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The socially optimal energy storage incentives for microgrid: A real option game-theoretic approach

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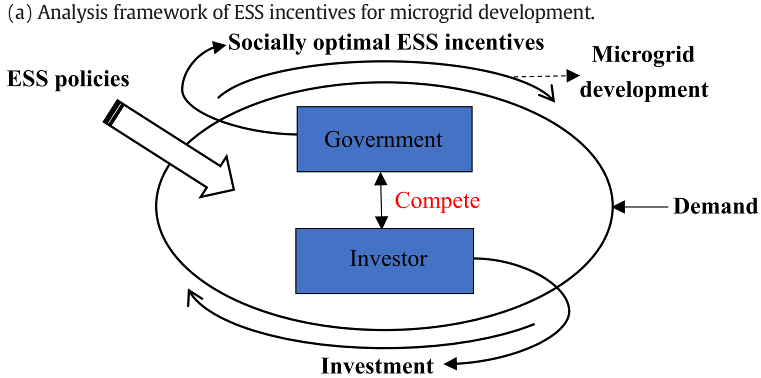
HIGHLIGHTS

- We explore the socially optimal energy storage incentives for microgrid.
- Costs and benefits of government and investor for power investment are identified.
- A real option game model is developed for exploring the socially optimal energy storage incentives for microgrid.
- The feed-in tariffs for ESS has the greatest effect on microgrid development.

GRAPHICAL ABSTRACT

(a) Analysis framework of ESS incentives for microgrid development.



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ABSTRACT

Nowadays, as microgrid development has been limited by the high cost of its energy storage system (ESS), many relevant literatures on applied energy have emphasized the role of ESS incentive policies for microgrid. However, since energy storage technology in microgrid is complex, it still remains an issue of high difficulty to derive the optimal ESS incentives for microgrid development. In this study, a real option game model, which combines evolutionary game theory with real options, is developed to explore the socially optimal ESS incentive policies for microgrid by utilizing the fluctuation amplitudes and equilibrium positions of microgrid development under different ESS policy options, that include the initial cost subsidy, the feed-in tariffs (FIT), and the production tax credit. Moreover, we provide a numerical example to simulate and compare the fluctuation results of microgrid development under different ESS incentive policies. The results indicate that the FIT has the greatest effect on microgrid development. However, regarding the limitations of government's incentive mechanisms, its combination with other ESS incentive policies, e.g., initial cost subsidy, and tax credit, is shown to be more effective for microgrid development than the FIT only. In addition, appropriately extending the implementation period of FIT can also help to overcome the limitations of FIT mechanism so as to effectively facilitate the development of microgrid.

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1. Introduction

With the increasing pressure on global resource and environment, the issue of utilizing renewable energy sources (RES) has become more and more important in the world. While electric power is an indispensable energy for modern world, renewable power has been emerged as an effective way for promoting the development of renewable energy (Wang and Zhan, 2019). Nevertheless, although generation from distributed RES is constantly increasing, severe challenges are posed in the current energy system due to its volatility, which may cause stability, reliability and power quality problems (Mengelkamp et al., 2018). Microgrid (MG), as a system composed of micro-sources and loads, appears to provide efficient solutions to these technical dilemmas (Yoldaş et al., 2017). It has become one of the most promising power technologies in electric industry. As of 2018, 24,981 MW of total MG capacity have either been proposed, under development, or in operation globally (Navigant Research, 2018).

So far, while microgrid has many advantages, such as suppressing power fluctuation of RES, black start, and supporting active/reactive power, there are some challenges that need to be overcome for microgrid development, including substantial capital investment and uncertain environment associated with its investment and deployment (Soshinskaya et al., 2014). Note that energy storage system (ESS), as an indispensable component of MG, has become the most critical element for microgrid development (Zubieta, 2016), in this study, we give emphasis on the issue of ESS in microgrid. The storage system in microgrid could deal with the arduous imbalance between power supply and demand as well as suppress probable power fluctuation caused by the volatility of distributed generation (Faisal et al., 2018). But it has a high capital investment cost, which makes ESS value and functionality to be undermined, and causes low technical-economic efficiency of the electric system. Take China as example, the ESS initial investment occupies nearly one third of the entire cost of MG (Yu et al., 2017a, 2017b). Additionally, although a set of ancillary services like arbitrage and peak shaving are easily achieved when ESS has been inserted in microgrid, it still remains difficult for utilities to achieve the economic justification for utilizing the ESS, which can significantly discourage MG investment (Schmidt et al., 2017). In this regard, without suitable financial incentives for ESS, microgrid development must be far slower than socially anticipated.

Nomenclature

Acronyms

ESS	energy storage system
MG	microgrid
FIT	feed-in tariffs
PTC	production tax credit
RES	renewable energy resources
DGs	distributed generators
DER	distributed energy resource
BESS	battery energy storage system
EMS	energy management system
CS	central storage
PEI	power electronic interface
GBM	geometric Brownian motion

Indices and parameters

t	index of model time unit
L	lifetime of power generation project
L_{ES}	ESS lifetime
L_{CL}	ESS cycle life
φ	energy storage efficiency
Ep^e	selling price of electricity
Ep^d	market price of electricity
ω	market price of carbon emission
UI	unit investment cost
$uomc_t$	unit operation and maintenance cost
EPb_t	unit price subsidy
Csb_t	unit cost subsidy for ESS
Psb_t	unit price subsidy for electricity released from ESS
θ	production tax credit for electricity released from ESS
IC	quantity of installed capacity
Eq_t^e	quantity of electricity per generating capacity
Eq^s	energy storage capacity
q_t^c	quantity of carbon emissions per unit power
γ	tax rate
LR	long distance electricity transmission loss rate
Fr	fill rate of the power generation project
r	return rate of power generation project

Decision variables

x_1	probability of government with no support for MG strategy
y_1	proportion of investors with MG investment strategy
P_{DE}	probability of MG development
P_{DE}^*	equilibrium probability of MG development
P_{DE}^h	higher limit of MG development probability

Random variables

α	drift rate of power demand
σ	volatility rate of power demand

In recent years, there have been many studies in the field of energy storage, highlighting the economic viability of ESS in microgrid. Most of them focus on optimal investment and dispatch of the storage system. For example, Gil-Gonzalez et al. (2019) develop a semidefinite programming model for optimal economic dispatch of energy storage system in DC microgrid with application in real-time operating conditions. Wu et al. (2018) present the energy management strategy for a grid-connected microgrid with battery energy storage system (BESS) considering the efficiency of BESS, and formulate it using nonlinear programming. Aghamohammadi and Abdolahinia (2014), Fossati et al. (2015) and Jacob et al. (2018), among others, propose different methods for optimally sizing the ESS in microgrid, and then verify the suitability of their approach by applying to typical MG system using real world data. While Levron et al. (2013) propose an algorithm for globally optimizing power flow of microgrids with inspection of the storage devices integrated in a general power network, Korkas et al. (2016) also consider demand response. Mahmoodi et al. (2015) introduce distributed dispatching strategies for optimal operation of a microgrid with multiple storage systems. Morstyn et al. (2016) review control strategies that are specifically designed for coordinating distributed energy storage systems in microgrid. Alharbi and Bhattacharya (2018) present a novel stochastic planning framework for determining the optimal capacity of energy storage system in isolated microgrid. By establishing a building based virtual ESS model, Jin et al. (2017) explore the dynamic economic dispatch problem of a hybrid microgrid to effectively use ESS and reduce the daily operation cost.

However, since the incentives should be given for ESS in microgrid to internalize the positive externalities of energy storage, related studies are still limited in number. Recently, with the status of energy storage for promoting MG development was confirmed, suitable incentive policies to facilitate ESS installation has become a topic to be urgently explored. Zame et al. (2018) and Yu et al. (2017a, 2017b) describe the economic challenges of energy storage to be widely used in microgrid, and make suggestions to overcome them with effective financial support mechanisms. Romer et al. (2012) employ a qualitative interview method to investigate the role of energy storage for smart grid by conducting and analyzing interviews with field experts in Germany. The findings show that ESS plays a key role for smart grid development, and providing monetary incentives can be an effective measure to promote ESS installation in smart grid. Chen et al. (2019) propose a real option-evolutionary game model for evaluating the ESS subsidy policies for microgrid considering the long-term performance of project businesses, and apply their methodology in a small electricity network. Since there exist market arrangements during this game process, the optimal investment capacity for each market participator is determined based on a multi-objective programming. Our paper in comparison with others, is the one that evaluates the most comprehensive list of ESS incentive policies for microgrid. In addition, rather than exploring the energy storage incentives for MG with a project business perspective, this study investigates the ESS incentives for microgrid from society perspective (social welfare maximization) so as to efficiently promote MG investment as well as consider the limitations of government's incentive mechanisms, which would be of more practical significance.

The main goal of this paper is to explore socially optimal ESS incentive policies for the development of microgrid. Since microgrid development can be defined as the diffusion process of microgrid technology, it is essentially a process where MG, as a new innovative technology, spread within and across the electricity market over time. Besides, with the exploitation of electricity technical innovation, there exist periodical fluctuations during the process of MG development, which are mainly caused by the volatility of investment expenditures (Kaldor, 1954; Chen et al., 2019). Based on this, an evolutionary game model, which combines with real options, is proposed to evaluate the impacts and limitations of government's ESS incentive policies for microgrid by utilizing the periodical fluctuation within its development. The main contributions of this paper are: (1) We provide a comprehensive analytical framework for assessing the option values of government and investor in the process of power investment, which includes microgrid. (2) After analyzing costs and benefits of both the government and an investor for power investment, we evaluate the economic impacts of ESS incentive policies on investor as well as their impacts on social welfare to examine the effect of ESS incentives for microgrid development in the view of society.

The remainder of the paper is structured as follows: Section 2 gives the description of available energy storage system in microgrid. Section 3 analyzes the costs and benefits of the stakeholders and presents the methodology for estimating the effect of ESS incentive policies for MG. And then, the results of a numerical example based on real world data are presented in Section 4. Finally, some conclusions and policy implications of the paper are given in Section 5.

2. Energy storage system (ESS) in microgrid

2.1. The ESS benefits for microgrid

The storage system, as an indispensable component of MG, functions as energy buffer or backup to improve the power imbalance, power quality, stability and reliability between the output of distributed energy resource (DER) and loads (Kittner et al., 2017). A general framework of ESS benefits in electricity value chain is illustrated in Fig. 1, which consists of the links including fuel/energy source, power generation, power transmission, distribution and demand-side services (Chen et al., 2009). As shown in Fig. 1, ESS in microgrid can provide practical solutions for the stabilization and quality problems caused by distributed energy generation as well as the interrupted condition existing in the electric power system. As a result, substantial benefits of energy storage, such as frequency regulation, peak shaving, reserve capacity supply, and emergency power back-up, are produced for microgrid. A wide spectrum of ESS technologies permeate into the power system (i.e., MG) to allow the flexibility and reliability of microgrid.

2.2. The operation of ESS in microgrid

In general, the operation of ESS in microgrid can be divided into three main stages: central storage stage, power transformation stage, and energy control stage (Faisal et al., 2018). In central storage stage, the energy management system (EMS) in microgrid suffers a surplus of energy (i.e., energy supply exceeds demand), electrical energy will be stored after transforming into another energy form, e.g., mechanical or chemical energy. At this time, ESS is under the state of "charging", where the excess energy is stored. And when energy supply fails to meet demand, the energy will be released by transforming into electrical energy in the central storage (CS) through a power electronic interface (PEI). PEI is located between the CS and the electric power system. This stage is the power transformation stage, where the ESS is under the state of "discharging". In the control stage, the measuring devices, e.g., sensors are used to determine the status of ESS, i.e., charging or discharging. And the specific dispatch strategies of ESS are developed through interacting with the EMS of microgrid. During the ESS operation process, multiple dynamics occur simultaneously apart from the charging and discharging process, such as aging phenomena and thermal phenomena. Each of them has different time-scales, and different storage systems have different categories of dynamics (Zou et al., 2018). These dynamics interact with each other and then influence the operation of ESS in microgrid.

2.3. Selection of ESS technologies

According to the above, the operation of ESS can be regarded as a process of storing surplus electrical energy in another energy form, and converting the energy back into electrical energy when electric power is shortage. Based on energy form stored in ESS, energy storage technologies can be categorized into mechanical storage system

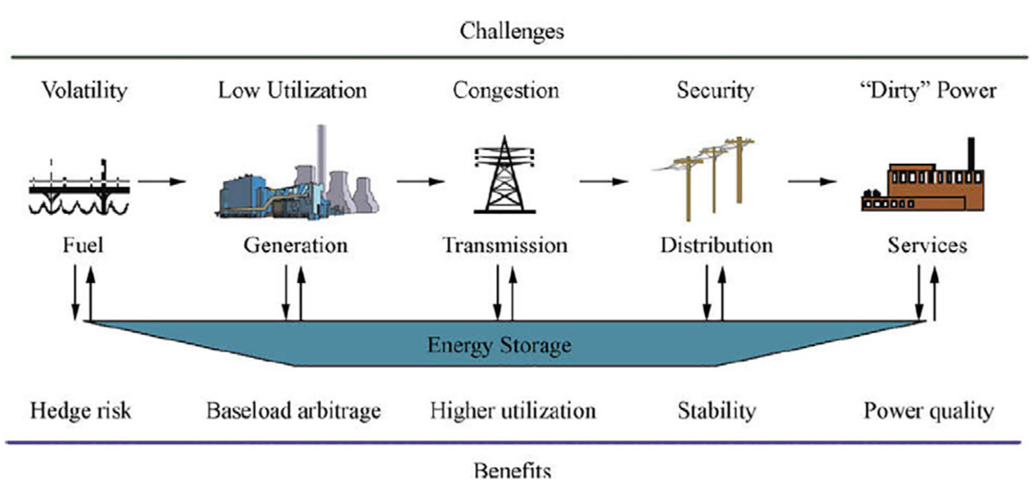


Fig. 1. The benefits of energy storage system.

(e.g., pumped hydro storage, compressed air storage, and flywheel storage), electrochemical storage system (e.g., various batteries), chemical storage system (e.g., hydrogen storage), electrical storage system (e.g., supercapacitor storage and super magnetic energy storage), thermal storage system (e.g., low or high temperature thermal storage), and hybrid energy storage system (Zhao et al., 2015). For ESS selection, many aspects should be taken into consideration, such as power rating, power density and energy density, time response, efficiency, cycle life, and the investment cost, since different ESS technologies have their own characteristics, and each has advantages and disadvantages (Zafirakis et al., 2013). Among these characteristics, ESS ability to store energy and to provide electric power is the most distinctive one for ESS determination. Since there exist a wide variety of microgrids, ESS selection could be determined according to the characteristics of their DER and loads (Tan et al., 2013; Yoldaş et al., 2017). Currently, the most frequently used ESS technologies are compressed air storage, flywheel storage, batteries, superconducting magnetic energy storage, hydrogen storage, and hybrid storage in MG project (Faisal et al., 2018).

3. Methodology

In this study, the evolutionary game theory is used in combination with real options to study the decision-making of two main stakeholders (the government and an investor for new power investment) for microgrid development under different ESS policy incentives. In subsequent sections, we firstly analyze the costs and interests of the main stakeholders for power investment (Section 3.1). Next, in Section 3.2 the ESS policy options for microgrid are formulated specifically, which include the initial investment subsidy, feed-in tariffs (FIT) mechanism, and production tax credit (PTC) mechanism. Finally, we present the game-theoretic model between the government and the investor for microgrid development in Section 3.3.

3.1. Benefits and costs analysis for power investment

Before to explore the ESS incentive policies for microgrid, it is essential to make analysis of the costs and interests of the main stakeholders, including government and an investor for new power generation investment. As distributed generation and MG share the commonality of using distributed generators (DGs) for power generation, we focus on the power generation project with DGs in the analysis.

3.1.1. The benefits of the power investment

For the power generation investment with DGs, the benefits can be split into direct and indirect. Firstly, we consider the economic benefit of the power generation project from selling electricity. Later, in comparison with the main power grid, the power generation project with DGs has the benefits of saving electricity loss for avoiding long distance transmission due to its direct distribution in demand-side (Li et al., 2019). Additionally, when the project is for renewable energy generation, it exists the environmental benefits because of nearly zero emissions comparing with non-renewable energy generation. Thus, the power investment has the economic benefits and environmental benefits, which are detailed as follows:

3.1.1.1. Economic benefits from electricity sale. The power generation system could transfer the energy into electric power, and the generated electricity would be input power grid and sold at the price of electricity. Hence, the economic benefits of the power generation project can be expressed by:

$$ER_t = Ep_t^e \cdot Eq_t^e \tag{1}$$

where Eq_t^e is the quantity of electricity to be sold, and Ep_t^e refers to the price of electricity.

And for the renewable generation project, the electricity will be sold with feed-in tariffs. In this paper, we suppose that once the project investment is completed, the FIT for the electricity will be determined and kept constant within the entire lifetime of project. Then we get

$$Ep_t^e = Ep_t^d + EPb_t \tag{2}$$

where Ep_t^d is the market price of electricity, and EPb_t denotes the electricity price subsidy. And when the project is for non-renewable generation, $EPb_t = 0$.

3.1.1.2. Benefits of the loss saving for avoiding long distance electricity transmission. As for the power generation project with DGs, the distribution is close to the location of load, it mitigates the electricity loss for avoiding long distance transmission. The benefits of the transmission loss saving can be given as follows:

$$\mathrm{TSR}_t = Sr \cdot Eq_t^e \cdot Ep_t^e \tag{3}$$

where Sr is the electricity transmission loss saving rate of the power-generation project, and $Sr = LR \cdot \mathrm{Fr}$, in which LR denotes the long distance electricity transmission loss rate and Fr refers to the fill rate of the power generation project to the local residents.

Among these projects, as microgrid owns the ability to satisfy the electric power demand itself by using the energy in ESS when there exists power shortage, the electricity transmission loss of MG is nearly 0 (Ma et al., 2017). Thus, MG has a lower dependence on the main power grid than distributed generation project, and has a higher fill rate of the power generation project. As a result, the electricity transmission loss saving rate of microgrid is higher than that of distributed generation.

3.1.1.3. Environmental benefits through power generation. Renewable energy can be seen as environmentally benign alternatives. Hence, when the project is for renewable energy generation, there exist environmental benefits since it has the advantages of nearly zero emissions comparing with non-renewable energy generation, such as coal and gas fired power generation (Gibon et al., 2017). In this paper, we assume that the amount of carbon emissions from renewable energy generation equals to zero. Suppose that ω is the degree of society's environmental benefits with unit carbon emission reduced (i.e., the market price of unit carbon emission), and q_t^c represents the quantity of carbon emissions reduced for generating unit electric power. And at present, as coal-fired power generation remains the predominance in the field of fossil fuel generation globally, we introduce coal-fired power as the weighted objective to quantify the environmental benefits of power generation. Then, we obtain that

$$CER_t = \omega \cdot q_t^c . Eq_t^e \tag{4}$$

It should be noted that if the project is for non-renewable generation, the degree of society's environmental benefits could be negative.

3.1.2. The costs of the power investment

The costs of a power generation project usually comprise of three terms, which include the initial investment cost of the power generation project, operation & maintenance cost during daily operation, and tax expenditure. We then derive the formulas as following.

3.1.2.1. Initial investment cost. The initial investment cost of a power generation project is dependent on technology development. Hence, we consider the investment cost as a technological factor, which includes the purchase cost of equipment, construction cost, and other costs. Mathematically, the initial investment cost of the power generation project is expressed as follows:

$$I_t = IC \cdot UI_t \tag{5}$$

where IC is the quantity of installed capacity, and UI_t denotes the unit investment cost.

3.1.2.2. Operation and maintenance cost. To maintain the daily operation of a power generation project, there exists cost of operation and maintenance. In this paper, the operation and maintenance cost of the power generation project is formulated as follows:

$$OMC_t = Eq_t^e \cdot uomc_t \tag{6}$$

where $uomc_t$ refers to the operation and maintenance cost for unit electricity output of the power project.

3.1.2.3. Tax expenditure. The tax expenditure corresponds to the revenues of a power generation project obtained through economic benefits from selling electricity minus the operation and maintenance cost. Mathematically, we derive the following formula:

$$Tax_t = \gamma \cdot (ER_t - OMC_t) \tag{7}$$

where γ represents the tax rate.

3.2. Characterization of the ESS incentive policies for microgrid

Currently, the ESS incentive policies are mainly consist of the initial cost subsidy, FIT mechanism, and PTC mechanism (Yu et al., 2017a, 2017b; Miller and Carriveau, 2018). We then derive the corresponding formulas of these ESS incentive policies for microgrid as follows:

3.2.1. Initial cost subsidy

With regard to the ESS initial cost subsidy, the ESS can be subsidized with a fixed payout for unit installed capacity. As a result, the investment cost of MG project is decreased to promote the deployment of microgrid. While ESS lifetime is different from the lifetime of microgrid, we suppose that L is the project lifetime, and L_{ES} denotes the lifetime of ESS in microgrid. Mathematically, the ESS initial cost subsidy can be represented by

$$ICS_t = (INT(\mathrm{L}/L_{ES}) + 1) \cdot CSb_t \cdot \mathrm{Eq}^s \tag{8}$$

where CSb_t is the initial cost subsidy for unit capacity of ESS, and $\mathrm{E}q^s$ denotes the installed capacity of ESS in microgrid.

3.2.2. The FIT mechanism

The FIT mechanism corresponds to the price of electricity that is released from the storage system. An adequate FIT for the ESS, that is implemented for a certain period, could increase the yearly cash flow of MG project, and then promote microgrid development. Mathematically, the price subsidy for ESS in year t can be formulated as follows:

$$PS_t = 1/L_{ES} \cdot L_{CL} \cdot \varphi \cdot \mathrm{Eq}^s \cdot Psb_t \tag{9}$$

where L_{CL} is the ESS cycle life, φ represents the efficiency of the storage system, and Psb_t denotes the price subsidy for unit electricity of ESS.

3.2.3. The PTC mechanism

Considering the PTC mechanism, it is a tax credit for electricity released from ESS (Gençer and Agrawa, 2016). Then, the tax expenditure of microgrid could be reduced, and promote the MG investment. Mathematically, the production tax credit for ESS of microgrid in year t can be expressed by:

$$TC_t = \theta \cdot \gamma \cdot (Ep_t^e - uomc_t) \cdot 1/L_{ES} \cdot L_{CL} \cdot \varphi . \mathrm{Eq}^s \tag{10}$$

where θ denotes the tax credit for unit electricity released from the energy storage system.

In this paper, we suppose that the tax credit for ESS will be determined and kept constant during the whole lifetime of microgrid once its investment is completed.

3.3. The real option-evolutionary game model between government and investor

In this subsection, we propose a real option-evolutionary game model to present the interaction relationship between the government and the investor for microgrid development. During the game process, the government plays the role of initiator and facilitator to promote the development of microgrid, and the investors seeks to maximize net present value from the investment in power generation project. In this evolutionary game model, we firstly identify the net present values (payoffs) of the government and investor's strategy choice. Under different set of ESS incentive policies for microgrid, the strategy choice of both the government and investor for microgrid development could change. Then, the government and investor will achieve a Nash equilibrium, and the periodical fluctuation of probability of microgrid development could reflect the effect of ESS incentives for microgrid.

3.3.1. Net present value of investor's strategy for power investment

(1) The value of investor's strategy without ESS incentive policies

Consider an investor makes investment in a power generation project with lifetime L in year t. Assume that the project construction can be instantaneously completed (Kumbaroğlu et al., 2008). Given that the value of the investor for the power project investment depends on many uncertain factors within the project lifetime, it is reasonable to express the value using E[·]. Thus, the total net present value of the investor for the power project investment can be given as follows:

$$V_{i,t} = E\left[\int_t^{t+L} e^{-r(s-t)} \pi_{i,s} ds - I_t\right] \tag{11}$$

where r is the discount rate of the power project, $\pi_{i,s}$ refers to the yearly cash flow in year s, and I_t denotes the initial investment cost.

The yearly cash flow of the investor to invest in the power project usually comprises the economic benefits through electricity sale ER_t, operation and maintenance cost OMC_t, and tax expenditure Tax_t. We then have

$$\pi_{i,t} = ER_t - OMC_t - Tax_t \tag{12}$$

Since the electricity demand denotes an uncertain variable, that can be influenced by various factors (e.g., market environment and policies, etc.), we then model the electricity demand as following formula, which is govern by the geometric Brownian motion (GBM):

$$dEq_t^e = \alpha Eq_t^e dt + \sigma Eq_t^e dz(t) \tag{13}$$

where $dz(t)$ is the increment of a standard Wiener process $dz(t) = \varepsilon_t \sqrt{dt}$, ε_t denotes a normally distributed random variable with zero mean and unit standard deviation (i.e., the expected value of Eq_t^e is $E[Eq_t^e] = Eq_0^e e^{\alpha t}$). α is the drift parameter of the electric demand, and σ represents the volatility parameter of the electric demand.

We then let $F_i(Eq_t^e)$ denotes the investor's value before the power project investment. Assume that the investor is risk-neutral, and the investor's value $F_i(Eq_t^e)$ must be the solution of the following equilibrium differential equation (Azevedo and Paxson, 2014), that can be described as follows:

$$\frac{1}{2}\sigma^2(Eq_t^e)^2\frac{\partial^2 F_i(Eq_t^e)}{\partial(Eq_t^e)^2}+(r-\delta)Eq_t^e\frac{\partial F_i(Eq_t^e)}{\partial Eq_t^e}-rF_i(Eq_t^e)=0 \quad (14)$$

where $\delta = r - \alpha$ refers to the rate of return shortfall, representing the income gap between holding the option and starting to invest. Besides, to ensure the convergence of solution, we assume that $\delta > 0$ (i.e., $r > \alpha$).

To ensure that the investor invests at the time when the "option to invest" is maximized, the differential Eq. (14) must be solved subject to the boundary conditions (15) and (16), which are formulated as follows:

$$F_i\left(Eq_{i,t}^{e*}\right)=\frac{\pi_{i,t}\left(Eq_{i,t}^{e*}\right)(1-e^{-\delta L})}{\delta}-I_t \quad (15)$$

$$F_i'\left(Eq_{i,t}^{e*}\right)=\frac{\pi_{i,t}'\left(Eq_{i,t}^{e*}\right)(1-e^{-\delta L})}{\delta} \quad (16)$$

where $Eq_{i,t}^{e*}$ denotes the value of Eq_t^e that triggers the investor's investment in the power generation project, i.e., the investment threshold.

The boundary condition (15) denotes the value-matching condition, which states that the investor's option is exercised its net payoff at this moment, and the boundary condition (16) denotes the smooth-pasting condition, which is devoted to guarantee the exercise trigger is determined to maximize the value of the option. We then obtain the closed-form solutions for the investor's investment threshold $Eq_{i,t}^{e*}$ and value function $F_i(Eq_t^e)$ through this procedure, which are represented as follows:

$$Eq_{i,t}^{e*}=\frac{\vartheta}{\vartheta-1}\cdot\frac{I_t\cdot\delta}{\pi_{i,t}'(Eq_t^e)\cdot(1-e^{-\delta L})} \quad (17)$$

$$F_i(Eq_t^e)=\begin{cases}\dfrac{I_t}{\vartheta-1}\left(\dfrac{Eq_t^e}{Eq_{i,t}^{e*}}\right)^{\vartheta} & Eq_t^e<Eq_{i,t}^{e*}\\ \dfrac{\pi_{i,t}\cdot(1-e^{-\delta L})}{\delta}-I_t & Eq_t^e\geq Eq_{i,t}^{e*}\end{cases} \quad (18)$$

where, $\vartheta=\frac{1}{2}-\frac{\alpha}{\sigma^2}+\sqrt{\left(\frac{\alpha}{\sigma^2}-\frac{1}{2}\right)^2+\frac{2r}{\sigma^2}}>1$

As $Eq_{i,t}^{e*}$ is the investment threshold, only when the quantity of electricity Eq_t^e is above the investor's investment threshold $Eq_{i,t}^{e*}$ (i.e., $Eq_t^e \geq Eq_{i,t}^{e*}$), the investor would invest in the power project, and if Eq_t^e is lower than the threshold $Eq_{i,t}^{e*}$ (i.e., $Eq_t^e < Eq_{i,t}^{e*}$), the option value of the investor would be the value to wait. Thus, we assume that the electricity demand is enough to trigger the investor's investment for the power generation project. The value function(payoff) of the investor can be expressed as follows:

$$V_{i,t}=\frac{\pi_{i,t}\cdot(1-e^{-\delta L})}{\delta}-I_t \quad (19)$$

(2) The value of investor's strategy with ESS incentive policies

If the investor chooses to invest in microgrid, and can receive initial cost subsidy from the government, the initial investment cost of investor to invest in MG I_t' consists of the initial investment cost I_t and the ESS initial cost subsidy ICS_t. We obtain that

$$I_t'=I_t-ICS_t \quad (20)$$

Meanwhile, considering the FIT mechanism and the PTC mechanism from the government, both of them will increase the yearly cash flow of the MG project. Mathematically, we derive the following formula:

$$\pi_{i,t}'=\pi_{i,t}+PS_t+TC_t \quad (21)$$

where $\pi_{i,t}'$ denotes the yearly cash flow of MG project with FIT mechanism and PTC mechanism for its storage system.

Since the FIT mechanism for the storage system is implemented for a certain period, we assume the implementation period is t_{ES}. Then, the net present value of the investor with ESS incentive policies can be formulated as follows:

$$V_{i,t}'=E\left[\int_t^{t+t_{ES}}e^{-r(s-t)}\pi_{i,s}'ds+\int_{t+t_{ES}}^{t+L}e^{-r(s-t)}\left(\pi_{i,t}'-PS_t\right)ds-I_t'\right] \quad (22)$$

3.3.2. Net present value of government's strategy: value of social welfare

(1) The value of the government's strategy without ESS incentive policies.

For the government, it seeks the objective of maximizing the economic benefits and environmental benefits of the power generation project. Hence, we define the government's payoff as the social welfare function, which comprises of the economic surplus, tax income from investor's investment in power generation project Tax_t, power transmission loss saving TSR_t, and environmental benefits of the power generation project CER_t. Since the economic surplus is obtained through the project's output minus the costs incurring this output (Baran and Paul, 1966), it can be formulated as follows:

$$Pr_t=E\left[\int_t^{t+L}e^{-r(s-t)}(ER_t-OMC_t)ds-I_t\right] \quad (23)$$

Additionally, as for renewable energy generation project, there exists policy expenditure of the FIT for unit renewable electricity PSE_t, in which $PSE_t = EPb_t \cdot Eq_t^e$. The yearly cash flow of the government should minus this expenditure when the power project is for renewable generation. Thus, we obtain that

$$\pi_{g,t}=ER_t-OMC_t+Tax_t+TSR_t+CER_t-PSE_t \quad (24)$$

And the total net present value of the government can be expressed as follows:

$$V_{g,t}=E\left[\int_t^{t+L}e^{-r(s-t)}\pi_{g,s}ds-I_t\right] \quad (25)$$

Let $F_g(Eq_t^e)$ denotes the government's value before the project investment. And also assume that the government is risk-neutral, and the government's option value $F_g(Eq_t^e)$ must be the solution of the following equilibrium differential equation (Azevedo and Paxson, 2014), which can be described as follows:

$$\frac{1}{2}\sigma^2(Eq_t^e)^2\frac{\partial^2 F_g(Eq_t^e)}{\partial(Eq_t^e)^2}+(r-\delta)Eq_t^e\frac{\partial F_g(Eq_t^e)}{\partial Eq_t^e}-rF_i(Eq_t^e)=0 \quad (26)$$

To ensure that the investor invests at the time when the "option to invest" is maximized, the differential Eq. (26) must be solved subject to the boundary conditions (27) and (28). Mathematically, the formulas are given as follows:

$$F_g\left(Eq_{g,t}^{e*}\right)=\frac{\pi_{g,t}\left(Eq_{g,t}^{e*}\right)(1-e^{-\delta L})}{\delta}-I_t \quad (27)$$

$$F'_g\left(Eq^{e*}_{g,t}\right) = \frac{\pi'_{g,t}\left(Eq^{e*}_{g,t}\right)\left(1-e^{-\delta L}\right)}{\delta} \tag{28}$$

where $Eq^{e*}_{i,\ t}$ denotes the value of Eq^e_t that triggers the government to support the investment of the power generation project.

And the boundary conditions (27) and (28) are respectively the value-matching condition and the smooth-pasting condition, which have the same functions as the boundary conditions mentioned above for the investor. Then, the closed-form solutions for the government's support threshold $Eq^{e*}_{g,\ t}$ and value function $F_g(Eq^e_t)$ through this procedure are obtained, which can be represented as follows:

$$Eq^{e*}_{g,t} = \frac{\vartheta}{\vartheta-1}\cdot\frac{I_t\cdot\delta}{\pi'_{g,t}(Eq^e_t)\cdot(1-e^{-\delta L})} \tag{29}$$

$$F_g\left(Eq^e_t\right) = \begin{cases} \dfrac{I_t}{\vartheta-1}\left(\dfrac{Eq^e_t}{Eq^{e*}_{g,t}}\right)^{\vartheta} & Eq^e_t<Eq^{e*}_{g,t} \\ \dfrac{\pi_{g,t}\cdot(1-e^{-\delta L})}{\delta}-I_t & Eq^e_t\geq Eq^{e*}_{g,t} \end{cases} \tag{30}$$

As $Eq^{e*}_{g,\ t}$ is the threshold, only when the quantity of electricity Eq^e_t is above the government's support threshold $Eq^{e*}_{g,\ t}$ (i.e., $Eq^e_t \geq Eq^{e*}_{g,\ t}$), the government would support the investment of the power project. And when Eq^e_t becomes lower than the threshold $Eq^{e*}_{g,\ t}$ (i.e., $Eq^e_t < Eq^{e*}_{g,\ t}$), the option value of the government would be the value to wait. Thus, we then assume that the electricity quantity is enough to trigger the government to support the power project investment. The value function (payoff) of the government can be expressed as follows:

$$V_{g,t} = \frac{\pi_{g,t}\cdot(1-e^{-\delta L})}{\delta}-I_t \tag{31}$$

(2) The value of the government's strategy with ESS incentive policies

The government tries to set the levels of ESS incentive policies strategically to maximize the social welfare, which is also the payoff function of government. When the government decides to support microgrid development with ESS incentive policies, the government should pay for these ESS incentive policies. Then, the net present value of the government can be formulated as follows:

$$V'_{g,t} = V_{g,t}-PE_t \tag{32}$$

where PE_t refers to the policy expenditure of the ESS supporting policies for microgrid.

As we consider the ESS supporting policies including initial cost subsidy, the FIT mechanism, and the PTC mechanism. Mathematically, the ESS policy expenditures can be expressed by:

$$PE_t = E\left[\int_t^{t+t_{ES}} e^{-r(s-t)}(\,PS_t + TC_t)ds + \int_{t+t_{ES}}^{t+L} e^{-r(s-t)}\ TC_t ds\right] + ICS_t \tag{33}$$

Since the investor is the direct beneficiary of the ESS supporting policies for MG project, the government's ESS policy expenditures could be vary if the investor chooses to invest in distributed generation rather than MG project. It means the investor is not qualified to accept the policies' support when chooses to invest in distributed generation. And the government would be charged for a small portion ϕ of the ESS policy expenditures at this moment. Additionally, if the investor chooses to invest in MG project, but the government's strategy choice is not to support microgrid investment, there will cause the loss of social welfare from MG investment as without the government support, the implementation of microgrid might be not well-regulated in the electricity market since MG is still a new generation technology. Hereon, we consider the loss rate of social welfare is ρ for the government.

Table 1
Stage game of microgrid development.

		The investor	
		Investment(I)	No investment (NI)
The government	No support (NS)	V^{11}_g, V^{11}_i	V^{12}_g, V^{12}_i
	Support (S)	V^{21}_g, V^{21}_i	V^{22}_g, V^{22}_i

3.3.3. *Stage game of optimal ESS incentive policies for microgrid development*

Through the analysis above, Table 1 shows the stage game for microgrid development. The strategy space of the investor includes MG investment (I) or no input (NI), which can be defined as $S_i = \{I, NI\}$. And the strategy space of the government includes support MG investment with ESS supporting policies (S) or no support (NS), that can be defined as $S_g = \{S, NS\}$. Since this is a stage game, we then analyze the unique mixed strategy equilibrium. The payoff matrixes of the government and the investor are respectively defined as A and B, that can be expressed by:

$$\mathbf{A} = \begin{pmatrix} V^{11}_g & V^{12}_g \\ V^{21}_g & V^{22}_g \end{pmatrix}, \mathbf{B} = \begin{pmatrix} V^{11}_i & V^{12}_i \\ V^{21}_i & V^{22}_i \end{pmatrix} \tag{34}$$

In the stage game, pairs of the players are randomly drawn from two populations, and obtain the expected payoff in Table 1 (Friedman, 1998). For the government's payoff, we suppose that x_h denotes the probability when it takes the pure strategy $h \in S_g$, and y_k denotes the current proportion of the investor taking the pure strategy $k \in S_i$. Apparently, $x_h, y_k \geq 0$, $\sum_{h\in S_g} x_h = 1$, $\sum_{k\in S_i} y_k = 1$. Then, let the mixed strategy of the government and the investor for power investment are expressed by vectors **x** and **y**, respectively. The expected payoffs of the government and the investor are formulated as follows:

$$\begin{aligned} u_g(\boldsymbol{x},\boldsymbol{y}) &= \boldsymbol{x^T}.\boldsymbol{Ay} = (x_1 \quad 1-x_1)\begin{pmatrix} V^{11}_g & V^{12}_g \\ V^{21}_g & V^{22}_g \end{pmatrix}\begin{pmatrix} y_1 \\ 1-y_1 \end{pmatrix} \\ &= x_1\left[V^{11}_g y_1 + V^{12}_g(1-y_1)\right] + (1-x_1)\left[V^{21}_g y_1 + V^{22}_g(1-y_1)\right] \end{aligned} \tag{35}$$

$$\begin{aligned} u_i(\boldsymbol{x},\boldsymbol{y}) &= \boldsymbol{y^T}.\boldsymbol{B^T}\boldsymbol{x} = (y_1 \quad 1-y_1)\begin{pmatrix} V^{11}_i & V^{21}_i \\ V^{12}_i & V^{22}_i \end{pmatrix}\begin{pmatrix} x_1 \\ 1-x_1 \end{pmatrix} \\ &= y_1\left[V^{11}_{PI} x_1 + V^{21}_{PI}(1-x_1)\right] + (1-y_1)\left[V^{12}_{PI} x_1 + V^{22}_{PI}(1-x_1)\right] \end{aligned} \tag{36}$$

Thus, all the interactions between the government and the investor depend on x_1 and y_1, that are respectively chosen to maximize Eqs. (35) and (36). Then, the first order conditions are formulated as following:

$$\frac{\partial u_g}{\partial x_1} = V^{11}_g y_1 + V^{12}_g(1-y_1) - V^{21}_g y_1 - V^{22}_g(1-y_1) = 0 \tag{37}$$

$$\frac{\partial u_i}{\partial y_1} = V^{11}_i x_1 + V^{21}_i(1-x_1) - V^{12}_i x_1 - V^{22}_i(1-x_1) = 0 \tag{38}$$

Through this procedure, the solutions for Eqs. (37) and (38) are obtained. We then derive the mixed strategy equilibrium (x^*_1, y^*_1) as follows:

$$\left(x^*_1, y^*_1\right) = \left(\frac{V^{22}_i - V^{21}_i}{V^{11}_i - V^{12}_i + V^{22}_i - V^{21}_i}, \frac{V^{22}_g - V^{12}_g}{V^{11}_g - V^{21}_g + V^{22}_g - V^{12}_g}\right) \tag{39}$$

When the investor takes the strategy to invest in the MG project, and the government choose to support microgrid investment by using ESS policy incentives, there will lead to smooth development of microgrid. Hence, the probability for this event to take place is

$$P_{DE} = (1-x_1)y_1 \tag{40}$$

We then substitute Eq. (39) into Eq. (40) to obtain equilibrium position, which can be expressed as follows:

$$P_{DE}^* = (1-x_1^*)y_1^* \tag{41}$$

3.3.4. Stability analysis of periodical fluctuation for microgrid development in equilibrium state

During the game process, the replicator dynamics can be used to analyze the frequency-dependent selection of the two populations evolving over time (Taylor and Jonker, 1978). Consider two well-mixed population with a finite number of agents are programmed to play the pure strategy $h \in S_g$ and $k \in S_i$, respectively. Assume the payoffs are proportional to their reproduction rate of each individual, and a strategy profile is inherited. The replicator dynamics model of the two population are obtained, which are expressed as follows:

$$\frac{dx_h}{dt} = \left[\mathbf{A}\mathbf{y} - \boldsymbol{x}^{\boldsymbol{T}}.\mathbf{A}\mathbf{y}\right]\cdot x_h \tag{42}$$

$$\frac{dy_k}{dt} = \left[\boldsymbol{B}^{\boldsymbol{T}}\mathbf{x} - \boldsymbol{y}^{\boldsymbol{T}}.\boldsymbol{B}^{\boldsymbol{T}}\boldsymbol{x}\right]\cdot y_k \tag{43}$$

Substitute Eq. (34) into the replicator dynamics models (42) and (43), we have that:

$$\frac{dx_1}{dt} = x_1(1-x_1).\left[y_1\left(V_g^{11}-V_g^{21}\right) + (1-y_1)\left(V_g^{12}-V_g^{22}\right)\right] \tag{44}$$

$$\frac{dy_1}{dt} = y_1(1-y_1).\left[x_1\left(V_i^{11}-V_i^{12}\right) + (1-x_1)\left(V_i^{21}-V_i^{22}\right)\right] \tag{45}$$

Hereon, we investigate the stability of the fixed points in the above different equations by using Lyapunov's First Method, where a dynamically stable equilibrium concept of evolutionary equilibrium is applied (Friedman, 1998). According to Eqs. (44) and (45), the set of fixed points refers to $(x_1', y_1') = \{(1,0), (0,1), (1,1), (0,0), (x_1^*, y_1^*)\}$. By using linearization approximation to explore the stability of the nonlinear system at (x_1', y_1'), the Jacobi matrix and its corresponding eigenvalues, $\lambda_i (i = 1,2)$ are analyzed as follows:

$$\Phi = \begin{bmatrix} \partial x_1/\partial x_1 & \partial x_1/\partial y_1 \\ \partial y_1/\partial x_1 & \partial y_1/\partial y_1 \end{bmatrix}, \text{at } (x_1, y_1) = (x_1', y_1') \tag{46}$$

For the fixed point $(x_1', y_1') = (0,1)$, Φ can be evaluated as

$$\Phi = \begin{bmatrix} V_g^{11}-V_g^{21} & 0 \\ 0 & -V_i^{21}+V_i^{22} \end{bmatrix} \tag{47}$$

The corresponding eigenvalues of Jacobi matrix Φ are $\lambda_1 = V_g^{11} - V_g^{21}$ and $\lambda_2 = -V_i^{21} + V_i^{22}$. Since the eigenvalue λ_1 has positive value, the fixed point $(0,1)$ is not an evolutionary equilibrium. Following the same derivation, the fixed points $(1,0)$, $(1,1)$, $(0,0)$ are also not the evolutionary equilibrium. And to save space, we omit these computational details.

For the fixed point $(x_1^*, y_1^*) = \left(\frac{V_i^{22}-V_i^{21}}{V_i^{11}-V_i^{12}+V_i^{22}-V_i^{21}}, \frac{V_g^{22}-V_g^{12}}{V_g^{11}-V_g^{21}+V_g^{22}-V_g^{12}}\right)$, Φ is evaluated as follows:

$$\Phi = \begin{bmatrix} 0 & \omega_1 \\ \omega_2 & 0 \end{bmatrix} \tag{48}$$

where $\omega_1 = \frac{(V_i^{11}-V_i^{12})(V_i^{22}-V_i^{21})(V_g^{11}-V_g^{21}+V_g^{22}-V_g^{12})}{(V_i^{11}-V_i^{12}+V_i^{22}-V_i^{21})^2} > 0$,

$$\omega_2 = \frac{\left(V_g^{22}-V_g^{12}\right)\left(V_g^{11}-V_g^{21}\right)\left(V_i^{11}-V_i^{12}+V_i^{22}-V_i^{21}\right)}{\left(V_g^{11}-V_g^{21}+V_g^{22}-V_g^{12}\right)^2} < 0.$$

Thus, the Jacobi matrix's corresponding eigenvalues Φ in Eq. (48) are complex numbers with zero real parts, as below:

$$\begin{aligned} \lambda_{1,2} &= \pm i\sqrt{|\omega_1\omega_2|} \\ &= \pm i\sqrt{\frac{\left(V_g^{11}-V_g^{21}\right)\left(V_g^{12}-V_g^{22}\right)\left(V_i^{11}-V_i^{12}\right)\left(V_i^{21}-V_i^{22}\right)}{\left[V_g^{11}-V_g^{21}+V_g^{22}-V_g^{12}\right]\left[V_i^{11}-V_i^{12}+V_i^{22}-V_i^{21}\right]}} \end{aligned} \tag{49}$$

The system of differential equations could be stable limit cycle but it is not asymptotically stable. The trajectories of the replicator dynamics models (44) and (45) at the mixed equilibrium point can be represented by:

$$x_1 = x_1^* + x_1(0).\ cos\varphi t - y_1(0).\ sin\varphi t \tag{50}$$

$$y_1 = y_1^* + x_1(0).\ sin\varphi t + y_1(0).\ cos\varphi t \tag{51}$$

where $\varphi = \sqrt{|\omega_1\omega_2|}$, and the evolutionary functions (50) and (51) at $t = 0$ is $x_{10} = x_1(0) + x_1^*$, $y_{10} = y_1(0) + y_1^*$. Hence, the trajectories can be formulated as:

$$x_1 = x_1^* + A.\ \cos(\varphi t + \beta) \tag{52}$$

$$y_1 = y_1^* + A.\ sin(\varphi t + \beta) \tag{53}$$

where the amplitude denotes $A = \sqrt{x_1^2(0) + y_1^2(0)}$, and

$$\beta = \begin{cases} \arctan((y_1(0)/x_1(0))) & if((y_1(0)/x_1(0)))>0 \\ \pi + \ arctan((y_1(0)/x_1(0))) & if((y_1(0)/x_1(0)))\le 0 \end{cases} \tag{54}$$

Then, the trajectories of the strategies followed by the government and the investor can be described by closed orbit curves. While if it is near the equilibrium point (x_1^*, y_1^*), the trajectories would be circle orbit as following:

$$(x_1 - x_1^*)^2 + (y_1 - y_1^*)^2 = A^2 \tag{55}$$

According to Eq. (55), we can be found that x_1 and y_1 denotes the periodic fluctuations around the equilibrium point (x_1^*, y_1^*) in Eq. (39). Thus, it magnifies the probability of MG development. Since both the system variables x_1 and y_1 own phase delay in Eq. (52) and Eq. (53), it can be hardly to calculate precisely the maximum possibility of MG development. Therefore, a special case of the upper limit is considered, in which the probability of the government to support microgrid development $(1 - x_1)$ and the proportions of the investor to invest in microgrid simultaneously arrive at the maximum value. The higher limit of probability of MG development can be represented by:

$$P_{DE}^h = \left(1 - x_1^* + A\right)\left(y_1^* + A\right) \tag{56}$$

Based on Eq. (56), the probability of MG development depends on two main factors, which includes the equilibrium point (x_1^*, y_1^*) and the amplitude A (or the radius) of the limit cycle. While the equilibrium point (x^*, y^*) is affected by the corresponding parameters in Eq. (39), the amplitude A is affected by the initial state of microgrid development in the locality.

4. Numerical analysis

In this section, we apply the model using the data from photovoltaic power market in Zhejiang province, which is located on the southeastern coast of China, to explore the socially optimum ESS incentive policies for microgrid. Zhejiang province has rapid economic development and high urbanization level. At the end of 2018, Zhejiang's electric power consumption has increased to 453.28 billion kWh, and solar power, with its inexhaustible and non-polluting characteristics, only accounts for 0.59% of the total consumption (ZPBS, 2019). On the other hand, the amount of newly installed PV capacity in 2018 ranked third of all provinces and cities in China, behind Jiangsu and Hebei province. And at present, the PV installed capacity has reached about 11.38 million kW (NEA, 2019). Nevertheless, the scale is still inadequate for the development of PV power generation, which should be accelerated with the help of microgrid technology.

4.1. Data and assumptions

Assume that the PV power generation investment, which is sized to meet the additional electricity demand of local residents, equals to 10 MW. Besides, since the capacity of ESS is differential in microgrids, and is directly proportional to the DGs installed capacity of microgrid (i.e., the installed capacity of microgrid), we assume that the proportion between the ESS capacity and the capacity of MG project is 1:1. Table 2 presents the key technical and economic parameters needed in this numerical analysis, which are fact-oriented and origin from the local electricity company's statistics.

And some other parameters are described as follows: the amount of carbon emissions by unit coal-fired power and the long distance transmission loss rate of electricity are sourced from the Electric Power Development Planning (2016–2020) (NDRC, 2017), we obtain that $q_t^c = 0.83$ (kg/kWh) and $LR = 6.64\%$; the carbon emission price is 0.0998 (CNY/kg) collected from China emissions trade net (Access at: http://www.tanjiaoyi.com/); the discount rate of the PV distributed generation project and MG project are both evaluated by using the data of Energy Research Observer (Access at: http://www.chinaero.com.cn/), which respectively refer to $r = 0.08$ and $r = 0.1$. Additionally, the drift and volatility terms are estimated by applying the maximum-likelihood estimates method[1] with the data of electricity consumption in Zhejiang province during the past ten years (Zhang et al., 2016). We conclude that the drift term α is equal to 0.07 and that the volatility term σ is equal to 0.04. For the portion of the ESS policy expenditures, it is $\phi = 0.1$ when the government supports MG investment with ESS supporting policies, but the investor chooses to invest in distributed generation, and the social welfare's loss rate refers to $\rho = 0.18$ when the investor's strategy choice is to invest in microgrid without the government's support.

Table 2
Input data of the parameters.

Parameters	Description	Distributed generation	Microgrid
Local electricity market price, CNY/kWh	Ep_t^d	0.75	0.75
Unit cost per capacity of the PV generation, CNY/kW	UI_t	6500	15,000
Unit operation and maintenance cost, CNY/kWh	$uomc_t$	0.2	0.49
The generating capacity of unit solar PV system, kWh	Eq_t^e	1500	1800
Unit price subsidy, CNY/kWh	EPb_t	0.42	0.42
Lifetime of the photovoltaic system, years	L	25	25
Lifetime of the ESS, years	L_{ES}	–	10
Cycle life of the ESS, times	L_{CL}	–	4300
Efficiency of the storage system, %	φ	–	93
Fill rate of the solar PV system	Fr	0.8	0.98
Tax rates, %	γ	17	17

[1] $\alpha = \Delta\overline{Eq} + (1/2)\cdot s^2$, $\sigma = s$, where $\Delta\overline{Eq}$ and s are respectively the mean and standard derivation of $Eq_t - Eq_{t-1}$.

4.2. Scenario analysis of the optimal ESS supporting policies for microgrid

4.2.1. Initial state of microgrid development

To obtain optimum strategy of ESS incentive policies for the PV microgrid, we apply the model formulated in Section 3 by using the data described above. According to Eq. (56), the upper limit of microgrid development probability P_{DE}^h is influenced by two factors, which includes the amplitude associated with the initial state of microgrid development on the basis of Eq. (54), and the equilibrium state relevant to the strategy payoffs of each player for PV power generation investment in the light of Eq. (39). By 2017, the installed capacity of PV microgrid accounts for about 0.00731 of the total capacity of solar PV power generation in Zhejiang province, which is collected from Zhejiang Provincial Development and Reform Commission (Access at: http://fzggw.zj.gov.cn/).Hence, the possibility of MG development in reality is nearly 0.00731. Given the current MG development probability $P_{DE} = (1 - x_1)y_1 = 0.00731$, we assume that the initial values of MG development refer to $x_{10} = 0.25$, and y_{10}=0.00975, where a substantial probability of the government takes the strategy of supporting MG development, and few investors invest in microgrid. Then, we suppose the small values of the ESS incentive policies for microgrid, in which the initial cost subsidy for ESS denotes $Csb_t = 100$ (CNY/kWh), the electricity price subsidy denotes $Psb_t = 0.2$ (CNY/kWh), which would be implemented for 10 years,and the tax credit for the ESS denotes $\theta = 0.4$. In the light of Eq. (55), the development system of microgrid (x_{10},y_{10}) oscillates around the center (0.242, 0.0607) with frequency that equals to 217.523, and the amplitude that equals to 0.0516. And the trajectory exhibits an irregular circle for the initial scenario deviating from the center.

With the parameter values as given, the upper limit of the probability of MG development can be calculated as $P_{DE}^h = 0.0909$, and the right picture of Fig. 2 presents the periodical fluctuation of microgrid development probability. And it can be found in Fig. 2 that the upper limit of MG development is a little bit above the peak value as both the system variables x_{10} and y_{10} have phase delay. Meanwhile, we then change the initial states of microgrid development. As shown in Fig. 2, when the initial state of the government x_{10} is changed, there are significantly differences in the fluctuation amplitudes of microgrid development. More specifically, the fluctuating amplitude is $A = 0.0516$ under the initial scenario, while the amplitude increases to $A = 0.119$ when the initial state of the government is $x_{10} = 0.35$. However, even if the fluctuation amplitudes vary, little difference exist between the theoretical results of the left picture and the right picture in Fig. 2. As can be seen from Fig. 2, the equilibrium position of MG development possibility is determined, i.e., $P_{DE}^* = 0.046$, although the actual value of the probability would become larger under the initial state $x_{10} = 0.35$, and y_{10}= 0.00975. And this can also be applied to the change of the initial state of investor y_{10}. Therefore, we only discuss the relative benefit-cost derived from the players' different strategies under the initial state $x_{10} =$ 0.25, and y_{10}=0.00975.

4.2.2. Microgrid development with different ESS supporting policies

In the light of Eq. (39), all the payoffs of different strategies, including the government and the investor's payoffs, can affect the MG development probability in the equilibrium state. In addition, these benefit-costs can also influence the probability of microgrid development P_{DE} and the fluctuation trajectory of microgrid development system (x_1,y_1) in the light of Eqs. (40) and (55). Thus, under different ESS incentives, the fluctuation of microgrid development probability must be differential. We then examine the effects of ESS incentive policies for

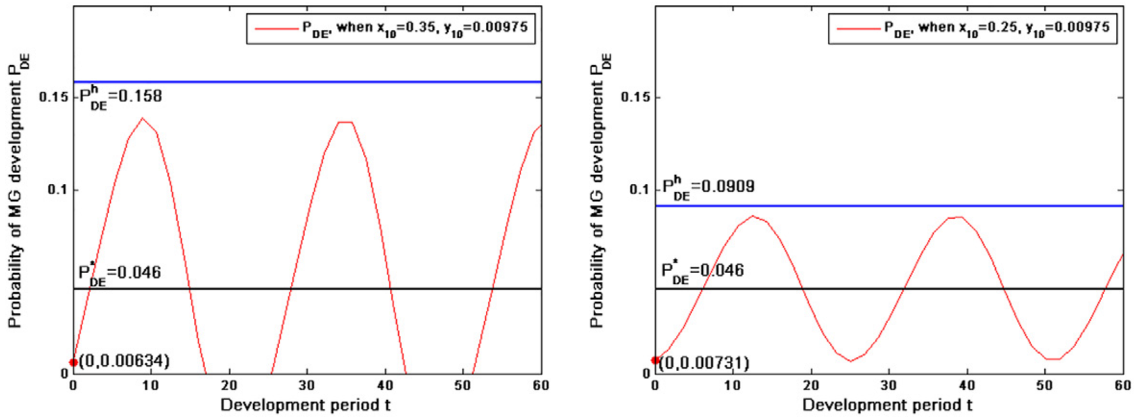


Fig. 2. Periodical fluctuation of microgrid development probability under different initial states.

microgrid by using the fluctuation amplitude and equilibrium position, which are analyzed as below:

(1) ESS initial cost subsidy

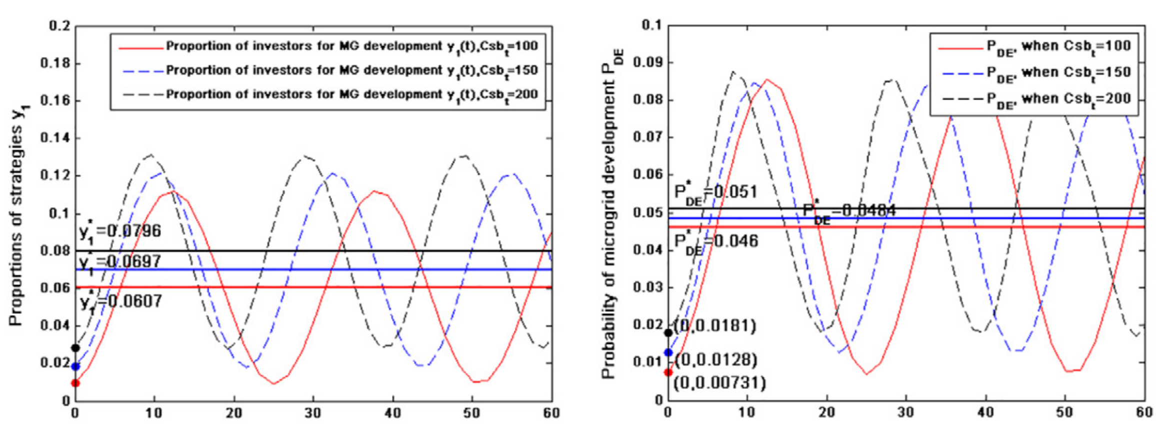
Considering the one-off investment subsidies, we suppose the larger ESS initial cost subsidies are $Csb_t = 150$ (CNY/kWh) and $Csb_t = 200$ (CNY/kWh), which are respectively increased by 50% and 100%. The new equilibrium proportions of investors to invest in MG project respectively rise to $y_1^* = 0.0697$, and $y_1^* = 0.0796$, which are raised by 14.83% and 31.14%. The new equilibrium probability of the government to support MG development decrease to $(1 - x_1^*) = 0.694$, and $(1 - x_1^*) = 0.641$, that are respectively reduced by 8.44% and 15.44%. And the new waves frequencies respectively increase to φ=253.717 and φ = 284.614. As a result, the equilibrium position of microgrid development probability grows to $P_{DE}^* = 0.0484$ and $P_{DE}^* = 0.051$, which are raised by 5.22% and 10.87%, respectively. Fig. 3 shows the comparison of the changes of the trajectory and the probability of microgrid development under different ESS initial cost subsidies.

In the light of right panel (b) in Fig. 3, the lager initial cost subsidies for ESS that provided by the government constitute lower threshold of the MG investment, which means more investors for power investment are qualified to invest in microgrid, and then improve the probability of microgrid development. And also, we can find that the growth of microgrid development possibility comes slowly with larger ESS initial cost subsidy. However, with the increase of initial cost subsidy, the motivation of the government to support MG development remains stable. Hence, the effect of initial cost subsidy for the ESS in microgrid has two sides and need to be further discussed.

(2) The FIT mechanism for ESS

Given that the added ESS price subsidies for microgrid are respectively $Psb_t = 0.3$ (CNY/kWh) and $Psb_t = 0.4$ (CNY/kWh), that are respectively increased by 50% and 100%. The new equilibrium proportions of investors to invest in MG project are $y_1^* = 0.084$ and $y_1^* = 0.115$, that are raised by 38.39% and 89.46%, respectively. The new equilibrium probability of the government to support MG development reduces to be $(1 - x_1^*) = 0.621$, and $(1 - x_1^*) = 0.527$, which are respectively decreased by 18.02% and 30.48%. And the new trajectories' wave frequency are respectively raised to φ = 296.132 and φ= 353.451. Hereon, the equilibrium position of microgrid development probability grows to $P_{DE}^* = 0.0522$ and $P_{DE}^* = 0.0606$, which are raised by 13.48% and 31.74%, respectively. The comparison of the changes of the trajectory and the probability of microgrid development under different ESS price subsidies are shown in Fig. 4.

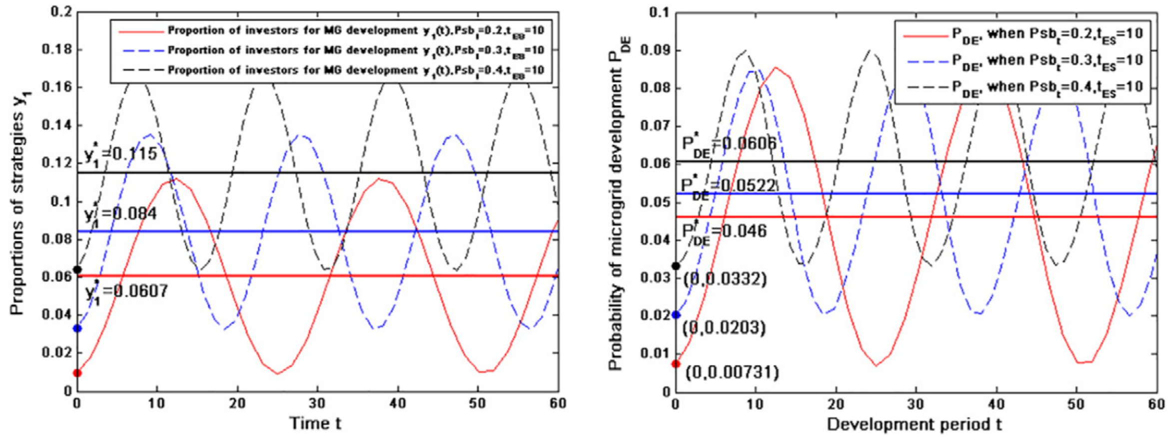
The light panel (b) of Fig. 4 provides important policy connotations. On one hand, with the larger price subsidies for the electricity released from the ESS in microgrid, there will be higher yearly cash flow for investing in MG project, which could arouse the investors' enthusiasm for MG investment, and then improve the microgrid development possibility. As shown in right panel (b) of Fig. 4, the probability of microgrid development grows fast with the larger ESS price subsidies for microgrid. Nevertheless, on the other hand, the probability of the



(a) Investors proportion for MG development

(b) Probability of MG development

Fig. 3. Periodical fluctuations considering the ESS initial cost subsidy.



(a) Investors proportion for MG development (b) Probability of MG development

Fig. 4. Periodical fluctuations considering the FIT mechanism for ESS.

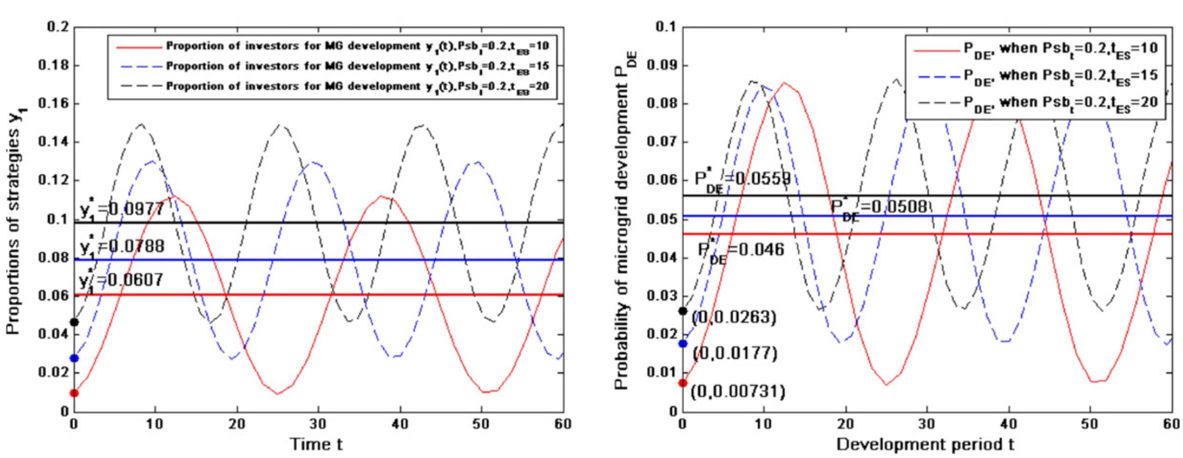
government to support microgrid investment descends rapidly when the ESS price subsidy level is increased. Therefore, although the FIT mechanism can effectively improve the probability of microgrid development, it cannot well guarantee the government's support for MG investment since it causes a certain social welfare loss. This could lead the development of microgrid becomes unstable. Therefore, a combination of the FIT mechanism with other incentive policies is recommended to ensure the government's support, e.g., initial cost subsidy, and tax policies.

Since the implementation period of the FIT mechanism for ESS could be changed and then affect the fluctuation trajectory of microgrid development. We also suppose the larger values for the implementation period of the FIT mechanism for ESS, which are respectively $t_{ES} = 15$ and $t_{ES} = 20$ (increased by 50% and 100%). The new equilibrium proportion of investors to invest in MG project denotes $y_1^* = 0.0788$ with the implementation period for the FIT mechanism $t_{ES} = 15$, while the equilibrium proportion denotes $y_1^* = 0.0977$ with the implementation period $t_{ES} = 20$. Hence, the new equilibrium proportion of investors to invest in MG project are increased by 29.82% and 60.96%, respectively. On the other hand, the new equilibrium probability of the government to support microgrid development become $(1 - x_1^*) = 0.645$, and $(1 - x_1^*) = 0.572$, respectively, which are reduced by 14.91% and 24.54%. Besides, the equilibrium position of microgrid development probability reaches $P_{DE}^* = 0.0508$ when the FIT implementation period denotes $t_{ES} = 15$, and the equilibrium position of microgrid development probability reaches $P_{DE}^* = 0.0559$ when the FIT implementation period denotes $t_{ES} = 20$, that are raised by 10.43% and 21.52%, respectively. And Fig. 5 shows the comparison of the changes of the trajectory and the probability of MG development under different implementation periods of the FIT mechanism for ESS.

In the light of the right panel (b) in Fig. 5, the total net present value for MG project rises with larger implementation period of the FIT mechanism for ESS, which stimulates the investor to invest in microgrid project. Thus, it can also facilitate microgrid development to extend the implementation period of the FIT mechanism for ESS, with which the probability of microgrid development are raised. As if the implementation period of the FIT mechanism for ESS is extended, the government's motivation to support microgrid also descends, but it is slower than raising the level of the price subsidy for ESS. Hence, a longer implementation period for the FIT mechanism is recommended to ensure the government's support for MG investment.

(3) The PTC mechanism for ESS

In case microgrid is provided with larger production tax credit for the electricity released from its ESS, which are respectively $\theta = 0.6$ and $\theta = 0.8$ (raised by 50% and 100%). The new equilibrium proportions of investors to invest in microgrid rise to $y_1^* = 0.0808$ and $y_1^* = 0.106$, that are respectively raised by 33.11% and 74.63%, the new equilibrium probability of the government to support microgrid decrease to $(1 - x_1^*) = 0.636$ and $(1 - x_1^*) = 0.548$, that are respectively reduced by



(a) Investors proportion for MG development (b) Probability of MG development

Fig. 5. Periodical fluctuations considering the FIT's implementation period.

16.09% and 27.7%, and the new waves frequencies respectively increase to φ=287.756 and φ = 340.604. Therefore, the probability of microgrid development in equilibrium state will achieve $P_{DE}^{*} = 0.0514$ with an increasing rate of 11.74%, and then reach $P_{DE}^{*} = 0.0597$ with an increasing rate of 29.78% under different tax credits as assumed. The comparison of the changes of the trajectory and microgrid development probability under different tax credits for ESS are shown in Fig. 6.

The PTC for the electricity from the ESS in MG would lighten tax burden of the project, and when the government increases the tax credit, there will be higher yearly cash flow for the MG project. The probability of microgrid development becomes higher in the light of the right panel (b) in Fig. 6. It should be noted that irregular crossings exist between different wave lines of the microgrid development probability considering the PTC mechanism for the ESS, which could be caused by the phase cancellation between the proportion of the government to support MG investment $(1 - x_1)$ and the investors to invest in MG y_1. Even though the tax credit can effectively promote the development of microgrid, the relationship between the government and investor for new power investment is not always noncooperative with regard to the policy implementation. The degree of noncooperation for the relationship could be changed under the differential effect of the incentive policy on their payoffs. And this can also be applicable to other ESS incentive policies.

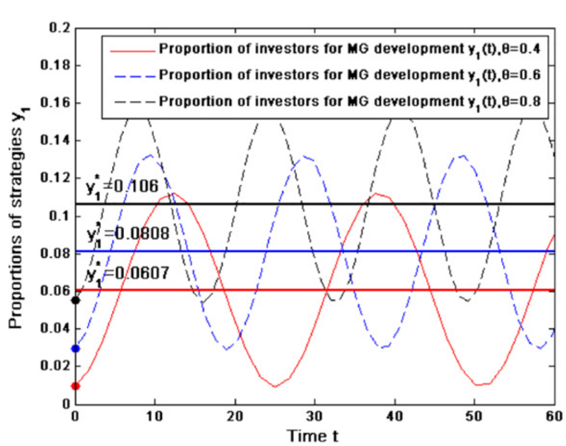
The fluctuation results of microgrid development under different ESS incentive policies are shown in Table 3. As can be seen from Table 3, the policy incentives for ESS in microgrid, including initial cost subsidy, the FIT mechanism and the PTC mechanism, all could improve the probability of MG development. And among these incentive policies, the FIT mechanism for ESS has the greatest effect on microgrid implementation, and then follow with the PTC mechanism for the storage system in microgrid. However, although raising the initial cost subsidy for ESS has limited effect for MG development, it could guarantee a certain level of government support for developing microgrid. In contrast, both the proportion of investors for MG development and the probability of microgrid development are sensitive to the change of price subsidy for electricity released from ESS in microgrid, but the possibility of the government to support microgrid descends rapidly when the ESS price subsidy level is raised. Hence, the FIT mechanism is recommended to combine with other ESS incentive policies to ensure the government's support, e.g., initial cost subsidy, and tax policies. Additionally, since longer implementation period of the FIT mechanism for ESS could help to ensure the support of the government, extending the implementation period of the FIT mechanism is recommended to effectively promote microgrid development. Further, as the PTC mechanism belongs to tax incentives, it eliminates the negative effects brought from the subsidy policies, e.g., overcapacity and lack of funds, and can be applied as a way to indirectly subsidize the ESS in microgrid. Therefore, the PTC mechanism for ESS has strong feasibility for its implementation so as to promote the development of microgrid.

5. Conclusions and policy implications

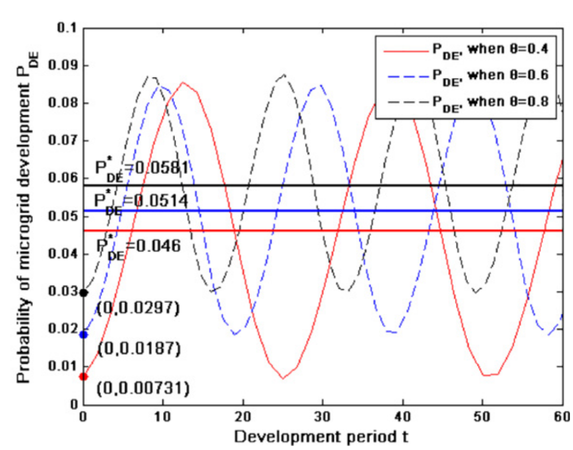
The energy storage system provides significant benefits to the operation of microgrid, but its high cost impedes the development of microgrid. Although the strategic role of providing policy support for energy storage system in microgrid has been emphasized, it still remains a high difficult issue to determine the optimal ESS incentive policies for microgrid due to the complexity of the energy storage technology and also its access to microgrid.

The significance of this paper is to provide a real option game model, which combines the evolutionary game theory with real options, for exploring the socially optimal ESS incentive policies for microgrid by using the periodical fluctuations of microgrid development under different ESS policy options, which includes the initial cost subsidy, feed-in tariffs (FIT) mechanism, and the production tax credit (PTC) for the ESS of microgrid. In the numerical example, the periodical fluctuation results show that the initial cost subsidy, the FIT mechanism and the PTC mechanism for ESS all can promote microgrid development, in which the FIT mechanism for ESS has the greatest effect and then follow with the PTC mechanism for the storage system. However, although the effect of ESS initial cost subsidy for microgrid development is limited, it could well guarantee the government support for MG development. And for the implementation of the FIT mechanism, the probability of the government to support MG development descends rapidly. Hence, the FIT mechanism for ESS is recommended to combine with other ESS incentive policies (e.g., initial cost subsidy) to effectively promote microgrid development. In addition, as longer implementation period for the FIT mechanism could help to ensure the government support for MG investment, the period is recommended to be extended when implementing the FIT mechanism. Finally, considering the tax attribute of the PTC mechanism for ESS, it has its own advantages to be implemented.

While our proposed model considers the actual power investment as much as possible, it inevitably has some limitations. Firstly, as we consider a stylized power system, the influencing factors in our study are relatively simple, and there are additional stakeholders who can affect the development of microgrid, e.g., customers and environmental nongovernmental organizations who can raise the low carbon awareness of both investors and customers. Secondly, because of the data limitation, we only use the economic surplus, transmission loss saving and carbon emission reduced to describe the social welfare that the government obtain. It may not be sufficient. Thirdly, the incentives for



(a) Investors proportion for MG development



(b) Probability of MG development

Fig. 6. Periodical fluctuations considering the PTC mechanism for ESS.

Table 3
The fluctuation results of microgrid development under different ESS incentive policies.

Parameter	Initial cost subsidy for ESS		The feed-in tariffs mechanism for ESS				Production tax credit for ESS	
			Price subsidy level		Implementation period			
	+50%	+100%	+50%	+100%	+50%	+100%	+50%	+100%
Equilibrium proportion of investors to invest in microgrid	14.83%	31.14%	38.39%	89.46%	29.82%	60.96%	33.11%	74.63%
Equilibrium probability of the government to support microgrid	−8.44%	−15.44%	−18.02%	−30.48%	−14.91%	−24.54%	−16.09%	−27.7%
Equilibrium probability of microgrid development	5.22%	10.87%	13.48%	31.74%	10.43%	21.52%	11.74%	29.78%

microgrid would also be taken into consideration, and a comparison between the effects of incentives for microgrid and the ESS incentives for microgrid may be carried out. In the future, there will be a more complete model to address these limitations, and then achieve the socially optimal ESS incentive policies for promoting microgrid development.

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