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Establishing decarbonization strategies for Chinese cities using rooftop PV integrated with EVs – A case study in Qingdao[#]

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ABSTRACT

To achieve carbon neutrality while maintaining economic stability, it is imperative to promote the widespread adoption of clean energy and further reduce emissions from fossil fuel use. With the decreasing cost of clean energy and the increasing penetration of electric vehicles (EV), utilizing EVs as the primary energy storage for photovoltaic (PV) systems can play a crucial role in constructing low-carbon cities. In this study, we conducted a technical and economic analysis of a combined rooftop PV generation and EV energy storage system in Qingdao, China. Our findings reveal that leveraging EV energy storage to address the bottleneck in urban distributed PV development holds immense potential. By 2030, carbon emissions in the electricity and vehicles part could be reduced by 73%, while energy costs could decrease by 35%. This study can provide a reference for the decarbonization in Qingdao and provide a research framework for smaller scale studies.

Keywords: Renewable energy, decarbonization, photovoltaic, electric vehicles, Qingdao

NONMENCLATURE

Abbreviations	
PV	Photovoltaics
EV	*Electric Vehicles*
FIT	Feed-in-tariff
V2H	Vehicle to Home
NPV	Net present value

1. INTRODUCTION

For a very long time, fossil fuels were a major source of energy for economic growth and urban construction, which generated significant carbon emissions, however, clean energy has become an important way to address this issue[1]. After the Paris Agreement, clean energy is booming, with the photovoltaic industry growing rapidly worldwide[2]. As one of many low-cost clean energy sources, photovoltaics has become one of the cheapest in some areas, and prices keep dropping[3]. At the same time, the carbon-reducing capabilities of EV are being emphasized by various countries[4]. EV are also gaining popularity worldwide and the market is rising exponentially[5].

In China, the government stated a "dual carbon target" in 2020, which is to strive for carbon peaking by 2030 and carbon neutrality by 2060[6]. As a response to the goals, the cumulative PV installed capacity has reached 610 GW at the end of 2023, officially surpassing hydropower[7]. Meanwhile, EV penetration has reached 35.2% in 2023[8], accounting for about 60% of global EV sales[5]. Therefore, it is becoming increasingly important to fully utilize the role of PVs and EVs in carbon neutrality.

There have been many studies on the decarbonization potential of PV-EV systems. the combination of PV and EV in residential scenarios in cities such as Kyoto[9], Fukushima[10] and Jakarta[11] has proved to be a low-cost and very effective way of decarbonization. Studies in Japan[12], China[13], Thailand[14], and France[15] have also demonstrated that the combination of PV and EV at the urban scale can adequately compensate for the mismatch between PV power generation and urban power loads.

In this study, we investigate the decarbonization potential of PV versus EV at different scales with a more refined economic and technical analysis.

2. STUDY AREA

Qingdao is a regional center city in northern China with 10.34 million residents and an administrative area of 11,293 square kilometers. In terms of the power structure, coal-fired power, clean energy, and extra-urban power transmission account for 44.2%, 5.3%, and 50.5% respectively, with a relatively low self-sufficiency rate in clean energy. PV installations amount to 1,001.6 MW, with a total power generation of 857 million kWh,

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constituting 4.5% of the total power generation[16]. Roof area data used in this study was obtained from[17].

3. METHODOLOGY

3.1 Techno-economic analysis on a city scale

Techno-economic analysis aims to assess the interaction between technology and the economy. In the city scale analysis, we followed the idea of our previous study[12,18]. The city was considered as a “power system” with rooftops, vehicles and electricity load. PV generation, power usage, and storage, which determines how much the system can save on energy costs, supply electricity, and reduce carbon emissions[12,18,19]. Following factors were taken into account in the analysis: (a) PV: solar and weather conditions, tilt, losses and degradation, installation and O&M cost; (b) EV: battery capacity, driving pattern, driving energy cost, EV extra cost, charging rules, battery degradation, V2H system cost; (c) economics factors: inflation rate, discount rate, tariff structures.

We used an open resource software, System Advisor Model(SAM, version 2020.2.29)[20] for techno-economic analysis. We set up 6 scenarios (No FIT: a. PV Only with 2018 technology cost, b. PV Only for 2030, c. PV+EV for 2030; With FIT: d. PV Only for 2018, e. PV Only for 2030, f. PV+EV for 2030) to compare with each other, and with the base scenario (grid electricity and gasoline vehicles). NPV was used to find the optimal PV capacity for each scenario, using the PV capacity corresponding to the maximum value of NPV.

3.2 Weather data

We used the climate reanalysis data “MERRA-2”[21] for 2018 and reprocessed it using "SIREN"[22] to produce a weather file so that it can be read directly by SAM. One point that needs to be clarified is that, based on previous studies in Kyoto[9], we found that the PV potential was overestimated. Therefore, we adjusted the radiation values to 65% of their original values following observation data[23].

3.3 Electricity load

In China, hourly load profiles for cities are typically unavailable, only monthly data is available[24]. Therefore, we extracted the daily power load from [25] pixel by pixel via Python, and calculated the hourly electricity loads according to the hourly trend in Figure 1. For the growth rate of electricity consumption, we use real electricity growth data from 2018-2023[26], and for data after 2023 we use the expected values from the Qingdao Energy Development Plan[16].

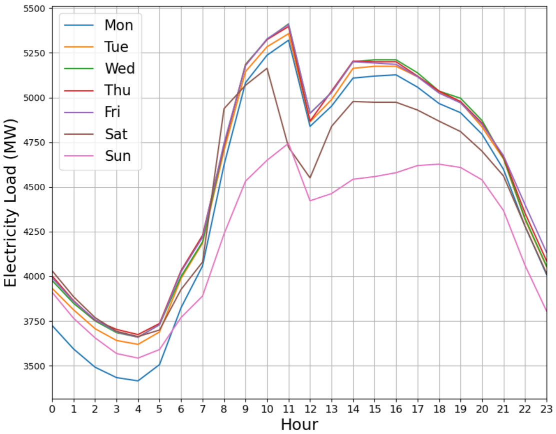


Fig. 1 Average hourly electricity load of each day in a week from 2016 to 2017

3.4 Economics factors

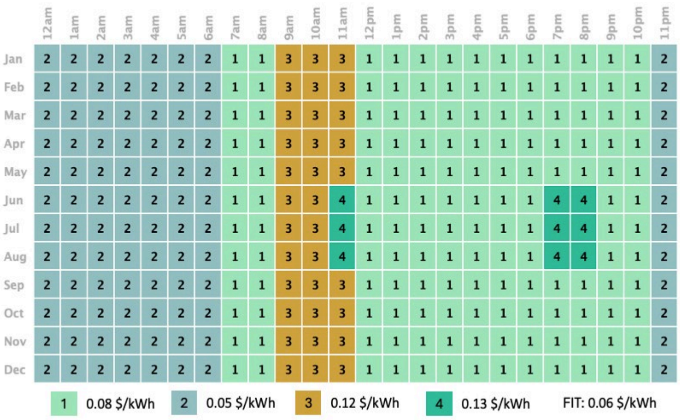
The exchange rates utilized in this paper are based on the average exchange rate published by the National Bureau of Statistics of China in 2018 (1 USD = 6.6174 CNY)[27]. For Chinese photovoltaic (PV) projects, some studies have used a discount rate above 8%[28,29]; however, due to the rapid development of the PV industry in recent years, the use of a higher discount rate is no longer appropriate. In our previous research on Japan, we used a value of 3%, so we conservatively adopted a discount rate of 6.37% based on[30] as a reference. The inflation rate is taken as the average of the past decade, at 2.25%[31].

3.5 Tariff structures and FIT

The peak-valley electricity pricing system is widely adopted in China, including in Qingdao where both residential and industrial/commercial electricity consumption primarily operate under this pricing mechanism[32]. The electricity usage in Qingdao is categorized into industrial and commercial electricity (55.09%), residential electricity (17.82%), and other types of electricity (27.08%)[24]. Given that agricultural production electricity consumption is significant within the "other" category and its electricity price is close to that of residential electricity, to simplify our model, we have recalculated the peak-valley electricity pricing suitable for the SAM model by combining the proportions of each electricity type with the electricity prices[33] in Shandong Province. A FIT of $0.06[34] was used in this study and details of the price can be found in Figure 2.

3.6 Cost of PV and EV system

The price of PV systems is rapidly decreasing[35]. Although PV system prices in China have consistently



	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
Jan	2	2	2	2	2	2	2	1	1	3	3	3	1	1	1	1	1	1	1	1	1	1	1	2
Feb	2	2	2	2	2	2	2	1	1	3	3	3	1	1	1	1	1	1	1	1	1	1	1	2
Mar	2	2	2	2	2	2	2	1	1	3	3	3	1	1	1	1	1	1	1	1	1	1	1	2
Apr	2	2	2	2	2	2	2	1	1	3	3	3	1	1	1	1	1	1	1	1	1	1	1	2
May	2	2	2	2	2	2	2	1	1	3	3	3	1	1	1	1	1	1	1	1	1	1	1	2
Jun	2	2	2	2	2	2	2	1	1	3	3	4	1	1	1	1	1	1	1	4	4	1	1	2
Jul	2	2	2	2	2	2	2	1	1	3	3	4	1	1	1	1	1	1	1	4	4	1	1	2
Aug	2	2	2	2	2	2	2	1	1	3	3	4	1	1	1	1	1	1	1	4	4	1	1	2
Sep	2	2	2	2	2	2	2	1	1	3	3	3	1	1	1	1	1	1	1	1	1	1	1	2
Oct	2	2	2	2	2	2	2	1	1	3	3	3	1	1	1	1	1	1	1	1	1	1	1	2
Nov	2	2	2	2	2	2	2	1	1	3	3	3	1	1	1	1	1	1	1	1	1	1	1	2
Dec	2	2	2	2	2	2	2	1	1	3	3	3	1	1	1	1	1	1	1	1	1	1	1	2

1 0.08 $/kWh
2 0.05 $/kWh
3 0.12 $/kWh
4 0.13 $/kWh
FIT: 0.06 $/kWh

Fig. 2 Qingdao Peak-Valley Tariff Structure and FIT

been lower than in other countries worldwide, it is anticipated that the price will decrease from $1.08/W in 2018[35] to $0.5/W by 2030[3,13]. Also, the operating costs will be reduced from 7.96$/kW-yr in 2018[13] to 3.40$/kW-yr in 2030[3].

The prices of EVs are rapidly declining in China[36], with brands like BYD representing lower prices and higher battery capacities. However, due to the limited adoption of V2H technology in China, this study continues to use the Nissan Leaf as the model EV, also, assuming 70% of vehicles are electric. Specific parameters of this vehicle can be found in our previous research[12].

4. RESULTS

4.1 Overview of 6 scenarios

The impact of FIT and EV energy storage on PV systems is significant. This is consistent with our previous findings regarding Japan. Also, due to the larger scale of Chinese cities, there exists substantial rooftop PV potential. We use five evaluation metrics to assess the economic-technical analysis results of the scenario: (a) self-consumption: the proportion of PV electricity used within the city compared to the total PV electricity generated; (b) self-sufficiency: the proportion of PV electricity used within the city in comparison to the city's demand considering a supply and demand balance; (c) energy sufficiency: the proportion of total PV electricity generated compared to the electricity demand in the city; (d) cost saving: the percentage of potential energy cost savings compared to the base scenario costs; (e) CO_2 emission reduction: the percentage of potential CO_2 emission reduction compared to the base scenario CO_2 emissions. For detailed results, please refer to Table 1.

4.2 Energy penetration and self-sufficiency

In the absence of FIT, even with cost reduction more than half(from $1.08/W to $0.5/W), due to the mismatch between PV generation and electricity consumption, self-sufficiency only increases from 25% to 32%, while corresponding self-consumption decreases from 97% to 78%. The importation of EVs mitigates well the wastage of electricity caused by the rising number of PVs, allowing the city to further increase the penetration of PVs while maintaining high self-consumption(Fig.3).

When the system can sell electricity to the grid, the increase in PV penetration is no longer limited by the city's electrical load. Because a city is viewed as an integrated system in this study, power that exceeds the city's load can be consumed by other cities. Nevertheless, with the PV capacity of the scenarios with FIT much larger than the scenarios without FIT, the self-sufficiency of PV Only with FIT for 2018 (31%) and PV Only with FIT for 2030(46%) is still lower than that of scenario PV+EV without FIT for 2018 (50%).

4.3 Economic and environmental benefit

Introducing PV with EV can reduce the total system cost compared to the base scenario. When FIT is not considered, PV Only for 2018, PV Only for 2030, and PV+EV for 2030 can bring average annual cost savings of $91 million, $367 million, and $1.30 billion, respectively. When FIT is considered, this rises to $96 million, $598 million, and $1.73 billion. In the case where system generation can cover 50% of the city's electricity load

Table 1 Results of techno-economic analysis under different conditions

Scenarios	2018 PV Only	2030 PV Only	2030 PV+EV	2018 PV Only	2030 PV Only	2030 PV+EV
FIT		Without FIT			With FIT	
self-consumption	97%	78%	95%	87%	23%	40%
self-sufficiency	25%	32%	50%	31%	46%	72%
Energy sufficiency	26%	42%	53%	35%	196%	179%
Cost saving	2%	7%	25%	2%	27%	35%
CO_2 emission reduction	18%	25%	52%	24%	38%	73%

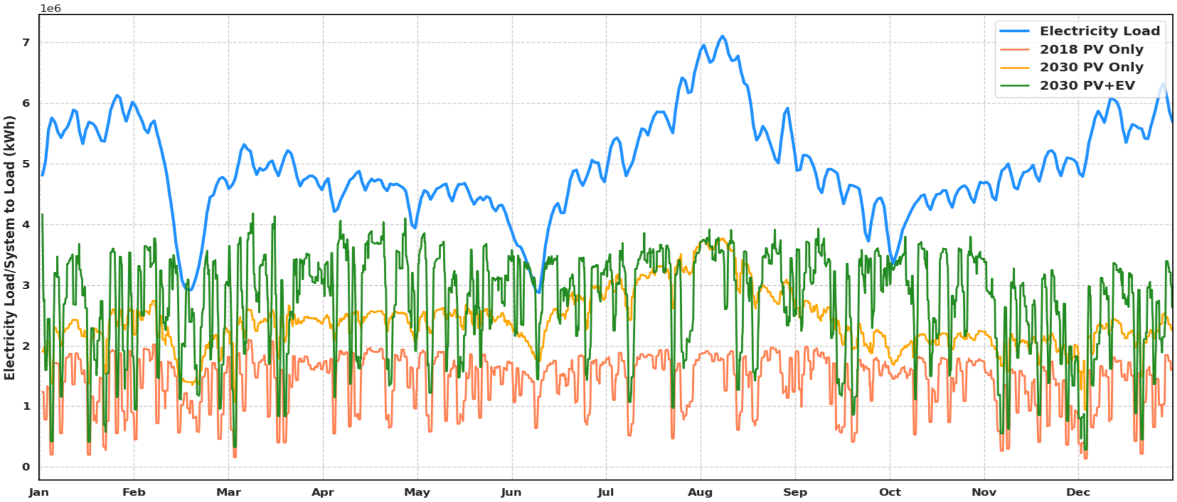


Fig. 3 Electricity load and PV to load in different scenarios

(scenario c), the discounted payback period is 5.8 years. In a larger scale PV scenario, where the system generation covers 72% of the urban electricity load, the discounted payback period is only 7.9 years (scenario f).

The carbon reduction potential of the system rises with PV installation. When FIT is considered, the 2030PV scenario and the 2030PV+EV scenario can reduce CO_2 13.49 Mt and 28.05 Mt, respectively. Since Qingdao's grid carbon emission factor is higher than the national average, the system will have a higher potential for carbon reduction as clean energy penetration gradually increases.

5. DISCUSSION

With PV costs falling and EV penetration rising, the combination of PV and EV will have considerable economic and environmental benefits in the future. As one of the countries with the lowest PV costs and one of the highest EV penetration rates, it is necessary for China to utilize the strong impetus of both to help reform the power system. Similar to our previous study[12,18], Qingdao can further accelerate carbon neutrality by increasing PV penetration to improve energy self-sufficiency. However, like many other regional center cities in China, for example Wuhan[37], despite high urbanization rate, residential buildings in the urban area are predominantly high-rise, and the rooftop that can be used for PV installations is very limited, with a large percentage of rooftop located in rural areas and other areas far from the city center. Therefore, how to promote grid connectivity between rural and urban areas through EVs deserves further research.

Currently, FIT policies are implemented nationwide in China as a policy tool to promote the development of the PV industry and increase the share of clean energy. Although in our study we assume that the stored electrical energy in EV can only used to power the building's electricity load, not sold back to the grid, surplus solar energy generation is difficult to accept by the grid if it is not sufficiently consumed at certain times. In central and western cities of China, where renewable energy has not yet become the primary source of electricity, curtailment of solar power has already been observed. In 2023, the overall utilization rate of PV power generation in China was 98%, with utilization rates in western regions such as Qinghai and Gansu provinces at 95%, and Tibet at only 78%.[38] Therefore, policy makers need to consider introducing EVs as energy storage to ease the bottleneck of PV development during the transition period of power system reform.

6. CONCLUSIONS

With the decreasing costs of clean energy and the increasing penetration of EV, leveraging EV to alleviate the bottleneck period encountered during PV development holds significant potential. We conducted a techno-economic analysis of a PV-EV system in Qingdao, China, and found that by 2030, the PV-EV system could increase CO_2 emission reduction from a single PV by 24% to 73%, while also saving costs by 35%. Therefore, policymakers need to consider integrating EV as the primary energy storage solution for accommodating PV, thereby further promoting the widespread adoption of clean energy and the development of low-carbon cities.

REFERENCE

[1] Abbasi KR, Shahbaz M, Zhang J, Irfan M, Alvarado R. Analyze the environmental sustainability factors of China: The role of fossil fuel energy and renewable

energy. Renewable Energy 2022;187:390–402. https://doi.org/10.1016/j.renene.2022.01.066.

[2] Teske S, editor. Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5°C and +2°C. Springer Nature; 2019. https://doi.org/10.1007/978-3-030-05843-2.

[3] IRENA. Renewable power generation costs in 2022. 2022.

[4] Rietmann N, Hügler B, Lieven T. Forecasting the trajectory of electric vehicle sales and the consequences for worldwide CO2 emissions. Journal of Cleaner Production 2020;261:121038. https://doi.org/10.1016/j.jclepro.2020.121038.

[5] International Energy Agency. Global EV Outlook 2023: Catching up with Climate Ambitions. OECD; 2023. https://doi.org/10.1787/cbe724e8-en.

[6] Wang Y, Guo C, Chen X, Jia L, Guo X, Chen R, et al. Carbon peak and carbon neutrality in China: Goals, implementation path and prospects. China Geology 2021;4:720–46. https://doi.org/10.31035/cg2021083.

[7] National Energy Administration. National Electricity Industry Statistics 2023 2024. https://www.gov.cn/lianbo/bumen/202401/content_6928723.htm (accessed April 3, 2024).

[8] Shang W-L, Zhang J, Wang K, Yang H, Ochieng W. Can financial subsidy increase electric vehicle (EV) penetration---evidence from a quasi-natural experiment. Renewable and Sustainable Energy Reviews 2024;190:114021. https://doi.org/10.1016/j.rser.2023.114021.

[9] Kobashi T, Yoshida T, Yamagata Y, Naito K, Pfenninger S, Say K, et al. On the potential of “Photovoltaics + Electric vehicles” for deep decarbonization of Kyoto’s power systems: Techno-economic-social considerations. Applied Energy 2020;275:115419. https://doi.org/10.1016/j.apenergy.2020.115419.

[10] Kobashi T, Choi Y, Hirano Y, Yamagata Y, Say K. Rapid rise of decarbonization potentials of photovoltaics plus electric vehicles in residential houses over commercial districts. Applied Energy 2022;306:118142. https://doi.org/10.1016/j.apenergy.2021.118142.

[11] Dewi RG, Siagian UWR, Asmara B, Anggraini SD, Ichihara J, Kobashi T. Equitable, affordable, and deep decarbonization pathways for low-latitude developing cities by rooftop photovoltaics integrated with electric vehicles. Applied Energy 2023;332:120507. https://doi.org/10.1016/j.apenergy.2022.120507.

[12] Kobashi T, Jittrapirom P, Yoshida T, Hirano Y, Yamagata Y. SolarEV City concept: building the next urban power and mobility systems. Environ Res Lett 2021;16:024042. https://doi.org/10.1088/1748-9326/abd430.

[13] Liu J, Li M, Xue L, Kobashi T. A framework to evaluate the energy-environment-economic impacts of developing rooftop photovoltaics integrated with electric vehicles at city level. Renewable Energy 2022;200:647–57. https://doi.org/10.1016/j.renene.2022.10.011.

[14] Jittayasotorn T, Sadidah M, Yoshida T, Kobashi T. On the Adoption of Rooftop Photovoltaics Integrated with Electric Vehicles toward Sustainable Bangkok City, Thailand. Energies 2023;16:3011. https://doi.org/10.3390/en16073011.

[15] Deroubaix P, Kobashi T, Gurriaran L, Benkhelifa F, Ciais P, Tanaka K. SolarEV City Concept for Paris. Applied Energy 2023;350:121762. https://doi.org/10.1016/j.apenergy.2023.121762.

[16] General Affairs Office of Qingdao Municipal People’s Government. Qingdao 14th Five-Year Plan for Energy Development 2021. http://www.qingdao.gov.cn/zwgk/xxgk/bgt/gkml/gwfg/202112/t20211203_3902158.shtml (accessed April 8, 2024).

[17] Zhang Z, Qian Z, Zhong T, Chen M, Zhang K, Yang Y, et al. Vectorized rooftop area data for 90 cities in China. Sci Data 2022;9:66. https://doi.org/10.1038/s41597-022-01168-x.

[18] Kobashi T, Say K, Wang J, Yarime M, Wang D, Yoshida T, et al. Techno-economic assessment of photovoltaics plus electric vehicles towards household-sector decarbonization in Kyoto and Shenzhen by the year 2030. Journal of Cleaner Production 2020;253:119933. https://doi.org/10.1016/j.jclepro.2019.119933.

[19] Hoppmann J, Volland J, Schmidt TS, Hoffmann VH. The economic viability of battery storage for residential solar photovoltaic systems – A review and a simulation model. Renewable and Sustainable Energy Reviews 2014;39:1101–18. https://doi.org/10.1016/j.rser.2014.07.068.

[20] Version 2020.2.29 - System Advisor Model - SAM. 2020. https://sam.nrel.gov/download/version-2020-2-29-1.html (accessed April 3, 2024).

[21] Gelaro R, McCarty W, Suárez MJ, Todling R, Molod A, Takacs L, et al. The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). Journal of Climate 2017;30:5419–54. https://doi.org/10.1175/JCLI-D-16-0758.1.

[22] King A. SIREN: SEN’s Interactive Renewable Energy Network Tool. In: Sayigh A, editor. Transition Towards 100% Renewable Energy, Cham: Springer International

Publishing; 2018, p. 197–205. https://doi.org/10.1007/978-3-319-69844-1_19.

[23] Rixian Cui. The Analysis of Spatiotemporal Variation Characteristics of Global Solar Radiation in Shandong Province. Journal of Natural Resources 2014;29:1780–91. https://doi.org/10.11849/zrzyxb.2014.10.013.

[24] Qingdao Bureau of Statistics. Qingdao Statistical Yearbook 2019. 2019.

[25] Dong H, Gao Y, Meng X, Fang Y. A Multifactorial Short-Term Load Forecasting Model Combined With Periodic and Non-Periodic Features - A Case Study of Qingdao, China. IEEE Access 2020;8:67416–25. https://doi.org/10.1109/ACCESS.2020.2986031.

[26] Qingdao Bureau of Statistics. Qingdao Statistical Yearbook 2023. 2023.

[27] National Bureau of Statistics. Statistical Bulletin on National Economic and Social Development 2018. 2019.

[28] Yuan J, Sun S, Zhang W, Xiong M. The economy of distributed PV in China. Energy 2014;78:939–49. https://doi.org/10.1016/j.energy.2014.10.091.

[29] Qiu S, Wang K, Lin B, Lin P. Economic analysis of residential solar photovoltaic systems in China. Journal of Cleaner Production 2021;282:125297. https://doi.org/10.1016/j.jclepro.2020.125297.

[30] Rong Y, Sun X. Discount Rate of China’s New Energy Power Industry. ENERGY 2021;119:315–29. https://doi.org/10.32604/EE.2022.015485.

[31] World Bank. World Bank Open Data Nan. https://data.worldbank.org (accessed April 4, 2024).

[32] Lin B, Chen J, Wesseh PK. Peak-valley tariffs and solar prosumers: Why renewable energy policies should target local electricity markets. Energy Policy 2022;165:112984. https://doi.org/10.1016/j.enpol.2022.112984.

[33] State Grid Shandong Province Power Company. Shandong Power Grid Sales Tariff Table 2021.

[34] People’s Daily Online. Subsidies out, grid parity! Shandong photovoltaic enterprises ushered in the policy “good”? 2021. http://sd.people.com.cn/n2/2021/0617/c166192-34780476.html (accessed April 4, 2024).

[35] IRENA. Renewable power generation costs in 2019. 2019.

[36] Wang H, Feng K, Wang P, Yang Y, Sun L, Yang F, et al. China’s electric vehicle and climate ambitions jeopardized by surging critical material prices. Nat Commun 2023;14:1246. https://doi.org/10.1038/s41467-023-36957-4.

[37] Chen X, Gou Z, Gui X. A holistic assessment of the photovoltaic-energy storage-integrated charging station in residential areas: A case study in Wuhan. Journal of Building Engineering 2023;79:107947. https://doi.org/10.1016/j.jobe.2023.107947.

[38] National New Energy Consumption Monitoring and Early Warning Center. National New Energy Grid Integration and Consumption in 2023 2023. http://mp.weixin.qq.com/s?__biz=MzU5NDg1OTc5MQ==&mid=2247484477&idx=1&sn=dad6b34f4726007ca0d3c310d2dfb579&chksm=fe7b865dc90c0f4b925f29f7fdc6319a65a0be147939b18db163e1aaa59e88660b47267fd9c8#rd (accessed April 8, 2024).