proposed model focuses on the local electricity markets, the retailer is assumed as a price taker in the wholesale markets, i.e., they must accept the prevailing wholesale electricity prices. Hence, the function of a retailer's profits can be described as

$$f^{\text{profit}} := \sum_{n\in\mathcal{N}} p^{\text{r2p}}_{n,t} \cdot \pi^{\text{rt}}_t \cdot \Delta t - \left[\sum_{n\in\mathcal{N}} \left(p^{\text{r2p}}_{n,t} + p^{\text{p2r}}_{n,t}\right) \cdot \pi^{\text{wh}}_t \cdot \Delta t\right], \tag{14}$$

where f^{profit} is the objective function of the profits of a retailer.

When a retailer decides the retail prices, the following maximum/minimum price limits need to be considered as

$$\pi^{\text{rt,min}}_t \leq \pi^{\text{rt}}_t \leq \pi^{\text{rt,max}}_t, \forall t \in \mathcal{T}, \tag{15}$$

where $\pi^{\text{rt,min}}_t$ and $\pi^{\text{rt,max}}_t$ are the minimum and maximum limits of the retail electricity price at the scheduling time t. The minimum and maximum limits are set by regulators as the floor and cap of the retail electricity price, respectively, to ensure a fair energy market. For instance, in the GB energy market, the regulator, Office of Gas and Electricity Markets (Ofgem) sets a price cap since 2017 to limit the rates at which a supplier can charge from consumers [27].

Therefore, the profits maximization problem of a retailer can be described as

$$\begin{aligned} \max_{\pi^{\text{rt}}_t} : \ & f^{\text{profit}}, \forall t \in \mathcal{T}, \\ \text{s.t.} \ & \text{Eq. (15).} \end{aligned} \tag{16}$$

C. Cooperative Stackelberg Game-Theoretic Problem

The interactions between a retailer and its $|\mathcal{N}|$ prosumers were modeled as a Stackelberg game-theoretic problem, through which the retailer acts as a leader to determine the retail electricity pricing, and $|\mathcal{N}|$ prosumers act as the followers to determine the volume of electricity exchange with the retailer. The prosumers themselves play a cooperative game to negotiate the volume and price of the peer-to-peer electricity trading between themselves. Therefore, this leads to a 1-leader and $|\mathcal{N}|$-follower cooperative Stackelberg game-theoretic problem. The procedure of this cooperative Stackelberg game is as follows:

Step 1: The leader (retailer) determines the retail electricity prices, by solving its optimization problem, i.e., objective function Eq. (16) constrained by Eq. (15), based on the daily prediction of power exchange with prosumers as

$$\mathcal{S}_L = \left\{\pi^{\text{rt}*}_t | t \in \mathcal{T}\right\}, \tag{17}$$

where $\mathcal{S}_L$ is the decision space of the leader.

Step 2: With the leader's strategy, each individual prosumer decides the responding strategies by solving its own optimization problem, i.e., objective function Eq. (13) constrained by Eqs. (2) - (12), as

$$\begin{aligned} \mathcal{S}_{F,n} = \Big\{ & p^{\text{p2r}*}_{n,t}, p^{\text{p2p}*}_{n,m,t}, \pi^{\text{p2p}*}_{n,m,t}, p^{\text{r2p}*}_{n,t}, d^{\text{hp}*}_{n,t}, q^{\text{ts}*}_{n,t}, \\ & q^{\text{hp}*}_{n,t}, d^{\text{ts}*}_{n,t}, d^{\text{h}*}_{n,t}, s^{\text{ts}*}_{n,t}, \tau^{*}_{n,t} | t \in \mathcal{T}\Big\}, \forall n \in \mathcal{N}, \end{aligned} \tag{18}$$

where $\mathcal{S}_{F,n}$ is the decision space of the follower n.

Step 3: The followers cooperatively negotiate the volume and price of the electricity to be exchanged with each other in an iterative manner. The iterative negotiation is self-enforced by the standardized auction procedures on the Blockchain based platform of peer-to-peer trading, which will be detailed in Section III. In every iteration of negotiation, a prosumer decreases/increases its selling/buying prices to clear the unmatched supply/demand. The price decrement/increment of different prosumers would be different depending on their idiosyncratic responsiveness. To model these idiosyncratic responsiveness, this research extends the concept of price elasticities of a seller/buyer from microeconomics [28]. The price elasticities of a seller/buyer describe the relative changes in the electricity supply/demand resulting from a change in selling/buying prices. Since the relative change in the electricity supply/demand is unknown prior to the next iteration of negotiation, our research uses the ratio of the unmatched supply/demand to matched supply/demand to replace it. The price elasticities of a prosumer as an electricity seller and buyer are defined as (19) and (20), respectively.

$$\xi^{\text{s}}_n := \frac{p^{\text{unmatched}}_{n,t}(\iota)/p^{\text{matched}}_{n,t}(\iota)}{\Delta\pi^{\text{p2p}}_{n,m,t}/\pi^{\text{p2p}}_{n,m,t}(\iota)}, \tag{19}$$

$$\xi^{\text{b}}_n := \frac{d^{\text{unmatched}}_{n,t}(\iota)/d^{\text{matched}}_{n,t}(\iota)}{\Delta\pi^{\text{p2p}}_{n,m,t}/\pi^{\text{p2p}}_{n,m,t}(\iota)}, \tag{20}$$

where ξ^{s}_n and ξ^{b}_n are the price elasticities of the prosumer n as an electricity seller and buyer, respectively, ι is the iteration number of the negotiation, $\Delta\pi^{\text{p2p}}_{n,m,t}$ is the change of the selling/buying price of the prosumer n negotiated with the prosumer m at the scheduling time t from the iteration ι to $(\iota+1)$, i.e., $\Delta\pi^{\text{p2p}}_{n,m,t} = \pi^{\text{p2p}}_{n,m,t}(\iota+1)$-$\pi^{\text{p2p}}_{n,m,t}(\iota)$, $p^{\text{unmatched}}_{n,t}(\iota)$ is the unmatched electricity supply of the prosumer n at the scheduling time t which has not been accepted by any buyer until the iteration ι, $p^{\text{matched}}_{n,t}(\iota)$ is the matched electricity supply of the prosumer n at the scheduling time t which has already been accepted by other buyers before the iteration ι, $d^{\text{unmatched}}_{n,t}(\iota)$ is the unmatched electricity demand of the prosumer n at the scheduling time t which has not been satisfied by any seller until the iteration ι, and $d^{\text{matched}}_{n,t}(\iota)$ is the matched electricity demand of the prosumer n at the scheduling time t which has already been satisfied by other sellers before the iteration ι. Given that the total amount of the scheduled peer-to-peer electricity trading of the prosumer n at the scheduling time t equals to the sum of matched and unmatched amount at any iteration, we have

$$\sum_{m\in\mathcal{N}} p^{\text{p2p}*}_{n,m,t} = \begin{cases} p^{\text{unmatched}}_{n,t}(\iota) + p^{\text{matched}}_{n,t}(\iota), & \text{if } \sum_{m\in\mathcal{N}} p^{\text{p2p}}_{n,m,t} > 0, \\ -\left[d^{\text{unmatched}}_{n,t}(\iota) + d^{\text{matched}}_{n,t}(\iota)\right], & \text{if } \sum_{m\in\mathcal{N}} p^{\text{p2p}}_{n,m,t} < 0. \end{cases} \tag{21}$$

At the initial iteration, we have

$$\pi^{\text{p2p}}_{n,m,t}(\iota = 1) = \pi^{\text{p2p}*}_{n,m,t}, \tag{22}$$

$$\begin{cases} p^{\text{unmatched}}_{n,t}(\iota = 1) = \sum_{m\in\mathcal{N}} p^{\text{p2p}*}_{n,m,t}, & \text{if } \sum_{m\in\mathcal{N}} p^{\text{p2p}}_{n,m,t} > 0, \\ d^{\text{unmatched}}_{n,t}(\iota = 1) = -\sum_{m\in\mathcal{N}} p^{\text{p2p}*}_{n,m,t}, & \text{if } \sum_{m\in\mathcal{N}} p^{\text{p2p}}_{n,m,t} < 0, \end{cases} \tag{23}$$

$$p^{\text{matched}}_{n,t}(\iota = 1) = d^{\text{matched}}_{n,t}(\iota = 1) = 0. \tag{24}$$

Next, a prosumer adjusts its selling or buying price in every iteration according to its price elasticity, until the unmatched supply or demand is accepted. For an electricity seller, if there still exists unmatched electricity supply at the iteration ι, i.e., $p^{\text{unmatched}}_{n,t}(\iota) > 0$, this seller would decrease the selling price, i.e., $\Delta\pi^{\text{p2p}}_{n,m,t} < 0$. According to Eq. (19), we have

$$\pi^{\text{p2p}}_{n,m,t}(\iota + 1) = \pi^{\text{p2p}}_{n,m,t}(\iota) + \frac{\pi^{\text{p2p}}_{n,m,t}(\iota) \cdot p^{\text{unmatched}}_{n,t}(\iota)}{\xi^{\text{s}}_{n} \cdot p^{\text{matched}}_{n,t}(\iota)}. \tag{25}$$

For an electricity buyer, if there still exists unmatched electricity demand at the iteration ι, i.e., $d^{\text{unmatched}}_{n,t}(\iota)>0$, this buyer would increase the buying price, i.e., $\Delta\pi^{\text{p2p}}_{n,m,t} > 0$. According to Eq. (20), we have

$$\pi^{\text{p2p}}_{n,m,t}(\iota + 1) = \pi^{\text{p2p}}_{n,m,t}(\iota) + \frac{\pi^{\text{p2p}}_{n,m,t}(\iota) \cdot d^{\text{unmatched}}_{n,t}(\iota)}{\xi^{\text{b}}_{n} \cdot d^{\text{matched}}_{n,t}(\iota)}. \tag{26}$$

Step 4: This negotiation is iteratively proceeded until the cooperative equilibrium [29] is reached. At the cooperative equilibrium, not any prosumer wants to deviate its strategy. Let $\iota^\star$ denote the iteration of reaching the cooperative equilibrium.

Theorem 1: The cooperative game converges to the cooperative equilibrium when the following three criteria hold simultaneously:

• Prosumers exchange electricity with each other as much as possible at their optimal price $\{\pi^{\text{p2p}*}_{n,m,t} | t \in \mathcal{T}\}$.

• For the electricity sellers whose supply is not accepted until the iteration $\iota^\star$, their selling prices would decrease to the wholesale electricity price. For the electricity buyers whose demand is not satisfied until the iteration $\iota^\star$, their buying prices would increase to the retail electricity price as

$$\pi^{\text{p2p}}_{n,m,t}(\iota^\star) = \begin{cases} \pi^{\text{wh}}_t, & \text{if } p^{\text{unmatched}}_{n,t}(\iota^\star) > 0, \\ \pi^{\text{rt}}_t, & \text{if } d^{\text{unmatched}}_{n,t}(\iota^\star) > 0. \end{cases} \tag{27}$$

• At the iteration $\iota^\star$, there is no unmatched supply (if the total demand is higher than the total supply of all prosumers) or unmatched demand (if the total supply is higher than the total demand of all prosumers) for any prosumer as

$$\begin{cases} p^{\text{unmatched}}_{n,t}(\iota^\star) = 0, \forall n \in \mathcal{N}, \text{ if } \sum_{n\in\mathcal{N}} p^{\text{p2p}}_{n,m,t} < 0, \\ d^{\text{unmatched}}_{n,t}(\iota^\star) = 0, \forall n \in \mathcal{N}, \text{ if } \sum_{n\in\mathcal{N}} p^{\text{p2p}}_{n,m,t} > 0. \end{cases} \tag{28}$$

Proof: For the criteria of Eqs. (27) and (28), *1)* if $p^{\text{unmatched}}_{n,t}(\iota) > 0$, according to Eq. (25), the selling price would decrease, i.e., $\pi^{\text{p2p}}_{n,m,t}(\iota + 1) < \pi^{\text{p2p}}_{n,m,t}(\iota)$, and if $d^{\text{unmatched}}_{n,t}(\iota) > 0$, according to Eq. (26), the buying price would increase, i.e., $\pi^{\text{p2p}}_{n,m,t}(\iota + 1) > \pi^{\text{p2p}}_{n,m,t}(\iota)$. The iterative negotiation continues; *2)* if $p^{\text{unmatched}}_{n,t}(\iota) = 0$ or $d^{\text{unmatched}}_{n,t}(\iota) = 0$, the selling or buying price would remain unchanged, i.e., $\pi^{\text{p2p}}_{n,m,t}(\iota + 1) = \pi^{\text{p2p}}_{n,m,t}(\iota)$. The iterative negotiation converges; *3)* The iterative negotiation will diverge only if $\pi^{\text{p2p}}_{n,m,t}(\iota) < \pi^{\text{wh}}_t$ (when $p^{\text{unmatched}}_{n,t}(\iota) > 0$), or $\pi^{\text{p2p}}_{n,m,t}(\iota) > \pi^{\text{rt}}_t$ (when $d^{\text{unmatched}}_{n,t}(\iota) > 0$), i.e., $\pi^{\text{p2p}}_{n,m,t}$ exceeds the boundaries of $[\pi^{\text{wh}}_t, \pi^{\text{rt}}_t]$, which means that the seller/buyer would export/import the electricity to/from the retailer at $\pi^{\text{wh}}_t/\pi^{\text{rt}}_t$ to minimize the electricity costs, rather than trading with other prosumers. ■

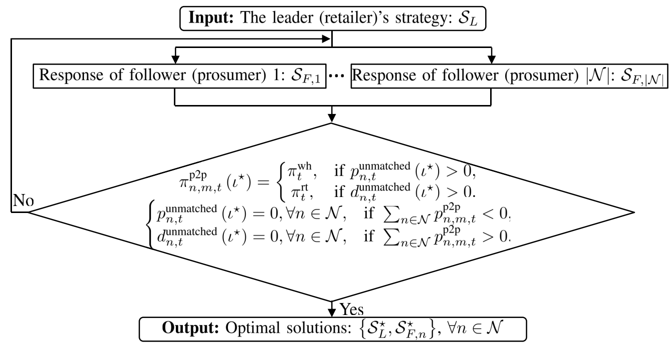


Fig. 2. Flowchart of the cooperative Stackelberg game between the leader and followers.

Step 5: The remaining supply or demand of prosumers which has not been matched during the peer-to-peer electricity trading will be exchanged with the retailer at the wholesale or retail electricity price. The outputs of the cooperative Stackelberg game are the optimal solutions for both the retailer and its $|\mathcal{N}|$ prosumers, denoted as $\{\mathcal{S}^\star_L, \mathcal{S}^\star_{F,n}\}$, $\forall n \in \mathcal{N}$.

The flowchart of the cooperative Stackelberg game between the leader and followers is presented in Fig. 2.

III. Blockchain Based Platform for Peer-to-Peer Electricity Trading

This section introduces the architecture of Blockchain networks, and two standardized forms of smart contracts for negotiating the volume and price of peer-to-peer electricity trading among prosumers.

A. Architecture of Blockchain Networks

A Blockchain based platform for the peer-to-peer electricity trading was developed to integrate the negotiation information and trading decisions of prosumers as shown in Fig. 3. The states of smart contracts and accounts, transactions, and receipts are structured into three modified Merkle Patricia Tries [30] stored in the block body, in order to improve the verifiability and searching efficiency of trading information. The root hashes of these three modified Merkle Patricia Tries are stored in the block header to guarantee the tamper-resistance. The blocks are chronologically chained through including the hash of the previous block header into the current block, forming a Blockchain [31]. Market operators operate full nodes to manage the trading platform and validate all transactions. Prosumers operate simplified payment verification (SPV) [32] clients to access Blockchain networks for negotiation and trading. The SPV clients only store the block headers and verify their related transactions with lower computational and storage requirements compared to the full nodes.

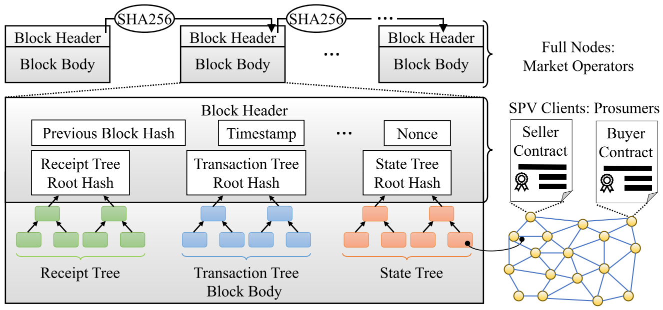


Fig. 3. Architecture of Blockchain based platform for the peer-to-peer electricity trading. The states of smart contracts and accounts, transactions, and receipts are structured into three modified Merkle Patricia Tries. The Blockchain is formed through chronologically including the hash of the previous block header into the current block. Market operators operate full nodes and prosumers operate simplified payment verification.

B. Smart Contracts

Two standardized forms of smart contracts were designed for electricity sellers and buyers, respectively, with the procedures of the contract deployment, auction, winner selection, and ownership exchange. In the smart contracts of sellers, a number of buyers bid with a higher price in competition with each other. Once the auction ends, the buyer with the highest buying price wins. In the smart contracts of buyers, a number of sellers offer with a lower price in competition with each other. Once the auction ends, the seller with the lowest selling price wins. Both the seller's contracts and the buyer's contracts are used in the day-ahead market, to negotiate the price and volume of electricity for the following day. These two standardized forms of smart contracts are replicable for all prosumers, which prevents unforeseen trading behaviors and reduces the costs for processing the information of negotiation and trading. Each smart contract can be deployed by an individual prosumer and multiple prosumers can deploy their own smart contracts simultaneously by specifying their own time of the auction end. Let i and j denote the indices of the electricity seller and buyer, respectively. The detailed trading procedures in the smart contracts of sellers and buyers are described as follows.

1) Smart Contracts of Sellers:

Step 1 (Deployment of Seller): An electricity seller i deploys the selling contracts by providing the information of the seller's address id_i, network serial number ϕ_i, start time t_i and end time $t_i+\Delta t_i$ of the supplied electricity, supplied amount p_i, minimum accepted buying price $\pi_i^{\min}$, and auction end time θ_i, which can be described as $\mathcal{C}_i$ $(id_i, \phi_i, t_i, t_i+\Delta t_i, p_i, \pi_i^{\min}, \theta_i)$, where $\mathcal{C}_i$ is the set of the smart contracts deployed by the seller i. The network serial number is used to help prosumers find their neighboring prosumers. The seller/buyer address is in the *payable* property, which means it can receive the payment from the smart contracts after the auction ends.

Step 2 (Auction of Buyers): For a seller's contracts, a number of buyers can enter the smart contracts to compete by biding with a higher price. There are three conditions which allow a buyer to enter the smart contracts:

- The auction is not ended, i.e., now $\leq \theta_i$;
- The network serial number of the buyer matches that of the seller, i.e., $\phi_j = \phi_i$;
- The buyer's buying price, denoted as π_j, is higher than the minimum accepted buying price of the seller, i.e., $\pi_j > \pi_i^{\min}$;
- The buyer's buying price is higher than the current highest buying price, denoted as $\pi_i^\star$, i.e., $\pi_j > \pi_i^\star$.

Once a buyer enters the seller's smart contracts, the submitted buying value $(\pi_i^\star \cdot p_i \cdot \Delta t_i)$ will be charged from the buyer's account and frozen by the smart contracts. Every time when a buyer with a higher buying price π_j' replaces the previous highest buying price π_j, the smart contracts will firstly transfer the frozen buying value $(\pi_j \cdot p_i \cdot \Delta t_i)$ back to the previous highest buyer's address, and then charge $(\pi_j' \cdot p_i \cdot \Delta t_i)$ form the current highest buyer's address. The Blockchain networks update the information of the current highest buyer's address, denoted as id_j, i.e., $j^\star = id_j$ and its buying price, i.e., $\pi_i^\star = \pi_j'$.

Step 3 (Pay to Seller): Once the auction ends, i.e., now $> \theta_i$, the highest buyer becomes the winner. After the delivery time $t_i+\Delta t_i$, the smart meter of the highest buyer sends the delivery signal to the smart contracts. The smart contracts subsequently transfer the frozen value to the seller's account, after meeting three conditions:

- The delivery is ended, i.e., now $> t_i + \Delta t_i$;
- The paying value is non-zero, i.e., $(\pi_i^\star \cdot p_i \cdot \Delta t_i) > 0$;
- The pay-to-seller function has not been called, i.e., paid = false.

Step 4 (Adjustment): For the case of the over-delivery due to the uncertainty of solar generation, if a seller supplies more energy than its promised volume in the day-ahead market, i.e., $(\hat{p}_i \cdot \Delta t_i) > (p_i \cdot \Delta t_i)$, where $\hat{p}$ is the actual delivered power of the seller i, the over-delivered energy, i.e., $(\hat{p}_i \cdot \Delta t_i - p_i \cdot \Delta t_i)$, will be purchased by the retailer at the wholesale price π_t^{wh} through calling the transfer function by the retailer. For the case of the under-delivery due to the uncertainty of solar generation, if a seller supplies less energy than its promised volume in the day-ahead market, i.e., $(\hat{p}_i \cdot \Delta t_i) < (p_i \cdot \Delta t_i)$, this seller needs to purchase the under-delivered energy, i.e., $(p_i \cdot \Delta t_i - \hat{p}_i \cdot \Delta t_i)$ from the retailer at the retail price π_t^{rt} through calling the transfer function, in order to meet the demand of its buyers. Since the wholesale price is lower than the selling price and retail price is higher than the buying price, the seller would be incentivized to accurately predict its solar generation in the day-ahead market to maximize its tradeoff.

2) Smart Contracts of Buyers:

Step 1 (Deployment of Buyer): An electricity buyer j deploys the buying contracts by providing the information of the buyer's address id_j, network serial number ϕ_j, start time t_j and end time $t_j + \Delta t_j$ of the electricity demand, demand amount p_j, maximum accepted selling price $\pi_j^{\max}$, and the auction end time θ_j, which can be described as $\mathcal{C}_j$ $(id_j, \phi_j, t_j, t_j+\Delta t_j, p_j, \pi_j^{\max}, \theta_j)$, where $\mathcal{C}_j$ is the set of the smart contracts deployed by the buyer j.

Step 2 (Buyer Deposit): The electricity buyer j deposits the value $(\pi_j^{\max} \cdot p_j \cdot \Delta t_j)$ into the smart contracts. This deposit is frozen by the smart contracts until a seller enters the smart contracts.

Step 3 (Sellers Auction): For a buyer's contracts, a number of sellers can enter the smart contracts to compete by offering

Algorithm 1 Selling Contracts

input: seller's address (payable) id_i, network serial number ϕ_i, supply start time t_i, supply end time $t_i + \Delta t_i$, supplied amount p_i, minimum accepted buying price $\pi_i^{\min}$, auction end time θ_i
function: buyers auction (called by buyers)
  input: network serial number ϕ_j, buying price π_j
  require: now $\leq \theta_i$
  require: $\phi_j = \phi_i$
  require: $\pi_j > \pi_i^{\min}$
  require: $\pi_j >$ highest buying price $\pi_i^{\star}$
  if $\pi_i^{\star} \neq 0$
    smart contracts transfer $(\pi_i^{\star} \cdot p_i \cdot \Delta t_i)$ back to previous highest buyer's address
  end
  output: update current highest buyer's address $j^{\star}$=id_j and its buying price $\pi_i^{\star} = \pi_j'$
function: pay-to-seller
  input: paying value $(\pi_i^{\star} \cdot p_i \cdot \Delta t_i)$
  require: now $> t_i + \Delta t_i$
  require: $(\pi_i^{\star} \cdot p_i \cdot \Delta t_i) > 0$
  require: paid = false
  smart contracts transfer $(\pi_i^{\star} \cdot p_i \cdot \Delta t_i)$ to seller's address
  output: paid = true
function: adjustment
  input: actual delivery $(\hat{p}_i \cdot \Delta t_i)$, submitted volume $(p_i \cdot \Delta t_i)$, wholesale price π_t^{wh}, retail price π_t^{rt}
  require: paid = true
  if $(\hat{p}_i \cdot \Delta t_i) > (p_i \cdot \Delta t_i)$
    smart contracts transfer $[(\hat{p}_i\text{-}p_i) \cdot \Delta t_i \cdot \pi_t^{\mathrm{wh}}]$ from the retailer to the seller
  else if $(\hat{p}_i \cdot \Delta t_i) < (p_i \cdot \Delta t_i)$
    smart contracts transfer $[(p_i\text{-}\hat{p}_i) \cdot \Delta t_i \cdot \pi_t^{\mathrm{rt}}]$ from the seller to the retailer
  output: adjustment completed

Algorithm 2 Buying Contracts

input: buyer's address (payable) id_j, network serial number ϕ_j, demand start time t_j, demand end time $t_j + \Delta t_j$, demand amount p_j, maximum accepted selling price $\pi_j^{\max}$, auction end time θ_j
function: buyer deposit (called by the buyer)
  input: deposit
  require: deposit = $(\pi_j^{\max} \cdot p_j \cdot \Delta t_j)$
  output: deposit transferred from id_j to smart contracts
function: sellers auction (called by sellers)
  input: network serial number ϕ_i, selling price π_i
  require: now $\leq \theta_j$
  require: $\phi_i = \phi_j$
  require: $\pi_i < \pi_j^{\max}$
  require: $\pi_i <$ lowest selling price $\pi_j^{\star}$
  if $\pi_j^{\star} = 0$
    smart contracts transfer $(\pi_j^{\max} \cdot p_j \cdot \Delta t_j\text{-}\pi_i' \cdot p_j \cdot \Delta t_j)$ back to the buyer's address
  else
    smart contracts transfer $(\pi_j^{\star} \cdot p_j \cdot \Delta t_j\text{-}\pi_i' \cdot p_j \cdot \Delta t_j)$ back to the buyer's address
  end
  output: update the current lowest seller's address $i^{\star}$=id_i and its selling price $\pi_j^{\star} = \pi_i$
function: pay-to-seller
  input: paying value $(\pi_j^{\star} \cdot p_j \cdot \Delta t_j)$
  require: now $> t_j + \Delta t_j$
  require: $(\pi_j^{\star} \cdot p_j \cdot \Delta t_j) > 0$
  require: paid = false
  smart contracts transfer $(\pi_j^{\star} \cdot p_j \cdot \Delta t_j)$ to seller's address
  output: paid = true
function: adjustment
  input: actual delivery $(\hat{p}_i \cdot \Delta t_j)$, submitted volume $(p_j \cdot \Delta t_j)$, wholesale price π_t^{wh}, retail price π_t^{rt}
  require: paid = true
  if $(\hat{p}_i \cdot \Delta t_j) > (p_j \cdot \Delta t_j)$
    smart contracts transfer $[(\hat{p}_i\text{-}p_j) \cdot \Delta t_j \cdot \pi_t^{\mathrm{wh}}]$ from the retailer to the seller
  else if $(\hat{p}_i \cdot \Delta t_j) < (p_j \cdot \Delta t_j)$
    smart contracts transfer $[(p_j\text{-}\hat{p}_i) \cdot \Delta t_j \cdot \pi_t^{\mathrm{rt}}]$ from the seller to the retailer
  output: adjustment completed

with a lower price. There are three conditions which allow a seller to enter the smart contracts:

- The auction is not ended, i.e., now $\leq \theta_j$;
- The network serial number of the seller matches that of the buyer, i.e., $\phi_i = \phi_j$;
- The seller's selling price, denoted as π_i, is lower than the maximum accepted selling price of the buyer, i.e., $\pi_i < \pi_j^{\max}$;
- The seller's selling price is lower than the current lowest selling price, denoted as $\pi_j^{\star}$, i.e., $\pi_i < \pi_j^{\star}$.

Once a seller with price π_i' enters the buyer's smart contracts, the smart contracts would refund the difference between the previous deposit $(\pi_j^{\star} \cdot p_j \cdot \Delta t_j)$ and current selling value $(\pi_i' \cdot p_j \cdot \Delta t_j)$ to the buyer's address. The Blockchain networks update the information of the current lowest seller's address, i.e., $i^{\star} = id_i$ and its selling price, i.e., $\pi_j^{\star} = \pi_i'$.

Step 4 (Pay to Seller): Once the auction ends, i.e., now $> \theta_i$, the lowest seller becomes the winner. After the delivery time $t_j + \Delta t_j$, the smart meter of the buyer sends the delivery signal to the smart contracts. The smart contracts subsequently transfer the frozen value to the lowest seller's account, after meeting three conditions:

- The delivery is ended, i.e., now $> t_j + \Delta t_j$;
- The paying value is non-zero, i.e., $(\pi_j^{\star} \cdot p_j \cdot \Delta t_j) > 0$;
- The pay-to-seller function has not been called, i.e., paid = false.

Step 5 (Adjustment): For the case of the over-delivery due to the uncertainty of solar generation, if a seller supplies more energy than the demanded volume in the day-ahead market, i.e., $(\hat{p}_i \cdot \Delta t_j) > (p_j \cdot \Delta t_j)$, the over-delivered energy, i.e., $(\hat{p}_i \cdot \Delta t_j - p_j \cdot \Delta t_j)$, will be purchased by the retailer at the wholesale price π_t^{wh} through calling the transfer function by the retailer. For the case of the under-delivery due to the uncertainty of solar generation, if a seller supplies less energy than the demanded volume in the day-ahead market, i.e., $(\hat{p}_i \cdot \Delta t_j) < (p_j \cdot \Delta t_j)$, this seller needs to purchase the under-delivered energy, i.e., $(p_j \cdot \Delta t_j - \hat{p}_i \cdot \Delta t_j)$ from the retailer at the retail price π_t^{rt} through calling the transfer function, in order to meet the demand of its buyers.

Remark 1: The minimum accepted buying price of the seller and maximum accepted selling price of the buyer are the initial prices yielded by solving their own optimization problems, which corresponds to the Eq. (22). For the buyers' auction, how a buyer bids with a higher price is modeled by Eq. (26). For the sellers' auction, how a seller offers with a lower price is modeled by Eq. (25).

Remark 2: There are two time domains defined in our research: *1)* the time for prosumers' day-ahead energy scheduling, in which the time interval (Δt) corresponds to every half-hour for the following day and time horizon $(|\mathcal{T}|)$ corresponds to the total 48 half-hour intervals. We have $(\Delta t, |\mathcal{T}|) = (0.5, 48)$; *2)* The time of the auction end (θ_i and θ_j), only before which buyers or sellers can enter the smart contracts for the real-time negotiation on the price and volume of electricity for the following day.

C. Advantage Remark

The proposed Blockchain smart contracts have the following advantages compared to the existing Blockchain-based mechanisms on the peer-to-peer electricity trading:

1) The optimal decisions on the price and volume of peer-to-peer electricity trading are integrated into the Blockchain platform as the inputs, without interventions from power system operators or market operators.

2) The negotiation and price clearing mechanisms modeled by the cooperative game are standardized by the designed smart contracts, which could be automatically executed in a self-enforcing manner. This reduces the costs for processing the information from the trading and negotiation.

3) The idiosyncratic smart contracts are designed specifically for the auctions of 1-buyer, multiple-seller or 1-seller, multiple buyers to adapt dynamic supply-demand balance of local energy markets.

4) The prosumers can operate the SPV clients, which reduces the requirements on computation and storage, so that they are able to participate in the peer-to-peer electricity trading with smart meters or smart phones.

IV. Case Studies

Case studies have been conducted on 7 households in England, served by the same electricity retailer. The prosumers 1, 3, 4 and 7 are equipped with roof-top solar panels, whereas the prosumers 2, 5, and 6 are without roof-top solar panels. The generation profiles of the roof-top solar panels were collected from Renewables.ninja [33] with the installed capacity of 6 kW. The scheduling horizon is 24 h for the next day in the 0.5 h interval. £0.065/kWh of the average wholesale price in 2020 from the GB energy market [34] was used. The minimum and maximum limits of the retail electricity price were decided by choosing the minimum and maximum historical retail electricity prices in the GB energy markets, in which $\pi_t^{\text{rt,min}} = £0/\text{kWh}$ and $\pi_t^{\text{rt,max}} = £0.35/\text{kWh}$. The input data of the solar generation and ambient temperature in a typical winter day was selected to investigate the impacts of heating systems. The parameters of heating systems used in the case studies are listed in Table II. The specific value of price elasticities for each prosumer is determined by the average historical values of the changes of electricity consumption resulting from the changes of retail electricity prices. The smart contracts were written in the Solidity language [30] and deployed on the Remix - Ethereum IDE [35]. The optimization problems were programmed by the MATLAB and solved by the artificial immune algorithm [36]. The simulations were performed on a machine with the Intel Core i7-4470HQ CPU at 2.20 GHz.

TABLE II
PARAMETERS OF HEATING SYSTEMS USED IN THE CASE STUDIES

Parameter	Value	Parameter	Value	Parameter	Value
τ_n^{min}	291.15 K	τ_n^{max}	294.15 K	$q_n^{\text{hp,max}}$	12 kW
ϵ_n^{hp}	4	$d_n^{\text{ts, max}}$	6 kW	$q_n^{\text{ts, max}}$	6 kW
$s_n^{\text{ts, max}}$	7 kWh	u_n	409.09 W/K	c_n	1.75e6J/kgK

TABLE III
COMPARISON OF ASSUMPTIONS OF CASES

	Case 1	Case 2	Case 3	Case 4
Variable Indoor Temperature	✓	✗	✗	✓
Thermal Energy Storage	✓	✓	✗	✓
Peer-to-Peer Trading	✓	✓	✓	✗

To evaluate the benefits of the designed architecture of local electricity markets in terms of the peer-to-peer electricity trading and flexibility provision from heating sources, four cases have been analyzed and compared:

- *Case 1 (Proposed Model):* All prosumers are equipped with thermal energy storage and able to participate in the peer-to-peer electricity trading. The indoor temperature can be flexibly controlled within the comfort range of prosumers.
- *Case 2 (Constant Indoor Temperature):* The indoor temperature of a household is assumed to be constant to specifically investigate how to strategically run the air-source heat pump and thermal energy storage in responding to retail electricity prices.
- *Case 3 (No Thermal Energy Storage):* To investigate how the thermal energy storage affects the flexibility of electricity exchange, this case removes the thermal energy storage and assumes the constant indoor temperature.
- *Case 4 (No Peer-to-Peer Electricity Trading):* To investigate the impacts of the peer-to-peer electricity trading, this case removes the option of exchanging electricity among prosumers themselves.

The comparison of assumptions of these four cases is summarized in Table III.

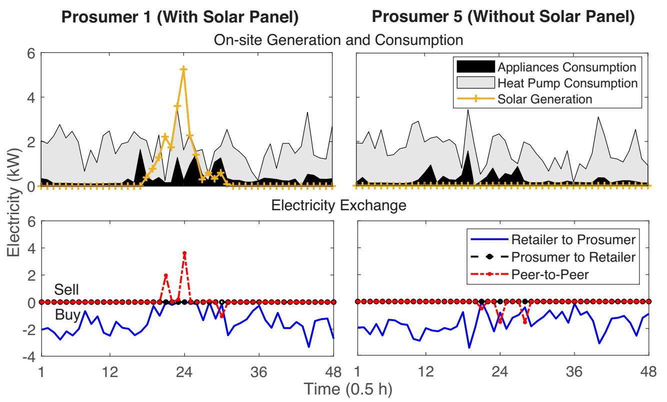


Fig. 4. Comparison of the electricity on-site generation, consumption, and exchange between the prosumer 1 and prosumer 5. The x axes indicate the scheduling time and the y axes indicate the electricity. The stacked areas in the top two sub-figures indicate the total electricity consumption. The positive value of the electricity exchange indicates a prosumer sells electricity to other prosumers or the retailer, and the negative value of the electricity exchange indicates a prosumer buys electricity from other prosumers or the retailer.

A. Impacts of On-Site Electricity Generation

To investigate the impacts of the on-site solar generation on the electricity exchange, the prosumer 1 with the solar panel installed and prosumer 5 without the solar panel installed under the case 1 are sampled for comparison as presented in Fig. 4. With the installation of the roof-top solar panel, the prosumer 1 is able to generate electricity from 9:00 - 15:30. As a result, the electricity import from the retailer to the prosumer 1 during this period is close to zero. By contrast, without the installation of the roof-top solar panel, the prosumer 5 has to rely on the electricity import from other prosumers or the retailer during the entire scheduling horizon. This causes higher daily electricity costs for the prosumer 5 (£ 5.72), compared to the daily electricity costs for the prosumer 1 (£ 4.76), under the same scale of the electricity demand.

During the periods when there is no solar radiation, both prosumers and consumers have to rely on the electricity import from the retailer. During the periods when there is solar radiation, the total on-site generation is lower than total demand of all prosumers. The electricity sellers therefore prefer to sell their electricity to other prosumers at higher agreed prices, rather than selling to the retailer at the wholesale price. For this reason, the electricity exported from all electricity sellers (prosumers 1, 3, 4, and 7) to the retailer over the entire scheduling horizon is zero. In addition, the reason for a prosumer still buying electricity from the retailer instead of other prosumers, e.g., the prosumer 5 at 12:30, is that the total on-site generation is lower than the total demand and this buyer cannot be satisfied due to providing a lower buying price compared to the prices provided by other buyers.

B. Performance of Heating Systems

The heating performances of the prosumer 1 in the Case 2 are presented in Fig. 5. To specifically investigate how to strategically run the air-source heat pump and thermal energy storage in responding to retail electricity prices, the indoor temperature is assumed to be maintained at 291.15 K during the entire scheduling horizon. During the period from 4:30 to 8:00, the highest thermal demand is supplied by ramping up the air-source heat pump and discharging of the thermal energy storage to the maximum levels. During the period from 11:30 to 13:30, the lowest thermal demand is primarily supplied by the discharging of the thermal energy storage instead of the air-source heat pump, since the electricity demand by other electrical appliances increases. During the period from 16:00 to 21:00 when the retail electricity prices are relatively high, the air-source heat pump reduces the heating supply to avoid higher electricity costs. To complement this reduced heating supply, the discharge from the thermal energy storage increases.

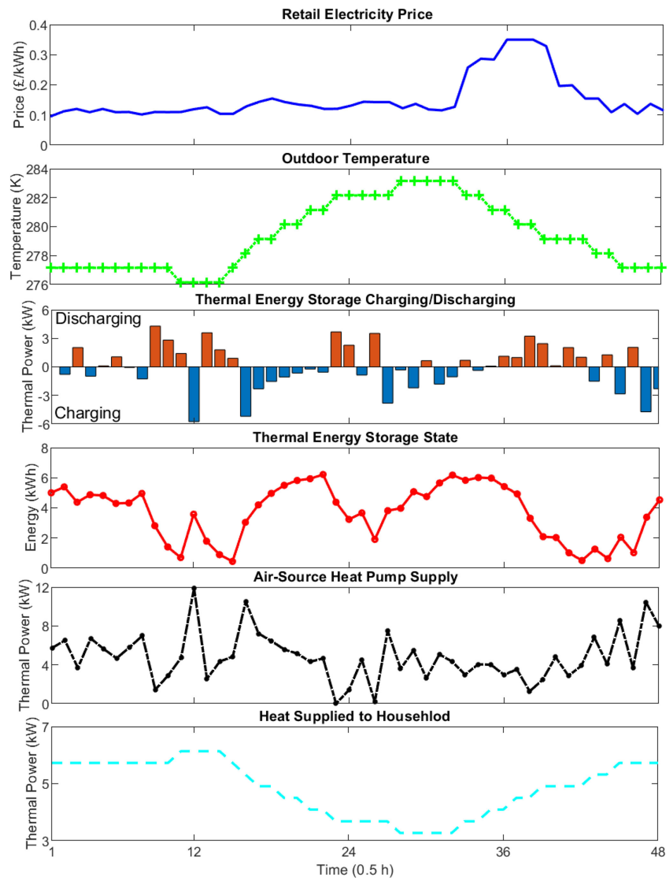


Fig. 5. Heating performances of the prosumer 1 in the Case 2. The x axes indicate the scheduling time. The y axis in the first sub-figure indicates the retail electricity price, the y axis in the second sub-figure indicates the outdoor temperature, the y axes in the third, fifth, and sixth sub-figures indicate the thermal power, and the y axis in the fourth sub-figure indicates the stored thermal energy. The heat supplied to a household comes from the air-source heat pump and thermal energy storage.

To investigate how the thermal energy storage affects the flexibility of using grid electricity, the Case 2 is compared with Case 3 in which the only source for supplying heat demand is the air-source heat pump. The comparison of the electricity import from the retailer to prosumer 1 between the Case 2 and Case 3 is presented in Fig. 6. It can be seen that during the period when the retail electricity prices are relatively high as indicated in the blue box, the electricity import in the Case 2 is lower than that in the Case 3 due to the increase of discharge from the thermal energy storage.

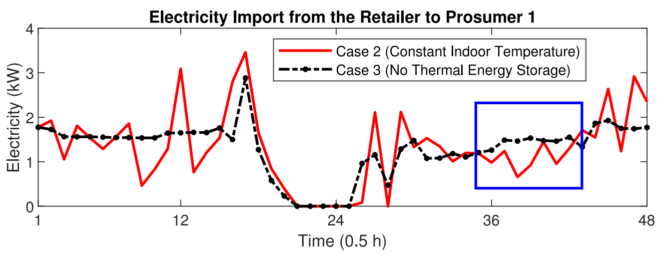


Fig. 6. Comparison of the electricity import from the retailer to the prosumer 1 between the Case 2 and Case 3. The x axis indicates the scheduling time and the y axis indicates the electricity.

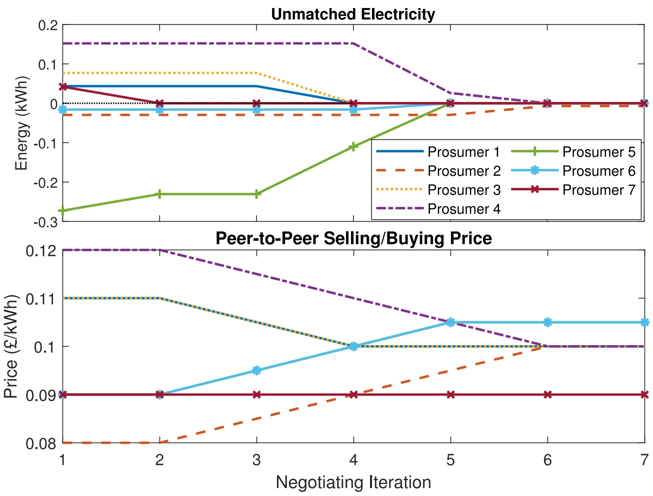


Fig. 7. Unmatched electricity supply/demand and selling/buying prices with the proceeding of the negotiating iterations. The x axes indicate the iteration number. The y axis in the top sub-figure indicates the unmatched electricity supply/demand, and the y axis in the bottom sub-figure indicates the peer-to-peer selling/buying price. The positive values of the unmatched electricity indicate the prosumers sell electricity to other prosumers, and the negative values of the unmatched electricity indicate the prosumers buy electricity from other prosumers.

C. Demonstration of Cooperative Negotiation

To demonstrate the iterative negotiation among prosumers, the peer-to-peer electricity trading for the twenty-eighth time interval in the Case 1 is sampled. The changes of unmatched electricity supply/demand and selling/buying prices with the proceeding of the negotiating iterations are presented in Fig. 7. The prosumers 1, 3, 4, and 7 are electricity sellers, and the prosumers 2, 5, and 6 are electricity buyers. At the first iteration, the initial selling/buying amounts and prices are obtained from solving the optimization problem of each prosumer. At the second iteration, 0.042 kWh of electricity supply from the seller 7 is accepted by the buyer 5 at £ 0.090/kWh of the agreed price. The unmatched sellers and buyers keep adjusting their prices until the fourth iteration, at which 0.044 kWh and 0.077 kWh of electricity supply from the sellers 1 and 3, respectively, are accepted by the buyer 5 at £ 0.100/kWh of the agreed price. At the fifth iteration, 0.110 kWh and 0.016 kWh of electricity demand from buyers 5 and 6, respectively, are accepted by the seller 4 at £ 0.105/kWh of the agreed price. At the sixth iteration, the rest 0.026 kWh of electricity supply from the seller 4 is accepted by the buyer 2 at £ 0.100/kWh of the agreed price. Since the total supply of sellers is lower than the total demand of buyers, there is 0.007 kWh of electricity demand from the buyer 2 which needs to be imported from the retailer.

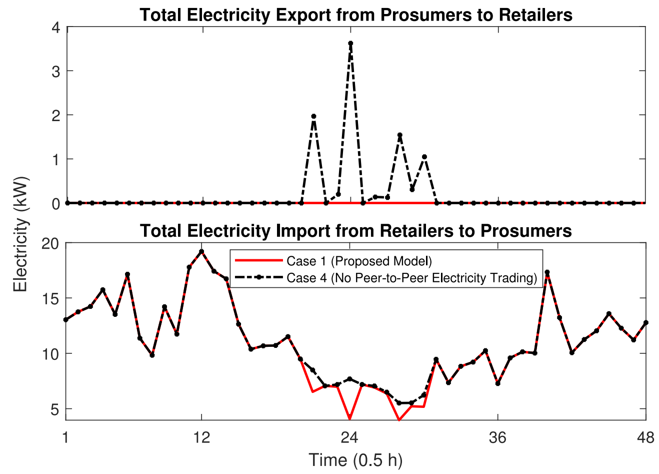


Fig. 8. Comparison of the total electricity exchange between all prosumers and the retailer with and without the peer-to-peer electricity trading. The x axes indicate the scheduling time and the y axes indicate the electricity.

D. Impacts of Peer-to-Peer Electricity Trading

To investigate the impacts of the peer-to-peer electricity trading, our proposed model in Case 1 is compared to the case without the peer-to-peer electricity trading in Case 4, under which the prosumers who have extra electricity can only export to the retailer. The comparison of these two cases in terms of the total electricity exchange between all prosumers and the retailer is presented in Fig. 8. With the peer-to-peer electricity trading during the period from 9:00 to 15:30, instead of selling/buying the electricity to/from the retailer at the wholesale/retail electricity prices, prosumers prefer to trade with other prosumers at their agreed prices. For this reason, the total export during this period is close to zero and the total import during this period is reduced compared to the Case 4, which indicates an improved local energy balance.

E. Scalability Evaluation

To evaluate the scalability in terms of the cost reduction and computational efficiency, our proposed model is tested under the cases of *1)* 7-prosumer, 1-retailer, 4-solar panel, *2)* 200-prosumer, 4-retailer, 100-solar panel, *3)* 500-prosumer, 10-retailer, 250-solar panel, and *4)* 1000-prosumer, 20-retailer, 500-solar panel. The comparison of the computational time and total daily electricity costs with and without the peer-to-peer electricity trading is presented in Fig. 9. With respect to the computational efficiency, it can be seen from the figure that the computational time linearly increases with the increase of the system scale, and the proposed model spends more time in every case due to the computational burden of the cooperative game among prosumers. The computational time under the scale of 1000-prosumer, 20-retailer, 500-solar panel is still within an acceptable range. With respect to the total daily costs, the average daily costs for each prosumer/consumer

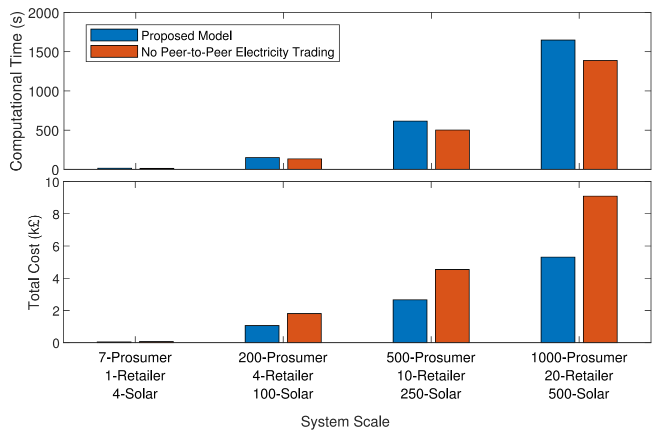


Fig. 9. Comparison of the computational time and total daily electricity costs of all prosumers with and without the peer-to-peer electricity trading, under the cases of *1)* 7-prosumer, 1-retailer, 4-solar panel, *2)* 200-prosumer, 4-retailer, 100-solar panel, *3)* 500-prosumer, 10-retailer, 250-solar panel, and *4)* 1000-prosumer, 20-retailer, 500-solar panel. The *x* axes indicate the system scale. The *y* axis in the top sub-figure indicates the computational time, and the *y* axis in the bottom sub-figure indicates the total daily electricity costs of all prosumers.

with the peer-to-peer electricity trading over the four cases are £ 5.40, whereas the average daily costs for each prosumer/consumer without the peer-to-peer electricity trading over the four cases are £ 9.19. The peer-to-peer electricity trading reduces 41.24% of average daily electricity costs for each prosumer/consumer. For prosumers with the installation of solar panels, the cost reduction primarily comes from the on-site generation. For consumers without the installation of solar panels, they can also save their costs by buying electricity from neighboring prosumers.

V. Conclusion

This paper proposed a Blockchain based local electricity markets with the flexibility provision from heat sources. The negotiation of the volume and price of the peer-to-peer electricity trading among prosumers was modeled by a cooperative game, and automatically self-enforced by two standardized forms of smart contracts. The interaction between a retailer and its ensemble of prosumers was modeled as a Stackelberg game, in order to find optimal decisions for maximizing profits for retailers and minimizing electricity costs for prosumers. Case studies show that the roof-top solar panels help prosumers reduce their dependence on buying grid electricity from the retailer. The thermal energy storage is able to complement the heat supply from the air-source heat pump, in responding to the variation of retail electricity prices. The peer-to-peer trading in local electricity markets helps prosumers save the electricity costs and improve the local energy balance.

As a future work, we will investigate the responsibilities and assets accounting of prosumers in local electricity markets from the regulatory perspective. For instance, how to charge for the use of distribution networks and allocate carbon credits when prosumers participate in the peer-to-peer electricity trading? How to audit for both physical assets, e.g., air-source heat pump, and non-physical assets, e.g., transaction information, for prosumers?

References

[1] C. Zhang, J. Wu, Y. Zhou, M. Cheng, and C. Long, "Peer-to-peer energy trading in a microgrid," *Appl. Energy*, vol. 220, pp. 1–12, Jun. 2018.

[2] W. Tushar *et al.*, "A coalition formation game framework for peer-to-peer energy trading," *Appl. Energy*, vol. 261, Mar. 2020, Art. no. 114436.

[3] M. Yan *et al.*, "Blockchain for transacting energy and carbon allowance in networked microgrids," *IEEE Trans. Smart Grid*, vol. 12, no. 6, pp. 4702–4714, Nov. 2021.

[4] J. Li, Y. Ye, and G. Strbac, "Stabilizing peer-to-peer energy trading in prosumer coalition through computational efficient pricing," *Electr. Power Syst.*, vol. 189, Dec. 2020, Art. no. 106764.

[5] W. Tushar *et al.*, "Grid influenced peer-to-peer energy trading," *IEEE Trans. Smart Grid*, vol. 11, no. 2, pp. 1407–1418, Mar. 2020.

[6] H. Haggi and W. Sun, "Multi-round double auction-enabled peer-to-peer energy exchange in active distribution networks," *IEEE Trans. Smart Grid*, vol. 12, no. 5, pp. 4403–4414, Sep. 2021.

[7] A. Grubler *et al.*, "A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies," *Nat. Energy*, vol. 3, no. 6, pp. 515–527, 2018.

[8] F. Nematkhah, S. Bahrami, F. Aminifar, and J. P. S. Catalão, "Exploiting the potentials of HVAC systems in transactive energy markets," *IEEE Trans. Smart Grid*, vol. 12, no. 5, pp. 4039–4048, Sep. 2021.

[9] W. Liu, D. Qi, and F. Wen, "Intraday residential demand response scheme based on peer-to-peer energy trading," *IEEE Trans. Ind. Informat.*, vol. 16, no. 3, pp. 1823–1835, Mar. 2020.

[10] R. Jing, M. N. Xie, F. X. Wang, and L. X. Chen, "Fair P2P energy trading between residential and commercial multi-energy systems enabling integrated demand-side management," *Appl. Energy*, vol. 262, Mar. 2020, Art. no. 114551.

[11] L. Langer, "An optimal peer-to-peer market considering modulating heat pumps and photovoltaic systems under the German Levy regime," *Energies*, vol. 13, no. 20, p. 5348, 2020.

[12] T. Chen, S. Bu, X. Liu, J. Kang, F. R. Yu, and Z. Han, "Peer-to-peer energy trading and energy conversion in interconnected multi-energy microgrids using multi-agent deep reinforcement learning," *IEEE Trans. Smart Grid*, vol. 13, no. 1, pp. 715–727, Jan. 2022.

[13] H. Zhang, S. Zhang, X. Hu, H. Cheng, Q. Gu, and M. Du, "Parametric optimization-based peer-to-peer energy trading among commercial buildings considering multiple energy conversion," *Appl. Energy*, vol. 306, Jan. 2020, Art no. 118040.

[14] P. Danzi, M. Angjelichinoski, Č. Stefanović, and P. Popovski, "Distributed proportional-fairness control in microgrids via blockchain smart contracts," in *Proc. IEEE Int. Conf. Smart Grid Commun. (SmartGridComm)*, Dresden, Germany, 2017, pp. 45–51.

[15] L. Thomas, Y. Zhou, C. Long, J. Wu, and N. Jenkins, "A general form of smart contract for decentralized energy systems management," *Nat. Energy*, vol. 4, no. 2, pp. 140–149, 2019.

[16] C. Brandstätt, G. Brunekreeft, and N. Friedrichsen, "Improving investment coordination in electricity networks through smart contracts," Bremen Energy Working Papers, Bremen, Germany, Rep., 2011. [Online]. Available: https://www.econstor.eu/handle/10419/103342

[17] "The Sun Exchange Inc." Jan. 2022. [Online]. Available: https://thesunexchange.com/

[18] C. Liu, K. K. Chai, X. Zhang, and Y. Chen, "Peer-to-peer electricity trading system: Smart contracts based proof-of-benefit consensus protocol," *Wireless Netw.*, vol. 27, pp. 4217–4228, Feb. 2019.

[19] D. Han, C. Zhang, J. Ping, and Z. Yan, "Smart contract architecture for decentralized energy trading and management based on blockchains," *Energy*, vol. 199, May 2020, Art. no. 117417.

[20] J. Abdella, Z. Tari, A. Anwar, A. Mahmood, and F. Han, "An architecture and performance evaluation of blockchain-based peer-to-peer energy trading," *IEEE Trans. Smart Grid*, vol. 12, no. 4, pp. 3364–3378, Jul. 2021.

[21] P. Alstone, D. Gershenson, and D. M. Kammen, "Decentralized energy systems for clean electricity access," *Nat. Clim. Change*, vol. 5, no. 4, pp. 305–314, 2015.

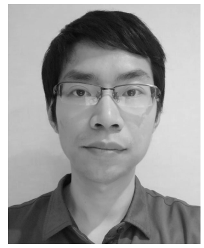
[22] Y. Parag and B. K. Sovacool, "Electricity market design for the prosumer era," *Nat. Energy*, vol. 1, no. 4, pp. 1–6, 2016.

[23] S. Pauliuk *et al.*, "Global scenarios of resource and emission savings from material efficiency in residential buildings and cars," *Nat. Commun.*, vol. 12, no. 1, pp. 1–10, 2021.

[24] A. Schneiders, M. Fell, and C. Nolden. "Peer-to-peer energy trading and the sharing economy: Social, markets and regulatory perspectives," 2020, doi: 10.20944/preprints202008.0266.v1.

[25] V. Buterin *et al.*, “A next-generation smart contract and decentralized application platform,” White Paper, vol. 3, no. 37, 2014. [Online]. Available: https://blockchainlab.com/pdf/Ethereum_white_paper-a_next_generation_smart_contract_and_decentralized_application_platform-vitalik-buterin.pdf
[26] A. Ashouri, S. S. Fux, M. J. Benz, and L. Guzzella, “Optimal design and operation of building services using mixed-integer linear programming techniques,” *Energy*, vol. 59, pp. 365–376, Sep. 2013.
[27] “Default Tariff Cap.” Dec. 2021. [Online]. Available: https://www.ofgem.gov.uk/energy-policy-and-regulation/policy-and-regulatory-programmes/default-tariff-cap
[28] R. M. Ayers and R. A. Collinge, *Microeconomics: Explore and Apply and Companion Website PLUS*. Hoboken, NJ, USA: Prentice-Hall, 2003.
[29] B. Tołwiński, “A concept of cooperative equilibrium for dynamic games,” *Automatica*, vol. 18, no. 4, pp. 431–441, 1982.
[30] C. Dannen, *Introducing Ethereum and Solidity*. Berkeley, CA, USA: Springer, 2017, vol. 318.
[31] M. Swan, *Blockchain: Blueprint for a New Economy*. Sebastopol, CA, USA: O’Reilly Media, Inc., 2015.
[32] I.-C. Lin and T.-C. Liao, “A survey of blockchain security issues and challenges,” *Int. J. Netw. Security*, vol. 19, no. 5, pp. 653–659, 2017.
[33] “renewables.ninja.” Sep. 2021. [Online]. Available: https://www.renewables.ninja/
[34] “Data Portal.” Sep. 2021. [Online]. Available: https://www.ofgem.gov.uk/data-portal
[35] “Remix IDE.” Sep. 2021. [Online]. Available: https://remix.ethereum.org/
[36] W.-Y. Chiu, H. Sun, and H. V. Poor, “A multiobjective approach to multimicrogrid system design,” *IEEE Trans. Smart Grid*, vol. 6, no. 5, pp. 2263–2272, Sep. 2015.

Weiqi Hua (Student Member, IEEE) received the M.Sc. and Ph.D. degrees in engineering from the University of Durham, U.K., in 2017 and 2020, respectively, and then took the postdoctoral position with Cardiff University in 2020. Since 2021, he has been with the University of Oxford, U.K., as a Postdoctoral Researcher. His research interests include the energy system modeling, energy system digitalization, and peer-to-peer energy trading. He served as a Guest Editor of *IET Smart Grid* on the topic of peer-to-peer energy trading and *Water* on the topic of energy-water nexus.



Yue Zhou (Member, IEEE) received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from Tianjin University, China, in 2011, 2016 and 2016, respectively. He is a Lecturer of Cyber–Physical Systems with the School of Engineering, Cardiff University, Wales, U.K. His research interests include demand response, peer-to-peer energy trading, and cyber–physical systems. He is a Managing Editor of *Applied Energy* and an Associate Editor of *IET Energy Systems Integration*, *IET Renewable Power Generation*, and *Frontiers in Energy Research*. He is the Chair of CIGRE U.K. Next Generation Network (NGN) Committee. He is also a Committee Member of IEEE PES U.K. and Ireland Chapter.

Meysam Qadrdan (Senior Member, IEEE) is a Reader of Cardiff University. His research focuses on modeling and analysis of integrated energy systems.

Jianzhong Wu (Senior Member, IEEE) received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from Tianjin University, China, in 1999, 2002 and 2004, respectively. He is a Professor of Multi-Vector Energy Systems and the Head of the School of Engineering, Cardiff University, U.K. His research interests include integrated multi-energy infrastructure and smart grid. He is Co-Editor-in-Chief of *Applied Energy*. He is the Co-Director of U.K. Energy Research Centre and EPSRC Supergen Energy Networks Hub.

Nick Jenkins (Fellow, IEEE) received the B.Sc. degree from Southampton University, Southampton, U.K., in 1974, the M.Sc. degree from Reading University, Reading, U.K., in 1975, and the Ph.D. degree from Imperial College London, London, U.K., in 1986. He is currently a Professor with Cardiff University, Cardiff, U.K. Before moving to academia, his career included 14 years of industrial experience of which 5 years were in developing countries. While at university, he has developed teaching and research activities in both electrical power engineering and renewable energy.