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• **Supplementary File** •

Rating-protocol optimization for blockchain-enabled hybrid energy trading in smart grids

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Appendix A The structure diagram of the proposed system

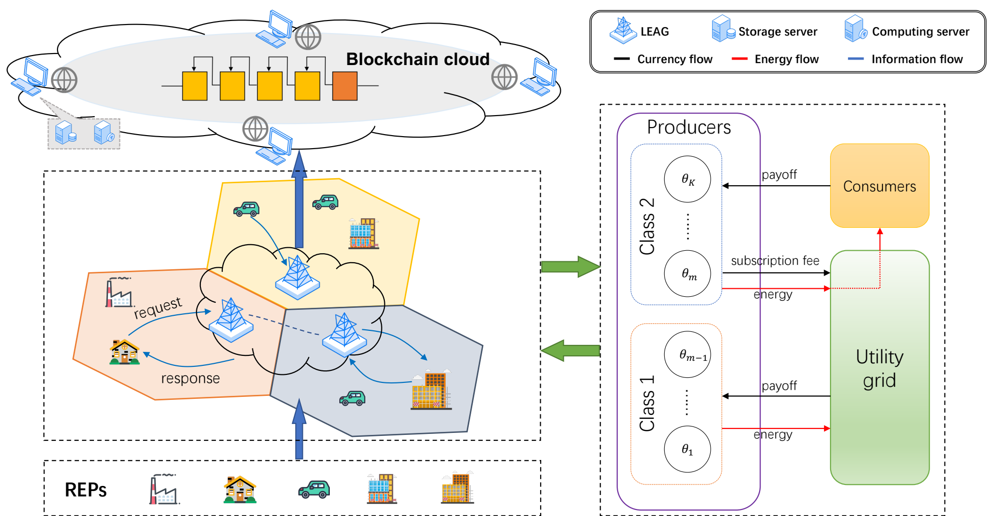

Figure A1 Consortium BC-based hybrid energy trading system.

Figure A1 shows how blockchain can be used in hybrid-energy-trading applications [1–3]. It can be seen from the left side of Figure A1 that consortium blockchain [4] is the operating basis of the proposed system. For one thing, it provides secure data storage for transaction information. For another, it optimizes energy distribution [5] through smart contracts. This paper adopts the PoS+PoW consensus among miners. Considering the energy consumption and efficiency of the consensus mechanism, we first use PoS to screen out miners with high stakes to reduce the scale of miners participating in the competition. Subsequently, considering the security of the consensus, we further use PoW to select the final accounting node. Although the REPs are the subjects of trading, they only act as lightweight nodes [6] in the blockchain. The LEAGs who do not participate in the transaction serves as full nodes (miners) to maintain the blockchain network. They complete the processes of collecting transaction information [7], verifying user identities [8], participating in the consensus process, validating block, and uploading it to the blockchain. The right side of Figure A1 indicates that the rating-protocol optimization method deployed on smart contract regulates the users' trading behavior by adjusting the pricing and subscription fees of producers to maximize social welfare.

After initializing the blockchain network with LEAGs as miners, REPs join the network as transaction users. Then the rating protocol deployed on the smart contract is automatically executed, where a series of optimal strategies for the producers are formulated. During each block generation period, the producers publish their information of energy surplus and selling price to the network. Subsequently, the consumers/utility grid initiate the corresponding transaction request according to the strategy of producers, and the amount of energy is then allowed for use. The transaction process is automatically completed by the smart contract, where the purchased energy flows from the producers to the consumers through the public grid, meanwhile the producers get payoff. Finally, the miners in the network package all of the transactions during this period. After miners verifying the transactions through consensus, the new data blocks are then added to the blockchain automatically as secured records.

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Appendix B Proofs in the body of the letter

Appendix B.1 The Proof of Proposition 1

Proposition 1. The rating protocol P are feasible if, and only if, it satisfies the following conditions:

$$\mathcal{A} = \{1, \ldots, m-1\}\,,\ \mathcal{B} = \{m, \ldots, K\}\,,\ 1 \leqslant m \leqslant K+1, \tag{B1}$$

$$p_{min} = p_0 \leqslant p_i \leqslant p_k \leqslant p_{max}, \forall i, k \in \mathcal{B},\ i < k, \tag{B2}$$

$$\theta_j p_0 \geqslant p_k \varphi_j(p_k) - \delta_k,\ \forall j \in \mathcal{A}, \forall k \in \mathcal{B}, \tag{B3}$$

$$p_k \varphi_k(p_k) - \delta_k \geqslant \theta_k p_0,\ \forall k \in \mathcal{B}, \tag{B4}$$

$$p_k \varphi_i(p_k) - p_i \varphi_i(p_i) \leqslant \delta_k - \delta_i \leqslant p_k \varphi_k(p_k) - p_i \varphi_k(p_i), \forall i, k \in \mathcal{B},\ i < k. \tag{B5}$$

Proof. Eq. (B1) stipulates the value range of m, where $\mathcal{A}$ is the set of class 1 producers, and $\mathcal{B}$ is the set of class 2 producers. When $m = 1$, we conclude that $\mathcal{A} = \emptyset$ and $\mathcal{B} = \mathcal{K}$. Similarly, when $m = K+1$, we conclude that $\mathcal{A} = \mathcal{K}$ and $\mathcal{B} = \emptyset$. Eq. (B2) stipulates the value range of p_0 and p_k, and it shows an increasing trend of p_k about θ_k. Eq. (B3) indicates that a class 1 producer will obtain a reduced utility if it chooses any strategy designed for class 2 producers. Eq. (B4) indicates that once a class 2 producer chooses to join class 1, its utility will decrease as well. Eq. (B5) is equivalent to

$$\begin{cases} p_k \varphi_k(p_k) - \delta_k \geqslant p_i \varphi_k(p_i) - \delta_i \\ p_i \varphi_i(p_i) - \delta_i \geqslant p_k \varphi_i(p_k) - \delta_k \end{cases} \quad \forall i, k \in \mathcal{B},\ i < k, \tag{B6}$$

which shows that if a class 2 producer of rating k adopts a strategy (p_i, δ_i) designed for the other rating (no matter the rating is higher or lower), $i \neq k$, the reward it receives is less than the reward when adopting (p_k, δ_k).

Appendix B.2 The Proof of Theorem 1

Problem 1 (Optimal Rating Protocol)

$$\begin{aligned} &\max_{\substack{m,\\ \{(p_k,\delta_k),\forall k \in \mathcal{B}\}}} \omega\left(\sum_{k\in\mathcal{A}} N_k\theta_k\right) - \sum_{k\in\mathcal{A}} p_0 N_k \theta_k + \sum_{k\in\mathcal{B}} N_k\delta_k \\ &\text{s.t.} \quad (B1),\ (B2),\ (B3),\ (B4),\ (B5) \end{aligned}$$

Proof. As to Problem 1, we can see that the first two items of the SO utility are generated by class 1 producers and the third item is generated by class 2 producers. If we assume that m is constant, then Problem 1 can be divided into two independent sub-problems and the values of the first two items $\omega\left(\sum_{k\in\mathcal{A}} N_k\theta_k\right) - \sum_{k\in\mathcal{A}} p_0 N_k\theta_k$ are not affected by strategy $\{(p_k,\delta_k), \forall k \in \mathcal{B}\}$. In this case, the process of maximizing Problem 1 can be transformed into the process of maximizing $\sum_{k\in\mathcal{B}} N_k\delta_k$.

Appendix B.3 The Proof of Theorem 2

Problem 2 (Optimal Subscription Fees)

$$\begin{aligned} &\max_{\{\delta_k,\forall k\in\mathcal{B}\}} \quad \sum_{k\in\mathcal{B}} N_k\delta_k \\ &\text{s.t.} \quad (B3),\ (B4),\ (B5) \end{aligned}$$

Proof. When Problem 2 obtains the maximum value, δ_k corresponding to each rating is also maximal. According to (B3), (B4), and (B5), we can obtain all the optimal subscription fees starting from the critical rating m:

$$\delta_m^* = p_m\varphi_m(p_m) - \theta_m p_0, \tag{B7}$$

$$\delta_k^* = \delta_{k-1}^* + p_k\varphi_k(p_k) - p_{k-1}\varphi_k(p_{k-1}). \tag{B8}$$

Next, we hope to find a new function of $\sum_{k\in\mathcal{B}} N_k\delta_k$ with respect to p_0 and $\{p_k, \forall k \in \mathcal{B}\}$. We introduce s_k to denote the total number of producers from rating k to K:

$$s_k = \sum_{i=k}^{K} N_i,\ \forall k \in \mathcal{B}. \tag{B9}$$

The maximal profit that SO gathers from class 2 producers, that is, the optimal subscription fees charged, can be rewritten as

$$\sum_{k\in\mathcal{B}} N_k\delta_k = \sum_{k\in\mathcal{B}} f_k(p_k), \tag{B10}$$

where

$$f_k(p_k) = \begin{cases} -s_k\theta_m p_0 + s_k p_k\varphi_k(p_k) - s_{k+1}p_k\varphi_{k+1}(p_k), & k = m \\ s_k p_k\varphi_k(p_k) - s_{k+1}p_k\varphi_{k+1}(p_k), & m < k < K \\ s_k p_k\varphi_k(p_k), & k = K \end{cases}. \tag{B11}$$

The above-mentioned operation is aimed at deriving a series of $f_k(p_k)$ that are mutually independent. Moreover, each of them has a single variable p_k. The objective problem has been further simplified as optimizing the selling price $\{p_k, \forall k \in \mathcal{B}\}$.

Appendix B.4 The Proof of Theorem 3

Problem 3 (Optimal Price Assignment)

$$\max_{\{p_k,\forall k\in\mathcal{B}\}} \omega\left(\sum_{k\in\mathcal{A}} N_k\theta_k\right) - \sum_{k\in\mathcal{A}} p_0 N_k\theta_k + \sum_{k\in\mathcal{B}} f_k(p_k)$$
$$\text{s.t.} \quad (B2)$$

Proof. From the composition of Problem 3, while m is determined, p_0 is a parameter that affects the values of the first two items. Conversely, the value of p_0 affects the participation enthusiasm and satisfaction of class 1 producers in the trading system. If the SO merely considers the benefits obtained from class 1 producers and blindly lowers p_0, class 1 producers may exit the system. Therefore, we previously declared that the SO gives $p_0 = p_{min}$ in (B2), which corresponds with its own interests. Consequently, while solving Problem 3, m and p_0 are fixed and the following problem must be resolved.

$$\begin{aligned} \max_{p_m,\ldots,p_K} \quad & \omega\left(\sum_{k\in\mathcal{A}} N_k\theta_k\right) - \sum_{k\in\mathcal{A}} p_0 N_k\theta_k + \sum_{k\in\mathcal{B}} f_k(p_k) \\ \text{s.t.} \quad & p_0 \leqslant p_m \leqslant \ldots \leqslant p_K \leqslant p_{max} \end{aligned} \tag{B12}$$

Each $f_k(p_k)$ is mutually independent, so we first calculate $p_k^{\dagger}$ to satisfy the maximum of $f_k(p_k)$ without the constraint in (B12):

$$p_k^{\dagger} = \arg\max_{p_0\leqslant p_k\leqslant p_{max}} f_k(p_k). \tag{B13}$$

Once the $\{p_k^{\dagger}, \forall k \in \mathcal{B}\}$ satisfies the constraint in (B12), the optimal pricing strategy is directly derived as $p_k^* = p_k^{\dagger}, \forall k \in \mathcal{B}$. However, in general, $\{p_k^{\dagger}, \forall k \in \mathcal{B}\}$ is likely not to satisfy the constraint. We previously pointed out that $\varphi_k(p_k) = \alpha_k \ln(p_{max} + 1 - p_k) + \beta_k$ is the expected amount of sellable energy, where $\varphi_k'(p_k) < 0$, and $\varphi_k''(p_k) < 0$. If $\alpha_k > \alpha_{k+1} > 0, \forall k \in \mathcal{B}$, when $k = K$,

$$\frac{df_k(p_k)}{dp_k} = s_k[\varphi_k(p_k) + p_k{\varphi_k}'(p_k)], \tag{B14}$$

$$\frac{d^2 f_k(p_k)}{d{p_k}^2} = s_k\left[{\varphi_k}'(p_k) + {\varphi_k}'(p_k) + p_k{\varphi_k}''(p_k)\right] < 0. \tag{B15}$$

When $k < K$,

$$\frac{df_k(p_k)}{dp_k} = s_k\left[\varphi_k(p_k) + p_k{\varphi_k}'(p_k)\right] - s_{k+1}\left[\varphi_{k+1}(p_k) + p_k{\varphi_{k+1}}'(p_k)\right], \tag{B16}$$

$$\begin{aligned} \frac{d^2 f_k(p_k)}{d{p_k}^2} &= s_k\left[{\varphi_k}'(p_k) + {\varphi_k}'(p_k) + p_k{\varphi_k}''(p_k)\right] - s_{k+1}\left[{\varphi_{k+1}}'(p_k) + {\varphi_{k+1}}'(p_k) + p_k{\varphi_{k+1}}''(p_k)\right] & \text{(B17)} \\ &= 2\left[s_k{\varphi_k}'(p_k) - s_{k+1}{\varphi_{k+1}}'(p_k)\right] + p_k\left[s_k{\varphi_k}''(p_k) - s_{k+1}{\varphi_{k+1}}''(p_k)\right] & \text{(B18)} \\ &= \frac{2}{p_{max}+1-p_k}\left(-\alpha_k s_k + \alpha_{k+1}s_{k+1}\right) + \frac{p_k}{(p_{max}+1-p_k)^2}\left(-\alpha_k s_k + \alpha_{k+1}s_{k+1}\right) < 0. & \text{(B19)} \end{aligned}$$

As a result, function $f_k(p_k)$ is proved to be strictly concave. The Lagrange multiplier λ_k associated with the linear constraint in (B12) is introduced as follows:

$$L(\boldsymbol{p},\boldsymbol{\lambda}) = -\sum_{k\in\mathcal{B}} f_k(p_k) + \lambda_0(p_0 - p_m) + \sum_{k=m}^{K-1} \lambda_k(p_k - p_{k+1}) + \lambda_K(p_K - p_{max}). \tag{B20}$$

The dual problem is

$$\begin{cases} \frac{\partial L(\boldsymbol{p},\boldsymbol{\lambda})}{\partial \boldsymbol{p}} &= 0 \\ \frac{\partial L(\boldsymbol{p},\boldsymbol{\lambda})}{\partial \boldsymbol{\lambda}} &\leqslant 0 \\ \lambda_k &\geqslant 0,\ k = 0, m, \ldots, K \\ \lambda_0(p_0 - p_m) &= 0 \\ \lambda_k(p_k - p_{k+1}) &= 0,\ k = m, \ldots, K-1 \\ \lambda_K(p_K - p_{max}) &= 0 \end{cases}.$$

After solving the dual problem, we can finally obtain $\{p_k^*, \forall k \in \mathcal{B}\}$. Concurrently, we get the the optimal subscription fees $\{\delta_k^*, \forall k \in \mathcal{B}\}$ represented by price.

Since m is known in advance, after the subsequent solution process, we obtain the optimal price assignment $\{p_k^*, \forall k \in \mathcal{B}\}$ that is relevant to a certain m. We stipulate that $m \in \{1, \ldots, K+1\}$ in this study, namely, m is discretely finite. Then, by traversing all possible values, we can find the optimal m when the SO benefits the most, and the optimal strategy is derived.

Appendix C The workflow of the proposed system

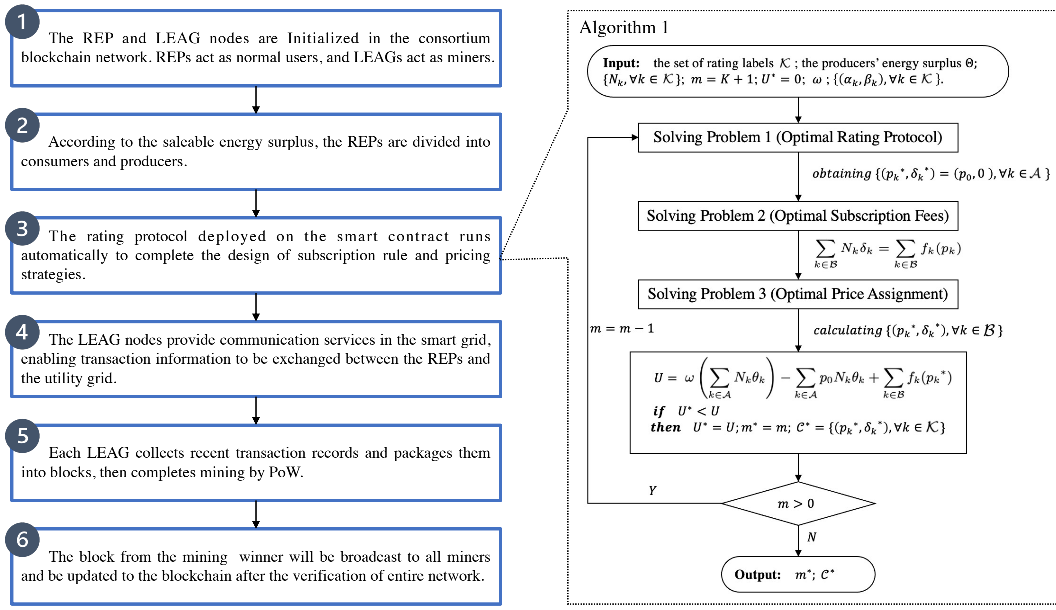

Figure C1 Workflow of BC-enabled hybrid energy trading.

Because the value range of m is $[1, K+1]$, in Algorithm 1, m is initially $K+1$. Each round of the algorithm solves problems 1 to 3, then records the current optimal rating protocol and maximal social welfare corresponding to m. If the maximal social welfare is updated, the current m is the optimal rating division. In the next round, $m = m-1$, and the above process is repeated until $m = 0$. Finally, output the global optimal m^* and $\mathcal{C}^*$.

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