Contract-based Incentive Mechanism Design for Renewable Energy Trading Markets

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Abstract

With the projected benefits, including a decrease not only in greenhouse gas emissions but also energy costs, renewable energy sources (RES) are increasingly deployed day by day. As a result, research on renewable energy has attracted extensive attention. However, most of the studies on RES focuses on RES's harvested energy supply. With the popularity of RESs, harvested energy from RESs is a highly competitive product. It thus needs to have effective incentive mechanisms for renewable energy trading markets in such a way that economic benefits related to renewable energy trading are guaranteed. In this study, we proposed an incentive mechanism design for renewable energy trading markets based on contract theory framework. The simulation results illustrate that our proposed approach can not only maximize the profit of the local energy aggregator (LEA) but also outperforms compared to take-or-leave-it contract approach in term of LEA's total profit.

Key word: Energy trading, renewable energy sources (RES), contract theory.

1. Introduction

With the projected benefits including a decrease not only greenhouse gas emissions but also energy costs, renewable energy sources (RES) are increasingly deployed day by day [1], [2]. Using RESs is a key technology for global energy transformation.

Most of researches on RES focus on their harvested energy supply. In [3] they consider a scenario wherein RESs is integrated with Smart Grid. Then, they then designed the demand response algorithm for that residential smart grid considering energy amount from RES. Beyond researched related to integrating RES Into the smart grid, other study direction is coordination of electric vehicle charging with renewable energy [4, 5]

In the hope of that in the future electricity generation of smart grid is 100% from RESs [6]. At that time, harvested energy from RESs is a highly competitive product. We thus need to design the incentive mechanism in such a way that economic benefits are guarantee. Related to economic benefits, pricing mechanism has played an important role in providing incentive for both sides, supply and demand, [7]. Naturally, suppliers are selfish, they do not want to share their private information. Therefore, demanders cannot observe that unshared information. Contract theory is powerful tool providing an effective solution to way to solve this kind of information asymmetry trading problem [8].

Inspired by above reasons, in this paper we propose an incentive mechanism design for renewable energy trading markets based on contract theory, where the LEAs is buyer and RESs are sellers. The contract theory guarantee that the buyer has ability to reveal private information of RESs by offering the reasonable contract items to the RESs. As a result, The LEA not only achieves maximal benefit but also motivate RESs to selling their harvested energy.

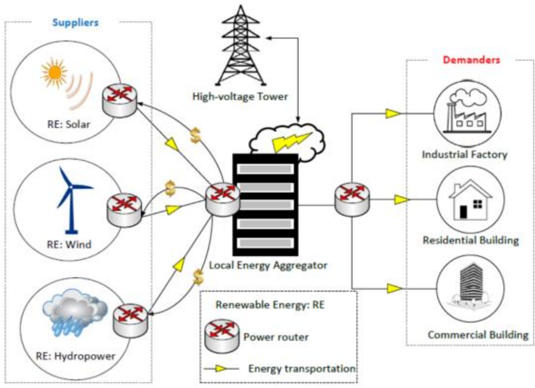

Figure 1: System model illustration

The remainder of this paper is organized as follows. We describe our proposed system model in Section 2. The problem formulation is presented in section 3. Simulation results are shown in section 4. We summarize the paper works in section 5.

2. System model

In this study, we consider a model system illustrated in Fig.1 composed of two types of entity: one local energy aggregator (LEA) capable of harvesting energy charging set of n renewable energy resource entities (REs) $R = \{r_1, r_2, \ldots, r_n\}$ distributedly deployed around LEA. The LEA is responsible as a broker for trading energy harvested by REs to demanders. After receiving energy request from demanders, the LEA call a trade to purchase harvested energy from RESs.

3. Contract-based Incentive Mechanism Design for Renewable Energy Trading Markets

In this section we propose a contract-based price mechanism to motive RESs to share their harvested energy.

3.1. LEA modeling

In this work, the LEA wants to buy a certain energy amount from the RESs in the renewable energy trading market. LEA is selfish and rational, it thus wants to maximize its profit by optimally deciding how much energy it should purchase from each of the RES and how much money it should pay back to these traded RESs.

We denote the energy amount purchased from RES i ω_i. As a reward, the LEA gives a payment p_i back to the RES i accordingly. Noticeably, if the total energy offered by all RESs is equal or greater than total energy requested by all demanders, then LEA starts the procedure of electing RVs who it should trade with. Whereas, the total energy offered by all RESs is smaller than total energy requested by all demanders, the shortage of energy is supplemented by the grid. The energy price of grid is denoted as p_g.

With a contract (ω_i, p_i), the LEA's utility is computed as the difference between the grid payment (if LEA buy amount a from grid) and the RES payment of i given as follows,

$$U_{LEA} = p_g * \omega_i - p_i (1)$$

3.2. RES modeling

Each RES i send an energy trade agreement to LEA if they want to sell its harvested energy by remotely submitting their transaction (ω_i, p_i). Since the RES i sells ω_i units of its harvested energy, it receives benefit from the payment p_i.

Then the total utility of RES i can be defined as,

$$U_i = p_i - \pi_i \omega_i \ (2)$$

where π_i is the cost that RES i spend to produce one renewable energy unit.

The set of RESs is naturally heterogeneous, then we categorize them into H types according to their production cost, $\mathcal{H} = \{1,2, \dots, H\}$. The RES i is recognized as h –type if its production is c_h, $h \in \mathcal{H}$. We suppose that higher production cost leads to higher type expressed as $\pi_1 < \pi_2 \dots < \pi_H$.

In this study, our objective is to maximize LEA utility. We thus need to design incentive mechanism in such a way that the LEA can adopts reasonable price strategies toward different types of RES.

3.3. Contract Game Formulation

In this study, the LEA wants to buy harvested energy from the RESs in the renewable energy trading market. To maximize the utility, the LEA needs to determine different reasonable contracts to different types of RES. Recall that the types of RES are observed based on their production costs. However, this information is naturally only known by RES itself. There is no guarantee that these RESs honestly inform their correct production costs. Contract theory is known as a famous powerful framework that can solve the trading problem under information asymmetry [8]. By designing an incentive mechanism based on contract theory, the LEA can efficiently offer different contract items to different types of RES.

To design a feasible contract set for all RESs, the LEA need to ensure that two contract-constraints are satisfied.

i) The individual rational constraint (IR): If a RES falls into h –type, then the utility of this h –type RES is always non-negative expressed as follows,

$$U_h(\omega_h, \rho_h) \geq 0, \ \forall h \in \mathrm{H} \ (3)$$

ii) The incentive compatible constraint (IC): a h –type RES has the maximal utility if only if it chooses the right contract designed for its own h – type expressed as follows,

$$U_h(\omega_h, \rho_h) \geq U_h(\omega_{h'}, \rho_{h'}), \ \forall h, h' \in \mathrm{H}, \ h \neq h' \ (4)$$

This constraint explains the reason why price mechanism designed based on contract theory guarantee that sellers will truthfully expose its production cost.

Beyond the IR and IC constraints, the buying energy amount of each contract item must not exceed the maximum supplying capacity of that type, defined as follows.

$$0 < \omega_h \leq \omega_h^{max} (5)$$

In addition, the total energy purchased from all types of RESs must not to exceed the required demand of LEA, D_{LEA}, defined as follows.

$$\sum_{h=1}^{H} \varphi_h \omega_h \leq D_{LEA} (6)$$

where φ_h is the total number RES of h –type.

Then, the LEA designs the incentive mechanism design for renewable energy trading markets by solving its own contract optimization problem defined as follows.

$$\max_{\{(\omega_h, \rho_h), h \in H\}} \sum_{h=1}^{H} \varphi_h (\rho_g \omega_h - \rho_h) \qquad (7)$$

$$\text{s.t.} \qquad (3), (4), (5), \text{and } (6)$$

In this study, we solve the problem (7) by using the GUROBI optimizer [9].

4. Simulation Results

In this section, we conduct simulations to evaluate the performance of our contract-based incentive mechanism design for renewable energy trading markets. We consider a system with 1 LEA and 35 RESs. The sellable harvested energy capacity of RESs is uniformly [50 KW, 100 KW] [10]. We randomly choose the demand of LEA within the range of [1,4] MWh. The electricity grid price is assigned to 1$/KWh. The production cost of RES is presented in table 1 [11].

Firstly, we do simulation to demonstrate the correctness of two keys contract constraint, IR and IC, as shown in Fig. 2. The Figure 2 shows the average utility of

EVs under different contract types. We can obverse that each RES only can get its maximal utility at the contract item designed for its own type.

	(USD/KWH)
Bioenergy	0.062
Geothermal	0.072
Hydro	0.047
Solar photovoltaics	0.085
Concentrating solar power	0.185
Offshore wind	0.127
Onshore wind	0.056

Table 1: Renewable Power Production Cost

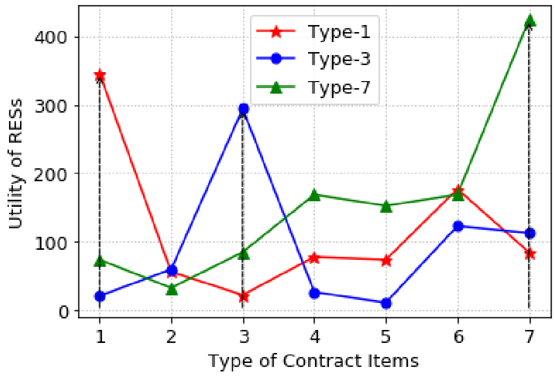

Figure 2: Utility of EVs under different contract strategies.

Next, we compare our proposed mechanism with the take-it-or-leave contract proposed in [10]. In this method, the LEA determines the price threshold p_{th}, then RESs have production cost higher or equal to p_{th} will accept the contract, otherwise they will refuse the contract. The Fig. 3 shows the total profit of the LEA under different algorithms. We can see that our proposed method always outperforms the take-or-leave-it contract-based mechanism. The LEA not only motivate more RESs to sell their harvested energy but also minimizes its own payment.

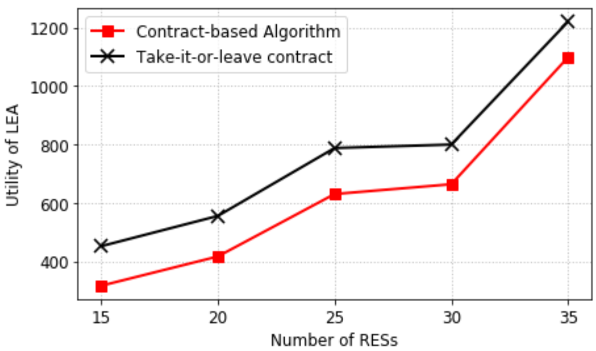

Figure 3: Performance under different algorithms.

5. Conclusion

In this study, we proposed an incentive mechanism design for renewable energy trading markets based on contract theory framework. We do simulation to illustrate that our proposed approach can maximize profit of the LEA by motivating more RESs to trade their harvested energy. In addition, our proposed algorithm outperforms the take-it-or-leave contract algorithm in term of total profit.

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