

Article

The Impact of Government Subsidy on Renewable Microgrid Investment Considering Double Externalities

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Abstract: Since microgrids require public support to make economic sense, governments regularly subsidize renewable microgrids to increase their renewable energy market penetration. In this study, we investigated the optimal subsidy level for governments to correct the market failure of microgrids and analyzed the impacts of regulation on the interaction between a microgrid and a distribution network operator (DNO). Specifically, we proposed economic rationales for government subsidies for microgrids regarding public interest benefits in relation to double externalities (learning spillover effect and environmental externality). We incorporated the double externalities into a three-echelon game model in an electricity supply chain with one regulator, one microgrid, and one DNO, in which the regulator decides the subsidy level to achieve maximal social welfare. We found that the double externalities and double marginalization caused underinvestment in microgrid capacity in the scenario without government intervention. The government could choose the appropriate subsidy level to achieve the system optimum, which led to a triple win for the microgrid, the DNO, and the social planner. Our analytical results also showed that the microgrid gained more benefits from regulation than the DNO. The microgrid may offer a negative wholesale price to the DNO in exchange for more opportunities to import electricity into the grid, especially when the investment cost is sufficiently low. Our study suggests that supporting microgrids requires a subsidy phase-out mechanism and alternative market-oriented policies with the development of the microgrid industry.

Keywords: microgrid; distribution network operator; double externalities; subsidy

1. Introduction

Alongside issues such as increasingly serious environmental pollution, energy supply security, greenhouse gas emissions, and climate change, there is a global consensus that all nations should strive together to reduce carbon emissions. Many countries seek approaches to gradually adjust their energy supply structure. As one of the contracting states of the Paris Climate Agreement, China promised to contribute to limiting the temperature increase of 1.5 °C through low-carbon development in the energy field. Renewable energy plays a key role in the process of energy structure transition, for which China faces the dual challenges of energy demand growth and carbon emission reduction. Microgrids are a prospective and accessible technology that can use distributed renewable energy resources to generate electricity and are also important components of smart grids. Some key benefits of microgrids can be summarized as follows:

Microgrids make the most use of local distributed renewable energy and reduce transmission losses by satisfying local consumers.

The smart energy management system and storage devices enable microgrids to manage intermittent renewable energy and realize real-time power balancing within the system.

Microgrids can provide cooling, heating, and electricity at the same time (e.g., the combined cooling, heating, and power, CCHP, system), which satisfies multidimensional service requirements [1].

Since microgrids can operate either grid-connected or islanded, they are more flexible, controllable, and reliable than distributed generation systems [2]. This helps to reduce the effects of major power disruption events and buffer the impact of intermittent renewable energy generation on power grids, which increases the opportunities for microgrids to access the power network.

Microgrids can provide differentiated services for sensitive users who may require higher power quality and a more resilient energy system (e.g., hospitals and data centers) [3].

The market practice of combining battery swap stations for electric vehicles and microgrids provides a possible channel to efficiently shift the peak electricity load [4].

China realized that its energy structure heavily relied on thermal power for its rapid economic growth, which limited high-quality development and green innovation in Chinese industry. China is devoted to supporting the efficient utilization of renewable energy and making efforts to deepen power system reform. The installed generation capacity share of thermal power, including coal and gas, decreased from 73.44% in 2010 to 60% in 2018 (Figure 1). Meanwhile, the installed generation capacity of renewable energy has maintained rapid development. The cost of renewable energy generation has declined gradually with technical progress, which has somewhat enhanced the competitive power of renewable energy.

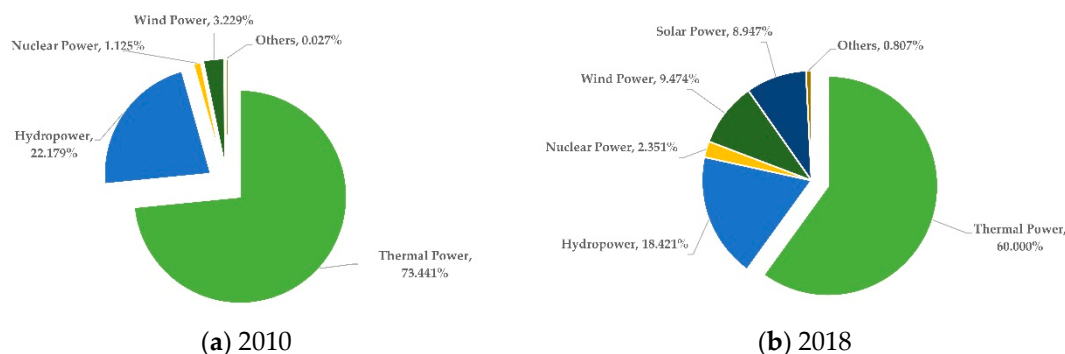


Figure 1. Gross installed generation capacity in China in 2010 and 2018 (source: China Electricity Council).

In July 2015, the China National Energy Administration elaborated on the significance of developing renewable microgrids and put forward the first batch of microgrid demonstration projects. Subsequently, another 24 grid-connected and 4 isolated microgrids were afforded renewable microgrid demonstration projects in May 2017. China learned international microgrid experience from both government-sponsored pilot projects and commercial projects [5], and a supporting document, “Proposed regulation for promoting the construction of grid-connected microgrids”, was also announced by the National Energy Administration in July 2017.

Though microgrids have attracted much attention as an innovative technology, and the government spares no effort in advancing the microgrids industry, this industry is still in the early stages of development, and most of the projects are built for demonstration and research purposes. The low growing rate and the lack of investment are mainly due to the high initial investment cost and unfavorable economic benefits. The total proposed, under development, and operational power capacity of global microgrids reached 24,981 MW in 2018 [6]. There is no doubt that microgrid investment and operation costs will decrease as the microgrid industry matures and thus realizes large-scale commercial applications. Some incentive schemes, such as renewable energy investment subsidies, tax reductions, and feed-in tariffs, have been widely recognized [7]. However, the Chinese government does not publish detailed subsidy schemes for renewable microgrids. It is notable

that renewable microgrids can receive renewable energy subsidies, which have been established for distributed generators using renewable sources. Since there are differences of technology systems, market features, and stages of development between microgrids and large-scale distributed generation, the current incentive mechanism for distributed generators may not be appropriate for microgrids [8].

Therefore, in this study, we first attempted to answer the following question:

What are the economic rationales of government subsidies for renewable microgrids?

Although some researchers have determined that the deployment of renewable microgrids can boost employment, ensure energy security, adjust the energy supply structure, share investment risks, and so forth, these are insufficient reasons to implement government subsidies from the perspective of the free market economy. In this paper, we argue that the economic rationales for government subsidies for renewable microgrids derive from market failures along with double externalities. One rationale for such subsidies is the learning spillover effect. Key microgrid technologies, such as distributed energy storage, controls and supervisory systems, and protection and automation, still require an immense amount of research. The R&D of an individual company is beneficial for the whole microgrid industry through the spillover effect and significantly contributes to microgrid cost reduction. Therefore, it is necessary to offer subsidies for microgrids due to the weak protection of intellectual property rights since China is still in a transition stage. Another rationale is the environmental externality of renewable energy. While microgrids can reduce carbon emissions by substituting for electricity generated by fossil fuels, the societal benefits cannot be included in the profit function of an individual microgrid. Consequently, the market price fails to signal the real cost of a microgrid when competing with conventional power. Simply put, we maintain that the economic rationales of renewable microgrid subsidies derive from their public interest benefits, in terms of both technology and the environment, and government intervention helps to internalize the double externalities.

Based on the above-stated reasoning, we built a three-echelon Stackelberg model consisting of a social planner, a renewable microgrid, and a distribution network operator (DNO) to address the following questions:

How should the government determine the optimal subsidy level in order to maximize social welfare? What are the effects of government subsidies on the interaction between a microgrid, a DNO, and social welfare?

Our model incorporated the double externalities to investigate the optimal subsidy level and the loss of social welfare without government intervention. The results showed that government subsidies lead to a lower wholesale price, which may be negative, and the DNO also benefits from the microgrid incentive scheme. Incremental social welfare is mainly determined by the spillover effect rate, environmental externality level, and potential demand.

The first contribution of this paper is analyzing the economic rationales of government subsidies for renewable microgrids and exploring the optimal subsidy scheme from the perspective of social welfare by incorporating the learning spillover effect and the environmental externality. Further, we introduce an electricity supply chain model with a microgrid and DNO and analyze how the government can achieve system coordination by offering an appropriate subsidy. Comparisons of some of the decision variables between the decentralized scenario and the government intervention scenario are also offered to illustrate the impact of subsidies on the interaction between the key stakeholders.

The rest of this paper is organized as follows: Section 2 reviews the literature related to microgrid subsidies. Section 3 outlines the model formulation and basic results under the centralized and decentralized scenarios. In Section 4, we introduce government subsidies to demonstrate their effects on the interaction between a microgrid and a DNO. Section 5 provides some numerical examples. Section 6 summarizes the article with some policy implications.

2. Literature Review

Our paper is related to the stream of literature on regulating technology spillover in R&D. Currently, most studies have found that a single firm cannot internalize the social benefits of R&D due

to the spillover effect and, therefore, a social planner should attempt to correct market failure by regular intervention, such as with subsidies. Howell [9] focused on the American Small Business Innovation Research (SBIR) grant program in the energy industry and demonstrated that early-stage grants help new ventures acquire more venture capital and patents because firms in emerging sectors face high technological uncertainty and financing constraints. Researchers have also analyzed the possible ways in which government subsidies positively affect a firm's innovation performance. First, from a resource-based perspective, government subsidies replenish the shortage of innovation resources, reduce output uncertainty, and share the risks for small firms [10–12]. Second, government subsidies are useful signals for small firms to attract private investors from the viewpoint of signal theory [13,14]. There is serious information asymmetry between firms and outside investors due to the uncertainty of innovation activities. The government plays a dominant role in a transition economy. Government subsidies can generate positive signals so that a firm's strategy can match government industry planning and the firm may maintain a good relationship with the government, which is beneficial for the firm to gain more innovative resources from outside and form alliances [15]. These papers addressed the impact of government subsidies on innovative enterprises and showed how government subsidies affect firms' innovation input and output, mainly from the industry level, and thus are quite different from our work.

This paper is also related to the stream of literature on technology and products with environmental externalities, particularly from the perspective of a social planner. For example, Drake et al. [16] considered a firm with both clean and dirty technologies and investigated its asset allocation reaction to different technologies under various governmental regulations, such as emissions tax, emissions cap-and-trade, and investment subsidies. Yu et al. [17] formulated a mathematical model to explore the effects of environmental awareness and green subsidies on manufacturers' production decisions regarding green products. The model was solved by a Euler algorithm, and a case involving automobiles with different green levels was proposed to validate the accuracy of the algorithm. Rayamajhee et al. [18] compared the impacts of exogenous and endogenous externality mitigation funds on hydroelectricity generation considering the negative environmental externality of crop damage. The results showed that an endogenous externality mitigation fund is better when weighing the income of energy production and externality damages. These papers focused on production and technology with external market effects which generate benefits or costs to society. The study scope included energy resources for heating in broiler production [19], electric vehicles [20,21], conventional and renewable energy investment [22], and so on. These papers, therefore, did not consider the electricity supply chain and learning spillover effect, which is our focus here.

This paper also builds on the operations management literature for microgrids. Along with the development of the microgrid industry, there has been a substantial amount of research on microgrid technical issues, such as microgrid control strategies [23], microgrid energy management [24], microgrid system resilience [25], and microgrid planning and design [26], in recent years. However, few studies have considered microgrid operations management, especially from the government's standpoint. Haghi et al. [27] analyzed the effects of a feed-in tariff (FIT) and capital grants on hydrogen production in a microgrid and found that it is more cost-efficient for a government to incentivize hydrogen production with grid electricity than with wind power, while hub operators prefer incentives for wind power. Chen et al. [28] investigated the impact of certified emission reductions on the deployment of solar photovoltaic community microgrids and verified that certified emission reductions can turn some unprofitable areas of deploying microgrids into profitable areas. Lo Prete et al. [29] used cooperative game theory to explore the optimal regulated electricity price for formulating microgrid cooperation among market players in a small electricity network. The intervention tool in their paper regulated the electricity retail price to achieve certain return requirements, which is different from our paper. Chen et al. [30] demonstrated the significant effect of price and cost subsidies on a microgrid energy storage system using a real options approach, which did not consider the electricity supply structure. Our paper is closely related to the works of Long and co-workers [8,31], who built

a multistage incentive model for a microgrid project considering the microgrid industry chain and studied the impacts of government subsidies on various participants. However, since their work did not consider the economic rationales of government intervention, the regulator's decision relatively lacked a theoretical basis. Unlike their model, we have incorporated the technology spillover effect and environmental externality into a three-player model, and the optimal subsidy level was obtained to correct market failure.

Finally, to the best of our knowledge, this paper is the first to analyze the cause and correction of microgrid market failure in the context of the electricity supply chain. The contribution of this paper is that we have analyzed microgrid incentives to coordinate a microgrid and a DNO, which benefits not only the participants in the electricity supply chain but also the environment and society. Our study reveals the economic rationales of government subsidies for microgrids and thus jointly considers two types of externalities in the electricity supply chain of a microgrid, which helps to avoid new distortions due to government intervention. In addition, our paper completes the existing literature on microgrid subsidies by demonstrating that the government must account for the interaction between a microgrid and a DNO when determining the optimal subsidy level.

3. Model and Preliminary Results

3.1. Question Description and Model Assumption

The problem is defined in Figure 2. The electricity generated by a microgrid firstly satisfies its own user, and the remaining electricity is sold to the DNO at the wholesale price ω , which is a general operation mode of renewable microgrids. The DNO determines the transmission price l and sells electricity to end consumers. Thus, the final electricity price p can be represented as $p = \omega + l$. This kind of microgrid project is known as “self-generation, self-consumption, and the remainder is exported to the grid”, which is the most encouraged pattern of renewable microgrids.

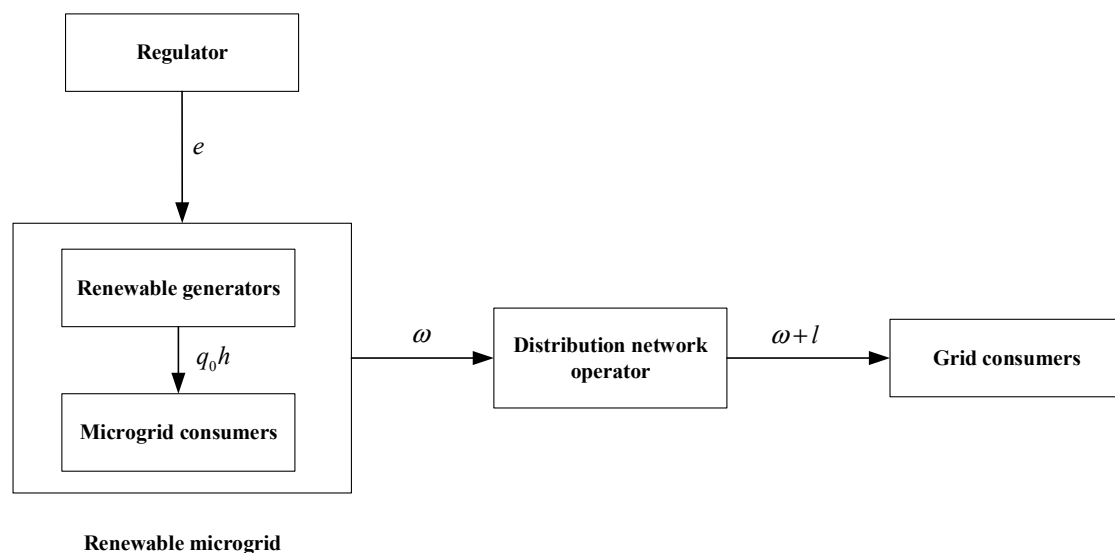


Figure 2. Model setting.

We considered the situation faced by a social planner who attempts to design an incentive policy to correct market failures of renewable microgrids with the spillover effect and environmental externality. The social planner offers the generation subsidy $S(q)$, which depends on the generated quantity q :

$$S(q) = e(q_0 + q_1) \quad (1)$$

where e denotes the marginal subsidy rate, and q_0 and q_1 are the electricity demands of the microgrid user and the end consumers, respectively. We also assumed that q_0 is an exogenous constant, and h

is the microgrid benefits from per unit of electricity, which is also consistent with reality, since the investment level and microgrid user demand are usually determined before deployment.

We assumed that the market demand which the DNO faces is as follows:

$$D = a - bp \quad (2)$$

where D is the electricity demand quantity, $a(a > 0)$ is the market size, and $b(b > 0)$ is the sensitivity coefficient of the electricity price. It is worth noting that the demand means the total electricity demanded by end consumers in the whole period of the project rather than the instantaneous energy consumption.

For simplicity, we assumed that the microgrid incurs zero generation costs. This is a common assumption because renewable energy resources (e.g., solar and wind energy) are theoretically inexhaustible. Thus, we mainly took the investment cost into consideration. The investment cost I is a function of the installed capacity of the renewable microgrid m . Similar to the work of K  k (2018) [22], the investment cost function was assumed to be

$$I(m) = cm \quad (3)$$

where c denotes the cost of unit installed capacity. Specifically, the generation quantity of renewable energy cannot always reach the maximum value of installed capacity owing to the intermittency of solar and wind power. The effective generation time of solar power is in the daytime, while the generation pattern of wind power heavily depends on the richness of wind resources in different geographical locations. The function of electricity quantity can be expressed as

$$q = \delta m \quad (4)$$

where the capacity availability δ shows the phenomenon of renewable energy intermittency. We assumed $\delta(0 \leq \delta \leq 1)$ is a constant for ease of analysis.

Microgrids are still in the early stage of industrial development, and most microgrids are implemented as demonstration projects which are approved and supported by the energy sector. One of the guiding principles of promoting microgrids is maximizing the utilization of renewable energy, such as solar, wind, biomass, and so forth. Microgrids possess a unique feature in that they have two aspects of externalities: the technology spillover effect and environmental externality. The total externalities of the microgrid are denoted by E_T , which is a function of both investment level and generation quantity:

$$E_T = \lambda I(m) + \theta q, \quad 0 < \lambda < 1 \quad (5)$$

where λ and θ are the spillover effect rate and the environmental externality level, respectively. Equation (5) shows that the spillover effect is related to both the investment level and the innovation environment in specific regions. Thus, $\lambda = 0$ means that the demonstration microgrid cannot contribute to industrial development, and $\lambda = 1$ implies complete spillover. The environmental externality of a microgrid derives from its substitution of the fossil fuels used in conventional generators.

In order to guarantee the intelligibility of this research, we assumed that the abovementioned parameters satisfy the following conditions:

$$c - c\lambda - \delta\theta > 0, \quad a\delta > bc \quad (6)$$

$$(a + b\theta)\delta + bc(\lambda - 1) \geq 0 \quad (7)$$

In the following analysis, the subscript $i \in \{m, g\}$ refers to the microgrid and the DNO, respectively, and the notation $j \in \{C, D, I\}$ denotes to the centralized scenario, the decentralized scenario, and the scenario with government intervention, respectively.

3.2. Centralized Scenario: Maximizing Social Welfare

As one benchmark scenario, we first studied the centralized scenario, where a social planner directly determines the generation quantity of the microgrid. The objective of the social planner is to optimize social welfare, which includes the microgrid's profit, consumer surplus, externality benefits, and government cost. The consumer surplus can be written as

$$v^C = \int_{p^*}^{p^{\max}} D(p) dp \quad (8)$$

where p^* and p^{\max} are the optimal electricity price and maximum price, respectively. The social welfare in the centralized scenario is given by

$$W_C = (a - bp)p + q_0h - \frac{c}{\delta}(a - bp + q_0) + \frac{1}{2b}(a - bp)^2 + \frac{\lambda c + \delta\theta}{\delta}(a - bp + q_0) \quad (9)$$

The social planner directly chooses the optimal electricity price to maximize social welfare. We obtained the following equation by solving for " $\partial W_C / \partial p = 0$ ":

$$p_C^* = \frac{c - c\lambda - \delta\theta}{\delta} \quad (10)$$

which is equivalent to

$$q_C^* = \frac{(a + b\theta)\delta + bc(\lambda - 1)}{\delta} \quad (11)$$

Thus, the optimal social welfare can be written as

$$W_C^* = \frac{(c(\lambda - 1) + \delta\theta)^2 b^2 + 2[(a + x) + q_0h]\delta + c(\lambda - 1)(a + q_0)]\delta b + a^2\delta^2}{2b\delta^2} \quad (12)$$

3.3. Decentralized Scenario: No Government Intervention

Under the scenario without government intervention, the problem was analyzed as a Stackelberg game, where the renewable microgrid acts as a leader, and the DNO is a follower. The microgrid investor maximizes its profit by deciding the optimal wholesale price. Then, the DNO chooses the transmission price to maximize the profit. The above problem was solved using backward induction. The DNO's profit function is given by

$$\pi_g^D = (a - b(l + \omega))l \quad (13)$$

The DNO's profit function π_g^D reaches optimization when the optimal transmission price is

$$l_D^* = \frac{a - b\omega}{2b} \quad (14)$$

The microgrid's profit function is

$$\pi_m^D = (a - b(\omega + l))\omega + q_0h - \frac{c}{\delta}(a - b(\omega + l) + q_0) \quad (15)$$

We substituted Equation (14) into Equation (15) and took the derivative of Equation (15) with respect to ω in order to optimize the microgrid's profit. Thus, we obtained the optimal wholesale price of the microgrid:

$$\omega_D^* = \frac{a\delta + bc}{2\delta b} \quad (16)$$

Substituting Equation (16) into Equation (14) yielded the equilibrium transmission price:

$$l_D^* = \frac{a\delta - bc}{4\delta b} \quad (17)$$

The electricity demand quantity of end consumers is

$$q_1^D = \frac{a\delta - bc}{4\delta} \quad (18)$$

Therefore, the optimal profits of the renewable microgrid and DNO are

$$\pi_g^D = \frac{(a\delta - bc)^2}{16b\delta^2} \quad (19)$$

$$\pi_m^D = \frac{(a^2 + 8bq_0h)\delta^2 - 2bc(a + 4q_0)\delta + b^2c^2}{8b\delta^2} \quad (20)$$

Under the scenario without government intervention, social welfare is characterized by the following function:

Social Welfare = Microgrid's Profit + DNO's Profit + Consumer Surplus + Externality Benefit.

Therefore, we obtained the social welfare:

$$W_D^* = \frac{3(a\delta - bc)^2}{32b\delta^2} + \frac{(a^2 + 8bq_0h)\delta^2 - 2bc(a + 4q_0)\delta + b^2c^2}{8b\delta^2} + \frac{(c\lambda + \delta\theta)((a + 4q_0)\delta - cb)}{4\delta^2} \quad (21)$$

3.4. Comparison between Centralized and Decentralized Cases

The main difference between the centralized and the decentralized cases is that the microgrid cannot internalize the spillover effect and environmental externality without intervention, while the social planner can take them and consumer surplus into consideration.

Proposition 1. *The optimal electricity quantity under the centralized case is higher than that under the decentralized case, and the social welfare is also higher in the centralized scenario; that is, $q_C^* > q_D^*$, $W_C^* > W_D^*$.*

Proof. Proposition 1 can be simply proved by demonstrating that

$$q_C^* - q_D^* = \frac{(4b\theta + 3a)\delta + 4(\lambda - \frac{3}{4})bc}{4\delta} \quad (22)$$

Since there is $0 < \lambda < 1$, we have $q_C^* - q_D^* > [(4b\theta + 3a)\delta - 3bc]/4\delta$. From Equation (7), we obtained $q_C^* - q_D^* > 0$. The social welfare loss of the decentralized case compared with the centralized case is

$$W_C^* - W_D^* = \frac{(4bc\lambda + 4b\delta\theta + 3a\delta - 3bc)^2}{32b\delta^2} \quad (23)$$

so that $W_C^* - W_D^* > 0$. \square

Proposition 1 states that the system tends to generate more electricity and reaches a higher level of social welfare in the centralized scenario. The social welfare loss is a joint result of double marginalization and double externalities. This suggests that the government has motivations to implement an incentive scheme to promote the microgrid owner to increase investment, since society receives externality benefits when the microgrid generates more electricity.

4. Analysis of Government Intervention

When the social planner attempts to overcome the market failure by providing certain subsidies corresponding to technology spillover and environmental externality, the timing in the three-echelon Stackelberg model is as follows. First, the government establishes its subsidy scheme to pursue social welfare maximization. Second, the microgrid investor determines the optimal electricity wholesale price. Third, the DNO chooses its optimal transmission price.

The DNO's profit can be written as

$$\pi_g^I = (a - b(l + \omega))l \quad (24)$$

We sought the values of transmission price l that maximize the DNO's profit. The optimal transmission price is

$$l_1^* = \frac{a - b\omega}{2b} \quad (25)$$

The microgrid's profit is given by

$$\pi_m^I = (a - b(\omega + l))\omega + q_0h - \left(\frac{c}{\delta} - e\right)(a - b(\omega + l) + q_0) \quad (26)$$

We substituted Equation (25) into Equation (26) and obtained the optimal electricity wholesale price by solving for " $\partial\pi_m^I/\partial\omega = 0$ ":

$$\omega_1^* = \frac{a\delta + bc - b\delta e}{2\delta b} \quad (27)$$

Hence, the optimal transmission price can be rewritten as

$$l_1^* = \frac{(a + be)\delta - bc}{4b\delta} \quad (28)$$

Proposition 2. *A higher government subsidy level results in higher transmission price and lower wholesale price.*

Proof. By taking the derivative of Equations (27) and (28) with respect to e , we obtained $\partial\omega_1^*/\partial e < 0$, $\partial l_1^*/\partial e > 0$. \square

Proposition 2 indicates that the government subsidy induces the microgrid to reduce the electricity wholesale price so that more electricity can be on sale to the power grid. Meanwhile, the DNO attempts to gain more profits from the subsidy by increasing the transmission price.

It is clear that social welfare can be concluded to be

Social Welfare = Microgrid's Profit + DNO's Profit + Consumer Surplus + Externality Benefit – Government Cost

$$W_I = (a - b(l + \omega))(l + \omega) + q_0h - \frac{c}{\delta}(a - b(\omega + l) + q_0) + \frac{1}{2b}(a - b(\omega + l))^2 + \frac{\lambda c + \delta\theta}{\delta}(a - b(\omega + l) + q_0) \quad (29)$$

We substituted Equations (27) and (28) into Equation (29) and took the derivative of Equation (29) with respect to e . The optimal subsidy rate can be found at $\partial W_I/\partial e = 0$ since there is $\partial^2 W_I/\partial e^2 < 0$:

$$e_1^* = \frac{4bc\lambda + 4b\delta\theta + 3a\delta - 3bc}{\delta b} \quad (30)$$

Proposition 3. *The optimal subsidy level increases with the spillover effect rate and the environmental externality level.*

Proof. By taking the derivative of Equation (30) with respect to λ and θ , respectively, we obtained $\partial e_I^* / \partial \lambda > 0, \partial e_I^* / \partial \theta > 0$. \square

According to Proposition 3, the economic rationales of government subsidies for microgrids derive from two aspects: (1) Since renewable microgrids are an emerging industry and some critical technology and business models are not mature in the early stage, microgrid demonstration projects play an import role in the spillover effect. (2) Renewable microgrids possess environmental externalities due to the substitution of conventional power generation. As the microgrid industry gradually matures, government subsidies should decrease with the lower spillover effect rate and environmental externality level.

Substituting the optimal subsidy rate into Equations (29) and (30) yields the optimal electricity wholesale price and transmission price:

$$\omega_I^* = \frac{(-2\theta\delta - 2c(\lambda - 1))b - a\delta}{b\delta}, l_I^* = \frac{(\theta\delta + c(\lambda - 1))b + a\delta}{b\delta} \quad (31)$$

Proposition 4. There is a threshold value such that (i) if $c \geq \bar{c}$, then $\omega_I^* \geq 0$; (ii) on the other hand, if $c < \bar{c}$, then $\omega_I^* < 0$, where we defined the threshold cost \bar{c} as $\bar{c} = \frac{\delta(2b\theta + a)}{2b(1-\lambda)}$.

This threshold value suggests that, for the microgrid whose marginal investment cost is low enough (i.e., $c < \bar{c}$), the renewable microgrid prefers offering a negative wholesale price to the DNO so that more electricity can be imported into the electricity grid. Proposition 4 can partially give insights into the common phenomenon of negative electricity prices in some free electric markets. Negative electricity prices have been found in some electricity spot markets, such as the United States, the European Union, and Australia, and it will likely appear more frequently with the increasing installed capacity of renewable energy [32]. Microgrids face the trade-off between the negative price and government subsidy under the situation that the electricity demand is lower than the power supply. Proposition 4 demonstrates that the microgrid induces a negative price to stimulate the DNO to purchase its excess power as long as the gain from the government subsidy can offset the transfer payments to the DNO.

Next, we considered the DNO's and microgrid's profits with government intervention:

$$\pi_g^I = \frac{((\delta\theta + c(\lambda - 1))b + a\delta)^2}{b\delta^2} \quad (32)$$

$$\pi_m^I = \frac{2(\delta\theta + c(\lambda - 1))^2 b^2 + 4\delta((a + q_0)\theta + \frac{1}{4}q_0 h)\delta + c(\lambda - 1)(a + q_0)b + 2a(a + \frac{3}{2}q_0)\delta^2}{b\delta^2} \quad (33)$$

Therefore, we obtained the social welfare:

$$W_I^* = \frac{(c(\lambda - 1) + \delta\theta)^2 b^2 + 2[(a + x) + q_0 h]\delta + c(\lambda - 1)(a + q_0)]\delta b + a^2 \delta^2}{2b\delta^2} \quad (34)$$

Proposition 5. The whole system can be coordinated if, and only if, $e = e_I^*$ where e_I^* is given in Equation (30), and the effects of government subsidies on the relative stakeholders are as follows:

- (i) The government can choose the appropriate subsidy rate to achieve the system optimum of social welfare.
- (ii) The government subsidy scheme always benefits both the microgrid and the DNO.
- (iii) The incremental social welfare under government intervention increases with both the spillover effect rate and the environmental externality level.

Proof. By Equations (12) and (34), we have $W_I^* = W_C^*$, which means the social welfare approaches its highest value in the centralized scenario when the regulator properly sets the subsidy level. Comparing the microgrid's profit and the DNO's profit between the decentralized scenario and the government intervention scenario, we obtained

$$\pi_g^I - \pi_g^D > 0, \pi_m^I - \pi_m^D > 0 \quad (35)$$

The incremental social welfare can be represented by

$$\Delta W = W_I^* - W_D^* = \frac{(4bc\lambda + b\delta\theta + 3a\delta - 3bc)^2}{32b\delta^2} \quad (36)$$

Differentiating, we obtained

$$\partial\Delta W/\partial\lambda > 0, \partial\Delta W/\partial\theta > 0 \quad (37)$$

□

Proposition 5 states that the incentive scheme makes the three parties better off, which demonstrates the economic necessity of government intervention for renewable microgrids. Proposition 5 also implies that government intervention not only internalizes the spillover effect and environment externality but also eliminates the double marginalization effect. With higher values of spillover effect rate and environmental externality level, the government is more willing to rectify the market failure. However, along with the developing and maturing microgrid industry, the government also needs to design a subsidy phase-out mechanism responding to declining spillover effect and environmental externality rates.

5. Numerical Examples

In this section, we present a numerical study to compare the equilibrium solutions between the decentralized scenario and the government intervention scenario and explore some sensitivity analyses with respect to the model parameters.

Our first numerical example focuses on the effects of government intervention on the optimal electricity quantity, stakeholders' profits, and social welfare. The following parameter values were used for the numerical example, which satisfied the conditions of (6) and (7). Although our choice of parameter values was somewhat arbitrary, they are easy for a regulator and manager to visualize:

$b = 1.2, q_0 = 1.3, h = 5, c = 2, \lambda = 0.4, \delta = 0.6, \theta = 1$, and $a_1 = 10, a_2 = 15, a_3 = 20, a_4 = 25$, and $a_5 = 30$.

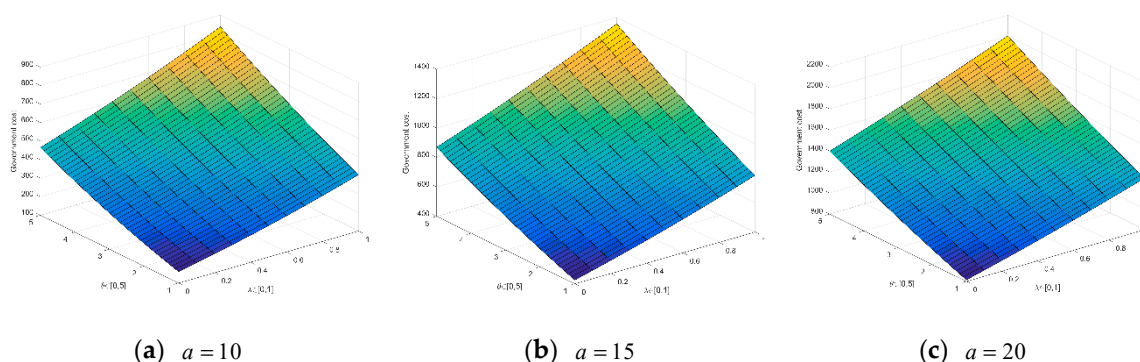
Table 1 summarizes the optimal electricity quantity imported into the grid, the microgrid's profit, the DNO's profit, and social welfare under the decentralized scenario and the government intervention scenario for a varying from 10 to 30. This table shows that, regardless of the potential market demand a , the government subsidy fostered the microgrid to increase investment and improve social welfare. Though the subsidized object was a microgrid, the DNO also took a share of the benefits by setting a reasonable transmission price. However, the microgrid extracted more benefits from the government subsidy than the DNO because of the first-mover advantage. Another observation from Table 1 is that incremental social welfare by government subsidy increased with the value of potential market demand a . It is not surprising that a higher potential market demand leads to more incremental social welfare, which creates more incentives for the government to encourage consumption. Meanwhile, the government faces bigger challenges due to the increased intervention cost.

Table 1. The effect of government intervention on the results.

Decentralized Scenario					Government Intervention			Incremental		
a	q_1^D	π_g^D	π_m^D	W_D^*	q_1^I	π_g^I	π_m^I	W_I^*	ΔW	$\frac{W_I^* - W_D^*}{W_D^*}$
10	1.50	1.88	5.92	15.26	8.80	64.53	162.87	37.47	22.21	1.46
15	2.75	6.30	14.77	33.67	13.80	158.70	367.45	84.55	50.88	1.51
20	4.00	13.33	28.83	61.20	18.80	294.53	655.37	152.47	91.27	1.49
25	5.25	22.97	48.10	97.84	23.80	472.03	1026.61	241.22	143.38	1.47
30	6.50	35.21	72.58	143.60	28.80	691.20	1481.20	350.80	207.20	1.44

Next, we considered a numerical example to address the sensitivity of government subsidy costs with respect to the spillover rate and environmental externality level. Let $b = 1.2$, $q_0 = 1.3$, $h = 5$, $c = 2$, and $\delta = 0.6$.

Figure 3 presents the impacts of the spillover rate λ and the environmental externality level θ on the government intervention cost when $a = 10$, $a = 15$, and $a = 20$. The overall policy cost to achieve social welfare maximization decreased with a lower value of λ and θ for three different market sizes. It can also be seen that the policy cost increased significantly as the market size a increased. This result provides insights into subsidy policy formulation in the long term. The government intervention cost is relatively low in the early stage of the microgrid industry, but it may hinder the government from achieving social welfare maximization as the market size becomes larger and larger. It is necessary and rational to design a subsidy phase-out mechanism in the long run for these reasons: (1) The learning spillover rate tends to decline with the microgrid industry gradually transforming into its mature stage. (2) The environmental externality decreases with the cleaner development trend of thermal power. Some microgrid support policies based on market mechanisms such as a renewable portfolio standard, tradable green certificates, and carbon cap-and-trade are some alternative options to motivate microgrid investment without relying on government financial support.

**Figure 3.** The effects of the learning spillover rate and environmental externality level on government subsidy cost.

In a third numerical experiment, we explored the effect of government subsidies on the profits of a microgrid, DNO, and social welfare. We considered a situation where $b = 1.2$, $q_0 = 1.3$, $h = 5$, $c = 2$, $\lambda = 0.4$, $\delta = 0.6$, $\theta = 1$, and $a_1 = 10$.

Figure 4 represents the social welfare, microgrid's profit, and DNO's profit as a function of the government subsidy coefficient e . As e increased, the microgrid's and DNO's profits increased significantly, especially when the subsidy nearly reached 55.94. However, the goal of the government was to maximize social welfare, and too high or too low subsidy levels were both harmful from the perspective of the social planner. The optimal subsidy coefficient in this case was 24.33, which was obtained by substituting the selected parameter values into Equation (30).

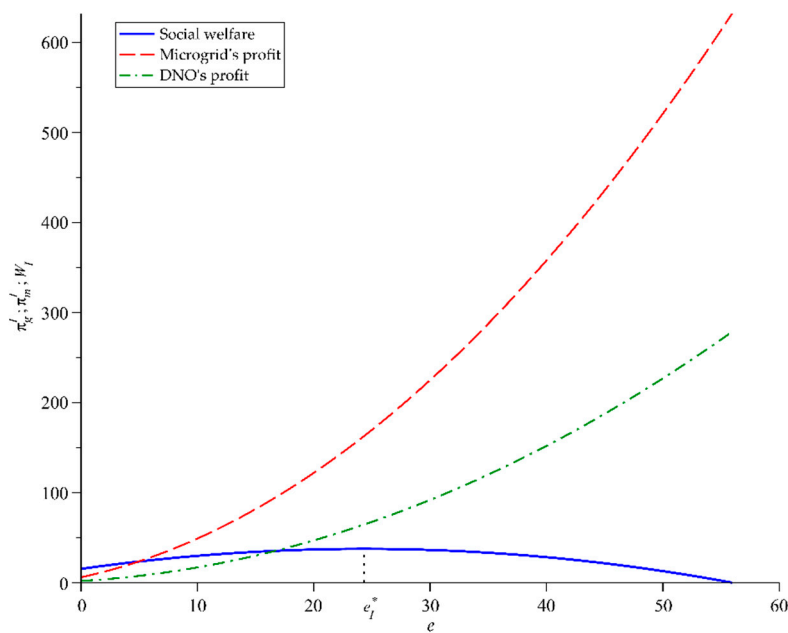


Figure 4. The effect of government subsidies on stakeholders' profits and social welfare.

6. Conclusions

The market practice of microgrid demonstration projects has attracted a considerable amount of interest because of the potential to boost renewable energy utilization. Making economic sense of microgrids with a premium cost requires profit-seeking investors to pursue public incentives in the early stage of the microgrid industry. Therefore, understanding the economic rationales of government intervention and exploring the effects of government subsidies on the interaction between a microgrid and a DNO is crucial.

What differentiates microgrids from other forms of power generation is that microgrids have learning spillover effects and environmental externalities at the same time. This paper examined the decision-making process of choosing the optimal government subsidy level to maximize social welfare and investigated the reactions of a microgrid and a DNO under three different scenarios. A framework was developed to address the economic rationales and impacts of government subsidies on renewable microgrids from the perspective of a social planner. To focus our attention on solving the market failure of renewable microgrids caused by the spillover effect and environmental externalities, we considered a three-stage Stackelberg model to present the necessity of government subsidies and their effects. Unlike the extant literature on government intervention for microgrids, we considered the double externalities and proposed a model of an electricity supply chain with a microgrid and a DNO to derive the optimal subsidy strategy to solve market failures by coordinating the electricity supply chain.

Our results suggest that the government can use subsidy instruments to achieve the system optimum compared with the scenario without government intervention, and the microgrid acquires more benefits than the DNO. In the presence of a government subsidy, the microgrid may offer a negative electricity price to the DNO to earn more opportunities to import electricity into the grid. We observed that, in addition to increasing social welfare and the microgrid's profit, coordinating the electricity supply chain also benefits the DNO and the consumers.

Our results demonstrate that we need to incorporate the spillover effect and environmental externality into the electricity supply chain for microgrids to correct market failure. There is an optimal subsidy level to coordinate the electricity supply chain, which is determined by the spillover effect rate, environmental externalities, and some other model parameters. Our study can provide useful guidelines for regulators to correct market failures. First, the regulator needs to design a subsidy phase-out mechanism, since the spillover effect and environmental externality gradually decline with

the development of the microgrid industry. Second, the government needs to strengthen intellectual property protection so that the learning spillover effect can be corrected by market means (e.g., patents). Lastly, some market-oriented policies, such as tradable green certificates, carbon trading, and so forth, could be analyzed and implemented to substitute subsidies, which would help to alleviate the government's financial burden.

We encourage extending our model to analyzing the impact of government subsidies on the electricity supply chain under uncertain demand. It would also be of interest to study the effects of government intervention on microgrids when considering electricity storage and investor's risk preference. Moreover, it would be useful to study other forms of government intervention on microgrids, such as a renewable portfolio standard, tradable green certificates, and carbon cap and trade.

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