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Incentivizing Energy and Carbon Rights Transactions among Network-Constrained Energy Hubs: Cooperative Game with Externalities

Wei Gan[a], Mingyu Yan[b*], Yue Zhou[a], Kangan Shu[c], Wei Yao[b], Jinyu Wen[b]

[a] *School of Engineering, Cardiff University, Cardiff CF24 3AA, UK*

[b] *State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China*

[c] *Guangdong Power Exchange Center Co., Ltd, Guangzhou 510062, China*

**Corresponding author. Email:* mingyuyan@hust.edu.cn

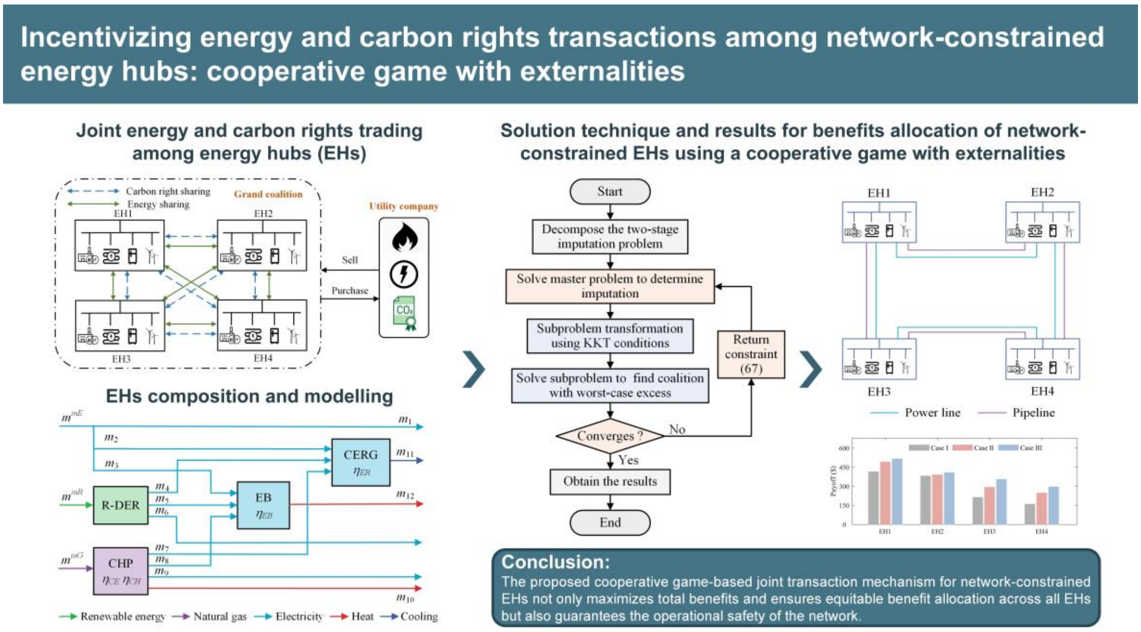
Abstract

Joint energy and carbon rights transactions for multiple energy hubs could boost the utilization of renewable distributed energy resources and reduce carbon emissions in energy sectors. The joint transaction mechanism based on the cooperative game is proposed, in which cooperative energy hubs form a grand coalition to share diverse forms of energy and carbon rights in order to maximise their total benefit. Furthermore, the grand coalition-based transaction mechanism is augmented with network constraints to account for the influence of network constraints on the trading behaviours of energy hubs, which is mathematically represented as a cooperative game with externalities. In addition, mathematical proof is provided to demonstrate the stability of the formed network-constrained grand coalition. To determine the trading behaviours and allocate payoff among energy hubs while satisfying both network constraints and coalition stability, a scalable two-stage optimization structure is provided, with the first stage ensuring coalition stability and the second preventing network constraint violations. A solution technique combined with Karush-Kuhn-Tucker conditions and Benders decomposition is proposed to solve the two-stage optimization problem. The effectiveness and scalability of the proposed joint transaction mechanism and the solution technique are supported by numerical results for the 4-EH and 33-EH systems. The introduction of the carbon market leads to a 20.6% reduction in carbon emissions and a 10.5% increase in total payoff by facilitating peer-to-peer trading of both energy and carbon rights.

Highlights

- Cooperative game-based joint energy and carbon right transactions for energy hubs.
- Develop network-constrained transaction using cooperative game with externalities.
- Propose a two-stage problem to ensure constrained networks and a stable coalition.
- Algorithm based on Karush-Kuhn-Tucker condition and Benders decomposition.

Graphical abstract



Incentivizing energy and carbon rights transactions among network-constrained energy hubs: cooperative game with externalities

Joint energy and carbon rights trading among energy hubs (EHs)

EHs composition and modelling

Solution technique and results for benefits allocation of network-constrained EHs using a cooperative game with externalities

Conclusion:
The proposed cooperative game-based joint transaction mechanism for network-constrained EHs not only maximizes total benefits and ensures equitable benefit allocation across all EHs but also guarantees the operational safety of the network.

Keywords

Energy hub, joint energy and carbon transactions, peer-to-peer trading, cooperative game with externalities, Karush-Kuhn-Tucker conditions, Benders decomposition.

Nomenclature

Abbreviations

EH	Energy hub
CHP	Combined heat and power
CERG	Compression electric refrigerator group

EB	Electric boiler
IES	Integrated energy system
DER	Distributed energy resource

Indices and Sets

i	Indices of energy hubs
b	Indices of energy hubs connected to the utility company
ij	Indices of lines/pipelines connecting EH *i* and *j*
Γ	Set of hours
L, GL	Set of power lines and gas pipelines
TB	Set of substation buses
ρ	Behaviour of the member outside coalition *S*

Parameters

N	The amount of EHs in the formed grand coalition
ρ^g	Natural gas price when EHs buy from the utility company
ρ_t^b	Electricity price when EHs buy from the utility company
ρ_t^s	Electricity price when EHs sell to the utility company
$m_{n,t}^{inR}$	Hourly renewable energy input of EH *i*
λ_i^E, β_i^E	Revenue coefficients for balancing electricity loads
λ_i^H, β_i^H	Revenue coefficients for balancing heat loads
λ_i^C, β_i^C	Revenue coefficients for balancing cooling loads
$P_i^{CP,max}$	Output limits of CHP in EH *i*
$P_i^{EB,max}, P_i^{ER,max}$	Output limits of EB and CERG in EH *i*
η_{CE}, η_{CH}	Natural gas to electricity (heat) efficiencies of CHP
η_{ER}, η_{EB}	Efficiencies of CERG and EB
$CA_i^{\max}$	Carbon right of EH *i*
$U_i^{\min}, U_i^{\max}$	Lower and upper limits for voltage magnitudes of EH *i*
G_{ij}, B_{ij}	Conductance and susceptance of line *ij*
$S_{ij}^{\max}$	Apparent power capacity of power line *ij*
$GF_{gl}^{\min}, GF_{gl}^{\max}$	Lower and upper limits for natural gas flow on pipeline *gl*
$GP_i^{\min}, GP_i^{\max}$	Lower and upper limits for gas pressure of EH *i*

h	Iteration index
ε	Small positive number
μ	Positive constant

Variables

$R_{i,t}$	Revenue of EH *i* at hour *t*
$F_{i,t}$	Cost of EH *i* at hour *t*
$U_{i,t}^{E}, U_{i,t}^{H}, U_{i,t}^{C}$	Revenue for balancing electricity, heat, and cooling loads of EH *i*
$L_{i,t}^{E}, L_{i,t}^{H}, L_{i,t}^{C}$	Electricity, heat, and cooling loads of EH *i* at hour *t*
$m_{t}^{buy}, m_{t}^{sell}$	Hourly purchased and sold electricity of the coalition
$m_{i,t}^{inE}, m_{i,t}^{inG}$	Hourly input to EH *i*, including electricity and natural gas
$m_{i,t}^{outE}$	Hourly electricity output of EH *i*
$m_{1,i,t}, \ldots, m_{12,i,t}$	Hourly energy flows in EH *i*
$CB_{i,t}, PB_{i,t}, GB_{i,t}$	Carbon right, electricity, and natural gas purchase from the utility company of EH *i* at hour *t*
$CS_{i,t}, PS_{i,t}, GS_{i,t}$	Carbon right, electricity, and natural gas sale to the utility company of EH *i* at hour *t*
$P_{i,t}, Q_{i,t}$	Active and reactive net power load of EH *i* at hour *t*
$P_{b,t}^{in}, Q_{b,t}^{in}, G_{b,t}^{in},$	Active power, reactive power, and natural gas imported from the substation bus.
$P_{b,t}^{out}, G_{b,t}^{out}$	Active power and natural gas exported to the substation bus.
$PL_{ij,t}, QL_{ij,t}$	Active and reactive power flow through line *ij* at hour *t*
$U_{i,t}$	Voltage magnitude of EH *i* at hour *t*
$\theta_{i,t}$	Voltage angle of EH *i* at hour *t*
$CF_{ij,t}$	Gas flow on the pipeline *ij* at hour *t*
$GP_{i,t}$	Gas pressure of EH *i* at hour *t* in the natural gas system
η	Auxiliary variable used in the problem decomposition

1. Introduction

Human industrial activities over the last century have resulted in superabundant carbon emissions, thus leading to global temperature increase and climate change [1]. According to a report from the World Meteorological Organization, the number of natural disasters has increased five times over the last five decades [2]. Most countries around the world have reached a consensus to control carbon emissions. Several countries have committed to achieving a net-zero energy system for sustainable development. The UK government passed a net-zero emission law, in which the UK government promised to reduce half of the carbon emissions over a decade and eliminate them by 2050 [3]. China pledges to achieve carbon neutrality before 2060 [4].

Decarbonization in the energy sectors is paramount for achieving net-zero emissions, as these sectors account for approximately 40% of carbon emissions [5]. The advancement of renewable energy sources, such as solar and wind, plays a significant role in the decarbonization efforts within these sectors, despite the considerable challenges in grid integration that come with their large-scale deployment. The strategic integration and coordination of diverse energy systems, capable of supporting large-scale, zero-carbon renewable energy resources like wind power, are viewed as essential solutions for decarbonizing the energy sectors [6]-[7]. In particular, the use of multiple energy conversion and storage facilities enables the efficient conversion and storage of excess wind power into various energy forms. Through sector coupling, the integrated energy system (IES) can improve system efficiency, reliability, resilience, and sustainability [8]. IES can be classified into transmission-level regional energy systems and community-level district energy systems. This study focus on the district energy system, which is generally modelled as an energy hub (EH) [9]. The EH optimizes its local energy production, conversion, and storage devices, including combined heat and power units (CHP), electrical boilers (EB), compression electric refrigerator groups (CERG), and renewable distributed energy resources (DERs) [10]-[11].

Appropriate market mechanisms play a crucial role in the development and evolution of energy hubs, on one hand, facilitating proper energy management and daily operations, and on the other hand, potentially motivating investment and planning decisions for energy hubs [12]-[13]. Traditional market mechanisms primarily focus on the interaction between energy hubs and the power grid [14]. In contrast, transactive energy enables flexible energy trading among EHs for reduced energy bills, significantly boosting investment in renewable DERs and accelerating the decarbonization of the district energy system [15]. Several studies have explored transactive energy trading among EHs. Ref. [16] studied the transactive energy framework for EHs based on the auction. Numerical results proved that the energy trading among EHs could reduce 20% the operation cost. To protect each EH's privacy, Refs. [17]-[18] provided a decentralized transactive energy market for EHs using the alternating direction method of multipliers, in which the Lagrange multiplier is served as the market-clearing price. Ref. [19] utilized the noncooperative game theory to analyze EHs' behaviours.

However, the marker-clearing results obtained by the alternating direction method of multipliers and noncooperative game approaches may be sub-optimal. Specifically, these methods may not maximize the total benefits for EH groups, potentially leading to dissatisfaction among EHs with the current market-clearing outcomes. To address this issue, the cooperative game framework provides a compelling solution. It incentivizes market participants to engage in energy trading that maximizes overall benefits, while simultaneously ensuring an equitable allocation of rewards among all participants. Moreover, the cooperative game approach offers a comprehensive payoff for different types of energy, thereby simplifying the transaction settlement process. Ref. [20] used the Nash bargaining cooperative game to model the cooperative behaviours of EHs. Ref. [21] assumed that all EHs would cooperate and engage in peer-to-peer energy trading to maximize their benefits and accommodate renewable DERs.

Besides, the carbon market is also an efficient method to achieve carbon emission reduction by charging extra fees for carbon emissions. Generally, the carbon market can be categorized as the carbon tax and cap-and-trade market [22]. Here this study considers the latter one, in which each carbon emitter has a carbon right. If the carbon emitter emits more CO_2 than its carbon right, it has to buy extra carbon rights to satisfy its production obligations. This emitter can sell the extra carbon rights to earn profits if the carbon emission is less than the carbon right. Considering the carbon market in the transactive energy system for EHs could accelerate the decarbonization process. However, studies about the joint energy and carbon rights transactions for the district energy system are still rare. Ref. [23] investigated the peer-to-peer energy and carbon trading framework for prosumers in the distribution power system based on the auction, while prosumer operation constraints and network constraints are not taken into account.

Table 1 Features of relevant references

References	Transactive energy	Joint energy and carbon markets	Network-constrained	Cooperative game-based	Grand coalition stability
[12]-[14]	×	×	√	×	×
[15]	√	×	√	×	×
[16]-[17]	√	×	×	×	×
[18]-[19]	√	×	√	×	×
[20]	√	×	√	√	×
[21]	√	×	×	√	√
[23]	√	√	√	×	×
This paper	√	√	√	√	√

However, several challenges remain to be solved while utilizing cooperative game theory for joint energy and carbon rights transactions for network-constrained EHs: 1) Interdependency of energy and carbon rights transactions: EHs trades multiple types of energy and carbon rights. If utility company energy is expensive, an EH may opt to purchase carbon allowances and generate energy using onsite DERs. Conversely, with high carbon allowance prices, EHs might buy energy from the external energy network rather than carbon right; 2) Energy network constraints: EHs' trading behaviors are interdependent via the energy network. Traditional cooperative game theory, focusing on coalition formation and shared benefits among participants, often lacks mechanisms to integrate the complex interdependencies and physical constraints inherent in energy networks. This gap challenges the applications of these approaches to scenarios where EHs share public energy networks, and the decisions of one EH can affect others. 3) Grand coalition stability: Stability depends on all participants benefitting more from joining the largest group than from operating alone or in smaller alliances. To maintain stability, the benefits distributed to each participant must surpass those they would achieve independently or in smaller coalitions. Inadequate benefit distribution risks destabilizing the grand coalition. The specific distinctions between the method proposed in this paper and relevant prior research is illustrated in Table 1.

To solve the above challenges, this paper incentivizes multiple energy hubs to transact with their peers by utilizing the cooperative game with the externalities. In summary, the main contributions are presented as follows:

1) A novel mechanism for joint energy and carbon rights transactions among EHs using cooperative game is proposed. This mechanism encourages EHs to collaborate and form a grand coalition, enabling the flexible and economical sharing of energy and carbon rights. The traditional method is enhanced by integrating energy network constraints, considering the impact of these constraints on EHs' trading behaviors. This mechanism is mathematically formulated as a cooperative game with externalities, with mathematical proof provided to validate the stability of network-constrained grand coalition.
2) A scalable two-stage optimization framework is developed to analyze trading behavior and distribute payoffs among EHs, ensuring compliance with network constraints and coalition stability. The first stage focuses on securing coalition stability, while the second stage aims to prevent network constraint violations.
3) Furthermore, a tailored solution technique that utilizes the Karush-Kuhn-Tucker (KKT) conditions and the Benders decomposition algorithm is employed. This technique transforms the optimization problem into a mixed-integer quadratically-constrained program, enabling precise resolution of the two-stage problem.

The rest of the paper is organized as follows. Section 2 describes the network-constrained energy and carbon rights transaction. Section 3 provides the grand coalition’s mathematical model and proves the stability of the grand coalition. Section 4 presents the proposed solution technique. Section 5 provides numerical results tested in 4-EH and 33-EH systems. Section 6 provides the discussion and Section 7 summarizes the conclusion.

2. Introduction for Energy and Carbon Rights Trading

2.1. Introduction for Energy Hub

Fig. 1 depicts the topology of EH considered in this paper, which converts electricity and natural gas to balance the local electricity, heat, and cooling load by utilizing CHP, EB, renewable DER, and CERG. The renewable DER and CHP shoulder the responsibility for balancing the electricity load. The renewable DER generates electricity with zero energy cost and carbon emission, while the CHP converts natural gas into electricity and heat. The EB converts electricity into heat and collaboratively balance the heat load with the CHP. The CERG solely balances the cooling load by consuming the electricity. The EH emits CO_2 since the CHP consumes fossil fuel, i.e., natural gas. Not only can the EH trade electricity, natural gas, and carbon rights with its counterparts, but also with the utility company.

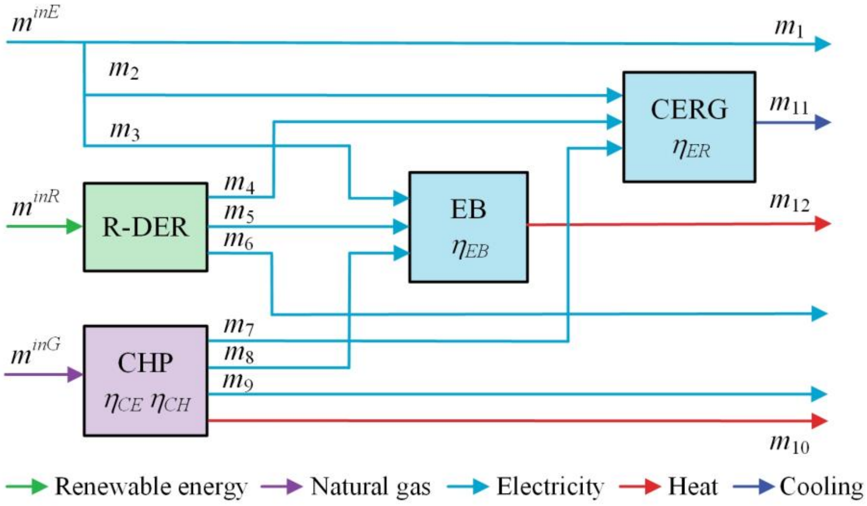


Fig. 1. Energy flows in the EH

2.2. Introduction for Cooperative Game with Externalities

In this paper, the cooperative game is used to incentivize EHs for trading their energy and carbon rights. EHs are the player in the game theory. The set of EHs is defined as $N=\{1,2,\ldots,n\}$. If all EHs cooperate with their counterparts, they will form a grand coalition *N*. Moreover, each subset of *N* can choose to cooperate and formulate a small coalition *S*. Here, this study considers the grand coalition game, in which all EHs cooperate and further equitably share the payoff of the grand coalition.

In practice, EHs' trading behaviours are constrained by the energy networks and are thus interdependent. Such interdependency would further impact EHs' payoffs. The cooperative game with the externalities can model such interdependency caused by the network limits. This study consider that some EHs formulate a coalition S, of which the payoff is $v(S,\rho)$ (ρ is utilized to represent EHs' behaviours that are outside the coalition). The following problem is provided for calculating the payoff of coalition S:

$$\begin{aligned} &\max\ v(S,\rho) \\ &s.t.\ C(S,\rho) \le 0 \end{aligned} \tag{1}$$

where $C(S,\rho)$ represents the operation constraints (e.g., energy network constraints) that will be introduced in detail in the following section. The whole problem payoff calculation problem (1) is represented as $v(S,\rho)$.

The framework for the joint energy and carbon rights trading based on the cooperative game is depicted in Fig.2. All EHs form a grand coalition in which they share different types of energy (i.e., electricity and natural gas) and carbon rights. In addition to trading with their peers, EHs can trade energy and carbon rights with the utility company in the form of a grand coalition. Take the electricity utility company as an example, EHs generally purchase electricity from the utility company at a high time-of-use price while selling electricity to the utility company at a low feed-in-tariff price.

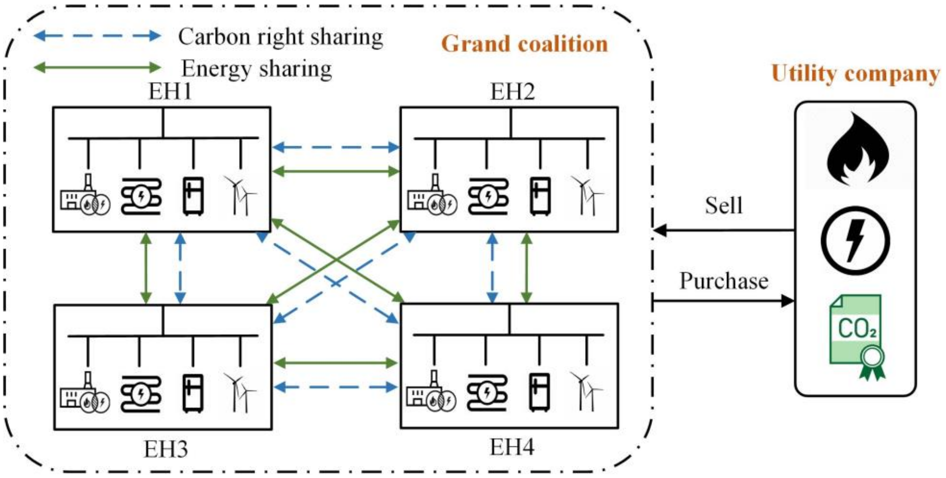


Fig. 2. Framework of joint energy and carbon rights trading

3. Mathematical Formulation of Grand Coalition

In the proposed mechanism, all EHs can share energy and carbon rights with each other and further trade with the utility company in the form of a grand coalition. All EHs aim at finding the maximum value of all EHs' total payoff, which is formulated as (2). The demand response of electricity, heat, and cooling loads are considered, i.e., these loads are not fixed. The total payoff is defined as the difference between the income and the energy cost. The revenue is achieved by satisfying various demands (e.g., electricity and cooling) and selling extra energy and carbon rights to the utility company, while the energy cost is caused by consuming fossil energy and purchasing energy and carbon rights from the utility company.

$$v(S,\rho)=\max \sum_i \sum_t (R_{i,t}-F_{i,t}) \tag{2}$$

$$R_{i,t}=U^E_{i,t}+U^H_{i,t}+U^C_{i,t}+p^{s,c}_t CS_{i,t} \tag{3}$$

$$U^E_{i,t}=\lambda^E_i L^E_{i,t}-\beta^E_i {L^E_{i,t}}^2 \quad \forall i,\forall t \tag{4}$$

$$U^H_{i,t}=\lambda^H_i L^H_{i,t}-\beta^H_i {L^H_{i,t}}^2 \quad \forall i,\forall t \tag{5}$$

$$U^C_{i,t}=\lambda^C_i L^C_{i,t}-\beta^C_i {L^C_{i,t}}^2 \quad \forall i,\forall t \tag{6}$$

$$F_{i,t}=p^{B,P}_i PB^t_i+p^{B,G}_i GB^t_i+p^{B,C}_i CB^t_i \quad \forall i,\forall t \tag{7}$$

The revenue of EH *n* at hour *t* is defined in constraint (3). Constraints (4)-(6) provides the revenue for balancing loads. Constraint (7) illustrates the hourly energy cost of EHs.

3.1 EH Operation Constraints

$$m^{inE}_{i,t}=m_{1,i,t}+m_{2,i,t}+m_{3,i,t} \quad \forall i,\forall t \tag{8}$$

$$m^{inR}_{i,t}=m_{4,i,t}+m_{5,i,t}+m_{6,i,t} \quad \forall i,\forall t \tag{9}$$

$$\eta_{CE} m^{inG}_{i,t}=m_{7,i,t}+m_{8,i,t}+m_{9,i,t} \quad \forall i,\forall t \tag{10}$$

$$\eta_{CH} m^{inG}_{i,t}=m_{10,i,t} \quad \forall i,\forall t \tag{11}$$

$$\eta_{ER}(m_{2,i,t}+m_{4,i,t}+m_{7,i,t})=m_{11,i,t} \quad \forall i,\forall t \tag{12}$$

$$\eta_{EB}(m_{3,i,t}+m_{5,i,t}+m_{8,i,t})=m_{12,i,t} \quad \forall i,\forall t \tag{13}$$

$$m_{1,i,t}+m_{6,i,t}+m_{9,i,t}=m^{outE}_{i,t}+L^E_{i,t} \quad \forall i,\forall t \tag{14}$$

$$m_{10,i,t}+m_{12,i,t}=L^H_{i,t},\ m_{11,i,t}=L^C_{i,t} \quad \forall i,\forall t \tag{15}$$

$$m^{inG}_{i,t}\le P^{CP,max}_i \quad \forall i,\forall t \tag{16}$$

$$m_{3,i,t} + m_{16,i,t} + m_{7,i,t} + m_{11,i,t} \le P_i^{EB,max} \quad \forall i, \forall t \tag{17}$$

$$m_{2,i,t} + m_{5,i,t} + m_{9,i,t} + m_{14,i,t} \le P_i^{ER,max} \quad \forall i, \forall t \tag{18}$$

$$m_{1,i,t}, \ldots, m_{18,i,t}, m_{i,t}^{inG}, m_{i,t}^{inE}, m_{i,t}^{outE}, m_t^{buy}, m_t^{sell} \ge 0 \quad \forall i, \forall t \tag{19}$$

Constraints (8)-(15) represent the energy flow of the EH shown in Fig. 1. Constraints (16), (17), and (18) respectively limit the outputs of CHP, EB, and CERG. Constraint (19) ensures the nonnegativity of energy flow. It should be noted that the modeling of EHs here adopts a linear approach, which is sufficient for hour-level EH energy management and trading. However, for scenarios requiring higher precision energy management on smaller time scales (such as minute-level), a more detailed model will be needed.

3.2 Carbon Constraints

$$CE_{i,t} = \beta_i^{CA} m_{i,t}^{inG} \quad \forall i, \forall t \tag{20}$$

$$\sum_i (CA_i^{\max} + \sum_t CS_{i,t}) = \sum_t \sum_i (CE_{i,t} + CB_{i,t}) \tag{21}$$

Constraint (20) enforces the amount of carbon emission of EH *i*. Constraint (21) represents the carbon balance of all EHs.

3.3 Power Network Constraints

$$P_{i,t} = m_{i,t}^{inE} - m_{i,t}^{outE} \quad \forall i, \forall t \tag{22}$$

$$\sum_i P_{i,t} = \sum_i (PB_{i,t} - PS_{i,t}) \quad \forall t \tag{23}$$

$$\begin{aligned} P_{i,t} &= \sum_j PL_{ji,t} - \sum_i PL_{ij,t} \quad \forall i, \forall t \\ Q_{i,t} &= \sum_j QL_{ji,t} - \sum_i QL_{ij,t} \quad \forall i, \forall t \end{aligned} \tag{24}$$

$$\begin{aligned} P_{i,t} + P_{i,t}^{in} - P_{i,t}^{out} &= \sum_j PL_{ji,t} - \sum_i PL_{ij,t} \quad \forall i \in TB, \forall t \\ Q_{i,t} + Q_{i,t}^{in} &= \sum_j QL_{ji,t} - \sum_i QL_{ij,t} \quad \forall i \in TB, \forall t \end{aligned} \tag{25}$$

$$\sum_i PB_{i,t} \le \sum_b P_{b,t}^{in}, \ \sum_i PS_{i,t} \ge \sum_b P_{i,t}^{out} \quad \forall t \tag{26}$$

$$\begin{aligned} PL_{ij,t} &= G_{ij}(U_{i,t} - U_{j,t}) - B_{ij}(\theta_{i,t} - \theta_{j,t}) \quad \forall ij, \forall t \\ QL_{ij,t} &= -G_{ij}(\theta_{i,t} - \theta_{j,t}) + B_{ij}(U_{i,t} - U_{j,t}) \quad \forall ij, \forall t \end{aligned} \tag{27}$$

$$PL_{ij,t}{}^2 + QL_{ij,t}{}^2 \le (S_{ij}^{\max})^2 \quad \forall ij, \forall t \tag{28}$$

$$U_i^{\min} \le U_{i,t} \le U_i^{\max} \quad \forall i, \forall t \tag{29}$$

Ensuring the safe and rational operation of the power network is crucial, with maintaining voltages and power flows within reasonable ranges being essential. Overlooking these constraints could lead to impractical or irrational decisions by EHs, ultimately threatening the safe operation of the power grid or rendering trading undeliverable [24]-[25]. Each EH is regarded as a bus in the power system. Constraint (22) demonstrates the net power load of EH. Constraint (23) represents the power balance in the whole district energy system. Constraints (24)-(25) represent active and reactive power injections respectively for common buses and substation buses. This study consider that EHs can only exchange electricity with the utility company through the substation buses. Constraints (27)-(28) restrict line power flow of power line *l* at hour *t*. Constraint (29) limits voltage magnitude of bus *i* at hour *t*. Note that the power flow model used here disregards network losses, which is acceptable for addressing the issue of benefits allocation among EHs. However, if future research involves the contribution of EH transactions to reducing network losses, a more refined power flow model will be necessary.

3.4 Natural Gas Network Constraints

$$G_{i,t} = m_{i,t}^{inG} - m_{i,t}^{outG} \quad \forall i, \forall t \tag{30}$$

$$\sum_t \sum_i G_{i,t} = \sum_t \sum_i (GB_{i,t} - GS_{i,t}) \tag{31}$$

$$\sum_j GF_{ji,t} - \sum_i GF_{ij,t} = G_{i,t} - GB_{i,t}^{ST} + GS_{i,t}^{ST} \quad \forall i, \forall t \tag{32}$$

$$\begin{aligned} &\frac{1}{A_{gl}}(GF_{ji,t+1} + GF_{ij,t+1} - GF_{ji,t} - GF_{ij,t}) + \frac{\Delta t}{L_{gl}}(GP_{j,t+1} - GP_{i,t+1} + GP_{j,t} - GP_{i,t}) \\ &\quad + \frac{\lambda \omega_{gl} \Delta t}{4 d_{gl} A_{gl}}(GF_{ji,t+1} + GF_{ij,t+1} + GF_{ji,t} + GF_{ij,t}) = 0 \quad \forall ij \in GL, \forall t \end{aligned} \tag{33}$$

$$\begin{aligned} &\frac{\Delta t}{L_{gl} A_{gl}}(GF_{ji,t+1} - GF_{ij,t+1} + GF_{ji,t} - GF_{ij,t}) + \frac{1}{c^2} GP_{j,t+1} \\ &\quad + \frac{1}{c^2} GP_{i,t+1} - \frac{1}{c^2} GP_{j,t} - \frac{1}{c^2} GP_{i,t} = 0 \quad \forall ij \in GL, \forall t \end{aligned} \tag{34}$$

$$\sum_j GF_{ji,t} - \sum_i GF_{ij,t} = G_{i,t} \quad \forall i, \forall t \tag{35}$$

$$\sum_i GB_{i,t} \le \sum_b G_{b,t}^{in}, \ \sum_i GS_{i,t} \ge \sum_b G_{b,t}^{out} \quad \forall t \tag{36}$$

$$GP_{g,t} = GP_{gw,0} \ \ \forall gw, \forall t \tag{37}$$

$$GP_i^{\min} \le GP_{i,t} \le GP_i^{\max} \ \ \forall i, \forall t \tag{38}$$

$$GF_{gl}^{\min} \le GF_{ij,t} \le GF_{gl}^{\max} \ \ \forall ij, \forall t \tag{39}$$

Each EH is regarded as a node in the natural gas network. The dynamic gas network model provided in Refs. [26]-[27] are utilized. Constraint (30) represents the net gas load of each EH. Constraint (31)-(32) illustrates the natural gas balance. Constraint (33) expresses the momentum transport in the continuum of natural gas. Constraint (34) illustrates the conservation of mass for the natural gas in the pipelines. The mass flow rate should be balanced at each node (35). Constraint (36) sets limits on natural gas purchases and sales. Constraint (37)-(38) limits the pressure for gas wells and nodes, respectively. Constraint (39) limits the gas flow of the pipeline.

3.5 Proof of Grand Coalition' Stability

Here, this study provides proof of the stability of the grand coalition. More specifically, this study proves that each EH is willing to join the grand coalition rather than deviating from the grand coalition. Firstly, several basic definitions are provided.

Definition 1 (Imputation): Consider that the payoff allocation to each EH is defined using the vector $\boldsymbol{x}$. The payoff allocation can be defined as *imputation* if two criteria are guaranteed:

1) *Efficiency*: $\boldsymbol{x}$ is defined as an efficient vector if the total payoff is shared to each EH, i.e., $\sum_i x_i = v(N)$.

2) *Individual Rationality*: $\boldsymbol{x}$ is defined as a rational vector if $x_i \ge v(\{i\},\rho)\ \forall i$, which means that EHs' payoffs are less if they deviate from the grand coalition.

***Definition 2 (γ-Core)*:** γ-core shown in (40) is a group of imputations, indicating that all EHs will gain more payoffs by joining the grand coalition rather than joining other potential coalitions. The behavior of the participant outside the coalition is considered. There is only one coalition in γ-core. The participants outside the coalition are assumed to act individually rather than formulating coalitions.

$$\left\{ \boldsymbol{x} \mid \sum_i x_i = v(N),\ \sum_{i \in S} x_i \ge v(S,\rho)\ \forall S \right\} \tag{40}$$

Definition 3 (Excess)*:** The excess can be interpreted as the dissatisfaction of coalition *S* with the respect to imputation ***x, which is shown as follow:

$$\varepsilon(x,S,\rho)=v(S,\rho)-\sum_{i\in S}x_i \tag{41}$$

If the imputation is a part of γ-core, the excess is negative for any coalition *S*. Excess reflects the fairness of the imputation. A small excess for coalition *S* means that the members in coalition *S* gain more economic benefits by joining the grand coalition. As a result, the members outside coalition *S* gain less payoff. Therefore, a small excess for coalition *S* is not fair for the members outside coalition *S*.

***Definition 4 (Balanced game)*:** The cooperative game with externalities can be defined as a balanced game if criteria (42)-(43) is satisfied.

$$\sum_{S}\alpha(S)\,v(S,\rho)\le v(N) \tag{42}$$

$$\sum_{S}\alpha(S)=1 \tag{43}$$

Definition 5 (Superadditivity): The proposed game is superadditive if (44) is guaranteed for any coalition $S,R\subseteq N$ and any ρ of $N-R\bigcup S$:

$$v(S\cup R,\{S\cup R\}\cup\rho)\ge v(S,\{S,R\}\cup\rho)+v(R,\{S,R\}\cup\rho) \tag{44}$$

Definition 6 (Positive homogeneity): Given a constant β, the proposed game is positively homogeneous if (45) is guaranteed for any $S,R\subseteq N$, μ and ρ of $N-R\bigcup S$:

$$H(\mu S,\mu\rho)=\mu H(S,\rho) \tag{45}$$

Lemma 1: If the γ-core exists (nonempty), the grand coalition is stable, i.e., all EHs are willing to cooperate [28].

Lemma 2: If a cooperative game with the externalities is balanced, the γ-core exists [29].

Theorem 1: The proposed joint energy and carbon transaction market for cooperative EHs has two characteristics: superadditivity and positive homogeneity.

Proof: In the proposed model, if two coalitions do not cooperate, extra constraints must be added to enforce that these two coalitions cannot cooperate. Therefore, the objective (i.e., total payoff) is decreased since extra constraints are added. Accordingly, equation

(44) is satisfied.

The proposed problem is a linear programming problem. For any constant β , the linear programming problem satisfies equations (46)-(47), which is equivalent to equation (45). Therefore, the proposed method is positively homogenous.

$$\max\ \beta v(S,\rho) = \max v(\beta S,\beta\rho) \tag{46}$$

$$\beta C(S,\rho) = C(\beta S,\beta\rho) \tag{47}$$

Theorem 2: The grand coalition in the proposed transaction mechanism for all participated EHs is stable.

Proof: First, this study proves that the proposed game is balanced.

$$\begin{aligned}\sum_S \alpha_S J(S,\rho) &= \sum_S J(\alpha_S S,\alpha_S\rho) \quad [\mathit{positive\ homogeneity}] \\ &\le J(\sum_S \alpha_S S,\sum_S \alpha_S\rho) \quad [\mathit{superadditivity}] \\ &= \sum_S J(\alpha_S S,\alpha_S\rho) \le v(N)\end{aligned} \tag{48}$$

According to equation (48), the proposed game is balanced. According to Lemma 2, γ-core is nonempty. Furthermore, the stability of the grand coalition is ensured according to the above Lemma 1.

4. Proposed Solution Technique

4.1 Two-stage Imputation Problem

Allocating the grand coalition’s payoff to each participant is challengeable, and a scalable payoff allocation is still in lack. Here, this study provides a two-stage imputation problem to fairly allocate the total payoff to each EH while ensuring the grand coalition’s stability. This problem searches the coalition with the minimum excess (defined as the worst-case excess) and further maximizes the excess. Accordingly, each coalition S has a satisfactory excess. More specifically, the grand coalition’s payoff is allocated to each EH at the first stage, and the worst-case excess is searched at the second stage.

$$\max_x \min_y \sum_{i\in S} y_i x_i - v(S,\rho) \tag{49}$$

$$\sum_i x_i = v(N) \tag{50}$$

$$v(S,\rho)-\sum_{i\in S}y_i x_i \le 0 \tag{51}$$

$$1\le \sum_{i} y_i \le N-1 \tag{52}$$

$$v(S,\rho)=\sum_{t}\sum_{i\in S} y_i\,(R_{i,t}-F_{i,t}) \tag{53}$$

$$R_{i,t},F_{i,t}\in \arg\left\{\max\ \sum_{t}\sum_{i\in S} k_i\,(R_{i,t}-F_{i,t});\ \ s.t.\ Constraints\ (55)-(61)\right\} \tag{54}$$

$$\sum_{i\in S} P_{i,t}=\sum_{i\in S}(PB_{i,t}-PS_{i,t})\ \forall t \tag{55}$$

$$\sum_{t}\sum_{i} G_{i,t}=\sum_{t}\sum_{i}(GB_{i,t}-GS_{i,t}) \tag{56}$$

$$\sum_{i}(CA_i^{\max}+\sum_{t} CS_{i,t})=\sum_{t}\sum_{i}(CE_{i,t}+CB_{i,t}) \tag{57}$$

$$P_{i,t}=PB_{i,t}-PS_{i,t}\ \ \forall i\notin S,\forall t \tag{58}$$

$$\sum_{t} G_{i,t}=\sum_{t}(GB_{i,t}-GS_{i,t})\ \forall i\notin S \tag{59}$$

$$CA_i^{\max}+\sum_{t} CS_{i,t}=\sum_{t}(CE_{i,t}+CB_{i,t})\ \forall i\notin S \tag{60}$$

$$\text{Constraints }(3)-(4),\ (7)-(20) \tag{61}$$

Constraint (49) represents the objective that minimizes the worst-case excess. Constraint (50) allocates the grand coalition's payoff to each EH. Constraint (51) guarantees that the obtained payoff allocation is in the γ-core. Constraints (52)-(53) represent payoff of coalition *S*, which is calculated using (54). Constraints (55)-(57) enforce the electricity, natural gas, and carbon balance for coalition *S*, while constraints (58)-(60) enforce the electricity, natural gas, and carbon balance for the EHs which are not in coalition *S*. Constraint (61) represents the electricity and gas network constraints.

The solution algorithm uses the Benders decomposition [30]-[31] and KKT conditions to solve the imputation determination problem. More specifically, the original problem is decomposed into two problems through the Benders decomposition algorithm, including the master problem and the subproblem. Additionally, this study applies KKT conditions to reformulate the subproblem. The compact form of the two-stage imputation problem is formulated as (62).

$$\begin{aligned}&\max_{\boldsymbol{x}}\min_{\boldsymbol{y}}\ \boldsymbol{\chi}\cdot\boldsymbol{x}+\boldsymbol{\delta}\cdot\boldsymbol{z}\\&s.t.\ \ \boldsymbol{\phi}\cdot\boldsymbol{x}\le\boldsymbol{L},\ \boldsymbol{\gamma}\cdot\boldsymbol{x}+\boldsymbol{\kappa}\cdot\boldsymbol{y}\le\boldsymbol{M}\\&\boldsymbol{z}\in\arg\left\{\max_{\boldsymbol{z}}\ \boldsymbol{\lambda}\cdot\boldsymbol{z};\ \boldsymbol{\mu}\cdot\boldsymbol{y}+\boldsymbol{\nu}\cdot\boldsymbol{z}\le\boldsymbol{N}\right\}\end{aligned}\tag{62}$$

4.2 Master Problem

The master problem stated as (63) determines imputation $\boldsymbol{x}$ for participated EHs while minimizing the worst-case excess:

$$\begin{aligned}&\max_{\boldsymbol{x}}\ \eta\\&s.t.\ \ \boldsymbol{\phi}\cdot\boldsymbol{x}\le\boldsymbol{L},\ \eta\ge\eta^{\min}\end{aligned}\tag{63}$$

4.3 Subproblem

The objective of the subproblem shown as (64) is to find the worst-case excess.

$$\begin{aligned}&\min_{\boldsymbol{y}}\ \boldsymbol{\chi}\cdot\boldsymbol{x}^*+\boldsymbol{\delta}\cdot\boldsymbol{z}\\&s.t.\ \boldsymbol{\gamma}\cdot\boldsymbol{x}^*+\boldsymbol{\kappa}\cdot\boldsymbol{y}\le\boldsymbol{M}\\&\boldsymbol{z}\in\arg\left\{\max_{\boldsymbol{z}}\ \boldsymbol{\lambda}\cdot\boldsymbol{z};\ \boldsymbol{\mu}\cdot\boldsymbol{y}+\boldsymbol{\nu}\cdot\boldsymbol{z}\le\boldsymbol{N}\right\}\end{aligned}\tag{64}$$

To solve the subproblem, this study transforms subproblem (64) into a single-level subproblem (65) by using the KKT condition.

$$\begin{aligned}&\min_{\boldsymbol{y}}\ \boldsymbol{\chi}\cdot\boldsymbol{x}^*+\boldsymbol{\delta}\cdot\boldsymbol{z}\\&s.t.\ \boldsymbol{\gamma}\cdot\boldsymbol{x}^*+\boldsymbol{\kappa}\cdot\boldsymbol{y}\le\boldsymbol{M},\ \boldsymbol{\mu}\cdot\boldsymbol{y}+\boldsymbol{\nu}\cdot\boldsymbol{z}\le\boldsymbol{N}\\&\boldsymbol{\nu}\cdot\boldsymbol{\pi}=\boldsymbol{\lambda},\ (\boldsymbol{\mu}\cdot\boldsymbol{y}+\boldsymbol{\nu}\cdot\boldsymbol{z}-\boldsymbol{N})\boldsymbol{\pi}=0\end{aligned}\tag{65}$$

where $\boldsymbol{\pi}$ represents the dual multiplication.

The nonlinear constraint $\boldsymbol{\pi}(\boldsymbol{\mu}\cdot\boldsymbol{y}+\boldsymbol{\nu}\cdot\boldsymbol{z}-\boldsymbol{N})$ in subproblem (65) can be linearized with the adoption of the big-M method. The excess of the coalition and the corresponding solution $\boldsymbol{z}^*$ is obtained after solving the subproblem. The iteration ends if criterion (66) is satisfied, which indicates that the worst-case excess is found and minimized. Otherwise, constraint (67) will be generated and added to master problem (63).

$$\left|\alpha^*-\left(\boldsymbol{\chi}\cdot\boldsymbol{x}^*+\boldsymbol{\delta}\cdot\boldsymbol{z}^*\right)\right|\le\varepsilon\tag{66}$$

$$\begin{aligned}&\boldsymbol{\gamma}\cdot\boldsymbol{x}+\boldsymbol{\kappa}\cdot\boldsymbol{y}^{h,*}\le\boldsymbol{M},\ \boldsymbol{\mu}\cdot\boldsymbol{y}^{h,*}+\boldsymbol{\nu}\cdot\boldsymbol{z}^h\le\boldsymbol{N}\\&\boldsymbol{\nu}\cdot\boldsymbol{\pi}^h=\boldsymbol{\lambda},\ (\boldsymbol{\mu}\cdot\boldsymbol{y}^{h,*}+\boldsymbol{\nu}\cdot\boldsymbol{z}^h-\boldsymbol{N})\boldsymbol{\pi}^h=0\end{aligned}\tag{67}$$

4.4 Procedures of the Solution Technique

In this subsection, this study provides the procedures of the solution technique. Also, the following Fig. 3 illustrates the flowchart of the proposed solution technique.

1) Input relevant parameters. Set h = 0;

2) Solve master problem (63) to calculate imputation.

3) Transform the original bi-level subproblem into a single-level subproblem by using the KKT conditions.

4) Solve subproblem (65) to find the coalition with maximum excess.

5) If (66) is guaranteed, output the imputation result. Otherwise, generate constraint (67) to master problem (63) and repeat the previous steps.

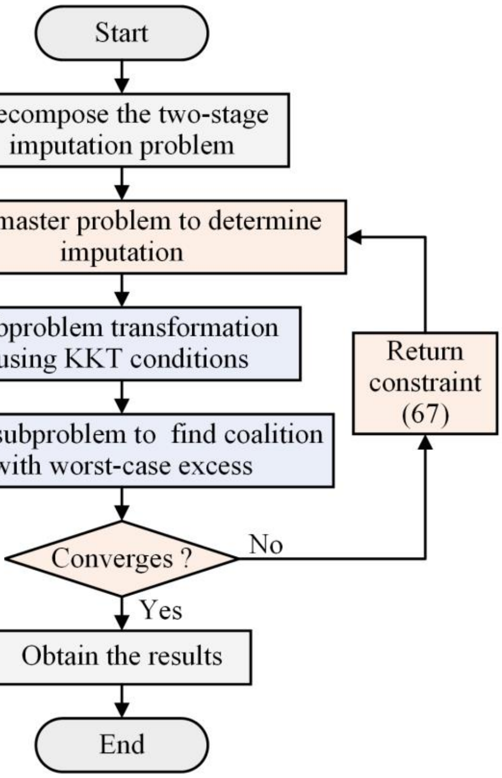


Fig. 3. Flowchart of the proposed solution technique

5. Case Studies

In the section, 4-EH and 33-EH systems are used to test the proposed joint market. The constitution of the EH is the same as that shown in Fig 1. The detailed parameters of EH are provided in Ref. [21]. All calculations are performed on a personal computer using a MATLAB 2020a platform in Gurobi 9.1.2 with Intel Core (TM) i5-1135G7 CPU (2.4

GHz) and 16 Gb of memory.

5.1 4-EH System

Fig. 4 provides the topology of the 4-EH system. In this system, three cases are provided to illustrate the proposed method.

Case I: EHs cannot trade energy or carbon rights with their peers.

Case II: EHs can only trade energy with their peers.

Case III: EHs can trade both energy and carbon rights with their peers.

In all three cases, EHs can trade energy and carbon rights with the utility company.

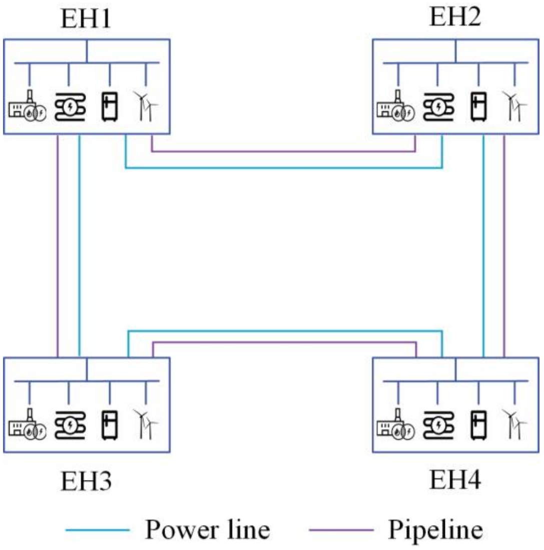


Fig. 4. Topology of the 4-EH system

Table 2 compares the optimal solutions in three different cases. The total payoff in Case I is the lowest since EHs can only trade expensive energy and carbon rights with the utility company. Accordingly, the energy and carbon rights traded with the utility company are the highest. In Case II, EHs are allowed to trade energy with their counterparts. Energy trading reduces EHs' dependency on the utility company; thus, the amount of energy traded with the utility company is reduced. Moreover, as EHs prefer to purchase cheap energy from their peers rather than buying expensive carbon rights from the utility company to generate its onsite energy, the carbon right traded with the utility company is reduced. In Case III, the implementation of flexible energy and carbon rights trading among EHs results in a total payoff increase of 10.5% ((1,586.22 - 1,435.76) / 1,435.76), representing the most significant payoff across the three cases. Furthermore, this case also records the lowest volume of energy and carbon rights traded with the utility company.

Table 2 Cost allocation in different cases

Cases	Total payoff ($)	Energy traded with the utility company ($)		Carbon right traded with the utility company ($)	
		Buy	Sell	Buy	Sell
Case I	1,176.98	670.72	30.12	10.64	2.17
Case II	1,435.76	308.32	0	5.43	2.17
Case III	1,586.22	207.81	0	2.16	0

Fig. 5 provides each EH's payoff in three cases. EHs 1 and 2 with a high penetration level of renewable DERs balance their onsite loads using renewable energy rather than fossil fuel (e.g., natural gas). Therefore, they can sell surplus energy and carbon rights for gaining more profits. In these three cases, the payoffs of EHs 1 and 2 are higher than the other two EHs, which indicates that the proposed market is effective in incentivizing the investment of renewable DERs. Each EH's payoff in Case III is higher than those in Cases I and II. Therefore, EHs are stimulated to transact energy and carbon rights. The proposed payoff allocation method guarantees fairness for the vulnerable participants (i.e., EHs 3 and 4) since they can earn more profits than EHs 1 and 2 by joining the grand coalition.

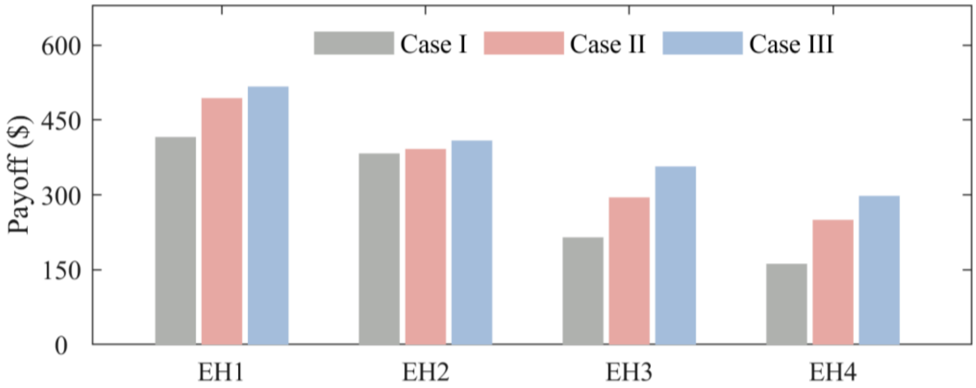


Fig. 5. Payoff of each EH in three cases

Table 3 further illustrates the iterative process of the proposed solution technique for allocating the payoff to each EH in Case III. The optimal payoff for each EH is obtained after 6 iterations. Compared with the existing methods, which usually require at least 2n-1 iterations, the proposed solution method can calculate the imputation in a scalable manner.

Table 3 Iterative process of the proposed two-stage imputation method

Iterations	EH's payoff ($)			
	EH1	EH2	EH3	EH4
1	416.84	793.22	215.14	161.02
2	416.84	383.58	215.14	570.66
3	416.84	383.58	624.78	161.02
4	555.60	419.01	332.15	279.47
5	501.32	437.10	350.24	287.56
6	518.46	410.61	358.17	299.00

5.2 33-EH System

The topology of the network is illustrated in Fig. 6, while the detailed parameters of the EH devices (e.g., CHP, EB) in the 33-EH system are the same as those in the 4-EH system, specific network and devices parameters can be referred to in Ref. [21] and [32]. First, two cases, respectively named ECT and ET, are conducted to validate the implementation of carbon market impacts the energy trading and payoff. In the ET case, there is only energy trading, and there are no taxes or limits on carbon emissions. In the ECT case, the joint energy and carbon rights transactions are considered.

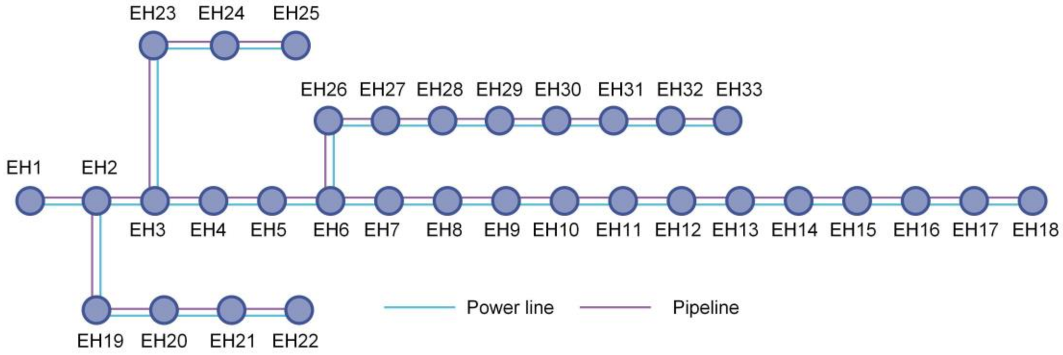
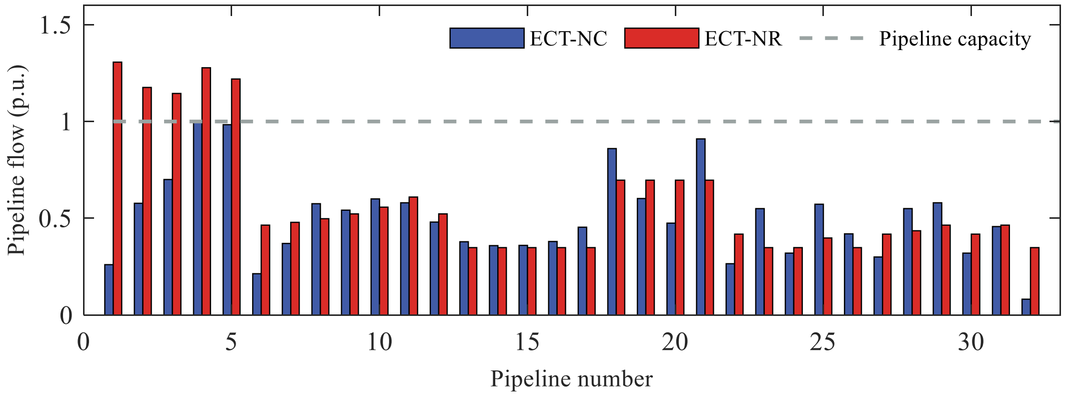


Fig. 6. Topology of the 33-EH system

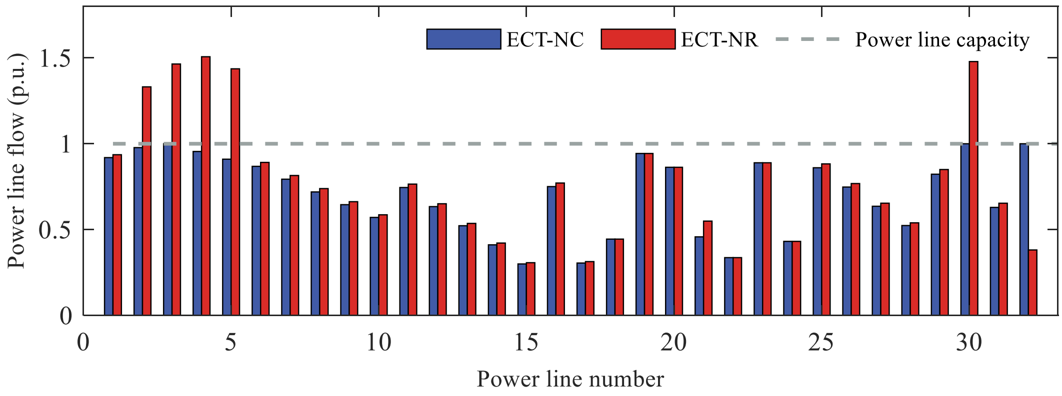
Table 4 Trading results and payoff in the cases with and without carbon markets

Cases	Total payoff ($)	Carbon emissions by all EHs (t)	Local energy generation of EH devices (kWh)
ET	26,158	87.49	95,997
ECT	25,284	69.48	76,230

Table 4 provides the trading results and payoff in the cases with and without carbon markets (i.e., ET and ECT cases). In the ET case, EH devices (e.g., CHP) do not need to pay taxes for carbon emissions. Additionally, there are no limitations on the amount of carbon emissions. Accordingly, EHs prefer the local energy generation via EH devices compared to buying electricity from the DSO. Therefore, the amounts of EH's local energy generation and the corresponding carbon emissions in the ET case are higher than those in the ECT case, where the carbon emissions are priced. When quantifying the carbon emissions differences in the two cases, the implementation of the carbon market brings a 20.6% (i.e., (87.49-69.48)/87.49) reduction in the amount of carbon emission and is conducive to the construction of a net-zero energy system.



(a) Natural gas network



(b) Electricity network

Fig. 7. Line capacities and line flows comparisons for ECT-NC and ECT-NR cases

To analyze network constraints' impact on line flows and trading results, another two cases are designed and compared, including the ECT-NC case and the ECT-NR case. In both two cases, the joint energy and carbon rights transactions are considered, while the considerations of network constraints are different. The ECT-NC case is network-constrained, while the network limits are relaxed in the ECT-NR case. The line capacity and line flow comparisons for the two cases are illustrated in Fig. 7, and the trading results and payoff in the two cases are provided in Table 5.

In the case of ECT-NR, energy sharing between different EHs is conducted without any line capacity restrictions. As shown in Table 5, the total traded energy and payoff in the ECT-NR case are greater than in the ECT-NC case. However, network flow limit violations will occur during energy delivery if network constraints are not considered during the energy trading phase. Fig. 7 depicts the line flow breaches, as well as the maximum flow of each line for the duration of the simulation (i.e., 24 hours). There are 5 pipelines and 5 power lines whose maximum line flows exceed their capacity in the ECT-NR case. As for the proposed ECT-NC case, all the maximum line flows are within the line capacities, which ensure energy delivery and networks security. Compared to the ECT-NR case, the ECT-NC case reduces the amount of traded energy to satisfy the network constraints. In contrast to the changes in the total traded energy, the total traded carbon right in the ECT-NC case is increased for local energy generation.

Table 5 Trading results and payoff in the cases with and without network constraints.

Cases	Payoff ($)	Energy traded among EHs (kWh)	Carbon right traded among EHs (t)
ECT-NC	25,284	13,829	20.67
ECT-NR	29,800	24,438	14.38

6. Discussion

Achieving carbon neutrality is a global objective, with countries worldwide actively exploring decarbonization across various sectors, including district energy systems, including those mentioned previously as energy hubs in district energy systems. Specifically, the increasing penetration of renewable energy sources within energy hubs, transforming them into both producers and consumers of energy, represents a global trend. Therefore, the cooperative game-based joint energy and carbon rights trading mechanism proposed for energy hubs holds universal application value across nations, not just limited to a specific country or region.

This research primarily introduces a joint transaction mechanism for network-constrained energy hubs, utilizing a cooperative game approach aimed at optimizing total benefits and ensuring equitable benefit allocation among all energy hubs. One limitation in our method, however, is its indirect contribution to energy network services. Although network constraints are considered to ensure safe operation, the model does not actively support the energy network's functioning by providing ancillary services such as peak shaving or reserves. Future directions could explore enhancing the model to actively contribute to the energy network’s operations, thereby not only ensuring the equitable distribution of benefits and operational safety but also bolstering the network's benefits through supportive services.

7. Conclusion

This paper provides a joint transaction mechanism based on the cooperative game, in which cooperative energy hubs form a grand coalition to share diverse forms of energy and carbon rights in order to maximise their total benefit. The grand coalition-based transaction mechanism is augmented with network constraints to account for the influence of network constraints on the trading behaviours of energy hubs, which is mathematically represented as a cooperative game with externalities. Moreover, this study proves that the proposed joint market for networked EHs is balanced, which indicates that the grand coalition is stable. A two-stage imputation problem is provided for allocating the grand coalition’s payoff to each EHs in a scalable manner. The solution technique based on Karush-Kuhn-Tucker conditions and Benders decomposition algorithm is proposed to find the optimal solution of the two-stage optimization problem.

Numerical results from both the 4-EH and 33-EH systems demonstrate the effectiveness and scalability of the proposed method, with key findings summarized as follows: 1) The introduction of the carbon market leads to a 20.6% reduction in carbon emissions and a 10.5% increase in total payoff by facilitating peer-to-peer trading of both energy and carbon rights. Moreover, the proposed imputation method guarantees fair payoff distribution among EHs and maintains the stability of the grand coalition in the cooperative game. 2) Incorporating network constraints and developing a cooperative game with externalities effectively prevent line violations across both natural gas and electricity networks. In contrast, the comparison case experiences constraint violations in 5 pipelines and 5 power lines. 3) The findings underscore that the carbon market plays a pivotal role in fostering a low-carbon energy system. The innovative cooperative game with externalities not only ensures secure energy delivery and network integrity but also promotes peer-to-peer trading, enhancing the system's overall sustainability.

Moreover, the joint energy and carbon market's impact on lowering emissions directly contributes to achieving sustainable energy goals and adheres to ESG criteria. Additionally, the application of cooperative game theory, with its emphasis on externalities and network constraints, offers practical guidance for the engineering of more secure and efficient energy networks. One limitation of the current method is its primary focus on the benefits of EHs, without directly offering services to energy networks. Future research will explore how P2P transactions between energy hubs, based on cooperative game theory with externalities, can proactively support the energy network's operation by offering such ancillary services.

Acknowledgments

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