Energy Policy 116 (2018) 86–94

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Socially optimal deployment strategy and incentive policy for solar photovoltaic community microgrid: A case of China

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ARTICLE INFO

Keywords:
Solar power
Community microgrid
Optimal deployment strategy
Emission permits trade

ABSTRACT

Aiming to meet the increasingly diversified demand of electricity and abate emissions of electricity sector, the solar photovoltaic-powered community microgrid (SPCM) is encouraged in China. Based on an understanding of the distributed solar radiation intensity (SRI) in China, this paper explored the socially optimal deployment strategies of SPCM. And by formulating a leader–follower Stackelberg game, we investigated the role that emission permits trade policy can play in inducing the choice of SPCM. The empirical results show that not all the areas in China are suitable for the promotion of SPCM. And the social emissions concern (ε) has a big impact on the socially optimal deployment strategy of SPCM. Two factors determine whether the SPCM is inducible in a specific area: the located SRI and the incentive policy. And for a specific area, resident makes the choice based on whether the SPCM could be profitable. The results also demonstrate that a high price of CERs can achieve the effect of feed-in tariff policy in inducing SPCM, and emission permits trade policy as a market incentive mechanism can also internalize the external costs of CO_2 emissions.

1. Introduction

In the past decade, the CO_2 emission growth of the electricity sector accounted for 32.1% of the world's and 49.1% of China's (Meng et al., 2017). And if viewed China's electricity sector as a country, it could be the third largest CO_2 emitter in the world (BP, 2017). The reason why emissions from China's electricity sector accounted for such a high proportion is that coal-fired power generation plays a dominant role in the power supply (Cui and Wei, 2017; Zhang and Peng, 2017). For the effective emissions abatement of electricity sector, a shift away from fossil energies towards renewable energies is inevitable (Abrell and Rausch, 2016; Delarue and Bergh, 2016).

In China, electrification has been mainly achieved by the central electricity grid. According to the blueprint drawn by (NDRC, 2015), the electrification ratio in China will reach 62% by 2050, and the electricity consumption in 2050 will be three times as the 2015 level. Meanwhile, with the improving of electrification ratio, the electric power demand also becomes diversified gradually (Liu et al., 2016). In order to meet the increasingly diversified demand of electricity, microgrid will be a necessary complement to the main grid (Bilich et al., 2017). Microgrid is a controllable power system which consists of distributed generation sources (generally renewable energy sources, such as solar), loads, power storage systems and decentralized operations of power grids (Lasseter, 2011; Wang and Huang, 2015). By the end of 2016, there were more than 1000 of microgrids put into operation in China, including on-grid and isolated type (Ali et al., 2017). The typical application scenarios cover areas such as communities, schools, commercial buildings and industrial factories.

Most distributed generation in microgrid are utilizing renewable energies as primary energy (Drechsler et al., 2017), which is conducive to improving the proportion of renewable energy consumption, as well as reducing CO_2 emissions. At present, the community microgrid in China is mainly using solar photovoltaic power generation (Chan et al., 2017). Such as a 2.06 MW solar photovoltaic-powered community microgrid (SPCM) located in Gonghe County, Qinghai Province and a 1.08 MW SPCM located in Yangzhou City, Jiangsu Province (Xie et al., 2017).

Solar energy is theoretically inexhaustible and emissions-free energy source, and the SPCM is close to the location of load, which can also eliminate the loss of power in large-scale and long-distance transmission process (Islam and Dincer, 2017). The Sun provides 1.4×10^5 TW power on the surface of the Earth for a year, and as about 3.6×10^4 TW of this power is usable, which is far greater than the world power consumption (Hosenuzzaman et al., 2015). China has a vast territory and a large number of communities, which means that the application prospect of SPCM is very huge (Hughes and Meckling, 2017).

SPCM is promising in China, but there are some obstacles in the

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https://doi.org/10.1016/j.enpol.2018.01.056
Received 29 October 2017; Received in revised form 30 December 2017; Accepted 28 January 2018
0301-4215/

promotion of SPCM, including substantial up-front capital investments and highly dependence on solar energy resources. Solar power is intermittent power source, and its stochastic features would be highly location-dependent. So the electricity generation of SPCM is highly dependent on the solar energy resources endowment of the located area (Grams et al., 2017). China's land area is relatively large, and the solar energy resource distribute variably in different regions. Therefore, in the early planning and design stage, there is a need for the government to adopt suitable policy tools to induce the choice of SPCM. Such tools may include emissions trading market, feed-in-tariff, and a variety of other incentive mechanisms (Liu et al., 2017).

In China, feed-in tariff policy is the most implemented policy to stimulate the choice of SPCM (Ye et al., 2017). Feed-in tariff policy is designed to induce the SPCM by offering a long-term guaranteed purchase price to resident for selling electricity to the grid corporation. However, feed-in tariff policy may inhibit a healthy market competition by giving a preferential price and increase financial burden on government (Alishahi and Moghaddam, 2012). In order to promote the development of SPCM, we should go beyond the feed-in tariff policy, and put forward some more market-oriented policies.

About how to induce the choice of SPCM is related to two ideas: one in microgrid technologies and another in formulating incentive policies. In the microgrid technology literatures, most researchers addressed the problem with respect to reducing costs and improving efficiency of SPCM (Eddy et al., 2017; Hanna et al., 2017; Jarnut et al., 2017; Mariam et al., 2016). In the incentive policies, most researchers focused on how to formulate policies to increase the choice of SPCM to the greatest extent (Mariam et al., 2016; Rahmann et al., 2016; Ravindra and Iyer, 2014; Wouters, 2015). These works analyzed how to induce SPCM without considering the located solar resource endowments. Photovoltaic power generation is greatly affected by the located solar energy resource endowments. Therefore, it is essential to explore the optimal deployment strategies on the basis of the solar energy resources endowment and country-scale. In this way, the government can minimize the negative impacts of emissions and maximize the social welfare by inducing a appropriate high share of SPCM.

The paper contributes in a useful manner to explore suitable deployment strategies based on an understanding of the solar energy resources endowment, and to evaluate the efficiency and limitations of government's incentive mechanisms. And the questions we aim to answer are: Under what circumstances can an SPCM be induced to install? What are the economic impacts of these incentive mechanisms, as well as impacts on CO_2 emissions and social welfare?

The remainder parts of this paper are organized as follows: Section 2 analyzes the costs and benefits among key SPCM stakeholders. Section 3 formulates a Stackelberg game model between government and resident. Then, Section 4 presents a empirical analysis of China, followed by some conclusions and policy implications of the paper in Section 5.

2. Costs and benefits among key SPCM stakeholders

Before to explore suitable deployment strategies and policy tools in inducing the choice of SPCM, it is necessary to analyze the costs and interests among key stakeholders. There are many models of SPCM. For simplification, this paper make an analysis of household invested SPCM, which is also the most popular model of SPCM in China (Xie et al., 2017). Under the model of household invested SPCM, the microgrid is invested and owned by the electricity users, and the excess or shortage power is traded to the grid corporation. A typical SPCM is illustrated in Fig. 1 (Wang and Huang, 2015), which is connecting to the main power grid, and including local distributed solar power supply as well as responsive household demand. Within the SPCM, there is a local solar power generation system, and an energy storage device utilized to charge and discharge power to smooth out the intermittent solar power generation (Abdi et al., 2017).

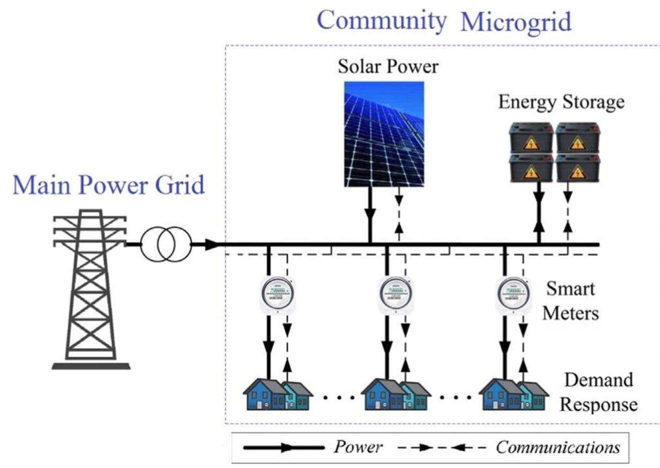

Fig. 1. A typical SPCM model.

2.1. Key stakeholders of SPCM

2.1.1. Resident

Resident is the investor and owner of the microgrid. They build SPCM through their own funds or financing, and their purpose of constructing microgrid is to save electricity costs. SPCM can provide electricity power for their daily lives, and they can also sell additional power to grid corporation when the microgrid has extra capacity. But when the SPCM's power is insufficient to guarantee household power, they also purchase electricity power from grid corporation. In addition, resident is always concerned about the future profits of SPCM project.

2.1.2. Government

The government plays the role of initiator and facilitator in the promotion of SPCM. Because there is a need of large initial investment for SPCM, it is critical for government to formulate incentive policies to motivate the choice of SPCM. The government is acting as a promoter in the development of SPCM, who has a number of incentive policy tools: feed-in tariff given to the household if it chooses to build SPCM, and the certified emission reductions (CERs). As represents interests of the whole society, the government pursues two goals: minimize the amount of emissions, and maximize the whole economic welfare.

2.1.3. Grid corporation

Grid corporation purchases electricity from power generation enterprises and sells electricity to power customers. Because the SPCM researched in this paper is not an isolated type microgrid, the grid corporation is a closely related stakeholder of the SPCM. The grid corporation not only has the right to sell electricity, but also can transmit power to electricity consumers. In the electricity market, grid corporation is directly contacting with SPCM owner for power pricing.

2.2. Costs of SPCM

The costs of SPCM include the cost of distributed generation equipment, the cost of power storage equipment, and the cost of operation and maintenance during daily operation.

2.2.1. Cost of distributed generation equipment

In this paper, photovoltaic generation system is the only distributed generation equipment in SPCM. The cost of distributed generation equipment is expressed as follows:

$$I_1 = G_1 C_1 \tag{1}$$

Where I_1 represents the cost of distributed generation equipment in SPCM, G_1 represents the installed capacity of photovoltaic power generation, and C_1 represents the cost per unit capacity of photovoltaic