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*Original Research*

# Estimating Incentive Contracts for Solar PV-based Microgrid Production Considering Cost-Benefit Uncertainty

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## Abstract

The solar PV-based microgrid, as a new mode of production and consumption of clean energy, backs up the variability of renewables and has important implications for mitigating global climate change. However, its further development is limited because of the high cost and uncertainty, which discourages its operators' investment willingness. To guide capital investment in microgrids, we construct a real options model to investigate the flexible investment of operators and the optimal incentive contract under uncertainty. The real options method can more accurately measure the value of real assets in an uncertain environment, and help decision-makers to assess investment costs and benefits. Moreover, a demonstration project in Hefei, China is provided as a case study to analyze the impact of the peak-valley price rates and cost changes on the incentive contract. The results demonstrate that subsidies are still necessary to accelerate the development of solar PV-based microgrids. However, subsidies in Hefei can be stopped until the investment cost drops to 6101.25 RMB/kW. Alleviating the cost pressure on operators can stimulate them to adopt the solar PV-based microgrid, but rapid cost reductions and fluctuations could hinder its development. We further uncover that raising the peak-valley price rate can help to reduce the government's financial burden caused by subsidies.

**Keywords**: solar energy, renewable microgrid investment, real options method, incentive contract, cost-benefit uncertainty

## Introduction

Traditional fossil fuel power plants not only pollute the environment but also aggravate climate change. It has become a consensus to develop green, low-carbon and renewable energy. Countries all over the world have realized the urgency of energy transformation. According to the roadmap made by the International Renewable Energy Agency [1], to achieve the climate targets outlined in the Paris Agreement, decarbonization in the power sector will require renewable energy generation to account for 85%

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of total electricity generation by 2050. This requires accelerating the deployment of renewable energy, especially solar photovoltaic (PV). Nevertheless, the power system has to cope with the fluctuations caused by the current interconnection of solar energy, which may cause problems in stability, reliability, and power quality [2, 3]. Renewable microgrids, which combine new storage technologies, renewable energy resources, loads, etc., appear to significantly update the current generation model of renewable energy and back up the variability of renewables, avoiding curtailment of power from this distribution generation. They can be connected to the utility grid (grid-connected mode) and operate independently when isolated from the utility grid (stand-alone mode) during faults or other external disturbances [4, 5]. These production forms can make the power supply more reliable and flexible, and promote renewable sources to become a major contributor to energy generation, thus increasing the quality of supply [6]. A Solar PV-based microgrid would be built in the High-tech industrial development zone of Hefei, China.

Consequently, microgrids are thought to be an increasingly relevant new power production technology for integrating renewable energy sources into electricity systems [7]. Fig. 1 shows the general framework of the solar PV-based microgrid (PV-MG). The core functionalities are power generation, conversion, energy storage, consumption, and control center [8]. Microgrids have inherent intelligence and data collection functions. The control center links energy generation, storage, and consumption of energy through the information stream and energy stream between them. When power supply exceeds demand (i.e., energy excess is available), the energy storage system will operate in “charging” mode and store the excess electricity through energy conversion. Then, power remains to be stored in systems until electricity supplies fail to cover the demand or some economic incentives appear for energy storage to deliver the power to the main power grid. Further, the PV-MG creates a great peer-to-peer electricity trading environment that promotes better use of local electricity among consumers.

Despite multiple advantages of microgrids, they still face major challenges in promoting microgrid system development and expansion. High-tech industries are generally subjected to high initial investment costs, long investment payback periods and operational uncertainty [9,10]. Apart from distributed generation equipment, a typical PV-MG also needs an energy storage device, a control system, protection devices, etc., which directly increases the project investment cost. In spite of the recent declines, the high cost of PV-MG makes it unable to compete with the existing distributed renewable generation [11]. The power generation of PV-MG is limited by solar radiation intensity and power generation capacity. Compared with the distributed photovoltaic generation, the investment payback period of a PV-MG is longer and the project’s market attractiveness is quite low [12].

Furthermore, given the globalization of procurement and today’s unstable economic environment, the operator has to take over the risks and be exposed to the market uncertainties as well as the financial disruption. According to the report issued by [5], the cost of a microgrid is highly variable and has fallen by half in the past 15 years. The electricity prices are also variable, and such fluctuations are becoming more frequent, especially after introducing the time-of-use pricing scheme, a more efficient pricing mechanism, in the electricity market. The uncertainties of the costs and benefits make operators hesitate to adopt microgrids. Even for a positive net-present-value (NPV) project, the operator has to assess opportunity costs [13]. Therefore, in an uncertain environment, postponing the investment to obtain more information may be an optimal decision for operators rather than investing immediately. Thus, the current adoption of PV-MG without incentives remains unlikely. The sustainable

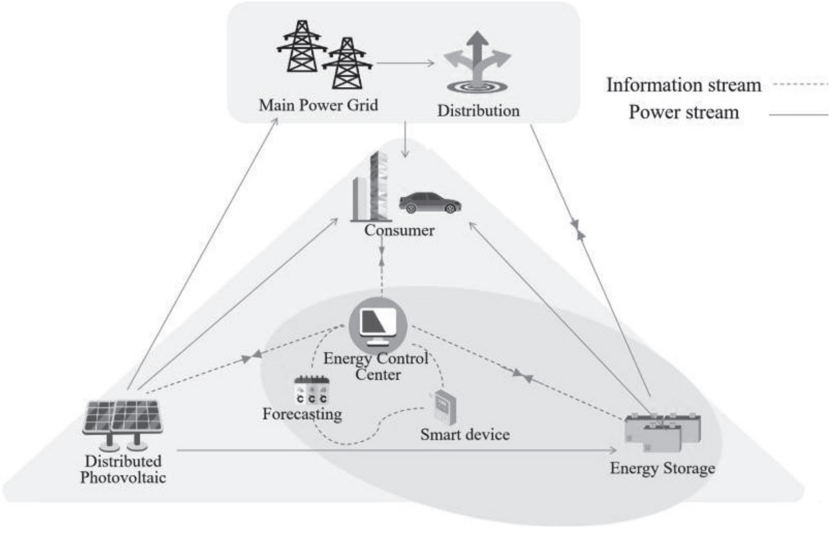

Fig. 1. A typical solar PV-based microgrid model.

market growth and long-term profitability of microgrid systems require timely, focused government action, which remains essential to support investment and accelerate the development of the PV-MG.

The relationship between the government and the operator is like the supplier and the operator in a clean power supply chain, the operator will consider whether to accept the contract and start producing clean electricity based on the electricity price subsidy offered by the supplier (the government). The subsidy contract defines a fixed payout for the unit electricity generated by renewable energy, which is considered as one of the most effective policies for encouraging investment in renewable energy [14]. How can incentive contracts motivate the operator to adopt this new technology and generate electricity actively when both costs and benefits change? When will that incentive policy be removed to allow renewable energy microgrids to compete in the market? These issues relate to the investment, production, and profitability of microgrids, which are critical to accelerating the expansion of renewable energy generation, alleviating energy constraints, and reducing carbon emissions. This paper will evaluate the value of the PV-MG project and try to give a preliminary solution to these problems by using a real options method.

Considering the operating environment with high uncertainties, this study builds a real options model to design an incentive contract for the government and operator. First, our model can ensure that the incentive contract attracts operators to invest in PV-MG power generation projects without adding an excessive fiscal burden to the government. Second, this study assumes operators have the right to decide either to invest immediately or to delay and then measures operators' opportunity cost under the uncertainty of investment costs. Third, to correctly estimate the income of the operator, this study calculates the time-of-use pricing changes into the cost-benefit analysis. Fourth, we identify the investment threshold, incentive function and subsidy estimation method under the uncertainty of electricity price and investment cost.

We find that alleviating the cost pressure on operators can stimulate them to adopt this new technology, i.e. PV-MG, but rapid cost reductions and fluctuations could hinder the development. In addition, we identify the conditions under which operators could benefit from the time-of-use pricing scheme and come to a conclusion: when peak-valley price rates exceed the inflection point, time-of-use pricing schemes would bring additional revenues to PV-MGs, thereby reducing subsidies paid by the government. Further, an increase (decrease) in peak-valley price rates and a decrease (increase) in component costs have a substitution effect for operators. Given that these factors are constantly in flux, governments should adjust subsidy contracts timely to encourage investment without burdening governments and other users too much.

## Related Work and Contributions

The renewable microgrid, as a new mode of production and consumption of clean electricity, has huge potential to enable high renewable energy shares in the electric system [8]. Nonetheless, there are major challenges in connecting the microgrid system to the distribution grid. One major obstacle here is the low enthusiasm of the market to invest in the microgrid. Such projects usually have typically higher capital costs than the conventional solar photovoltaic power generation. And due to technology and production uncertainties, operators need to bear greater market risk. If the microgrid deployment is not profitable, i.e., the microgrid revenue does not exceed the capital expenditure, the microgrid would not be deployed [15].

In many ways, the valuation of costs and benefits represents a classic problem in the contract design field [16, 17]. To overcome the problem of higher investment capital for renewable energy projects, Haghi et al. [18] surveyed the government, energy hub operators and consumers in Canada. They studied the effect and cost-efficiency of different incentives and the potential for hydrogen energy storage on the perceived viability of a microgrid project. Chen & Wei [19] analyzed a socially optimal construction strategy of the solar photovoltaic-powered community microgrid and found emission permits trade policy and feed-in tariff policy could play significant roles in encouraging investment as well as the operation of photovoltaic microgrids. Mahani et al. [20] presented an approach for optimizing the operation and maintenance strategies jointly for a solar-powered microgrid, considering the correlation between multiple policies. The proposed approach could be used to minimize the waste of money on both sides.

In a deterministic setting without the consideration of uncertainty and managerial flexibility, the above NPV methods are adequate and most used. However, the traditional NPV model is unable to consider the impact of the peak-valley price rate and technological progress effect because an investment can only be made once in the initial period. They neglected that the cost and benefit of the microgrid are constantly changing in both manufacturing and sales processes, which leads to uncertainties and will affect the formulation of incentive policies [13].

The real options approach was originally used in the field of financial research. It is a classical option valuation technique that is widely used [21]. More importantly, the method is found very effective for analyzing the costs and benefits due to its capacity to cope with uncertainty and flexibility [22]. By valuating this flexibility, the method can assess the value of real assets in an uncertain environment more accurately, and assist managers to evaluate costs and benefits [23, 24]. Quite a few scholars have undertaken to introduce the idea of the real options into incentive contracts estimation [13, 25]. The real options method has been increasingly recognized as a practical tool to deal with the variable factors in the production process of enterprises. We also apply the real options method and make the following contributions:

Firstly, we try to introduce the real options method into the production and operation of the PV-MG to reveal the conditions under which the operator could adopt a PV-MG project immediately or postpone such decisions for a period of time. There have been few studies exploring the flexible investment of operators under cost-benefit uncertainty. In fact, operators have some leeway about the timing of investment, and they can postpone action to get more information about the future.

Secondly, we have noticed that PV-MG has the characteristic of rapid cost change. Technical progress could reduce the prices of major modules, thus affecting the microgrid investment cost [10]. The cost will fluctuate significantly over time, which cannot be ignored for projects with high initial investment costs and long investment payback periods. The existing literature has not been able to respond to these questions well. This paper measures how cost fluctuations affect the government's subsidy decisions.

Thirdly, we identify the conditions under which operators can benefit from the time-of-use pricing scheme. While some related studies [25, 26] consider only a single-uncertain factor and didn't pay attention to changes in pricing markets, such as peak-valley price rates of the time-of-use electrical price scheme advocated by the government.

## Model Setting

We model the government as the supplier, who announces and commits to subsidy contracts at the beginning of each period. The investor, as the operator, has an option to accept a supply contract provided by a supplier. The operator determines whether and when to invest in PV-MGs, according to the costs and benefits analysis. Once operators decide to accept government subsidies, they will build microgrids and generate clean electricity. Then, clean electricity will enter the electricity market and replace electricity generated from fossil fuels, thus giving the government policy benefits. This analytical framework has several applications in interactions between government and investors [16, 19]. Moreover, the present degree of competition in the microgrid investment market is not high due to lacking potential entrants. Most operators make their decisions according to levels of the incentive but not the competition with their rivals, and their behaviors can be viewed as homogeneous. Hence, we study the strategic interaction between one incentive supplier and one representative operator.

Fig. 2 gives a schematic representation of the model. As shown in the left part of Fig. 2, upon accepting the supply contract, the operator is obligated to build PV-MGs and generate clean electricity, and the payment for each unit of power from the government is $S_p$. Operators have the right to choose when to start investing. As shown in the right part of Fig. 2, the uncertainty of the project returns is so great that they will not invest at time $t_0$, but delay the investment to obtain more market information that is useful for decision-making, such as option 1 or i. To avoid the problem of slow microgrid development caused by all operators delaying investments, the government will provide incentives to increase operators' project incomes, and eventually enable operators to actively invest in microgrid projects. Then, the whole society will benefit from environmental improvements and renewable energy development.

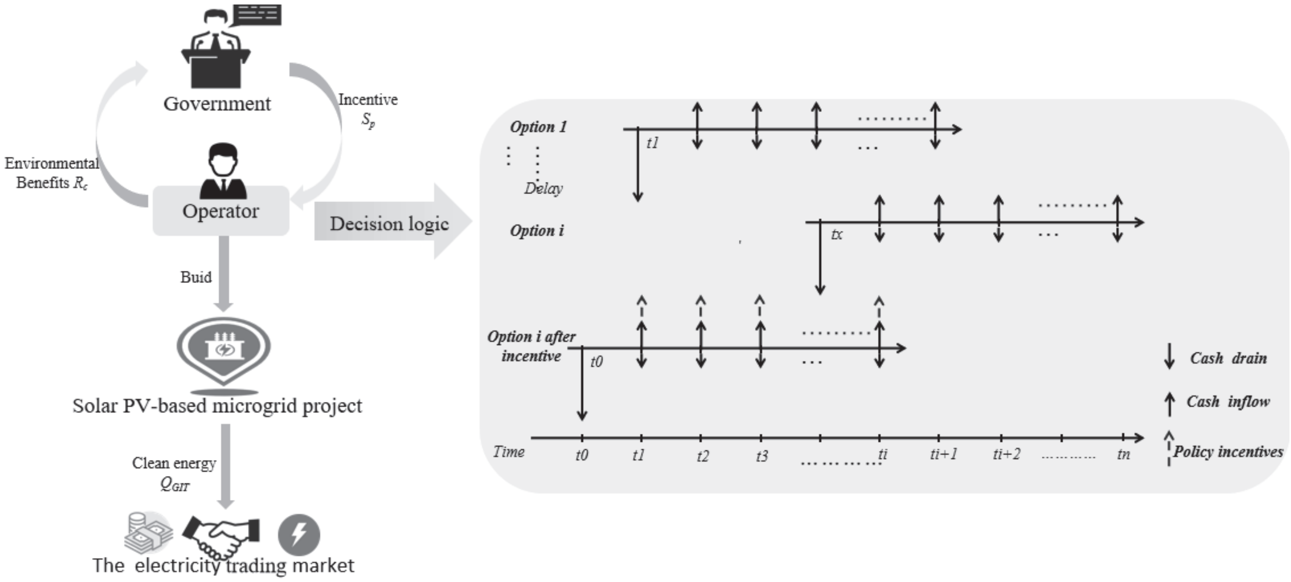

Fig. 2. The model structure under uncertainty.

## Costs and Benefits Analysis Using the Real Options

As with most high-tech projects, the PV-MGs are characterized by high initial costs, high investment risks, and long investment payback periods. The government aims to develop the PV-MGs to increase the proportion of renewable energy in the electricity system, while the profit-driven operators hesitate to adopt PV-MGs unless they bring considerable profits. Hence, the costs and benefits of operators need to be weighed to design the optimal subsidies. The NPV technique ignores the flexibility of operators' investment decision-making, and operators can constantly re-evaluate the market conditions and then choose the appropriate investment time to maximize the project benefit [19]. Real options can effectively combine the present and the future to weigh investment, and have advantages in dealing with uncertainty [27]. It is like an American call option.

### *Annual Income of PV-MG*

Operators also consume electricity generated by the PV-MG to meet their own needs while obtaining investment income. Hence, economic benefits include three parts: First, instead of purchasing electricity from the power company, users could directly use the power generated by the PV-MG to meet their daily needs. Second, because of the storage, the PV-MG could significantly benefit from generating power at peak hours to supply local loads and selling the excess power to the main grid. Third, operators can benefit from carbon emissions trading. The PV-MG has almost zero emissions compared with fossil energy generation, so environmentally friendly enterprises, i.e. the PV-MG operators, could benefit from selling carbon emission allowances. Thus, the annual income $Y_{in}$ is represented by the following equation:

$$Y_{in} = R_e + R_s + R_c \tag{1}$$

where $R_e$ is the market price of the self-use part, $R_s$ represents the income from selling electricity, and $R_c$ is obtained from selling carbon emission allowance.

(1) Consumed by the local loads

The distributed power generator can provide commercial consumers with daily electricity, so as to avoid buying power from the grid corporation. This means saving electricity bills for the operator. The calculations are as follows:

$$p_e = \begin{cases} p_{nor} & t \in T_{nor} \\ p_{val} : \quad p_{nor} \cdot z & t \in T_{val} \\ p_{peak} : p_{nor} \cdot z \cdot x & t \in T_{peak} \end{cases} \tag{2}$$

$$R_e = P_{nor} \cdot Q_1 + P_{val} \cdot Q_2 + P_{peak} \cdot Q_3 \tag{3}$$

$$R_e = P_{nor} \cdot Q_1 + P_{nor} \cdot z \cdot Q_2 + P_{nor} \cdot z \cdot x \cdot Q_3 \tag{4}$$

where $P_{nor}$, $P_{val}$, $P_{peak}$ indicate the normal time price, the valley time price, the peak time price, and $Q_1$, $Q_2$, $Q_3$ *are* the power quantity. $z$ is the price reduction during the period of valley time $T_{val}$, and $x$ is the price increase during peak time $T_{peak}$. Variable $x$ reflects the peak-valley price rate of the local time-of-use pricing scheme.

(2) Benefits of selling the surplus electricity energy

If the generated PV power exceeds the user's actual electricity demand, the surplus PV power can be sold to the power grid during peak price time, with the regulation of energy storage and control centers. It gains the benefit of the time-of-use pricing scheme through the spatiotemporal translation of electrical energy. The selling electricity benefits of PV-MG are expressed as follows:

$$R_s = P_{peak} \cdot Q_4 \tag{5}$$

$$Q_4 = Q_{GTI} - (Q_1 + Q_2 + Q_3) \tag{6}$$

where $Q_4$ is the excess electricity, and $Q_{GTI}$ represents the maximum power generation of PV-MG, which is decided by the located global tilted irradiation (GTI) [28, 29]. On the technical side, compared with the areas with sufficient GTI, project PV-MG will generate less electricity in the areas with insufficient GTI. The $Q_{GTI}$ will directly affect the project revenue, so the yearly income function is subject to the located GTI.

(3) Environmental benefits

Traditional fossil fuel power generation emits a large number of greenhouse gases. Compared with traditional fossil energy power generation, solar power generation has almost zero carbon emissions and does not produce air pollutants. When the PV-MG is for renewable energy generation, there will be environmental benefits. The carbon trading market can bring additional benefits to companies that reduce carbon emissions. The construction of the carbon trading market has become an important part of the policy response to climate change around the world [28, 30]. The basic principle of carbon trading is that one party pays the other to obtain permits for greenhouse gas emissions. Thus, if operators choose to build PV-MG, they could sell carbon emissions rights in the carbon market. And the profit function is expressed as:

$$R_c = Q_{GTI} \cdot \omega \cdot P_c \tag{7}$$

where $P_c$ represents the trading price in the carbon market, and $\omega$ is the coefficient to measure the carbon emission reduction.

### *Annual Expenditure of the PV-MG Project*

There are two major expenses for the operator: First, to ensure the daily operation of a power generation project, we need to calculate the operation and maintenance cost (*M*). Second, the PV-MG project must bear the expenditure of various taxes and charges (*Tax*). Thus, we derive the following formulas:

$$Y_{ex} = M + Tax \tag{8}$$

(1) Cost of operation and maintenance

Once the PV-MG project starts operation, there will be a small amount of operation and maintenance costs, including materials expenses, repair charges, and other expenses. This study assumes that the annual operation and maintenance cost remains unchanged, and it is related to the project scale. Mathematically, we get the following formula:

$$M = (R_e + R_s) \cdot m \tag{9}$$

where $m$ refers to the operation and maintenance cost coefficient of the power project.

(2) Tax expenditure

The various tax expenditures refer to the taxes on PV-MG projects and the administrative expenses from permitting, inspection and interconnection projects [20]. The types are mainly income tax, value-added tax, land-use tax, urban construction tax, and education surcharge. To focus on the optimal incentives, this study uses the comprehensive tax rate to calculate the total tax expenditure [25]. The function is expressed as:

$$Tax = (Y_{in} - M) \cdot \eta \tag{10}$$

where $\eta$ is the comprehensive tax rate. The tax expenditure is equal to the difference between the economic benefits obtained by the electricity sale and the operation and maintenance costs multiplied by the comprehensive tax rate.

### *Initial Investment Expenditure*

Initial investment cost accounts for a quite large proportion of the total cost of a PV-MG project, which greatly affects the operator's decisions. As a high-tech industry, the PV-MG uses new renewable energy technologies to maintain the reliable and economic operation of the system. For a PV-MG project, the initial investment expenditure is formed of the equipment acquisition cost, construction cost, and other costs. Thus, the initial investment cost is expressed as:

$$I_{initial} = UI \cdot IC \tag{11}$$

where $UI$ is the unit investment cost, and $IC$ represents the installed capacity.

In the high-tech field, there is an obvious inverse relationship between technological progress and cost. With the progress of technology, the price of major modules and the investment cost of the microgrid will decrease significantly. Along with technological progress, the initial investment cost will gradually decrease, but it is also affected by some uncertain factors, such as economic fluctuations, policy changes, changes in market supply and demand. This change in a variable is usually described by scholars as the geometric Brownian motion (GBM) [31, 32]. In this study, the uncertainties in PV-MG initial investment cost are also described as GBM stochastic process, which is expressed as follows:

$$dUI = \mu \cdot UI \cdot dt + \sigma \cdot UI \cdot dw \tag{12}$$

where $\mu$ represents the (expected) risk-neutral drift of the initial investment cost, $\sigma$ represents the volatility of the initial investment cost, $dw$ is an increment of a Wiener process $dw = \varepsilon_t \sqrt{dt}$ , and $\varepsilon_t \sim N(0,\ 1)$.

## Operators' Rational Decisions

Assume that the operator is risk-neutral, and has the right to choose when to start investing. We use *F(UI)* to express the value of investment opportunities in PV-MG projects, that is, how much the operator should be willing to pay today to have the option to invest in the PV-MG project. The project will not yield any cash flow until the investment is implemented. Before the investment, the appreciation of *F(UI)* is equal to its capital appreciation. Thus, as we saw in equation (13), *F(UI)* also meets the Bellman equation [22], and the formula is as follows:

$$E\left[dF(UI)\right] = r \cdot F\left(UI\right) \cdot dt \tag{13}$$

Equation (13) represents that over a time $dt$, the total return of the PV-MG project investment opportunity is equal to its capital expected increment rate. The total differential of $dF$ is derived as

$$dF = \frac{\partial F}{\partial t}dt + \frac{\partial F}{\partial UI}dUI + \frac{1}{2}\frac{\partial^2 F}{\partial\, UI^2}(dUI)^2 + \frac{1}{6}\frac{\partial^3 F}{\partial\, UI^3}(dUI)^3 + \cdots + \frac{1}{n!}\frac{\partial^n F}{\partial\, UI^n}(dUI)^n \tag{14}$$

By Ito's Lemma, $dF$ is as follows [33]:

$$dF = \frac{\partial F}{\partial t}dt + \frac{\partial F}{\partial UI}dUI + \frac{1}{2}\frac{\partial^2 F}{\partial\, UI^2}(dUI)^2 \tag{15}$$

The Bellman Equation (13) becomes the following second-order homogeneous differential equation that must be satisfied by F(UI):

$$\frac{1}{2}\cdot\sigma^2\cdot UI^2\cdot\frac{\partial^2 F(UI)}{\partial UI^2}+(r-\delta)\cdot UI\cdot\frac{\partial F(UI)}{\partial UI}-r\cdot F(UI)=0 \tag{16}$$

where $\delta = r - \mu$ represents the income gap between starting to invest and holding the option. To ensure that there is an opportunity cost for holding the option [24], we assume $\delta>0$ (i.e., $r>\mu$).

The investment opportunity is expressed as $F(UI) = A \cdot UI^{\alpha}$ with $\alpha=\frac{1}{2}-\frac{r-\delta}{\sigma^2}-\sqrt{\left(\frac{r-\delta}{\sigma^2}-\frac{1}{2}\right)^2+\frac{2r}{\sigma^2}}<0$ [13, 25].

To ensure that operators make decisions at the time when the "option to invest" can bring maximum benefits, the value of the option *F(UI)* must satisfy three boundary conditions, which are formulated as follows:

$$\begin{cases} F(UI^*)=(Y_{in}-Y_{ex})\cdot\rho_{(r,T)}-I_{total} & (17)\\ \lim\limits_{UI\to\infty} F(UI)=\max\{0,F(UI)\} & (18)\\ F^{-1}(UI^*)=-I_{initial}{}^{-1} & (19)\end{cases}$$

Equation (17) represents the value-matching condition, which means that when the investor exercises the option, the option value should be equal to the NPV. Condition (18) denotes that when the initial investment is very huge, it is almost impossible for an operator to begin the project. And Equation (19), the smooth-pasting condition, denotes the option value is continuous and smooth at $UI = UI^*$.

According to boundary conditions (17)–(19), the operator's investment threshold value $UI^*$ and the value of the option to invest *F(UI)* are calculated as (see Appendix 1 for proof):

$$UI^*=\frac{\alpha}{\alpha-1}\cdot\frac{(Y_{in}-Y_{ex})\cdot\rho_{(r,T)}}{IC} \tag{20}$$

$$F(UI)=\begin{cases}\dfrac{-(Y_{in}-Y_{ex})\cdot\rho_{(r,T)}}{\alpha-1}\cdot\left(\dfrac{UI}{UI^*}\right)^{\alpha} & UI>UI^* \quad (21)\\ (Y_{in}-Y_{ex})\cdot\rho_{(r,T)}-I_{total} & UI\le UI^* \quad (22)\end{cases}$$

where $UI^*$ is the investment threshold, which means the maximum investment critical value for operators. When *UI* is higher than the threshold $UI^*$, the value of the option to invest in project *F(UI)* is the value to wait. When *UI* is less than the threshold $UI^*$, *F(UI)* is equal to the expected difference between the total revenue and the cost of the investment project. The other variables are the same as above.

## The Optimal Subsidy Contracts

A popular incentive is subsidizing the unit profit of the renewable energy systems to enhance their market competitiveness. This kind of incentive has been implemented in many countries [34, 35]. We replace $UI^*$ with *UI* and $Y_{in}$ with $Y_{in}+S_p$ in Eq. (20). In other words, the unit profit is increased by $S_p$. The transformation and calculation results are expressed by the following equations:

$$UI=\frac{\alpha}{\alpha-1}\cdot\frac{\rho_{(r,T)}}{IC}\cdot(Y_{in}+S_p\cdot Q_{GTI}-Y_{ex}) \tag{23}$$

$$S_p=\left(\frac{\alpha-1}{\alpha}\cdot\frac{UI\cdot IC}{\rho_{(r,T)}}-Y_{in}+Y_{ex}\right)\Big/Q_{GTI} \tag{24}$$

$$S_p=\Big[\frac{\alpha-1}{\alpha}\cdot\frac{UI\cdot IC}{\rho_{(r,T)}}-P_{nor}\cdot(Q_1+z\cdot Q_2+z\cdot x\cdot Q_3 \\ +z\cdot x\cdot Q_4)(1-m)\cdot(1-\eta)-R_c\cdot(1-\eta)\Big]\Big/Q_{GTI} \tag{25}$$

where subsidy $S_p$ reduces the investment threshold $UI^*$ to the actual level of *UI*. Notes: If $UI\leq UI^*$, the PV-MG projects become profitable and operators will invest without subsidies, i.e., $S_p = 0$.

# Case Study

The demonstration project "High-tech industrial development zone microgrid" in Hefei, China, is selected for the case study. The data of the real case study is fact-oriented and collected from the official government website.

## Basic Data

The total investment of the project is $7.96\times10^7$ RMB, and the installed capacity is 8 MW, equipped with a 4 MW/8 MWh energy storage system and 600kW charging piles for electric vehicles [36]. Hence, the unit installed cost of photovoltaic generation is about 10000 RMB/kW. The key characteristic of microgrids is self-balancing [37]. Input parameters are listed in Table 1. The system generating capacity is related to solar energy resources, which come from the Global Solar Atlas. The drift and volatility parameters of investment cost are determined by using the maximum-likelihood estimate method according to the existing literature [32, 38]. The risk-free interest rate refers to the Economic Evaluation Methods and Parameters for Construction Project (3rd edition) [29, 39]. Additionally, the carbon emission price is collected from China's emissions trade net (Access at http://www.tanjiaoyi.com/). We obtain the emission factor from the baseline emission coefficient of China's regional power grid. Considering that PV-MGs have more components than distributed PV, this study assumes the annual operation and maintenance expenditure coefficient is 3%. Finally, there are tax incentives for renewable energy projects in China (i.e. the income tax and value-added tax can obtain deductions). Thus, we set the tax rate $\eta$ at 16.5%.

According to the "Microgrid engineering design standards GB/T51341-2018", this paper assumes that 50% of the electricity produced by the PV-MG project will be sent to the external grid, which means that half of the electricity could be sold at the peak time. The data of the time-of-use pricing scheme are obtained from the Anhui Province Development and Reform Commission. The valley time price is 60% of the normal time price, and the price of peak time is 253% of the valley time. The working hours of enterprises in the microgrid project park are from 7:00 to 19:00, hence $Q_1$, $Q_2$, $Q_3$, and $Q_4$ will satisfy the relationship:

$$\frac{Q_1}{Q_{GTI}}:\frac{Q_2}{Q_{GTI}}:\frac{Q_3}{Q_{GTI}}:\frac{Q_4}{Q_{GTI}}=0.25:0.04:0.21:0.5 \tag{26}$$

## Operators' Investment Decisions

We now show the operators' investment decision threshold of applying the case data and previously defined model. The investment cost threshold provides an important reference for operators' investment decisions and government subsidy contracts.

Table 1. Input data for variables.

| Variable | Description | Initial value |
|---|---|---|
| $Q_{GTI}$ | System generating capacity | 1385.175 (kWh/year) |
| $T$ | The lifetime of the PV-MG project | 25 years |
| $UI$ | Unit investment cost | 10000 (RMB/kW) |
| $\sigma$ | Volatility parameter | 0.06 |
| $\mu$ | Drift parameter | -0.06 |
| $r$ | Risk-free interest rate | 0.08 |
| $\omega$ | Emission factor | 0.79 ($tCO_2$/MWh) |
| $P_c$ | $CO_2$ price | 0.0998 (RMB/kg) |
| $m$ | Operation and maintenance cost coefficient | 3% |
| $\eta$ | Comprehensive tax rate | 16.5% |
| $T_{nor}$ | Normal time | 8:00-9:00, 12:00-17:00, 22:00-23:00 |
| $T_{val}$ | Valley time | 00:00-8:00, 23:00-24:00 |
| $T_{peak}$ | Peak time | 9:00-12:00, 17:00-22:00 |
| $P_{nor}$ | Normal time price | 0.6198 (RMB/kWh) |
| $P_{val}$ | Valley time price | 0.3716 (RMB/kWh) |
| $P_{peak}$ | Peak time price | 0.9389 (RMB/kWh) |

Investment threshold $UI^*$ is the maximum investment cost that operators can accept. The process of determining the investment cost threshold is shown in Fig. 3, the value of the investment opportunity and the NPV is on the left y-axis, and the subsidy $S_p$ for electricity prices is on the right y-axis, and the investment costs $UI$ is on the x-axis. The threshold $UI^*$ is determined by the tangency point of NPV and $F(UI)$. Specifically, when the project NPV exceeds the value of the option, it is economically viable to exercise the option. In this case, the maximum value of unit investment cost that prompts investment without any subsidy is $UI = 6101.25$ (RMB/kW). Obviously, according to Table 1, the current investment cost is about 10,000 yuan, thus the government needs to pay at least 0.48 (RMB/kWh) if they want to speed up the development of PV-MGs. Notes: If $UI \leq UI^*$, the PV-MG projects become profitable and operators will invest without subsidies, i.e., $S_p = 0$.

$UI^*$ is the investment threshold to ensure the profitability of operators. When the initial investment cost is less than $UI^*$, the operator will decide to start building a PV-MG project, which means raising the investment cost threshold for operators has a positive effect on MG development. Fig. 4a) shows how the investment cost threshold $UI^*$ varies with the volatility $\sigma$ under different time-of-use pricing schemes. The investment cost threshold increases, then shows a decreasing trend in the later stage and is stable in the end. The relationship means that the operators are more likely to adopt the PV-MG project in the case of stable major module prices. Besides, the investment cost threshold in mature trading markets ($P_{nor} = 1.11$ $x = 3$ ) is higher than that in immature trading markets ($P_{nor} = 0.94$ $x = 2.53$ and $P_{nor} = 0.74$ $x = 2$). The investment threshold in the case where $P_{nor} = 1.11$ $x = 3$ is also higher than that in the case where $P_{nor} = 0.94$ $x = 2.53$. The increase in $UI^*$ indicates that

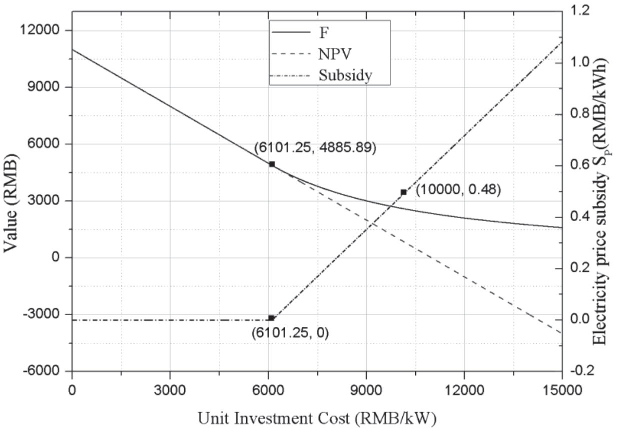

Fig. 3. Investment threshold and function image of electricity price subsidy $S_p$.

raising the peak-valley price rate could also encourage operators to invest.

Fig. 4b) is the relationship between $\mu$ and $UI^*$ with the given time-of-use pricing scheme. We choose $\sigma$ = 0.06 and $\mu \in \{-0.4, 0.0\}$ to high the influence of cost instantaneous drift. To compare the investment threshold of PV-MG under different time-of-use pricing schemes, we set three situations. The changes and trends of $UI^*$ are the same as curves in Fig. 4a).

## The Optimal Incentive Contracts under Uncertainty

The current investment cost of PV-MG is much higher than the investment threshold $UI^*$. Therefore, to speed up the development of PV-MGs, governments must adopt incentives. We now analyze the optimal subsidy contracts under uncertainty.

### *The Impact of the Investment Cost Fluctuation*

Fig. 5 shows that both low investment cost volatility σ and drift parameter μ correspond to fewer electricity price subsidies. On the contrary, large fluctuations in PV-MG investment costs will aggravate the uncertainty of the benefits of PV-MG projects. Excessive investment risks will make operators postpone project investment, which means the government has to pay operators more subsidies to incentive them to exercise investment options. There is a positive correlation between government subsidy and cost uncertainty. The relationship indicates that reducing sharp fluctuations in investment costs should be seen as an important policy objective of the government.

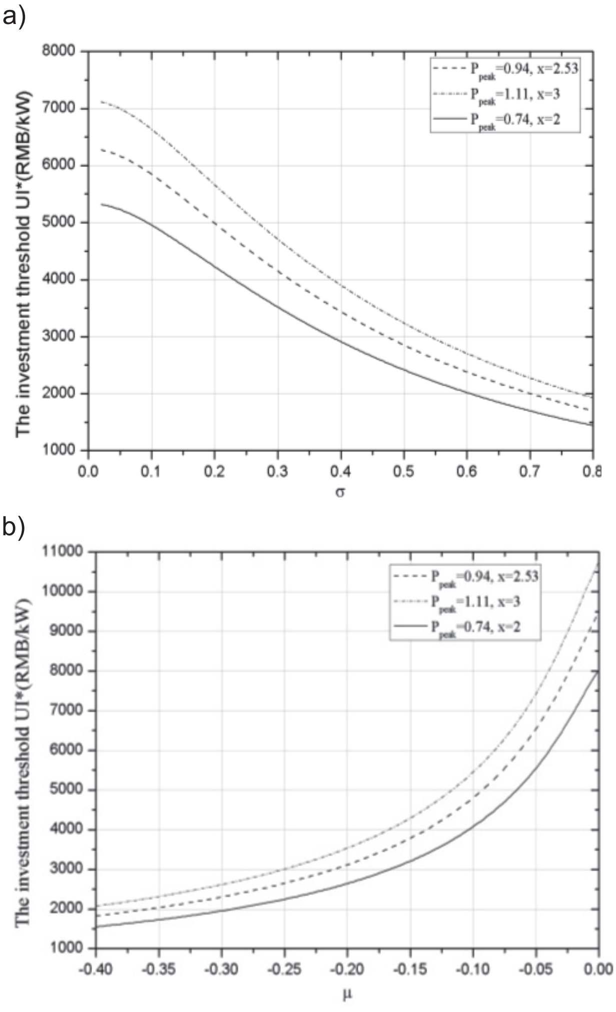

Fig. 4. The effect of the cost uncertainty and the time-of-use pricing scheme on the investment threshold.

### *The Impact of the Time-of-use Pricing Scheme*

The time-of-use pricing scheme for electricity charges a fixed price to customers for specific periods. To identify the conditions under which operators could benefit from time-of-use pricing schemes, we compare them with fixed-price systems and come to the following conclusions:

a) When $P_{nor} \cdot Q_1 + P_{val} \cdot Q_2 + P_{peak} \cdot Q_3 \geq P_e \cdot Q_{GTI}$, we have $x \geq \frac{Q_{GTI} - (Q_1 + z \cdot Q_2)}{z \cdot Q_3}$. Namely, the time-of-use pricing scheme will increase the revenue of microgrid operators, reducing their reliance on subsidies for microgrid development.

b) When $P_{nor} \cdot Q_1 + P_{val} \cdot Q_2 + P_{peak} \cdot Q_3 < P_e \cdot Q_{GTI}$, we have $x < \frac{Q_{GTI} - (Q_1 + z \cdot Q_2)}{z \cdot Q_3}$. Namely, the peak-valley price rate is too low, which leads to operators' inability to get more revenue from a time-of-use pricing scheme.

According to Table 1, we can get $x$ = 253% and

$$\frac{Q_{GTI} - (Q_1 + z \cdot Q_2)}{z \cdot Q_3} = 170\%$$

.

The value of the peak-valley price rate (253%) is larger than the threshold (170%), hence the

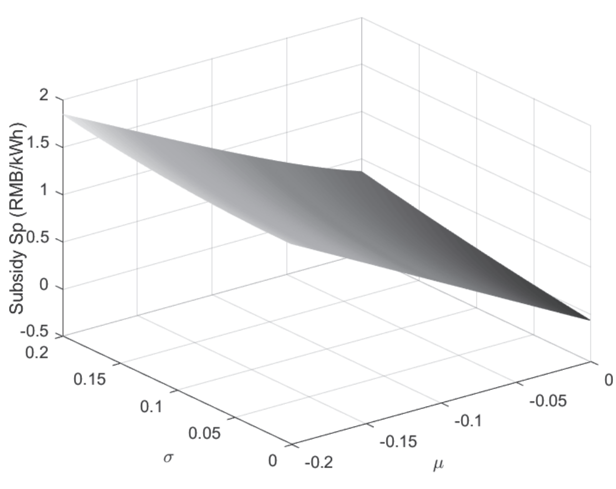

Fig. 5. Subsidies under varying cost uncertainty.

demonstration projects we studied could benefit from the time-of-use pricing scheme.

Besides, since the unpredictability of demand and supply, electricity price fluctuates tremendously is unavoidable. Fig. 6 shows how the optimal electricity price subsidy changes at the different values for peak-valley price rate.

Electricity price subsidy has a negative relationship with local GTI, as shown in Fig. 6. If the peak-valley price rate remains unchanged, the level of the optimal subsidy will decrease significantly with an increase in the GTI. Moreover, the larger the value of x, the wider the peak-valley difference of the local electricity price. The subsidy curve will shift to the left when the rate is widened because a higher rate implies that the revenue of the operator increases. However, the peak-valley price rate can't be arbitrarily increased, because an extortionate peak price will damage the social economy. At present, the peak-valley price rates in China are usually between 2 and 3, and the corresponding subsidy curves are all above the curve of $S_P = 0$, which indicates that in areas with GTI less than 2000, subsidies are indispensable.

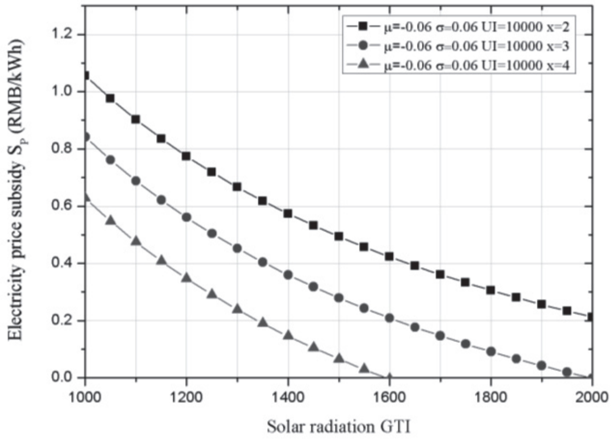

Fig. 6. Subsidies under different GTIs and peak-valley price rates.

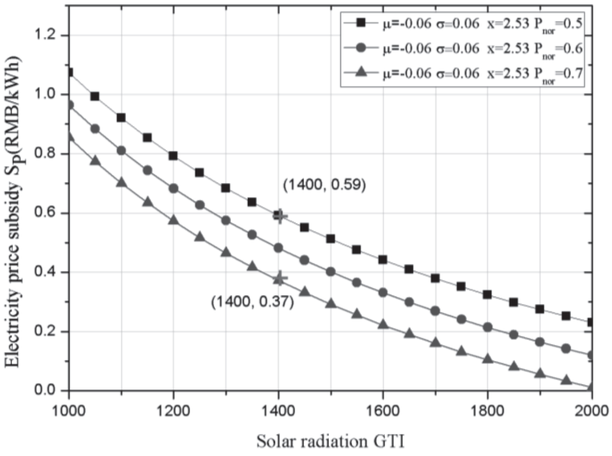

Fig. 7. Subsidies under different GTIs and normal time prices.

Fig. 7 illustrates that raising the normal time price of electricity is indeed conducive to decreasing the subsidy. For the area where GTI is 1400, if the electricity price in the normal period is increased from 0.5 (RMB/kWh) to 0.7 (RMB/kWh), the optimal subsidy should be reduced from 0.59 (RMB/kWh) to 0.37 (RMB/kWh), and the reduction of subsidy is larger than the variation of electricity price in normal period.

## Conclusion and Policy Implications

Due to its characteristics of being environmentally friendly, as well as its favourable function of mitigating energy shortages, the microgrid continues to attract increasing attention around the world. Providing incentives can accelerate the development of PV-MG projects. However, because of the complexity of evaluating costs and benefits, determining the optimal incentive contracts is still a quite difficult issue.

The significance of this study is to provide a real options model to explore how the government should adjust the incentive contracts under the operating environment with high uncertainties in investment costs and time-of-use pricing schemes. Given the globalization of procurement and the rapidly changing market environment, the risks faced by operators are gradually increasing. It is necessary to deeply understand the rational decisions relevant to operators from the perspective of product production and explore how to adjust incentive contracts in an operating environment with high uncertainties. In the basic scenario, a case of the microgrid demonstration project is used to examine the effects of cost and electricity price changes on operators' and government's decisions. More importantly, we have the following conclusions for decision-makers:

GTI/solar energy resource significantly influences the investment threshold, and the distribution of it has great regional differences. Subsidies for "High-tech industrial development zone microgrid" in Hefei can be stopped until the investment cost drops to 6101.25 (RMB/kW). However, as the level of GTI becomes higher, the operator would accept the subsidy contract at a higher starting investment cost expenditure. On the contrary, when the level of GTI is reduced, the operator is likely to accept the subsidy contract at a lower starting investment cost expenditure. This indicates that the government should take regional heterogeneity into full consideration when formulating incentive contracts. The unified environmental protection incentive policy is not efficient. The government should formulate regional policies through scientific calculation.

The results further reveal that alleviating the cost pressure on operators can stimulate them to adopt PV-MG, but rapid cost reductions and fluctuations could hinder its development. The cost and benefit of the microgrid are constantly changing in both manufacturing and sales processes. These uncertainties will increase market risk and make it harder for operators to accept government subsidy contracts. If this problem is not addressed, uncertainties will seriously hinder the development of renewable microgrids. Therefore, the government should focus on the rational decisions relevant to the incentive contracts and regularly release statistical information about photovoltaic industry development to prevent drastic price fluctuations caused by overcapacity and undercapacity. It is also helpful to strengthen operators' ability to reduce market risks by, for example, encouraging them to sign supply contracts with PV-MGs module suppliers and futures contracts with consumers as long-term risk-aversion strategies.

Adopt a variety of policy measures to encourage operators to invest in PV-MG. We suggest operators should be incentivized through a well-established carbon trading market and time-of-use pricing scheme. The carbon trading market scheme can ensure that operators obtain environmental benefits. Higher carbon prices correspond to higher project returns. Moreover, we identify the conditions under which operators benefit from the time-of-use pricing scheme. According to our model, increasing the peak-valley price rate and normal time prices plays an important role in increasing the operator’s income, thereby reducing subsidies paid by the government.

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## Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix

### Appendix 1. Proof of Equations (21) and (22)

Substituting $F(Q) = AQ^{\alpha}$ into Equations (17) and (19), we obtain the following formulas:

$$A\cdot UI^{\alpha} = (Y_{in}-Y_{ex})\cdot\rho_{(r,T)} - I_{initial} \tag{A1}$$

$$\alpha\cdot A\cdot UI^{(\alpha-1)} = -I_{initial}{}^{-1} \tag{A2}$$

Combining (A1) and (A2) with $F(Q) = AQ^{\alpha}$, we can obtain

$$\frac{UI^*}{\alpha} = \frac{(Y_{in}-Y_{ex})\cdot\rho_{(r,T)}}{-IC} + UI^* \tag{A3}$$

$$UI^* = \frac{\alpha}{\alpha-1}\cdot\frac{(Y_{in}-Y_{ex})\cdot\rho_{(r,T)}}{IC} \tag{A4}$$

According to (A2), the constant A is expressed as

$$A = \frac{-IC}{\alpha\cdot UI^{*(\alpha-1)}} \tag{A5}$$

Combining Equations (A4) and (A5), the value of the PV-MG project investment opportunity can be formulated as follows for $\forall UI > UI^*$:

$$\begin{aligned} F(UI) = A\cdot UI^{\alpha} &= \frac{-IC}{\alpha\cdot UI^{*(\alpha-1)}}\cdot UI^{\alpha} \\ &= \frac{-IC}{\alpha}\cdot\frac{\alpha}{\alpha-1}\cdot\frac{(Y_{in}-Y_{ex})\cdot\rho_{(r,T)}}{IC}\cdot\left(\frac{UI}{UI^*}\right)^{\alpha} \\ &= \frac{(Y_{in}-Y_{ex})\cdot\rho_{(r,T)}}{\alpha-1}\cdot\left(\frac{UI}{UI^*}\right)^{\alpha} \end{aligned} \tag{A6}$$

*F(UI)* of the PV-MG project can be formulated as follows for $\forall UI > UI^*$:

$$\begin{aligned} F(UI) &= \max_t\left[V-I,0\right] \qquad (0 \le t \le t_v) \\ &= V - I = (Y_{in}-Y_{ex})\cdot\rho_{(r,T)} - I_{total} \end{aligned} \tag{A7}$$

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