The Impact of Renewable Portfolio Standard Policy on Microgrid System

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Abstract. China's renewable energy policy is gradually transiting from subsidies to Renewable Portfolio Standard (RPS) policy. This paper establishes a two-stage game model consisting of prosumers and the grid in microgrid system under RPS policy. It is found that the social welfare shows an inverted "u" with increasing penalty and prosumers demand. The prosumers can be profitable only when the production cost factor is lower than the boundary value. Government can implement the RPS policy first in areas with lower production costs. Lower price for green certificates and mid-level penalty effectively incentive green energy production and consumption in microgrids. Government needs to control the price of green certificates to implement RPS successfully.

Keywords: RPS policy; microgrid system; green energy; social welfare.

1. Introduction

In recent years, with environmental problems becoming more and more serious, the reduction of carbon emissions has become an inevitable way for China to achieve carbon neutral[1]. Over the past decade, the energy sector accounted for 32.1% of global CO2 emissions growth and 49.1% of China's CO2 emissions growth[2]. According to the McKinsey Global Carbon Neutral Model, the global energy sector needs to reduce carbon emissions by more than 99% by 2050 to meet a temperature control target of 1.5 degrees Celsius, which means the energy sector needs to achieve near "net-zero emissions". Green electricity generation is the key to reducing emissions.

Microgrid is a small-scale electricity generation and distribution system consisting of distributed electricity sources, energy storage devices, energy conversion devices, loads, monitoring and protection devices, etc. As an efficient complement to the grid, microgrid systems can fully exploit renewable energy sources and solve the problem of grid connection and renewable energy absorption[3]. In many countries, placing green energy in microgrids has become a priority for sustainable energy development. It can reduce annual greenhouse gas emissions, improve energy efficiency, increase electricity system reliability, and reduce operation and maintenance costs. At present, community microgrids in China mainly use solar photovoltaic (PV) electricity generation, which has good prospect due to China's vast territory and abundant solar resources. Microgrid is now a popular research topic and there are many research results.

The Renewable Portfolio Standard (RPS) policy represents the minimum renewable energy electricity consumption ratio target for the whole society in each provincial administrative region as set by the state. Tradable Green Certificate(TGC) is a policy tool to promote the consumption of renewable energy through market-based instruments based on RPS. RPS and TGC have become important policy to promote the consumption of renewable energy.

Liu et al. proposed a leader-follower game model to formulate energy sharing for grid-connected microgrid including PV customers[4]. Zhu et al. explored the optimal government incentives and strategic choices of residents in the Chinese distributed PV market, obtaining conclusions such as the gradual elimination of the need for government subsidies for small capacity PV investments[5]. Fu et al. proposed an optimal operation strategy for microgrids based on demand response and reward-penalty ladder-type carbon trading mechanism. Fu et al. developed a collaborative multi-slave game optimization model with microgrid operator as leader and prosumers as follower.
[6]. Erol et al. developed a Stackelberg game model consisting of grid operators, prosumers and charging stations and found through simulation that considering the flexibility of prosumers can reduce the dependence of microgrids on the utility grid[7]. Zhuo et al. focused on the relationship between merchants and residential customers and found that government PV subsidies would significantly increase the revenue of system developers. However, it does not increase the installed capacity of the system or provide additional benefits to residential customers [8]. Chen et al. developed a microgrid system consisting of two phases, pricing and distribution, to maximize the utility of community microgrid customers through optimal pricing [9]. However, the above papers have studied the subsidy policy and have demonstrated its shortcomings. Based on the newly enacted RPS policy, Song et al. constructs a system dynamics model of a multi-market coupled trading system, including the renewable electricity market, the over-quota consumption market, and the tradable green certificate (TGC) market and finds that the RPS promotes renewable energy generation in China[10]. Yu et al. found that renewable energy portfolio standard policy has obvious advantages over feed-in tariff policy, but its incentives still need to be promoted[11].

Previous papers have mainly focused on the analysis subsidy policies or TGC. This paper establishes a stackelberg game model consisting of prosumers and the grid in a microgrid system with a penalty on the consumption side. It is to explore the influence of RPC policy of the profits of included members as well as the social welfare.

2. Model Formulation

2.1 Problem Description

It is assumed that the total amount of green electricity connected within the microgrid community is less than the grid green electricity consumption quota allocated by the government. According to the renewable energy electricity quota accounting method determined by the National Energy Administration of China, the renewable energy consumption ratio for an entity is defined as the amount of renewable energy consumption divided by the amount of electricity consumption of this entity. The entities regulated by a PRS policy are allocated a uniform quota of the renewable energy consumption ratio, which is denoted by \( \alpha \) (0 < \( \alpha \) ≤ 1). In other word, the renewable energy consumption ratio of an entity should be greater than the allocated quota. Or else, the entity will incur a financial penalty which is a certain percentage of the difference between actual and required renewable energy consumption.

The grid decides the feed-in-tariff (\( P_1 \)) and residential electricity price (\( P_2 \)). The profit of the grid is made up of revenue from the sale of electricity, the purchase of electricity from prosumers and other channels as well as the cost of penalty for insufficient green electricity consumption. We set the grid to buy green electricity from other channels is not enough to meet the consumption quota.

The prosumers in the microgrid system decides the electricity output of solar PV (\( E_1 \)). The profit of the prosumers includes the cost of purchasing electricity and penalty, as well as the revenue from selling electricity to the grid.
Table 1. Summary of notations.

<table>
<thead>
<tr>
<th>Notations</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>E₁</td>
<td>electricity output of solar PV</td>
</tr>
<tr>
<td>E₂</td>
<td>electricity demand of the prosumers</td>
</tr>
<tr>
<td>P₁</td>
<td>feed-in tariff</td>
</tr>
<tr>
<td>P₂</td>
<td>residential electricity price</td>
</tr>
<tr>
<td>P₃</td>
<td>the price at which the grid purchases electricity from other places</td>
</tr>
<tr>
<td>P₄</td>
<td>the price at which the grid sells electricity to other communities</td>
</tr>
<tr>
<td>Pₜ</td>
<td>unit price of green certificate</td>
</tr>
<tr>
<td>α</td>
<td>the ratio of green electricity consumption set by the government, 0&lt;α≤1</td>
</tr>
<tr>
<td>μ</td>
<td>cost factor of green electricity produced by prosumers</td>
</tr>
<tr>
<td>qᵣₑ</td>
<td>the amount of green electricity purchased from other channels</td>
</tr>
<tr>
<td>qᵣₜʰ</td>
<td>the amount of purchased electricity generated from conventional energy sources</td>
</tr>
<tr>
<td>M</td>
<td>environmental benefit per unit of green electricity</td>
</tr>
<tr>
<td>f</td>
<td>unit penalty paid by the consumer for not completing the green electricity consumption set by the government</td>
</tr>
<tr>
<td>π₉, πₚ, πₛ</td>
<td>revenue functions of government, prosumers and grid</td>
</tr>
</tbody>
</table>

2.2 Profit formulations

In the first stage, the grid decides the feed-in tariff P₁ and electricity price P₂ to maximize its own profit. Subsequently the prosumer decides the production quantity of green electricity (i.e. E₁). Based on different values of decision variable E₁, our analysis is based three possible cases under PRS policy:

Case 1. E₁ ≤ aE₂

In this case, the prosumer has shortages in both renewable energy consumption and energy production. As a result, the prosumer has to purchase electricity shortage from the grid and be penalized. The grid hence provides the electricity shortage to prosumer and also occurs a penalty, since the green electricity purchased from other channels can’t exceed the required renewable energy consumption. Consequently, the profits of the prosumers, the grid and the social welfare are given as follows.

\[
\piₚ^{c₁} = -f(aE₂ - E₁) - (E₂ - E₁)P₂ - uE₁^2 \tag{1}
\]

\[
\piₛ^{c₁} = (E₂ - E₁)P₂ - (qᵣₑ + qᵣₜʰ)P₃ - f(aE₂ - qᵣₑ) \tag{2}
\]

\[
\pi₉^{c₁} = \piₚ^{c₁} + \piₛ^{c₁} + f(aE₂ - E₁) + f(aE₂ - qᵣₑ) + E₁M \tag{3}
\]

Case 2. aE₂ ≤ E₁ < E₂

In this case, the prosumer produces green electricity that does not meet its own demand and needs to purchase electricity from the grid. But the prosumers achieves the percentage of green electricity consumption quota and does not need to pay the penalty. The profits of the prosumers, the grid and the government are given as follows.

\[
\piₚ^{c₂} = -(E₂ - E₁)P₂ - uE₁^2 \tag{4}
\]

\[
\piₛ^{c₂} = (E₂ - E₁)P₂ - (qᵣₑ + qᵣₜʰ)P₃ - f(aE₂ - qᵣₑ) \tag{5}
\]

\[
\pi₉^{c₂} = \piₚ^{c₂} + \piₛ^{c₂} + f(aE₂ - qᵣₑ) + E₁M \tag{6}
\]

Case 3. E₂ ≤ E₁ < (1 + a)E₂
In this case, the prosumers produce green electricity to meet its own needs, and the excess electricity goes to the grid. At this time, the prosumers as the consuming end completes the proportion of green electricity consumption quota, does not need to pay the penalty, and can trade the green certificate due to sell green electricity to the grid. But for the grid, because of realistic conditions, the grid does not meet the consumption quota so needs to pay a penalty. The profits of prosumers, grid and government are given as follows.

\[ \pi_p^c = (E_1 - E_2)(P_1 + P_c) - uE_1^2 \]  
\[ \pi_s^c = (E_1 - E_2)(P_4 - P_1 - P_c) - f((1 + \alpha)E_2 - E_1) \]  
\[ \pi_g^c = \pi_p^c + \pi_s^c + f((1 + \alpha)E_2 - E_1) + E_1M \]

By backward induction, the closed-form equilibrium outcomes of three cases are summarized in Table 2.

<table>
<thead>
<tr>
<th>Case</th>
<th>( E_1 \leq \alpha E_2 )</th>
<th>( \alpha E_2 &lt; E_1 &lt; E_2 )</th>
<th>( E_2 \leq E_1 &lt; (1 + \alpha)E_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_1^c )</td>
<td>( \frac{2uE_2 + f}{4u} )</td>
<td>( \frac{E_2}{4u} )</td>
<td>( \frac{2uE_2 + f + P_4}{4u} )</td>
</tr>
<tr>
<td>( P_2^c )</td>
<td>( \frac{uE_2 - f}{2} )</td>
<td>( uE_2 )</td>
<td>( \frac{f}{2} - \frac{P_4}{2} + \mu E_2 )</td>
</tr>
<tr>
<td>( \pi_g^c )</td>
<td>( \frac{M(f + 2\mu E_2)^2 - (f + 2\mu E_2)^2}{4\mu} - \frac{E_2^2}{16\mu} + \frac{ME_2}{4\mu} - \frac{P_3(q_{re} + q_{th})}{4\mu} )</td>
<td>( \frac{-E_2^2}{16\mu} + \frac{ME_2}{4\mu} - \frac{P_3(q_{re} + q_{th})}{4\mu} )</td>
<td>( 2M\mu - 4\mu^3\left(\frac{f}{2} + \frac{P_4}{2} + \mu E_2\right)^2 - \frac{P_4(E_2 - 2\mu)}{2} - 2\mu\left(\frac{f}{2} + \frac{P_4}{2} + \mu E_2\right) )</td>
</tr>
<tr>
<td>( \pi_p^c )</td>
<td>( \frac{f^2 + 12\mu E_2 - 16\mu f E_2 - 12}{16\mu} )</td>
<td>( \frac{-E_2^2(16\mu^2 - 4\mu + 1)}{16\mu} )</td>
<td>( \left[-E_2 - 2\mu\left(\frac{f}{2} + \frac{P_4}{2} + \mu E_2\right)\right] \left(\frac{f}{2} + \frac{P_4}{2} + \mu E_2\right)^2 - 2\mu \left(\frac{f}{2} + \frac{P_4}{2} + \mu E_2\right) )</td>
</tr>
</tbody>
</table>

3. Analysis Results

This section focuses the monotonic analysis of the parameters, the range of parameters for the three capacity scenarios under the RPS policy and the impact of environmental benefits on social welfare under each scenario.

Proposition 1.

a) \( \frac{\partial^2 \pi_g^c}{\partial f^2} < 0 \), \( \frac{\partial^2 \pi_s^c}{\partial E_2^2} < 0 \), \( \frac{\partial^2 \pi_p^c}{\partial E_2^2} < 0 \), \( \frac{\partial^2 \pi_p^c}{\partial f^2} < 0 \), \( \frac{\partial^2 \pi_s^c}{\partial E_2^2} < 0 \), and

b) \( \frac{\partial^2 \pi_p^c}{\partial P_4^2} = -2\mu^3 + 2\mu \).

With a RPS policy, social welfare is a strictly concave function on penalties and consumer demand. Therefore, there exists an optimal penalty and an optimal prosumer demand that maximizes social welfare. When \( E_2 \leq E_1 < (1 + \alpha)E_2 \), if the production cost factor is greater than 1, the social welfare is a strictly concave function about the selling price to other communities(\( P_4 \)). This implies that there is an optimal price \( P_4 \). The findings provide recommendations for the government to set penalties and guide residential electricity demand wisely.

In a microgrid system, there are three scenarios of green electricity production, i.e., the prosumer's production is less than the consumption amount, the prosumer's production meets the consumption amount but is not enough to meet its own demand, and the prosumer meets its own demand and has excess electricity to sell to the grid.

Proposition 2: \( E_1 \leq \alpha E_2 \), when \( \alpha \geq \frac{1}{2}, f < (4\alpha - 2)\mu E_2 \).
Proposition 2 demonstrates that if the consumption quota of the related microgrid system is higher than 50% and the unit penalty fee is relatively low, the prosumers prefer to reduce both amount of the renewable electricity consumption and electricity production. That is to say, the higher quota together with a less penalty fee failed in incenting the prosumers to consume more green electricity and produce more electricity.

Proposition 3: \( \alpha E_2 \leq E_1 < E_2 \), when \( \alpha < \frac{1}{4\mu} < 1 \).

Proposition 3 demonstrates that if the consumption quota of the related microgrid system is lower than \( \frac{1}{4\mu} \), then the prosumers prefer to reach green electricity consumption and reduce the renewable electricity production. That is to say, the lower quota gives some incentive to prosumers to consume green electricity, but fail in incentive prosumers to produce more electricity to meet their own demand.

Proposition 4: \( E_2 \leq E_1 < (1 + \alpha)E_2 \), when \( P_c < \frac{f^{+} + P_4 + 2\mu E_2}{2}, 2\mu E_2 - P_4 < f < 2\mu E_2(1 + 2\alpha) - P_4 \).

Proposition 4 demonstrates that if the unit price of green certificate of the related microgrid system is relatively low as well as the unit penalty fee is in mid-level, the prosumers prefer to increase both quantities in the renewable electricity consumption and electricity production. It means that the lower unit price of green certificate together with appropriate penalty successfully motivated the prosumers to consume more green electricity and produce more electricity. The lower price unit of green certificate demonstrates that if the green certificate overpriced, the government needs to control green certificate price in order to induce residential electricity production to the grid.

3.1 Revenue of prosumers in three scenarios

In this section, we aim to explore the lowest value of the unit penalty, prosumers demands, and production cost factor parameters \( f, E_2 \) and \( \mu \) that make the revenue of prosumers positive. It is easy to know that the prosumers profit of case 1 & 2 is constant less than 0, so we only explore the boundary value of case 3.

Based on the equilibria of three cases revenue of prosumers given in Table 2, the thresholds of parameter \( f, \mu, \) and \( E_2 \) under three cases are summarized in Table 3.

| Table 3. Boundary value of \( f, E_2, \) and \( \mu \) when revenue of prosumers is positive |
|----------|---------|-------------|---------|
| \( E_2 \leq E_1 < (1 + \alpha)E_2 \) | \( \mu \leq \frac{\sqrt{2}}{2} \) | \( E_2 \geq \frac{P_4(2\mu - 4\mu^3)}{8\mu^4 - 4\mu^2 + 2} \) | \( f \geq \frac{(8\mu^4 - 4\mu^2 + 2)E_2 - P_4(2\mu - 4\mu^3)}{2\mu - 4\mu^3} \) |

In case 3, when prosumers profit is positive, it is related to production cost factor, penalty, and the prosumers demand. That is to say, only when production cost factor is low, penalty is at high level, as well as prosumers demand is high, is it possible for prosumers to make a profit. Therefore, government can consider the profitability of the prosumers and implement a policy with higher penalty in microgrid systems with lower production cost factor and higher electricity demand in order to promote the RPS policy.

4. Conclusion

This paper establishes a stackelberg game consisting of prosumers and the grid under the PRS policy. The the optimal decisions of both parties under three scenarios are analyzed. The following conclusions are obtained.

Under the RPS, it is found that a high penalty does not lead to an increase in social welfare. The government should set a moderate penalty.
If $E_1 \leq \alpha E_2$, higher quota together with a less penalty fee fails to incentize the prosumers to consume and produce more electricity. But in case 2 if the consumption quota of the microgrid system is lower than $\frac{1}{4\mu}$, the prosumer prefers to reach green electricity consumption and reduce the renewable electricity production. Case 3 shows that the lower unit price of green certificates together with mid-level penalty successfully motivate the prosumers to consume more green electricity and produce more electricity. For the government, controlling the price of green certificates and setting appropriate penalty can be an effective incentive for microgrid system to consume and produce more green electricity.

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