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

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Dear editor,

Smart grids, with renewable energy technologies, provide an innovative approach for mitigating the energy crisis caused by the shortage of fossil fuel resources. However, the existing smart grids are confronted with several challenges [1,2]. Specially, the decentralization of resources and the inflexible trading patterns call for a secure infrastructure and an efficient energy management mechanism, respectively. Recently, blockchain (BC) is emerging as a new computing paradigm to provide decentralized and security-guaranteed network services [3,4], which has great potential to serve smart grids [5]. The blockchain-enabled smart grids have been investigated in many fields. For example, authors in [6] proposed a secure and efficient vehicle-to-grid (V2G) energy trading framework by exploring blockchain, contract theory, and edge computing. However, the solution to the energy hybrid trading scenario is rare, where the system can perform both prosumer-to-prosumer (P2P) and prosumer-to-grid (P2G) energy trading simultaneously. Compared with the existing studies [6–8], the main contributions of this study are as follows: (1) A novel hybrid energy trading model is proposed, in which the consortium BC ensures secure and effective energy trading of P2P and P2G simultaneously. (2) A novel rating protocol is designed to incentivize renewable energy generation, which can optimize the producers' utility and social welfare with high timeliness from both the satisfaction of users and the market.

System model. The system operator (SO) is responsible for the authorization and authentication of all renewable energy prosumers (REPs) in the system. Local energy aggregators (LEAGs) equipping the storage and computing servers, provide a series of services for REPs and maintain the BC. They act as miners of the BC network and as edge nodes of SO. The objective of SO is to simultaneously optimize the utilities of producers and social welfare. Thus, the SO designs a subscription-based rating protocol for producers, but the consumers can only purchase energy.

Definition 1. A rating protocol P is represented as a quadruple $(\mathcal{K}, \Theta, \psi, \sigma)$.

- $\mathcal{K} = \{1, 2, \ldots, K\}$ denotes the set of rating labels, where K represents the size of this set.
- $\Theta = \{\theta_1, \theta_2, \ldots, \theta_K\}$ denotes the producers' energy surplus aggregated at a certain rating.
- $\psi : \mathcal{K} \to \mathcal{S}$ denotes the subscription rule that SO uses to classify a producer:

$$\psi(k|k \in \mathcal{K}) = \begin{cases} A, & k < m, \\ B, & k \geqslant m. \end{cases} \tag{1}$$

The set of subscription statuses is $\mathcal{S} = \{A, B\}$, where A represents class 1 which prefers to conduct P2G trading, and B represents class 2 which prefers to conduct P2P trading. m is the critical rating for dividing two statuses.

- $\sigma : \mathcal{K} \times \mathcal{S} \to \mathcal{C}$ denotes the pricing scheme based on the producer's rating and subscription status. $\mathcal{C} = \{(p_k, \delta_k), \forall k \in \mathcal{K}\}$, where p_k denotes the price per unit of electric power and δ_k denotes the subscription fee.

Remark 1. The proposed rating protocol is constructed on the basis of contract theory [9], where the pricing strategy $\mathcal{C}$ reflects the part of contract theory. Besides, the proposed rating protocol focuses on hybrid trading, in which the subscription rule ψ can more clearly show the differences between the two trading patterns (P2P and P2G). While Ref. [9] mainly focused on a single trading pattern. The system structure diagram is shown in Appendix A.

Problem formulation. The class 1 producer directly injects all its saleable energy θ_k into the grid at a consistent unit price p_0, and it receives a payoff from the grid without any subscription fee. Its utility can be represented as

$$u_k\,(p_0, 0) = \theta_k p_0 - g_c(\theta_k), \tag{2}$$

where $g_c(\theta_k)$ is the cost function of energy generation θ_k.

The class 2 producer conducts P2P trading with consumers at unit price p_k and receives the reward from them

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by selling energy. Concurrently, it must pay a subscription fee to the SO. Its utility can be represented as

$$u_k(p_k,\delta_k)=p_k\varphi_k(p_k)-\delta_k-g_c(\theta_k), \tag{3}$$

where $\varphi_k(p_k)$ is the expected amount of sellable energy. We assume that $\varphi_k(p_k)=\alpha_k\ln(p_{\max}+1-p_k)+\beta_k$, where α_k and β_k are constant parameters. Let $\varphi_k'(0)=\theta_k$, $\varphi_k'(p_k)<0$, $\varphi_k''(p_k)<0$.

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

$$\mathcal{A}=\{1,\ldots,m-1\},\ \mathcal{B}=\{m,\ldots,K\},\ 1\leqslant m\leqslant K+1, \tag{4}$$

$$p_{\min}=p_0\leqslant p_i\leqslant p_k\leqslant p_{\max},\ \forall i,k\in\mathcal{B},i<k, \tag{5}$$

$$\theta_jp_0\geqslant p_k\varphi_j(p_k)-\delta_k,\ \forall j\in\mathcal{A},\forall k\in\mathcal{B}, \tag{6}$$

$$p_k\varphi_k(p_k)-\delta_k\geqslant\theta_kp_0,\ \forall k\in\mathcal{B}, \tag{7}$$

$$p_k\varphi_i(p_k)-p_i\varphi_i(p_i)\leqslant\delta_k-\delta_i\leqslant p_k\varphi_k(p_k)-p_i\varphi_k(p_i),\quad \forall i,k\in\mathcal{B},\ i<k. \tag{8}$$

This proposition guarantees that in a feasible rating protocol, producers of a specific rating will maximize their utility only when they adopt strategies that match their rating. See Appendix B.1 for the proof.

Optimal rating protocol. The optimal rating protocol is to maximize the SO utility which consists of three parts: (1) the utility of the electricity obtained from all class 1, (2) the payment to all class 1, and (3) the subscription fee obtained from all class 2. The SO utility represents the social welfare of the entire grid. We use N_k to represent the number of the k-th-rating producers. Thus, we propose the objective optimization problem below.

Problem 1 (Optimal rating protocol)

$$\max_{\substack{m,\\\{(p_k,\delta_k),\forall k\in\mathcal{B}\}}}\ \omega\left(\sum_{k\in\mathcal{A}}N_k\theta_k\right)-\sum_{k\in\mathcal{A}}p_0N_k\theta_k+\sum_{k\in\mathcal{B}}N_k\delta_k$$
$$\text{s.t.}\quad (4)\text{–}(8),$$

where $\omega(\cdot)$ is the utility function of generating energies.

Theorem 1. Given a critical rating m, P is optimal if and only if the subscription fees are optimal, namely, maximizing $\sum_{k\in\mathcal{B}}N_k\delta_k$. See Appendix B.2 for the proof.

We give priority to solving the sub-problem about maximizing subscription fees which are structured as follows.

Problem 2 (Optimal subscription fees)

$$\max_{\{\delta_k,\forall k\in\mathcal{B}\}}\ \sum_{k\in\mathcal{B}}N_k\delta_k\qquad \text{s.t.}\quad (6)\text{–}(8).$$

Theorem 2. Given a critical rating m, the subscription fee $\{\delta_k,\forall k\in\mathcal{B}\}$ is optimal if and only if the selling price $\{p_k,\forall k\in\mathcal{B}\}$ is optimal. See Appendix B.3 for the proof.

Then the optimal subscription fees are equivalently replaced in the form of price variables, $\sum_{k\in\mathcal{B}}N_k\delta_k=\sum_{k\in\mathcal{B}}f_k(p_k)$. We deal with the optimal price assignment in Problem 3.

Problem 3 (Optimal price assignment)

$$\max_{\{p_k,\forall k\in\mathcal{B}\}}\ \omega\left(\sum_{k\in\mathcal{A}}N_k\theta_k\right)-\sum_{k\in\mathcal{A}}p_0N_k\theta_k+\sum_{k\in\mathcal{B}}f_k(p_k)$$
$$\text{s.t.}\quad (5).$$

Theorem 3. Given a critical rating m, Problem 3 can obtain the global optimal solution if the function $\varphi_k(\cdot)$ holds $\alpha_k>\alpha_{k+1}>0,\forall k\in\mathcal{B}$. See Appendix B.4 for the proof.

Algorithm 1 (Steps to solve the optimal rating protocol)**.** By traversing all possible m from a finite set $\{1,\ldots,K+1\}$, we transform and solve the problems from Problems 1–3 in turn to obtain the optimal rating protocol and maximum social welfare corresponding to a specific m, and update the optimal result according to the traversal of m. See Appendix C for the workflow of the algorithm.

Remark 2. Given a set of REPs, the initialized $\mathcal{K}$ and Θ, we can obtain the optimal rating protocol P by following the steps of Algorithm 1 in a hybrid energy trading scenario.

Conclusion. In this study, we have proposed a rating-protocol optimization method for hybrid energy trading in a smart grid using BC technology. Specifically, a hybrid trading model ensures that prosumers can conduct P2P and P2G transactions satisfactorily, as well as ensures secure and efficient information aggregation and interaction. Furthermore, a rating protocol has been developed to motivate various REPs equipped with diverse energy surpluses to participate in energy trading, which can optimize the producers' utility and social welfare.

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Supporting information Appendixes A–C. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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