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The Energy-Economic-Environmental Multi-benefits of Urban Rooftop Photovoltaic Integrated with Electric Vehicles System

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ABSTRACT

PV integrated with EVs has become a promising way of utilizing PV generation in urban areas towards low carbon future. This paper aims to evaluate the technical and economic potentials of rooftop PV system integrated with EVs in 21 cities in Guangdong province, China, as well as the energy-economic-environmental effects of the PV+EV system, and shed light on how PV+EV system can be deployed within a region. The results show that PV+EV systems are cost-effective in all cities in the Guangdong province, EVs can increase the PV utilization in each city, making cities less dependent on external energy sources, reducing costs for the whole society, and providing more CO_2 emission reductions for most cities. However, cities vary in performance of PV potential and development capabilities, which should be taken into account in overall regional development plan.

Keywords: rooftop PV, PV+EV, energy-economic-environmental effects, region

NONMENCLATURE

Abbreviations	
PV	Photovoltaic
EV	Electric vehicle
NPV	Net present value
ICE	Internal combustion engine
PRD	Pearl River Delta

1. INTRODUCTION

The IPCC AR6 concluded that photovoltaic (PV) systems have the greatest potential to help energy sectors around the world meet their emissions reduction targets [1]. Distributed rooftop PV is considered a preferred renewable energy source that can play a key role in solving urban energy problems and combating climate change. The key issue for policy makers in promoting the development of distributed PV is to determine where to deploy distributed PV and the optimal capacity of PV, and how the distributed PV system can contribute to the multiple development goals of energy, economy and environment.

The rapid promotion of electric vehicles (EV) worldwide has provided an opportunity for improving PV generation utilization by providing energy storage service to the PV system, and possibly generating more profound co-benefits for the whole society.

This paper conducts a comparative study by looking into the various PV+EV system potentials and energy-economic-environmental effects of 21 cities of Guangdong province in China, and then proposes policy recommendations for regional rooftop PV development by taking into account the different social-economic backgrounds of cities.

2. METHODOLOGY

2.1 Methodology

This paper designs a research framework for assessing PV+EV system at city level within specific region. The analysis process generally consists of three steps: assessing the technical potential of PV capacity; calculating the optimum level of installed PV from economic perspective; assessing the energy-economic-environmental effects of PV+EV system for each city.

2.1.1 PV technical potential Estimation

Estimating the urban roof area is one of the most central steps in assessing the potential of PV technologies. Three different types of methods are often used to estimate urban roof area: top-down [2–4], bottom-up [5–7] and hybrid methods [8,9]. Most studies have now used top-down method (i.e., GIS data [10]) for urban roof identification. There is little up-to-date GIS data of the rooftop area in Guangdong province. In this regard, this paper considered a constant parameter method from top-down approach for assessing the rooftop area potential in cities in Guangdong province, that is, using the construction land area and building density based on the Urban Construction Statistical Yearbook 2020 [11] and 238 land use data of cities in Guangdong province, to calculate the building rooftop area. This paper identified five out of eight land use types, which are residential, industrial, administration, and public services, commercial and business facilities, logistics and warehouse [12], and calculated the rooftop area for each land use type, then aggregated to get the sum value for 21 cities respectively. And a 70% of rooftop area utilization rate was used to obtain the available rooftop area for PV installation[13].

2.1.2 PV optimal potential Estimation

The net present value (NPV) method was used to calculate the net cash flow of cost and revenue of different PV systems. Then we used the maximum NPV as the objective function to ensure that the installed capacity selected is the one with the highest economic return at the city scale. In the PV+EV system, the costs considered are the capital and O&M costs of the PV system, the capital costs of the EVs and the battery replacement costs, the fuel costs of the ICEs, and the revenues are the benefits of the PV generation replacing the grid and the feed-in tariff of the excess power, the oil fuel expense savings. By considering these costs and revenues, the NPV of PV+EV system in each city is calculated, and the PV installation with the highest NPV is selected as the optimum economic potential of PV+EV system in each city.

2.1.3 Energy-Economic-Environmental effects

We then use SAM software to simulate the interaction between the city's electricity demand and the PV output curve, and the EV energy storage service, to assess the energy-economic-environmental effects of PV+EV system in cities. The main indicators for the three effects are: self-consumption, self-sufficiency (energy effect), total cost and investment (economic effect), CO$_2$ emission reduction (environmental effect), respectively.

2.2 Scenario design

To better represent the additional impact of EV on the optimum PV development level and associated energy-economic-environmental effects, three scenarios were set up in this paper: 2020 PV only, 2030 PV only, and 2030 PV+EV scenarios. The 2020 PV only scenario explores the current maximum economic development potential of rooftop PV system in 21 cities in Guangdong province. The 2030 PV only scenario considers the dynamic impact of urbanization on the rooftop PV potential through building construction and urban population growth. The 2030 PV+EV scenario demonstrates the impact of EVs providing energy storage for PV systems on the optimal installation of PV in cities, and the energy-environment-economic effects of integrated PV+EV systems in each city in Guangdong province.

3. RESULTS

3.1 Rooftop PV potential

Since each city has a different level of urbanization and roof area varies from city to city, the potential for PV technology also varies in 2020 (Fig. 1). Dongguan has the largest PV technical potential in Guangdong Province (57.54 GWh yr-1), in contrast to the smallest PV technical potential in Heyuan at 1.65 GWh yr-1. There are also significant differences in PV potential between the four main regions of Guangdong province, with the highest average PV technical potential in the Pearl River Delta (PRD) region reaching 21.84 GWh yr-1 in 2020, since the PRD region is a densely populated, fast growing urban agglomeration with 61.91% of the province's population, so there is higher demand for buildings and consequently higher PV potential. The average potential in Eastern and Western Guangdong is much lower than that in the PRD region, at 7.29 and 6.69 GWh yr-1 respectively. While Northern Guangdong has the lowest average PV potential in the province (4.05 GWh yr-1) due to its large forest resources and lower level of urban development.

The PV technology potential of each city in 2030 will increase based on the 2020 level, but there are differences in the growth rate of each city, which is determined by the economic and demographic development rate of each city. The PRD region still has the highest PV potential in 2030, accounting for 74.22% of the province's total potential.

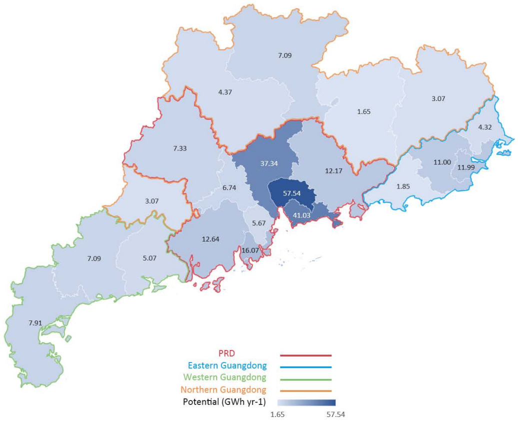

Fig. 1. Technical potential in Guangdong province in 2020

Due to the feed-in-tariff, the economically optimal installed capacity in the 2020 PV only and 2030 PV only scenarios has reached the maximum technical potential in each city. However, in the 2030 PV+EV scenario, the economically optimal installed capacity in four cities (Dongguan, Jiangmen, Shaoguan, and Jieyang) is below the maximum technical potential. This is because with the EV stores excess electricity, the number of battery charges and discharges increases, thus increasing the cost of battery replacement, making the NPV decrease when enough large PV deployment is added.

3.2 Energy effect

In 2020 PV only, the distribution of self-consumption in the cities ranges from 45% to 100% (Fig. 2), mostly concentrated in the interval of 70%-90%, and there are differences in the distribution of self-consumption among different regions, with the lower average self-consumption in PRD, and the lowest self-consumption is 45% in Zhuhai, which is due to the fact that the rooftop area is large relative to the electricity consumption, and most of the excess electricity is fed into the grid instead of the load. In the 2030 PV only scenario, self-consumption increases in each city (on average from 78% in 2020 to 86% in 2030 PV only) as electricity demand grows faster than rooftop area, which means the PV utilization rate will increase in the future.

With the addition of EVs, the self-consumption increases further, reaching 100% in almost all cities, except for Zhuhai where there is still a lot of electricity left over after charging into EVs and being delivered to the grid. The results show that the energy storage role of EVs can well improve the utilization rate of PV and solve the problem of PV abandonment in most cities in Guangdong province.

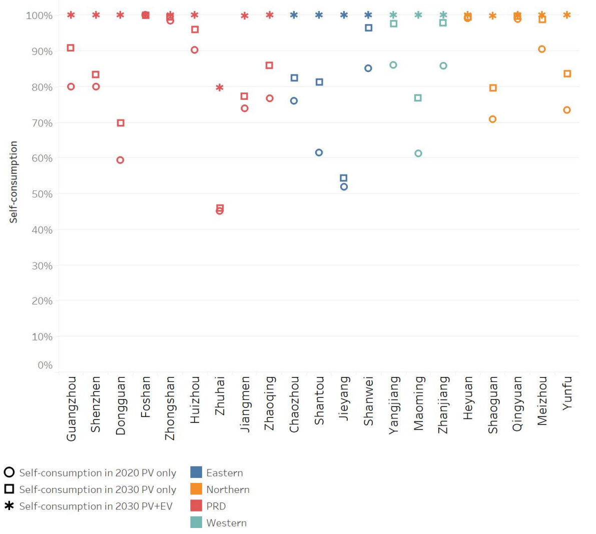

Fig. 2. Self-consumption under different scenarios in 21 cities

The self-sufficiency shows different trends in different cities (Fig. 3). In the 2020 PV only scenario, the self-sufficiency of cities ranges from 10% to 43%, with most cities having a self-sufficiency level of about 30%, indicating that rooftop PV can provide a significant portion of a city's electricity demand, which is critical for cities to improve energy security.

In the 2030 PV only scenario, due to the faster growth rate of future electricity demand, the percentage of energy support that PV can provide for cities decreases, as shown by the self-sufficiency of each city decreases in varying degrees, but the self-sufficiency of most cities remains between 28% and 35%, indicating that PV is still one of the effective solutions to future energy problems.

In the 2030 PV+EV scenario, the average self-sufficiency of the 21 cities is 26%, and the self-sufficiency of most cities still maintains a decreasing trend, with only three cities, Shenzhen, Zhuhai and Maoming, having a higher self-sufficiency than the 2030 PV only scenario. Zhuhai's self-sufficiency reaches 53%, which indicates that in some cities, the addition of EVs can enable more PV to be utilized at the load side and increase the share of PV in urban energy system, but the demand for electricity from EVs weakens this positive effect, resulting in a decrease in the share of PV in energy supply in 18 cities. As a result, PV+EV systems can significantly improve energy security in some cities, and although this effect is diluted by more demand for electricity in many cities, the self-sufficiency of up to 26% proves the contribution of PV+EV systems to urban energy systems.

Fig. 3. Self-sufficiency under different scenarios in 21 cities

3.3 Economic effect

It is obvious that the cost saving tends to increase among scenarios (Fig. 4). The cost saving of cities in 2020 PV only scenario is 1%-5%, in 2030 PV only scenario, the cost saving of the system will be improved due to the expected decrease of PV capital cost, ranging in 2%-13%. And in 2030 PV+EV scenario, the overall cost saving has been improved more significantly due to the reduction of fuel cost by EVs replacement ICEs, reaching from 14% to 25%.

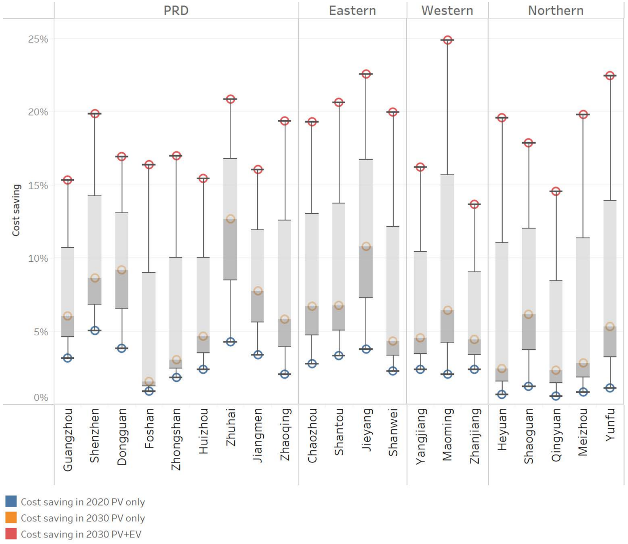

Fig. 4. Cost saving under different scenarios in 21 cities

3.4 *Environmental effect*

In 2020 PV only scenario, the CO_2 emission reduction can reach 0.61Mt to 13.26Mt (Fig. 5). In 2030 PV only scenario, more PV deployments contribute more CO_2 emission reductions, from 3.54Mt in 2020 to 4.96Mt on average, with Guangzhou contributing the most emission reductions at 16.11Mt. In 2030 PV+EV scenario, PV+EV system can provide more CO_2 emission reduction in most cities, although 8 cities have less CO_2 emission reductions than the 2030 PV only scenario, because EVs require more electricity, and the increased PV utilization and substitution effect of EVs on ICEs may not be enough to offset this increase in CO_2 emissions.

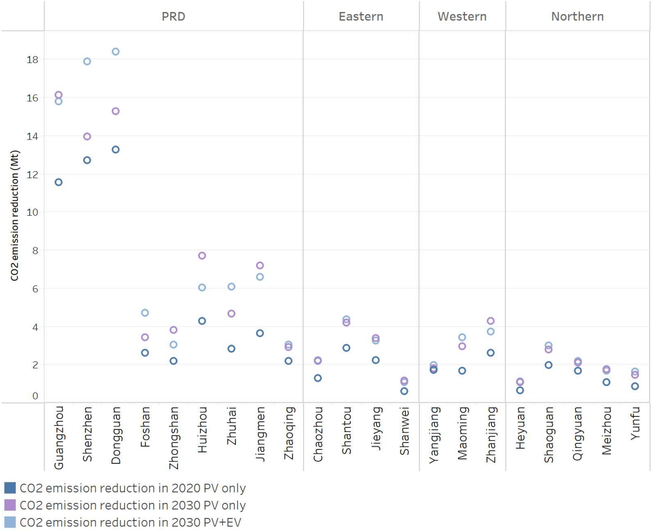

Fig. 5. CO_2 emission reduction under different scenarios in 21 cities

3.5 *Economic burden of PV deployment in cities*

Although different PV systems bring positive effects in energy, economic and environmental aspects, this does not mean that all cities can deploy the best installed PV capacity. Total initial investment/GDP can be used as a reference indicator to roughly measure the economic burden of PV deployment in a city (Fig. 6). In Guangdong province, the three cities with the highest economic burden for PV are Dongguan, Shaoguan and Jieyang, which is determined by both rooftop area and local GDP levels. The high ratio of Dongguan stems from its very high PV potential, and Shaoguan and Jieyang from their relatively low GDP levels. Overall, the PRD region has high rooftop PV potential along with a province-leading level of GDP, so for most cities in this region, rooftop PV deployment would not be an excessive economic burden.

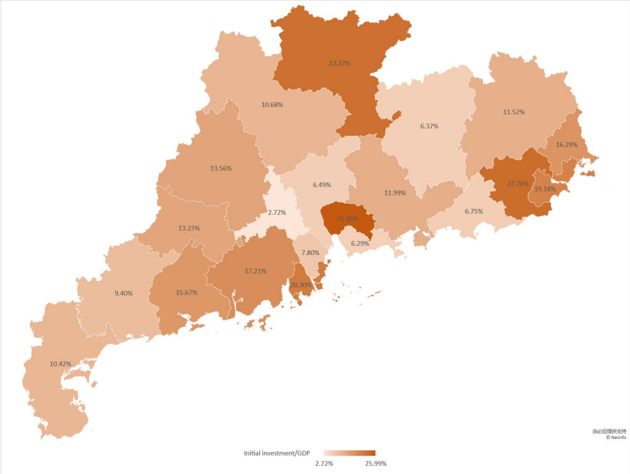

Fig. 6. Total initial investment/GDP in each city in 2020

For different cities, the proportion of total initial PV investment to GDP varies greatly, meaning that some city governments can invest in building their local PV systems by paying a smaller portion of their GDP for one year, while some cities may have financial difficulties with PV investment for local governments due to low levels of development or very large rooftop areas. So for such cities, consideration should be given to broadening PV-related financing channels and subsidy policies. Since the total investment will be distributed among several years, the real economic burden should be much lower.

4. CONCLUSION AND DISCUSSION

This paper aims to assess the energy-economic-environmental effects of different PV systems by performing a technical and economic assessment of the rooftop PV potential in 21 cities. The results illustrate that PV+EV systems behave differently in cities at different stages of development. PV+EV systems in cities located in the PRD region (like Guangzhou, Shenzhen, and Dongguan) have a more significant energy-economic-environmental effect in Guangdong province. In most cases, PV+EV systems can improve the utilization of rooftop PV (reaching 100% in almost all cities), increase the share of PV in urban energy supply, provide a contribution to urban energy security, and can lead to economic benefits and emission reductions. However, different cities have different capacities for PV deployment and regional differences will mean that PV development remains challenged.

ACKNOWLEDGEMENT

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