Feasibility study of emission policy for photovoltaic integrated building microgrids

Xundong Gong [1], *Mingfeng* Xue [1], *Bo* Yang[2], *Deshun* Wang[2], *Xu* Guo[3], *Yuanfei* Ge[3], and *Xiongwen* Zhang[3,]*

[1]Wuxi Power Supply Company of State Grid Jiangsu Electric Power Company Ltd., 214000, Wuxi, China
[2]China Electric Power Research institute, 210000, Nanjing, China
[3]MOE Key Laboratory of Thermo-Fluid Science and Engineering, Xi’an Jiaotong University, 710049, Xi’an, China

Abstract. The photovoltaics (PV) based microgrids play important role in the development of green buildings. This work investigates the effects of emission policy on the PV integrated commercial and residential building microgrids. The component sizes of microgrid are determined by simulated optimal power dispatch with an optimization algorithm based on minimizing the cost of energy (COE). The COE is computed with consideration of the capital depreciation cost, fuel cost, emissions damage cost and maintenance cost. The simulation results show that the emission policy and photovoltaic subsidy have little effect on sizing the commercial microgrid system. However, the component sizing design for residential microgrid system is sensitive to the emission policy. Increasing emission taxes and photovoltaic subsidy can effectively raise the proportion of PV in the system. The most important factor of restricting PV usage in microgrids is the cost of batteries. Increasing the battery lifetime or selecting the lower cost of battery can significantly increase the installation of PV, thus rise the green building standard.

1 Introduction

Due to the global concern over carbon emissions from conventional power generation sources [1], many countries are enhancing deployment of intermittent renewable energy sources (RES) for the reduction of greenhouse gas emissions [2]. Renewable energy resources, especially solar and wind, are the fastest growing and the most promising alternative sources [3]. As one of the cleanest, most practicable, most promising power generation system, photovoltaics (PV) systems have become cheaper and more efficient nowadays. It is easily integrated into the buildings, such as the solar roofing shingles, solar side-cladding, and even solar-powered glass windows. The PV power system will play an increasingly important role in the future energy network [4]. However, variations in solar irradiance cause fluctuations in power generation, reducing the quality and reliability of the PV power system [5]. The PV plants are generally integrated and managed together with batteries, diesel generators, fuel cells and microturbines through microgrid technology [6, 7]. The use of microgrid technology makes the possibility of the building-integrated photovoltaic (BIPV) connected or disconnected with the main grid.

At present, most of the researches on different renewable energy systems take the cost of energy (COE) as the calculation target for capacity optimization [8-14]. However, planning renewable energy systems does not only satisfy the techno-economic requirements but also carefully consider the environmental dimension [15,16]. The emission reduction of microgrid is strongly dependent on the size installation of PV, which is generally determined by the microgrid sizing optimization algorithm based on the economic assessment. Obviously, the emission policies directly influence the COE for the microgrid design. In particular, there are significant distinctions in the economic performance for the deployment of PV in different types of buildings [17]. Some of the approaches including HYBRID2, DER-CAM, HOMER, RETScreen and HOGA etc. have been used for techno-economic assessment on the microgrids and hybrid systems. Mostly, the criteria of sizing algorithm is based on the minimization of the cost and deficiency of the power supplies [18-21]. The lifetime reduction due to the usage of components is neglected. For actual operation, the power flow intensity has significant effect on the capital depreciation cost of components (e.g. batteries). The reference [22] presented a new economic model with consideration of battery capital depreciation cost in the COE evaluation. This work investigates the effects of the emission policies on the integrated PV commercial and residential building microgrids using the approach of references [17, 22].

2 Mathematical approach

A microgrid composed of BIPV and battery with main grid connection is studied in this work. The PV and battery are integrated by a DC bus and is connected to the main grid and load through a bi-directional electronic

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* Corresponding author: xwenz@mail.xjtu.edu.cn

converter. The COE of the microgrid is computed from the capital depreciation cost (C^{dep}), fuel cost (C^{fue}), emissions damage cost (C^{dam}), and system maintenance cost (C_{SXS}^{mai}) in terms of the per kWh energy within the time period [T_0, T]. The mathematical formation of COE is written as follows:

$$COE = \frac{\sum_{k=1}^{M}\sum_{i=1}^{N}\left(C_{i,k}^{dep} + C_{i,k}^{fie} + C_{i,k}^{dmm}\right) + C_{BoP}^{dep} + C_{SXS}^{mai}}{\sum_{k=1}^{M} d_k} \tag{1}$$

where N is the number of DERs. The C_{BoP}^{dep} is the capital depreciation cost of balance of plants (BoPs). M is the number of the discretized time interval given by

$$M = \frac{T - T_0}{\Delta t} \tag{2}$$

Within the time interval Δt , the capital depreciation cost based on physical lifetime for a component is calculated by

$$C_{phy}^{dep} = \Delta t \frac{wc^{cap}}{t_{phy}} | \tag{3}$$

where w is the size of DER. c^{cap} is specific capital cost. Some of DERs lifetimes (e.g. batteries) are highly dependent on the operation status. The capital depreciation cost according the lifetime throughput is given by

$$C_{run}^{dep} = p \frac{wc^{cap}}{P_{life}} \tag{4}$$

where p is the energy delivered by the DERs within Δt and P_{life} is the energy lifetime throughput with DERs. The capital depreciation costs for DERs are the higher value of C_{phy}^{dep} and C_{run}^{dep} given by:

$$C^{dep} = \max\left(C_{phy}^{dep}, C_{run}^{dep}\right) \tag{5}$$

The system maintenance cost C^{mai} only considers the manpower cost. The DER fuel cost C^{fue} is determined by

$$C^{fue} = p \frac{c^{fue}}{q_v \eta} \tag{6}$$

The emission damage cost is estimated according to the overall cost of controlling the release of the emissions. This work only considers the emission of CO2 in the model. The specific damage cost of CO2 is set to be 0.1637¥/kg according to the reference [23]. The damage cost for CO_2 emission is calculated by:

$$C^{dam} = 3600 p \frac{f_{C_2}^{emi} c_{CO_2}^{dm}}{\eta} \tag{7}$$

where f^{emi} is the emissions factor. Combining equations (3) to (7), the objective function of the optimization problem is formulated as follows:

$$\min\left\{\sum_{k=1}^{M}\sum_{i=1}^{N}\left[\begin{array}{l}\max\left(\Delta t \dfrac{w_i c_i^{cap}}{t_i^{phy}}, p_{i,k}\dfrac{w_i c_i^{cap}}{P_i^{life}}\right) \\ + p_{i,k}\dfrac{c_i^{fue}}{q_i \eta_i} + 3600 p_{i,k} \dfrac{f_{CO_2,i}^{emi} c_{CO_2,i}^{dam}}{\eta_i}\end{array}\right]\right\} \tag{8}$$

The constraints are given as follows [24]:

$$\sum_{i=1}^{N} p_{i,k} = d_k \quad \text{where } \mathrm{k} = 1, \cdots, M \tag{9}$$

$$\begin{cases} \max\left(-V_i^{\text{claxg}} I_{\text{MAX}}^{\text{chase}} \Delta t, -\dfrac{w_i}{\eta_i^{\text{chase}}}\right)\Bigg) \le p_{i,k} < 0 \\ 0 \le p_{i,k} \le \min\left(V_i^{\text{dischass}} I_{\text{Makix},t}^{\text{dischage}} \Delta t, w_i \eta_i^{\text{dischase}}\right) \\ 0 \le p_{i,k} \le \eta_i R_k w_i \Delta t \text{ for PV} \end{cases} \tag{10}$$

$$\begin{cases} 0 \le SOC_{i,k} = SOC_{i,k-1} + \dfrac{p_{i,k}}{\eta_i^{\text{diselange}}} \le 1 \text{ for } p_{i,k} > 0 \\ 0 \le SOC_{i,k} = SOC_{i,k-1} + \dfrac{\eta_i^{\text{chass}} \ p_{i,k}}{w_i} \le 1 \text{ for } p_{i,k} \le 0 \end{cases} \tag{11}$$

The sizing optimization problem is to obtain w by solving the objective function (8) with the constraint conditions (9)-(11). The solving processes are referred to reference [17].

A commercial office block (10000 m^2) and an independent villa at Xi'an of China are selected as the case study. The input daily load profile for the office building is referred to [25]. The power demand is approximately 550 kW in the daytime and is 80 kW in the night. The daily load profile for the villa is estimated from the references [26,27]. The components size of the microgrid system is determined according to the weekly power dispatch simulation. The input solar radiation profile is set by a stochastic reconstruction model based on the measured data [28]. The technical data employed in the computations are given in Table 1. The computations are implemented in MATLAB 7.14.

Table 1. Technical data input

Name	Symbol	Value	Source
Main grid			
Capital cost	c_{Grid}^{cap}	0	*e*
Electricity price	$c^{electric}$	Commercial: 1.2893¥/kWh Residential: 0.4983¥/kWh	[24]
Coal consumption	c_{coal}	0.333kg/kWh	[24]
Emission factor of coal	f_{coal}	0.68t/tce	[29]
Emission damage cost of CO2	$c_{\text{CO}_2}^{dam}$	0.1637¥/kg	[23]
PV			
Capital cost	c_{PV}^{cap}	433¥/m^2	*e*
Efficiency	η_{PV}	17.12%	*e*
Physical lifetime (Working Time)	t_{phy}	20 Years	*a*
Subsidy of PV power generation		0.42¥/kWh	[30]
Battery			
Capital cost	c_{Battery}^{cap}	666.67¥/kWh	*e*
Charge-discharge cycle		600 Times	*e*

Name	Symbol	Value	Source
Physical lifetime (Working Time)	t_{phy}	5 Years	*e*
Maximal charge current	$I_{\text{MAX},i}^{\text{charge}}$	0.3C	*a*
Maximal discharge current	$I_{\text{MAX},i}^{\text{discharge}}$	3C	*a*
Charge efficiency	$\eta_{\text{Battery}}^{\text{charge}}$	90%	*a*
Maximal depth of discharge		40%	*s*
Discharge efficiency	$\eta_{\text{Battery}}^{\text{discharge}}$	90%	*a*

Note: a- assumed values, e- estimated values, s-specified values.

3 Results and discussion

The computation results show that the lowest COEs for the commercial and residential building microgrids are 0.6982¥/kWh and 0.5459 ¥/kWh, respectively. The component sizes for the residential and commercial building microgrids are given in Table 2. As we can see from Table 2, the BIPV-based microgrid for commercial building reduces the energy costs from 1.2893 ¥/kWh to 0.6982 ¥/kWh, which is about 46% cost savings for customers. However, the BIPV-based microgrid for the residential building cannot reduce the energy bills for customers. The government needs to rise the subsidy of PV for the residential applications.

Table 3 shows the effects of emission cost on the cost of energy for building microgrids. It can be seen that the emission cost has little effect on the overall COE of commercial building microgrid. There is almost no change for the component sizes of system. This is because the cost of electricity from microgrid is much lower than electricity price of main grid. The sizing algorithm considers a large size PV as the preferred choice in the design of microgrid. For residential building microgrid, the emission effect is higher than that of commercial building microgrid. Comparatively, the electricity price of main grid for residential buildings is low, which therefore leads to high percentage of energy supply from main grid. As the emission damage cost is excluded in the microgrid design, the smaller sizes of PV and battery are preferred. For operation under main grid disconnection mode, significant increases in the sizes of PV and battery are required and also the COE increases by more than double times.

Table 2. The components sizes for residential/commercial building microgrids

	Main grid	**PV**	**Battery**	**COE**	**Grid electricity price**
	kW	m^2	kWh	¥/kWh	¥/kWh
Commercial building	629	3372	302	0.6982	1.2893
Residential building	2.17	7.45	5.16	0.5459	0.4983

Table 3. Effects of emission cost on the COE

		Main grid	**PV**	**Battery**	**COE**
		kW	m^2	kWh	¥/kWh
Commercial building	Including emission cost	629	3372	302	0.6982
	Excluding emission cost	625	3372	302	0.6760
Residential building	Including emission cost	2.17	7.45	5.16	0.5459
	Excluding emission cost	2.73	6.82	4.25	0.5111
	Zero emission	——	20.70	25.21	1.3697

Table 4. Effects of PV subsidy on the cost of energy for building microgrids

		Main grid	**PV**	**Battery**	**COE**
		kW	m^2	kWh	¥/kWh
Commercial building	With PV subsidy	629	3372	302	0.6982
	Without PV subsidy	652	3331	519	0.8910
Residential building	With PV subsidy	2.17	7.45	5.16	0.5459
	Without PV subsidy	3.30	5.36	2.04	0.6155

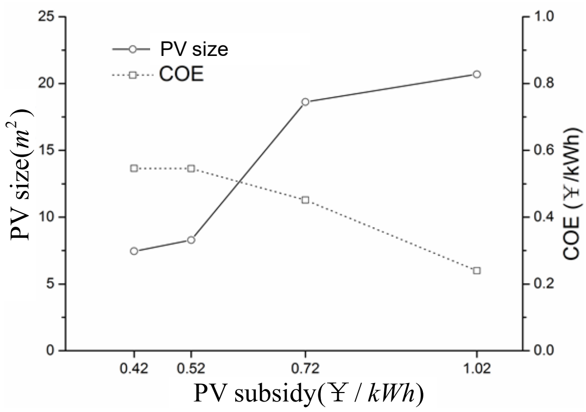

Fig. 1. Effects of PV subsidy on the sizing of PV and COE for residential building microgrid

Table 4 shows the effects of PV subsidy on the cost of energy for building microgrids. As we can see from the Table data, the case without PV subsidy leads to a slight decrease in the design of PV size for the commercial building microgrid. The rated power flow from main grid is allocated more so that the system can meet the peak load. The size of battery is significantly increased to carry more electricity from PV in daytime to meet the power demand in the night. This causes the COE increased by 0.2 ¥/kWh. Obviously, it can get significant economy benefit from the deployment of PV based microgrid for commercial buildings. On the other hand, the COE for residential building microgrid can be reduced around 0.07 ¥/kWh from the PV subsidy. The subsidy policy also significantly stimulates the deployment of PV in the residential building. Figure 1 shows the effects of PV subsidy on the sizing of PV and COE for the residential building microgrid. As shown in Fig.1, the size of PV increases rapidly with the increase of the subsidy from 0.52 ¥/kWh to 0.72 ¥/kWh. As the PV subsidy is over 0.72 ¥/kWh, the effect of continually increasing the subsidy becomes weak on the size design of PV. However, the subsidy almost linearly reduces the COE, creating economic benefit for building owner. This can encourage building owner install more PV in the building, and thus resulting in emission reduction.

4 Conclusions

This work proposed a component sizing method based on minimizing the cost of energy for PV integrated building microgrids. The effects of emission damage cost and PV subsidy on the commercial and residential building microgrids were investigated. The simulation results show that the emission damage cost and PV subsidy have little effect on the sizing of commercial building microgrid. On the other hand, they significantly influence the size design of PV for residential building microgrid. Increasing both the emission tax and the photovoltaic subsidy can effectively encourage building owner install more PV in the building energy system. Typically, the commercial building has similar load profile characteristic as the solar radiation. Therefore, the required battery size for specific area of PV in the commercial building microgrid is smaller than that of the requirement in the residential building microgrid. The replacement cost of battery is significant in the PV power system. There, compared to residential building microgrid, the commercial building microgrid with PV can reduce much more the electricity bill for customers. It has to be noted that the above conclusions are only applicable under current Chinese regulatory conditions.

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