Multi-party Energy Management of Energy Hub: A Hybrid Approach with Stackelberg Game and Blockchain

Nian Liu, Lu Tan, Linjie Zhou, and Qifang Chen

Abstract—**In an integrated energy distribution system (IEDS), an energy hub has been introduced and deemed to be a suitable tool for managing and integrating multi-party energy forms. Due to different energies having diverse characteristics and being coupled with each other, it is difficult for an energy hub to implement the optimal scheduling of multiple energy sources. Therefore, an energy optimization management model is proposed based on the Stackelberg game, which considers the exergy conversion of multi-party energy sources in different operation modes. The problem is solved by the two-layer distributed optimization algorithm, in which the energy hub acts as the leader and is followed by the users. Furthermore, in order to alleviate the deception, malicious tampering, subpeption, and other secure risks in energy trading, blockchain is introduced into the energy hub and the concept of exergy coin (EC) is proposed. A credit-based blockchain framework and concurrent block building consensus process is explored to reduce the calculation cost and promote the exergy trading efficiency. Finally, the case study shows how the proposed method can effectively optimize energy scheduling and configure a more reasonable energy solution.**

Index Terms—**Energy management, Stackelberg game, exergy coins (EC), exergy conversion, blockchain.**

I. Introduction

RECENTLY, with the increasingly serious energy crisis and environmental issues, in order to alleviate environmental pollution and improve the energy utilization efficiency, an integrated energy distribution system (IEDS) is proposed and considered as a promising solution [1]. In the IEDS, different energies are coupled with each other in a synergistic way, which includes natural gas/thermal/electricity/hot water and other various energy forms [2]. New concepts and tools are essential when considering the interactions among multiple energy forms. In turn, energy hub has been introduced and deemed to be a suitable tool for managing and integrating various energy forms due to its high efficiency [3]. In energy hub, multiple types of energy carriers are input at the imported interface which connect to energy producers, and are stored, converted, or transferred within it, then finally output to provide energy demands for users at the exported interface [4]. The coordination and optimization of various energy sources can improve the reliability and flexibility of energy utilization [5], [6]. However, despite the aforementioned advantages of energy hub, some challenges must be considered regarding multi-party energy management.

Firstly, different energies have diverse characteristics, and the optimal scheduling of multiple energy sources needs to be considered simultaneously, which brings about the difficulties for energy hubs when interacting with users. In order to solve the problem of energy optimization, exergy is presented. Exergy is based on the laws of thermodynamics. It acts as a measure of the energy quality, but unlike energy, it is not conserved [7], [8]. Based on a given environment, the maximum amount of energy that can be theoretically converted into "infinitely convertible energy" is called exergy, which means that it varies with the environmental reference [9]. Furthermore, exergy has received extensive attention from academia and industry [10]-[14]. In [10], the conversion models of electric power, heat, sensible heat, and chemical exergy are studied, in which the thermal process containing the energy and conversion process with exergy metrics is analyzed. A resource-based quantifier "extended exergy" is applied to the energy conversion systems in [11]. The authors in [12] present a novel systematic approach to evaluate the energy conversion processes based on an extended representation of their exergy flow diagram. An approach based on cumulative exergy consumption and thermo-economic methods is proposed in [13]. However, this work ignores the various exergy demands and operation modes of different seasons.

Secondly, an efficient security framework for energy trading between users and energy hubs is lacking. Considering the selfishness and rationality of users and energy hubs in the energy transaction, each participant wants to maximize their own profits. Therefore, the deception, malicious tampering, subpeption, and other security risks may exist, which bring about critical challenges for energy trading.

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In order to address the above-mentioned challenges, a hybrid approach to the multi-party energy management of energy hubs is proposed, which utilizes the exergy conversion, Stackelberg game, and blockchain technology. An energy optimization management scheme considering the exergy conversion of various energy sources in different seasons is proposed. Furthermore, the exergy interactions between the energy hub and users are modeled as a two-stage Stackelberg leader-follower game, in which the energy hub acts as the leader that is followed by the users.

Blockchain is essentially a distributed ledger database, which is a series of data blocks generated via cryptography [15], [16]. It can provide a secure and transparent energy trading environment for a distributed system without participation of third-party authority. The authors in [17] propose an efficient and secure framework for vehicle-to-grid (V2G) energy trading by utilizing blockchain and edge computing, and a proof-of-concept for a distributed energy trading system in a smart grid is introduced in [18] by exploring blockchain and multi-signature technologies. However, the calculation cost and resource consumption of the traditional consensus process are huge, which is impractical for the energy trading that involves high real-time requirements and high frequency between the energy hub and users. In this paper, for the sake of reducing the calculation cost and promoting the trading efficiency, a credit-based blockchain framework is proposed using a concurrent block building consensus process according to [19] and [20].

The main contributions of this paper are as follows:

1) A Stackelberg game model is proposed considering exergy conversion in three operation modes. In order to realize the unified and optimal dispatch of different qualities of energies in the commercial park, the exergy is presented. The exergy conversion models of electricity, cold, heat, and domestic hot water in the park are established, and all kinds of energies are unified into exergy. Therefore, all kinds of energies are involved in the Stackelberg game in the form of exergy to achieve the unified optimization management of multiple energy sources.

2) Blockchain is introduced into the energy hub and exergy coin (EC) is utilized, which is a virtual currency for the trade between the energy hub and users. A credit-based blockchain framework and concurrent block building consensus process is explored to reduce the calculation cost and time delay, and to promote exergy trading efficiency.

II. System Model

A. System Structure

The blockchain system structure is shown in Fig. 1. In the commercial park, there is an energy hub and several users who act as the participants. The energy hub owns the internal combustion (IC) engine in order to take responsibility for generating electricity and waste heat, and the gas-hot water operated lithium bromide absorption unit can use waste heat to produce cold, heat, and hot water. The energy hub also owns the boiler which can generate heat or hot water by burning natural gas, cold generating auxiliary equipment such as an electric centrifugal chiller, and domestic hot water conversion equipment such as a plate heat exchanger and heat pump.

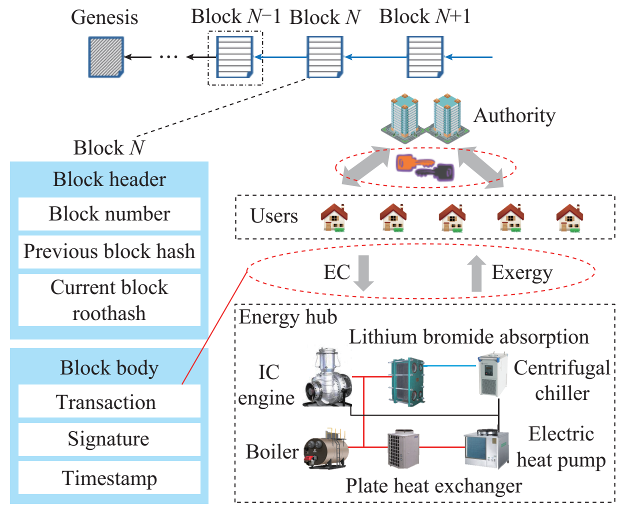

Fig. 1. System structure with blockchain.

B. Operation Mode

In order to meet the different energy demands of users in different seasons, there are three operation modes. Figures 2-4 are the structure diagrams of the centralized cooling, heating and transition season operation modes, respectively. In centralized cooling operation mode, all of the equipments in the energy hub participate in the efforts to provide cold, electricity, and hot water for users, while in the other two operation modes the users have no demands for cold. Thus, there is no need for the electric centrifugal chiller to participate in. However, in centralized heating operation mode, the boiler needs to generate heat and hot water at the same time [21].

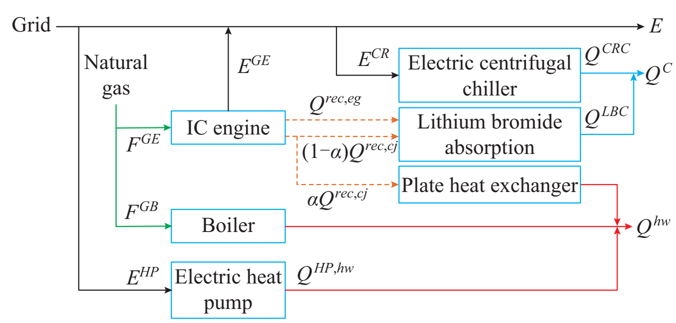

Fig. 2. Centralized cooling operation mode.

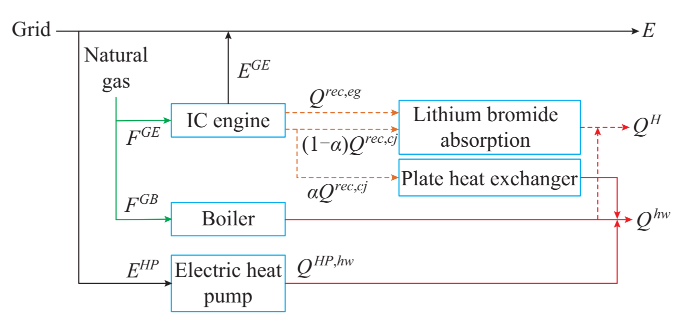

Fig. 3. Centralized heating operation mode.

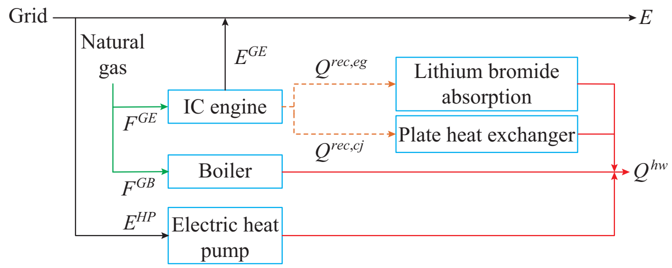

Fig. 4. Transition season operation mode.

C. Exergy Conversion Model

In order to realize unified regulation and control via the energy hub of different types of energies including electricity, cold, heat, and domestic hot water, energies are converted into exergy. The energy level coefficient is the ratio of the exergy in energy, so according to the energy level coefficient, each energy can be converted into exergy [22].

1) Electricity

Electricity is the highest grade of energy, so it can be completely converted into exergy and the energy level coefficient is equal to 1. The exergy of electricity can be defined as:

$$Ex^{E}=E \tag{1}$$

where Ex^{E} is the exergy of electricity; and E is the energy of electricity.

2) Cold

The energy level coefficient of cold can be defined as λ^{C} and the exergy of cold is $Ex^{Q^{C}}$:

$$\lambda^{C}=\frac{T}{T^{0}}-1 \tag{2}$$

$$Ex^{Q^{C}}=\lambda^{C}Q^{C} \tag{3}$$

where T is the temperature of the environment; T^{0} is the temperature of the heat source; and Q^{C} is the energy of cold.

3) Heat

The energy level coefficient of heat can be defined as λ^{H} and the exergy of heat is $Ex^{Q^{H}}$:

$$\lambda^{H}=1-\frac{T}{T^{0}} \tag{4}$$

$$Ex^{Q^{H}}=\lambda^{H}Q^{H} \tag{5}$$

where Q^{H} is the energy of heat.

4) Domestic Hot Water

The energy level coefficient of domestic hot water can be defined as λ^{hw} and the exergy of heat is $Ex^{Q^{hw}}$:

$$\lambda^{hw}=1-\frac{T}{T^{s}-T^{r}}\ln\frac{T^{s}}{T^{r}} \tag{6}$$

$$Ex^{Q^{hw}}=\lambda^{hw}Q^{hw} \tag{7}$$

where T^{s} is the supply water temperature; T^{r} is the return water temperature; and Q^{hw} is the energy of domestic hot water.

D. Basic Model

1) EC

In this paper, the concept of EC is proposed, which is calculated as the virtual currency in the trading process of the blockchain. In this model, EC is assumed to possess the currency value and is exchangeable with traditional currencies, which can be used for purchasing goods and services [16]. The actual purchasing power of EC p^{ex} is represented by:

$$p^{ex}=\zeta B \tag{8}$$

where ζ is the exchange rate between EC and CNY (i. e., CNY per unit of EC); and B is the total capacity of EC in circulation.

2) IC Engine

The energy hub uses the IC engine as the prime mover for generating electricity by burning natural gas to supply user demand, while combustion produces high-temperature flue gas. The recoverable unit of waste heat can be used to recover and reuse the residual heat of high temperature flue gas and cylinder liner water. The fuel energy ratio can be defined as:

$$R=\frac{Q^{rec}}{LF^{GE}} \tag{9}$$

where Q^{rec} is the recoverable heat from the IC engine; L is the low calorific value; and F^{GE} is the natural gas consumption.

Q^{rec} can be further divided into the recoverable heat from the flue gas $Q^{rec,eg}$ and the cylinder liner water $Q^{rec,cj}$, which account for the ratio of Q^{rec}, respectively.

$$Q^{rec}=Q^{rec,eg}+Q^{rec,cj} \tag{10}$$

The IC engine output E^{GE} can be defined as:

$$E^{GE}=F^{GE}(1-R-\eta^{loss})L \tag{11}$$

where η^{loss} is the energy loss rate of this process.

3) Boiler

A boiler is a pressure vessel that can provide hot water and thermal power for the user by burning natural gas, and the hot capacity generated from it can be calculated as:

$$Q^{GB}=F^{GB}\eta^{GB}=Q^{GB,hw}+Q^{GBH} \tag{12}$$

where F^{GB} is the natural gas consumption efficiency; η^{GB} is the energy conversion efficiency of a boiler; and $Q^{GB,hw}$ and Q^{GBH} are the hot water capacity and the heat of the boiler, respectively. When it is in centralized heating mode, a boiler generates hot water with the proportion of 0.6 and heat with the proportion of 0.4. In the other two modes, it only provides hot water.

4) Recoverable Unit of Waste Heat

The lithium bromide absorption unit operated by gas and hot water is adopted in this paper. The lithium bromide unit can utilize high-temperature flue gas and cylinder liner water generated by the IC engine to produce cold, heat, or hot water.

When it is centralized heating or cooling season, the residual heat enters the plate heat exchanger with the proportion of α and the lithium bromide unit with the proportion of $1-\alpha$. The cooling capacity and the calorific capacity of the lithium bromide unit are shown in (13) and (14), respectively. When it is transition season, the hot water capacity of the lithium bromide unit is shown in (15).

$$Q^{LBC}=[Q^{rec,eg}+(1-\alpha)Q^{rec,cj}]\cdot COP^{LBC} \tag{13}$$

$$Q^{LBH}=[Q^{rec,eg}+(1-\alpha)Q^{rec,cj}]\cdot COP^{LBH} \tag{14}$$

$$Q^{LB,hw}=Q^{rec,eg}\cdot COP^{LB,hw} \tag{15}$$

where COP^{LBC}, COP^{LBH}, $COP^{LB,hw}$ are the refrigeration coefficient, heating coefficient and hot water generation coefficient of lithium bromide unit, respectively.

5) Electric Centrifugal Chiller

An electric centrifugal chiller is adopted to operate for refrigeration. The cooling capacity of the unit is defined as:

$$Q^{CRC}=E^{CR}\cdot COP^{CRC} \tag{16}$$

where COP^{CRC} is the refrigeration coefficient of the electric centrifugal chiller; and E^{CR} is the power consumption for cooling.

6) Electric Heat Pump

An electric heat pump is an energy converter that utilizes electricity in order to satisfy the hot water demands of users. Its hot water capacity $Q^{HP,hw}$ is calculated as:

$$Q^{HP,hw}=E^{HP}\cdot COP^{HP,hw} \tag{17}$$

where $COP^{HP,hw}$ is the coefficient of the performance of the heat pump; and E^{HP} is the power consumption.

7) Preparation Device of Domestic Hot Water

The domestic hot water is prepared by using the cylinder liner water of the IC engine, and the water needs to pass through the plate heat exchanger to obtain the domestic hot water that meets the demand of the users. The domestic hot water can be defined as:

$$Q^{hw,p}=nQ^{rec,cj}\eta^{phe} \tag{18}$$

where η^{phe} is the efficiency of the plate heat exchanger; in the centralized cooling operation mode and the centralized heating operation mode, $n=\alpha$, and in the transition season operation mode, $n=1$.

8) Utility of Energy Hub

1) Cost of energy hub

The cost of the energy hub C^{eh} includes the cost of natural gas consumption C^{g}, the cost of interaction with the grid C^{elec}, and the maintenance cost C^{m}.

$$C^{eh}=C^{g}+C^{elec}+C^{m} \tag{19}$$

$$\begin{cases} C^{g}=p^{g}F^{GE} \\ C^{elec}=p^{s}\max(E^{grid},0)+p^{b}\min(E^{grid},0) \\ C^{m}=\sum p^{m}o^{m} \end{cases} \tag{20}$$

where p^{g} is the natural gas price; p^{s} is the electricity purchasing price of the grid; p^{b} is the electricity selling price of the grid; E^{grid} is the interaction electricity with the grid; p^{m} is the maintenance cost of devices; and o^{m} is the output of devices. In the centralized cooling operation mode, $C^{m}=p^{GE}E^{GE}+p^{ab}Q^{LBC}+p^{el}Q^{CRC}+p^{phe}Q^{phe}+p^{boil}Q^{GB,hw}+p^{hp}Q^{HP,hw}$. In the centralized heating operation mode, $C^{m}=p^{GE}E^{GE}+p^{ab}Q^{LBH}+p^{phe}Q^{phe}+p^{boil}(Q^{GB,hw}+Q^{GBH})+p^{hp}Q^{HP,hw}$. In the transition season operation mode, $C^{m}=p^{GE}E^{GE}+p^{phe}Q^{phe}+p^{ab}Q^{LB,hw}+p^{boil}Q^{GB,hw}+p^{hp}Q^{HP,hw}$. p^{GE}, p^{ab}, p^{el}, p^{phe}, p^{boil}, and p^{hp} are the maintenance costs of the IC engine, the lithium bromide unit, the electric centrifugal chiller, the plate heat exchanger, boiler, and heat pump, respectively.

2) Profit of energy hub

The energy hub earns profits by selling exergy to the user, which is calculated as:

$$P^{eh}=p^{ex}S^{ex} \tag{21}$$

where p^{ex} is the selling price of exergy which is equal to the actual purchasing power of EC. The reason is that the energy hub uses the EC to trade with the user and EC possesses currency value. So the actual purchasing power of EC and the selling price of exergy are equivalent. S^{ex} is the total exergy of all types of energies. In the centralized cooling operation mode, $S^{ex}=Ex^{E}+Ex^{Q^{C}}+Ex^{Q^{hw}}$; in the centralized heating operation mode, $S^{ex}=Ex^{E}+Ex^{Q^{H}}+Ex^{Q^{hw}}$; and in the transition season operation mode, $S^{ex}=Ex^{E}+Ex^{Q^{hw}}$.

The utility function of the energy hub is defined as:

$$U^{eh}=P^{eh}-C^{eh} \tag{22}$$

9) User's Utility

1) User's cost

The user's cost for purchasing exergy can be expressed as:

$$C^{u}=p^{ex}S^{ex} \tag{23}$$

2) User's profit

The user's profit can be expressed as:

$$P^{u}=K\ln(1+S^{ex}) \tag{24}$$

The utility function is $\ln(1+S^{ex})$ instead of $\ln(S^{ex})$, because when $S^{ex}=0$, $\ln(S^{ex})$ approaches infinity.

Thus, the user's utility can be defined as:

$$U^{u}=P^{u}-C^{u} \tag{25}$$

10) Balances and Constraints

1) Balances

In centralized cooling operation mode, the power balance, cold balance, and domestic hot water balance can be expressed as (26), (27), and (28), respectively.

$$E+E^{CR}+E^{HP}=E^{grid}+E^{GE} \tag{26}$$

$$Q^{C}=Q^{CRC}+Q^{LBC} \tag{27}$$

$$Q^{hw}=\alpha Q^{rec,cj}\eta^{phe}+Q^{HP,hw}+Q^{GB,hw} \tag{28}$$

In centralized heating operation mode, the power balance, heat balance, and domestic hot water balance can be expressed as (29), (30), and (31), respectively.

$$E+E^{HP}=E^{grid}+E^{GE} \tag{29}$$

$$Q^{H}=Q^{LBH}+Q^{GBH} \tag{30}$$

$$Q^{hw}=\alpha Q^{rec-cj}\eta^{phe}+Q^{HP-hw}+Q^{GB-hw} \tag{31}$$

In transition season operation mode, the power balance and domestic hot water balance can be expressed as (32) and (33), respectively.

$$E+E^{HP}=E^{grid}+E^{GE} \tag{32}$$

$$Q^{hw}=Q^{rec,cj}\eta^{phe}+Q^{HP,hw}+Q^{GB,hw}+Q^{LB,hw} \tag{33}$$

2) Constraints

The constraints of the exergy can be expressed as:

$$Ex^{E,\min}\leq Ex^{E}\leq Ex^{E,\max} \tag{34}$$

$$Ex^{Q^{C},\min}\leq Ex^{Q^{C}}\leq Ex^{Q^{C},\max} \tag{35}$$

$$Ex_{x}^{Q^{H},\min}\leq Ex_{x}^{Q^{H}}\leq Ex_{x}^{Q^{H},\max} \tag{36}$$

$$Ex_{x}^{Q^{hw},\min}\leq Ex_{x}^{Q^{hw}}\leq Ex_{x}^{Q^{hw},\max} \tag{37}$$

where $[Ex^{E,\min}, Ex^{E,\max}]$, $[Ex^{Q^C,\min}, Ex^{Q^C,\max}]$, $[Ex^{Q^H,\min}, Ex^{Q^H,\max}]$, and $[Ex^{Q^{hw},\min}, Ex^{Q^{hw},\max}]$ are the ranges of electricity exergy, cold exergy, heat exergy, and domestic hot water exergy, respectively.

III. Stackelberg Game and Blockchain

A. Stackelberg Game

In this subsection, the exergy interaction between the energy hub and users is studied by utilizing the Stackelberg game, which is an effective model for exploring the multi-level decision-making process between decision makers and responders [23]. In this paper, the objectives of the energy hub and each user are to maximize the utilities defined in (22) and (25). The energy hub is the leader who sets the exergy price first, and the users are the followers who respond to the exergy price by adjusting their exergy demands such as electricity, cold, heat, and hot water.

The model of the Stackelberg game can be described as:

$$M^S = \{(U \cup O); s^u; U^u; p^{ex}; U^{eh}\} \tag{38}$$

The main components of the Stackelberg game M^S in this paper are as follows.

1) In the Stackelberg game, there are two players. One is the energy hub O, and the other is the user U.

2) s^u is the set of strategies of each user, which varies with the operation modes.

3) U^u is the user's utility.

4) p^{ex} is the strategy of the energy hub, which represents the selling price of exergy.

5) U^{eh} is the utility of the energy hub.

1) Stackelberg Equilibrium (SE)

The players in the Stackelberg game could not increase their own utility by changing their own strategies [24] when it reached the SE. The strategies at SE can be defined as (s^{u*}, p^{ex*}).

For the energy hub and users, the set of strategies reaches an SE if and only if the following two inequalities are guaranteed:

$$U^u(s^{u*}, p^{ex*}) \geq U^u(s^u, p^{ex*}) \tag{39}$$

$$U^{eh}(s^{u*}, p^{ex*}) \geq U^{eh}(s^{u*}, p^{ex}) \tag{40}$$

where $s^{u*} = (Ex^{E*}, Ex^{Q^{C*}}, Ex^{Q^{hw*}})$ in the centralized cooling operation mode, $s^{u*} = (Ex^{E*}, Ex^{Q^{H*}}, Ex^{Q^{hw*}})$ in the centralized heating operation mode, and $s^{u*} = (Ex^{E*}, Ex^{Q^{hw*}})$ in the transition season operation mode.

Then the existence of the SE will be proven in this paper. If the following conditions are met at the same time, then there is an SE [25], [26]: ① U^u is a continuous function about s^u and p^{ex}; ② U^u is a quasi-convex function about s^u; ③ U^{eh} is a continuous function about s^u and p^{ex}.

According to the formulas inferred as (19) and (22), the utilities of the energy hub and users are continuous about the variables. Thus, ① and ③ are correct. Next, the correctness of ② needs to be proven. It is known that if the function is convex, it must be quasi-convex. So if it can be proven that the utility of user U^u is a convex function about Ex^E, ② can be proven. In (22), each part including Ex^E is convex about Ex^E. Thus, U^u is a convex function about Ex^E. Similarly, U^u is also a convex function about Ex^{Q^C}, Ex^{Q^H} and $Ex^{Q^{hw}}$. Therefore, U^u is a quasi-convex function about s^u, i.e., ② has been proved.

Based on the above results, the existence of the SE in this paper has been proven.

2) Algorithms of SE

In order to solve the problem and achieve SE, a two-layer distributed optimization method is applied. It can effectively reduce the calculation scale and protect the privacy of calculation participants. In addition, it can solve the problem that the variables of two objective functions mutually coupled as a model. The upper-layer algorithm is shown in Fig. 5, in which the energy hub aims at optimizing its utility and strategy. The lower-layer algorithm is called when the upper-layer algorithm is calculated, which is shown in Fig. 6. The user is the responder of the exergy price to get its utility and strategy. The result of the lower- layer algorithm will return to the upper-layer. The upper-layer adopts the differential evolution (DE) while the lower layer applies the fmincon, which is a kind of toolkit in MATLAB.

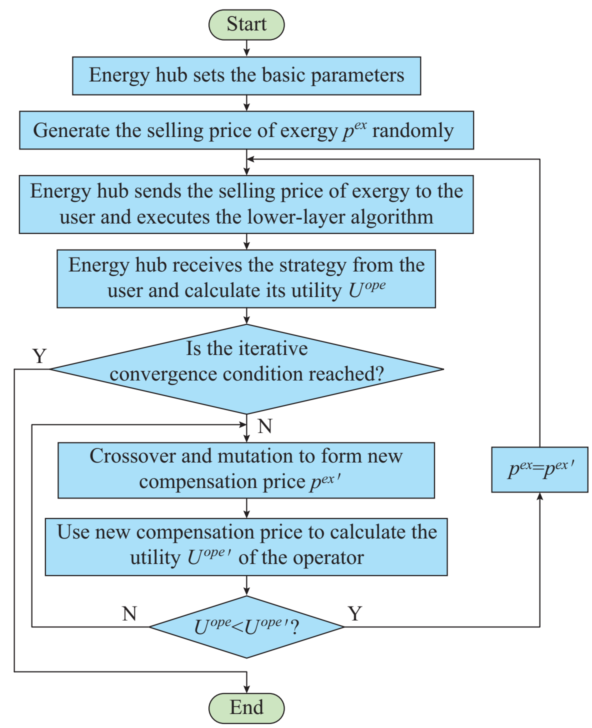

Fig. 5. Upper-layer algorithm.

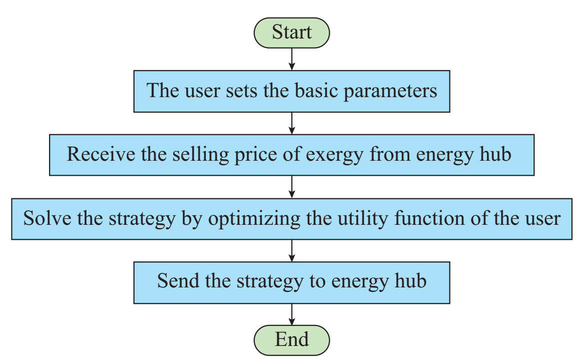

Fig. 6. Lower-layer algorithm.

B. Blockchain

After the game reaches SE, the equilibrium solution will spread through the blockchain to the entire system. Figure 7 shows the steps for implementing exergy trading based on the consortium blockchain in the commercial park.

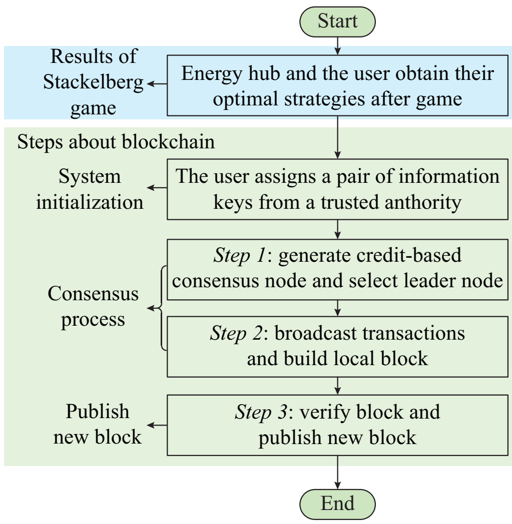

Fig. 7. Steps for implementing exergy trading based on consortium blockchain.

1) Preliminaries

1) Key generation

Each user i selects two secret large prime numbers p and q, and calculates $n=pq$ and $\phi(n)$ [27]:

$$\phi(n)=(p-1)(q-1) \tag{41}$$

where $\phi(n)$ is the Eulers function of n. Next, user i selects an integer e randomly, which satisfies:

$$1<e<\phi(n) \tag{42}$$

$$gcd(e,\phi(n))=1 \tag{43}$$

where $gcd(\cdot)$ is the operation of calculating the greatest common divisor. Then, user i calculates d, which satisfies:

$$de=1\,mod\ \phi(n) \tag{44}$$

The public key and private key of user i are $PK_i=(e,n)$ and $SK_i=(d,n)$, respectively.

In this paper, RSA is employed, an asymmetric encryption algorithm, in order to guarantee the authenticity and integrity of the transmitted information.

2) Signature and verification model

Assume m is the plaintext of the message to be transmitted, $H(m)$ is the hash digest of the message. The sender first uses its private key SK_i to encrypt $H(m)$, i.e.,

$$c=E_{SK_i}(H(m)) \tag{45}$$

Any receiver can decrypt ciphertext c by utilizing the senders public key PK_i, which is known by the whole network, i.e.,

$$H(m)=D_{PK_i}(c) \tag{46}$$

Since the encryption is finished by utilizing the private key SK_i which is the private information of the sender, thus the ciphertext c can be considered as the digital signature of the transmitted message, which can also verifiy message sources and data integrity, and the sender cannot deny the message sent [28].

2) System Initialization

First, each user i has to generate a pair of information keys, i.e., public/private key pair (PK_i, SK_i), and obtain a certificate Cer_i from a trusted authority to guarantee the authenticity of PK_i, which can specifically recognize the user by their registration information, which can be described as:

$$Cer_i=(PK_i, ID_i, T_c) \tag{47}$$

where ID_i is the identity of user i; and T_c is the timestamp of the certificate for guaranteeing its validity, only the registered user is allowed to join in the exergy blockchain. Furthermore, the authority will announce a wallet address $address_i$ to the user, and in order to ensure individual privacy and security, public keys such as random pseudonyms are utilized to replace the true address of the wallet. In this paper, the account of each user includes the information of wallet address $address_i$, account balance $balance_i$, current credit value $credit_i$, and certificate Cer_i. Similarly, the account of the energy hub includes wallet address $address_{EH}$, account balance $balance_{EH}$, and key pair (PK_{EH}, SK_{EH}).

3) Exergy Blockchain Implementation Process

Step 1: generate credit-based consensus node and select leader node.

The credit value of each node can be used to show its credibility and trustworthiness [29]. The credit value $credit_i$ of user i is assumed to satisfy $0<credit_i<1$. The larger the number is, the higher the credibility is. In the system initiation, the credit value of each new node that joins in the exergy blockchain is set as 0.5, and if $credit_i<\mu$, node i is regarded as a malicious node and could never be selected as the consensus node, where μ is the pre-set threshold of credit value. At the beginning of each round of the consensus process, the credit values of all nodes in the network are ranked and the top N nodes are selected as the current round consensus nodes, and $N\geq 3f+1$ is considered, where f is the maximum number of malicious nodes in the exergy blockchain.

Step 2: broadcast transactions and build local block.

After the Stackelberg game between the user and the energy hub, each user formulates a transaction tx_i of the final optimal strategies, which can be described as:

$$tx_i=(Sig_i, exergy_i, p_i, T_s) \tag{48}$$

where Sig_i is its digital signature; $exergy_i$ is the request exergy; p_i is the price of exergy which is set by the energy hub; and T_s is the timestamp of transaction generation. Then, user i broadcasts the transaction information of final optimal strategies to the whole network. Each consensus node n gathers the transaction records within a certain period, then firstly verifies the validity of the transaction by checking the timestamp and the public keys of the users, followed by building the local block concurrently [20], i.e., $localblock_n$. In order to guarantee verifiability and traceability, each newly created block in the exergy blockchain is linked to the prior blocks through a cryptographic hash. After all the nonleader consensus nodes finish building the local block, the leader sends its created block $\mathcal{B}$ with its signature to other consensus nodes for audit.

Step 3: verify block and publish new block.

Through verification and audit about the received block data, by comparing $\mathcal{B}$ with local block $localblock_n$, each nonleader consensus node n generates a feedback message about the results and then broadcasts the feedback message to the whole exergy blockchain. Once the created block is verified and accepted by $\mathcal{M}$ participants in the network, the current consensus process is ended, and the created block will be published and linked at the latest blockchain. Therefore, each nonleader consensus node and leader will be rewarded a credit increase δ_1 and δ_2 for its contribution on consensus. However, if over $\mathcal{N}$ nodes doubt the created block or the feedback message of node n, they will be punished by a credit decrease of $-\delta_1$ and $-\delta_2$, respectively [19]. Here, $\mathcal{M}$, $\mathcal{N}$, δ_1, and δ_2 are the pre-set parameters in the system initiation.

IV. Case Study

A. Basic Data

In this paper, users and an energy hub in a commercial park, Fujian Province, China, are taken as the study objects. The load data of electricity, cold, heat, and domestic hot water is collected from the commercial park. The basic parameters for calculation in this case are shown in Table I.

TABLE I
Basic Parameters in the Case

Subject	Parameter	Value
IC engine	L	9.9 $\text{kWh}\cdot\text{m}^{-3}$
	R	0.40
	a	0.60
	b	0.40
	η^{loss}	0.24
Recoverable unit of waste heat	α	0.4
	COP^{LBC}	1.4
	COP^{LBH}	0.9
	$COP^{LB,hw}$	0.8
Peak shaving device of cold load	COP^{CRC}	3.5
Heat pump	$COP^{HP,hw}$	2.0
Boiler	η^{GB}	0.8
Preparation device of domestic hot water	η^{phe}	0.8

B. Convergence Results

According to the intelligent algorithm proposed in this model, when the number of iterations is calculated to some extent, the results will converge. The iterative process of the algorithm is recorded and the convergence is judged.

Figure 8 shows the iterative process of the calculation accuracy of the utilities of the energy hub. Results show that the utilities are all stable at a fixed calculation accuracy value in different operation modes. In three different operation modes, the calculation accuracy of the utilities of the energy hub begins to converge when the number of iterations reaches the range of 20 to 40.

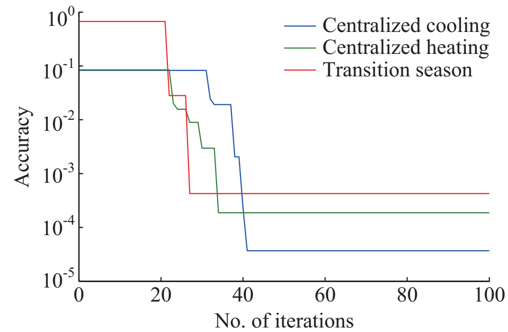

Fig. 8. Iterative process of calculation accuracy of operator utilities.

Figure 9 shows the the iterative process of the calculation accuracy of the utility of the users. They also begin to converge when the number of iterations reaches the range of 20 to 40 in three different operation modes like the energy hub. In the transition season operation mode, the utility starts to converge first, which uses about 100 s, followed by the centralized heating operation mode with about 130 s, and the centralized cooling operation mode with about 200 s.

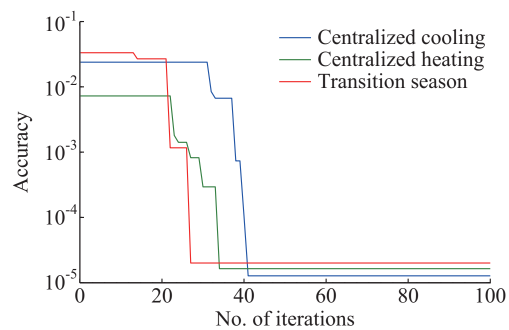

Fig. 9. Iterative process of calculation accuracy of user utility.

C. Selling Prices of Exergy and Purchasing Power of EC

The selling price of exergy is equal to the purchasing power of EC in this model. The reason is that the energy hub uses EC to trade with the user and EC possesses currency value. Thus, the actual purchasing power of EC and the selling price of exergy are equivalent. In the Stackelberg game model, the strategy of the energy hub is the selling price of exergy. In the centralized cooling operation mode, exergy includes electricity, cold, and domestic hot water; in the centralized heating operation mode, exergy includes electricity, heat, and domestic hot water; and in the transition season operation mode, exergy only includes electricity and domestic hot water.

Figure 10 shows the selling prices of exergy for the user in three different modes. The selling prices vary with the operation modes. In centralized cooling operation mode, the price peak appears at 13:00-14:00, while the price peak in centralized heating operation mode appears at 21:00-22:00, which is consistent with practical situations where users have more demands for cold in the afternoon in summer, while they have more demands for hot water and heat at night in winter, so the energy hub sets high exergy prices to shift the loads from peak time to valley time.

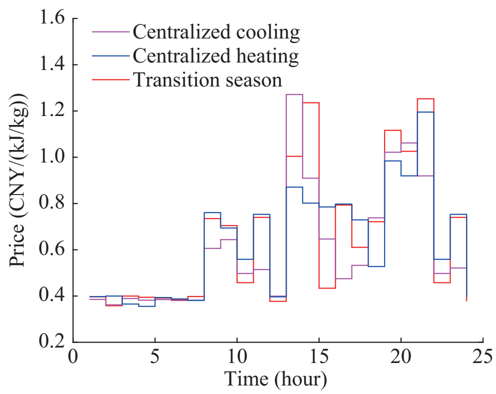

Fig. 10. Selling prices of exergy and purchasing power of EC for user.

D. Exergy Demands

Figure 11 shows the exergy demand of electricity. In all three operation modes, the user has a demand for electricity. In order to maximize user utilities, the exergy demand of electricity has changed from the original demand in different operation modes. In the original curve, the maximum value appears at 14:00. But in the centralized cooling, transition season curve, and centralized heating curve, it shifts to 12:00, 17:00, and 18:00, respectively.

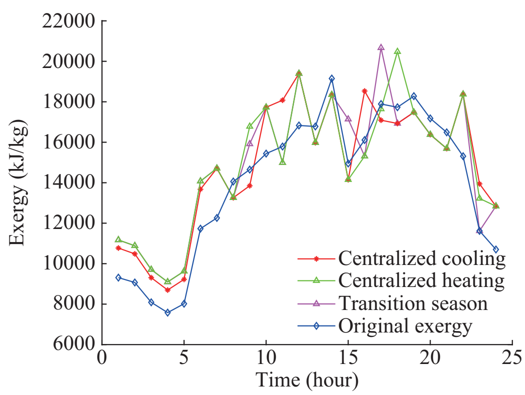

Fig. 11. Exergy demand of electricity.

Figure 12 shows the exergy demand of cold and Fig. 13 shows the exergy demand of heat, with the former situation only in the centralized cooling mode while the later only exists in the centralized heating mode. Both figures show that the exergy demands shift from high price time to low price time in order to maximize the utilities of users.

Figure 14 is the exergy demand of domestic hot water. It also exists in three modes like electricity. The trends are almost the same in the centralized cooling modes, the transition season, and they are similar to the original demand, and the load peak appears at night, but the load peak in the centralized heating mode is higher than the other three modes. The results are consistent with the living habits of users in that they have more hot water at night, especially in winter.

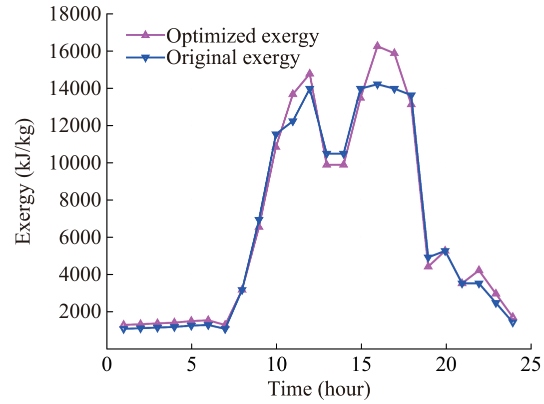

Fig. 12. Exergy demand of cold.

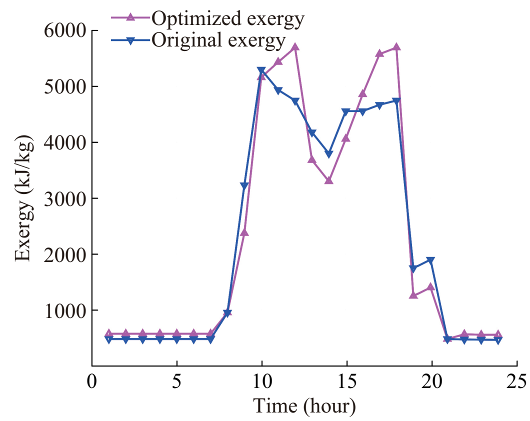

Fig. 13. Exergy demand of heat.

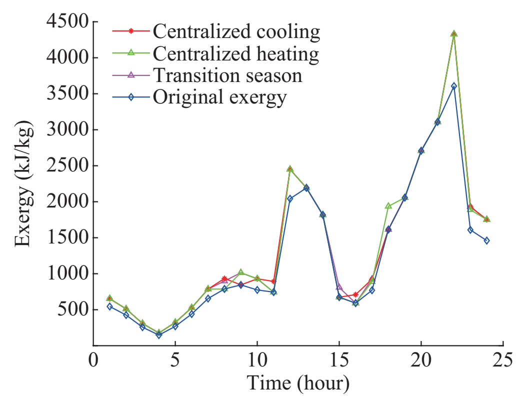

Fig. 14. Exergy demand of domestic hot water.

E. Privacy and Security Analysis of Blockchain

In this subsection, the privacy and security of the proposed blockchain based exergy trading are analyzed.

First, in system initialization, each user and energy hub has to obtain a certificate from a trusted authority, and only registered participants can join in the exergy trading, which can prevent lots of malicious users. Besides, to ensure individual privacy and security, each user can regenerate information keys periodically to avert the linking attack [17], and the true addresses of the wallet are replaced by random pseudonyms. Furthermore, each block in the exergy blockchain contains a cryptographic hash to the prior blocks in order to guarantee verifiability and traceability. Therefore, it is costly for a malicious attacker to revise the data in blockchain, and an asymmetric encryption algorithm is employed in order to guarantee the authenticity and integrity of transmitted information, which makes it difficult to tamper with and falsify data.

V. Conclusion

This paper introduces an energy management model based on the Stackelberg game framework in a commercial park with blockchain. And EC in the transaction process between the energy hub and the user as currency medium is proposed. Three operation modes are established according to the seasons, and in three different modes, the model of exergy conversion, the utility of the user, and the utility of the energy hub are established. Then the Stackelberg game is utilized to model the interaction between the energy hub and the users, and to solve the model via a two-layer optimization algorithm. The equilibrium solution spreads through the blockchain to the entire network. A credit-based blockchain framework and concurrent block building consensus process is explored to reduce the calculation cost and time delay, and to promote the exergy trading efficiency. Case study results show that the proposed algorithm finally achieves convergence. The energy hub and the users adjust the strategies separately in order to maximize their own utilities. The selling price of exergy for the user can be obtained which can reflect the scheduling strategies of users in different operation modes. Therefore, the results have shown the accuracy and efficiency of the proposed method.

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