Energy Proceedings
Vol 60, 2025
ISSN 2004-2965

Constraints on Global Solar Power Generation Development by 2050: Land, Policy, or Funding?

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ABSTRACT

Solar power generation is a crucial pathway toward achieving global carbon neutrality. However, many countries and regions lack a comprehensive understanding of the barriers to solar development from a global perspective. To address this issue, we selected 11 representative countries (or regions) worldwide and projected the electricity consumption and solar land demand of 665 first-level administrative units by 2050. Based on land, capital, and policy dimensions, we constructed PV development constraint scenarios and analyzed the developmental constraints and future pathways of solar power generation in these regions. The results indicate that: (1) Global electricity consumption and land demand will continue to grow. By 2050, only a few countries—such as Australia, Egypt, and South Africa—can largely meet their electricity demand using barren land alone, while only 19.94% of global first-level administrative units can do so; most regions must rely on composite land-use approaches such as construction land integration. (2) Based on combinations of land availability and economic conditions, PV development constraints can be categorized into four types: land-constrained, capital-constrained, land and capital-constrained, and policy-constrained. (3) Japan, South Korea, the European Union, Brazil, China, and the United States are land-constrained; Egypt and South Africa are capital-constrained; Thailand and India are land and capital-constrained; and Australia is policy-constrained. (4) At the first-level administrative unit scale, land-constrained areas are the most widespread (67.92%), while capital-constrained areas are the least common (4.05%). This classification framework provides a scientific theoretical basis and practical guidance for formulating differentiated and targeted regional PV development strategies.

Keywords: PV land use; electricity consumption forecasting; constraint scenarios

NONMENCLATURE

Abbreviations	
PV	photovoltaic
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
GDP	Gross Domestic Product
IMF	International Monetary Fund

1. INTRODUCTION

The intensification of global warming has further accelerated the transition of the global energy structure. To achieve the climate goals of the Paris Agreement and avoid the severe consequences of climate change, decarbonization plans around the world generally call for the widespread deployment of zero-carbon energy by 2050 or 2060, thereby achieving net-zero greenhouse gas emissions[1-3]。According to the IRENA and the IEA, nearly three-quarters of the global increase in power generation in 2024 came from renewable energy sources. By the end of 2024, the total installed capacity of global renewable power generation had reached 4,448 GW, with solar power accounting for 42%, ranking first among all renewable sources[4, 5].Thus, solar power has become the leading form of clean energy[6].

However, the development of solar power is constrained by multiple factors. Siddharth Sareen, using solar cities such as Jaipur, Jodhpur, and Lisbon as case studies, explored spatial patterns of solar power plant deployment under capital-constrained conditions, revealing how fiscal limitations affect solar infrastructure distribution[7]. Saori Miyake et al. assessed the relationship between solar power potential and land availability among the G20 countries and the European Union, highlighting the critical role of land resources[8]. Eric O'Shaughnessy et al. emphasized that policy plays a pivotal role in promoting technological innovation and deployment of solar energy in the United States, and that sustained policy

This is a paper for the 5th Applied Energy Symposium and Forum: Renewable Energy Matrix (REM2025), Oct. 29-31, 2025, Yancheng, China.

incentives can accelerate the realization of long-term decarbonization goals[9]. Govinda R. Timilsina et al. summarized the key barriers to solar technology deployment identified in other studies, categorizing them into technological, economic, and institutional obstacles[10]. Similarly, Obuseh Emmanuel Ewere et al. conducted a comprehensive review of renewable energy development barriers from five dimensions: technological, economic, social, environmental, and policy[11].

Overall, although existing studies have explored solar energy development from multiple perspectives—such as land, capital, and policy—the key limiting factors for PV development across different countries and regions remain unclear. A comprehensive and quantifiable classification framework for PV development constraints is still lacking, making it difficult to systematically identify the critical barriers to solar deployment worldwide. To address this gap, this study establishes a multi-scenario prediction framework based on the CNN-LSTM model, integrating variations in energy transition pathways, photoelectric conversion efficiency, and land availability. Eleven representative countries (or regions) and their 665 first-level administrative units were selected to simulate and evaluate electricity demand and PV land demand by 2050. By constructing an integrated analytical framework encompassing land, capital, and policy dimensions, this study identifies the key constraint factors and types of solar power development in each country or region, thereby providing a scientific basis for formulating PV development strategies tailored to national conditions.

2. DATA AND METHODS

2.1 Study Area Overview

We selected 11 countries (or regions) with a cumulative installed PV capacity of no less than 10 GW by 2024, including South Africa, Egypt, China, Japan, India, the European Union, the United States, Brazil, Australia, Thailand, and South Korea, encompassing a total of 665 first-level administrative units. The spatial distribution of the study area is shown in Figure 1. The selection of these countries (or regions) is based on the IEA-PVPS Global Photovoltaic Market Overview 2024[12]。The study area spans five continents—Asia, Europe, Africa, Oceania, and the Americas—and represents significant diversity in energy development levels, land resource endowments, and policy orientations, thereby offering strong representativeness for global PV development analysis.

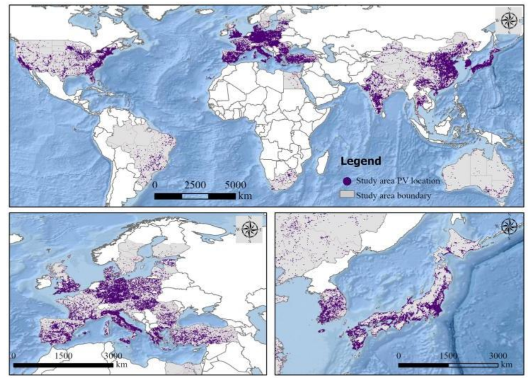


Fig.1 Study area location and PV distribution.

2.2 *Data*

To assess whether existing barren land resources can meet future electricity consumption demands, this study utilized the global electricity consumption dataset (2000–2019, 1 km × 1 km resolution) provided by[13]. This dataset was generated based on calibrated nighttime light imagery and estimated electricity consumption from the perspective of an adjusted actual growth rate. Model validation results show a high degree of goodness of fit between simulated and observed electricity consumption (R^2 = 0.96) and a root mean square error (RMSE) of 8.4×10^{10} kWh, indicating high accuracy and reliability suitable for subsequent electricity demand analysis.

To estimate the PV land area required to meet future electricity demand, we incorporated Global Horizontal Irradiance (GHI, kWh/m²) data. GHI represents the total shortwave solar radiation received on a unit horizontal surface and is a key meteorological parameter for evaluating solar energy potential. The GHI data used in this study were obtained from the Global Solar Atlas (https://globalsolaratlas.info/map), jointly released by the World Bank and the IRENA which provides essential support for PV resource assessment and land-use demand estimation.

As one of the most commonly used indicators of economic development, GDP was employed to evaluate the economic levels of secondary administrative units. We used the 2022 gridded per capita GDP dataset from[14]and adopted the IMF classification thresholds (U.S. dollars per capita): 500, 2,500, 10,000, and 25,000 to assess the economic development status across the study area.

2.3 Methods

2.2.1 Electricity Consumption Forecasting

The CNN-LSTM model is a hybrid deep learning framework that combines Convolutional Neural Networks with Long Short-Term Memory networks. In this study, CNN is employed for data preprocessing, enabling the identification of local patterns and extraction of higher-level features from time series data, while LSTM is used to model temporal dependencies and capture electricity consumption trends based on the key features extracted by CNN. The primary advantage of this hybrid model lies in its ability to simultaneously capture local and global characteristics, making it particularly suitable for long-term time series forecasting with significant nonlinear variations[15]。

2.2.2 Forecasting PV Land Area

Following the method of[16], we estimated the future PV land requirements under different scenarios of photoelectric conversion efficiency and PV share in total energy generation. This approach allows for assessing whether existing barren land can meet future electricity consumption demands.

$$E_I = R_i \times CA_I \times \varphi \times \eta \qquad (1)$$

Here, E_i represents the annual electricity generation potential of provincial-level administrative unit i (in 10^8 kWh/year); R_i is the geographic solar radiation of unit i (in 10^8 kWh/km²/year); CA_i denotes the land area suitable for PV development in unit i (in km²); ϕ is the area factor (i.e., the proportion of land covered by solar panels), for which this study adopts a minimum shading effect value of 70%[17]; and η is the PV system conversion efficiency, set at 35% for the year 2050 in this study.

2.2.3 Classification of PV Development Constraint Scenarios

At the land level, first-level administrative units are classified based on the proportion of barren land able to meet future PV land demand: Level 1 (≥50%) and Level 2 (<50%). At the GDP level, units are categorized into five levels following the IMF classification: Level 1 (≤500), Level 2 (500–2,500), Level 3 (2,500–10,000), Level 4 (10,000–25,000), and Level 5 (>25,000) U.S. dollars per capita. By combining land and GDP levels, PV development constraints are grouped into four types: land-constrained (Land Level 2 and GDP Level 1–3), capital-constrained (Land Level 1 and GDP Level 4–5), land and capital-constrained (Land Level 2 and GDP Level 4–5), and policy-constrained (Land Level 1 and GDP Level 4–5).

For first-level administrative unit classification, Land Level 1 indicates that barren land within the unit can meet PV land demand in 2050, whereas Land Level 2 indicates that barren land is insufficient to meet the 2050 PV land demand. This framework clarifies the key factors constraining PV development across administrative units.

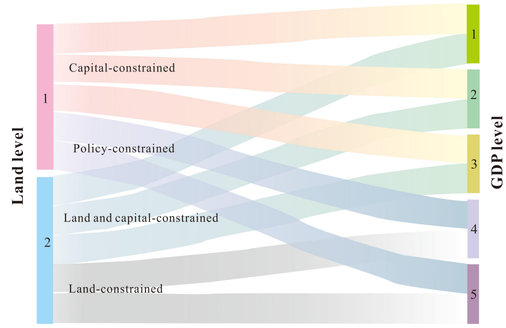


Fig.2 Classification criteria for PV development constraint scenarios.

3. RESULTS

3.1 Land Demand in 2050

As shown in Figures 3 and 4, by 2050, regions with high electricity consumption and PV land demand are still primarily concentrated in economically developed areas, including China, the United States, Japan, and central–western Europe. The study data indicate that the total electricity demand across the study area is projected to reach 27,870.20 TWh, with an average demand of 78.86 TWh per first-level administrative unit. In terms of total consumption, the United States (9,451.12 TWh), China (6,257.07 TWh), and the European Union (5,999.62 TWh) rank as the top three globally.

Regarding PV land demand, the total required area within the study region is estimated at 70,532.85 km², with the largest contributions from the United States (21,879.22 km²), European Union (18,538.92 km²), and China (16,300.34 km²).

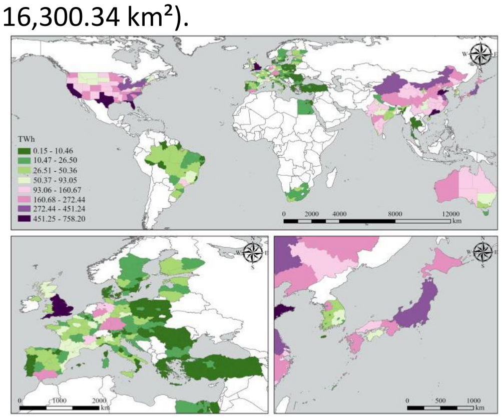


Fig. 3 Electricity demand in 2050.

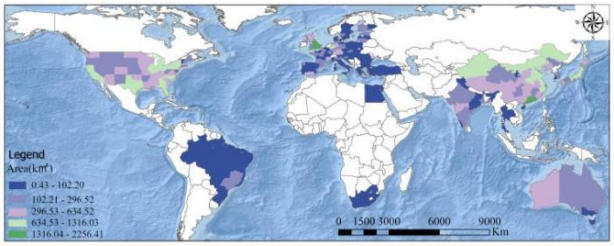


Fig. 4 PV land demand by region in 2050.

As shown in Figure 5, under the scenario where photoelectric conversion efficiency reaches 35% and PV accounts for 90% of electricity generation by 2050, barren land can meet the PV land demand in certain first-level administrative units, including western China, the United States, southern Europe, northern India, and most areas of South Africa, Egypt, and Australia. Specifically, in Egypt, South Africa, and Australia, more than 50% of first-level administrative units have sufficient barren land to meet PV land requirements (Level 1), whereas in Brazil, China, India, the United States, and the European Union, over 50% of units have insufficient barren land (Level 2).

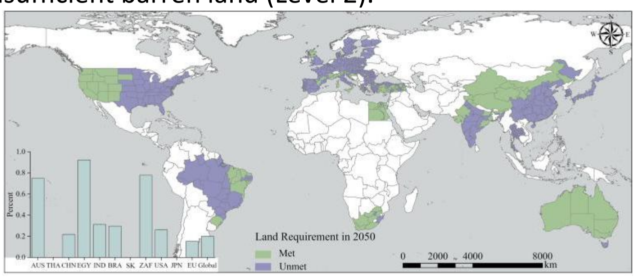


Fig. 5 Barren land availability for PV in 2050.

3.2 Classification of Countries and Regions

The classification of PV development constraint scenarios at the country (or regional) level is shown in Figure 6. Japan, South Korea, the European Union, Brazil, China, and the United States are land-constrained; Egypt and South Africa are capital-constrained; Thailand and India are land and capital-constrained; and Australia is policy-constrained.

At the first-level administrative unit scale, the distribution of constraint types is illustrated in Figure 7. Land-constrained units are the most widespread, accounting for 67.92%, mainly in most of Europe, eastern China, eastern United States, western Brazil, South Korea, and Japan. Land and capital-constrained units account for 11.99%, primarily in central India, Thailand, and parts of Brazil. Policy-constrained units represent 16.04%, mainly in western United States, western China, Egypt, South Africa, and Australia. Capital-constrained units are the least common, at 4.05%, mostly located in eastern Brazil, northern India, parts of China, and South Africa.

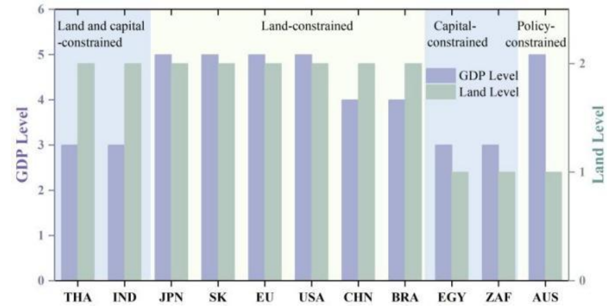


Fig. 6 Classification of constraint factors by country (or region). The x-axis represents country/region abbreviations, listed from left to right as: Thailand, India, Japan, South Korea, European Union, United States, China, Brazil, Egypt, South Africa, and Australia.

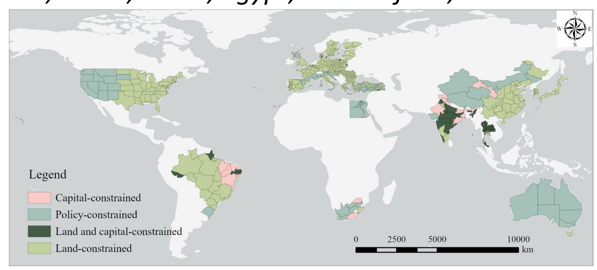
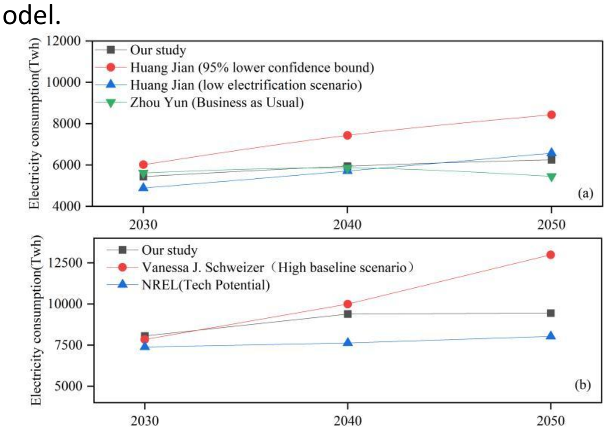


Fig. 7 Classification of constraint factors at the first-level administrative unit scale.

4. DISCUSSION

4.1 Comparison of Future Electricity Consumption Predictions with Existing Studies

We validated our future electricity consumption predictions for China, the United States, and the European Union in 2030, 2040, and 2050 by comparing them with existing studies[18-23]. The results indicate that the predicted trends in this study are consistent with previous research. Observed differences mainly arise from variations in electricity consumption datasets, socioeconomic assumptions, and energy structure evolution pathways. Overall, the results fall within a reasonable range, demonstrating the robustness and scientific reliability of the CNN-LSTM model.



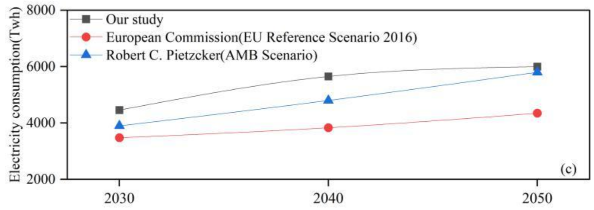


Fig. 8 Comparison of future electricity demand predictions. Panels: (a) China, (b) United States, (c) European Union. The electricity consumption predictions from Zhou Yun[19]were converted using the unit 1 × 10^8 tons of standard coal = 814 TWh.

4.2 Future PV Development Pathways

<u>4.2.1 Land-Constrained Countries (or Regions)</u>

For land-constrained countries or regions with strong economic development, such as China, the United States, and Japan, limited available land resources may lead large-scale ground-mounted PV plants to compete with agricultural, ecological, or urban land uses. Therefore, priority should be given to the development of high-efficiency PV technologies through coordinated innovation at the cell, module, and system levels[24]. Actively exploring "PV+" multifunctional integration models—such as agrivoltaics, aquavoltaics, and highway PV systems—can mitigate conflicts between PV deployment and food production, ecological conservation, and urban construction, reducing additional land pressure and enhancing land-use efficiency[25-27]. Governments should optimize land planning policies, protecting prime farmland while setting land-use efficiency standards for PV projects, ensuring "more electricity with less land" and preventing blind or inefficient expansion[28].

<u>4.2.2 Capital-Constrained Countries (or Regions)</u>

Capital-constrained countries or regions, such as Egypt and South Africa, face limited financial resources despite relatively low land pressure. Barriers include restricted financing capacity, insufficient grid and transmission infrastructure, and technology and labor shortages. To overcome these bottlenecks and promote large-scale PV deployment under limited fiscal conditions, it is essential to establish long-term renewable energy targets and stable feed-in tariff policies, and actively seek low-interest loans, risk guarantees, and technical assistance from international financial institutions and development banks, lowering financing barriers and attracting multinational enterprises and long-term investors[6, 29]Innovative financing approaches, such as green bonds or participation in carbon credit markets, can reduce capital costs and enhance project financial feasibility, leveraging more private and external investments[30]. Additionally, establishing renewable energy skill training centers, developing local PV manufacturing, and reducing module costs are crucial[6, 31, 32]. Governments should also increase subsidies, enhance high-voltage transmission capacity, improve substations and grid dispatching, and facilitate small-scale lending institutions at the local level. Supporting power purchase agreements and encouraging solar PV adoption among low- and middle-income households, as well as promoting economically viable solar/wind hybrid systems in rural areas, are recommended[29].

<u>4.2.3 Land and Capital-Constrained Countries (or Regions)</u>

Some countries or regions, such as Thailand and India, face dual constraints of limited land and financial resources. PV development planning should prioritize marginal land, implement high-efficiency PV technologies, and promote "PV+" multifunctional land use[25, 27, 33]. Introducing international and multilateral funding and policy incentives can reduce financing risks and barriers, attracting substantial private and international capital[6]. Strengthening international cooperation, such as cross-border green electricity trading within ASEAN or leveraging initiatives like Belt and Road, can support technology transfer, funding, and local industry chain development, enhancing operations and maintenance capacity[34].

<u>4.2.4 Policy-Constrained Countries (or Regions)</u>

For policy-constrained countries or regions with abundant land and strong economic conditions, such as Australia, ensuring sustainable PV development requires addressing policy uncertainty, setting long-term renewable energy targets, and providing stable expectations for investors and the market[6]. Encouraging PV-plus-storage models can increase renewable energy utilization. Leveraging national advantages, such as rich solar resources, key energy storage metals, and high-efficiency crystalline silicon technologies, can develop PV manufacturing, expand international markets, and promote green energy supply chains[35, 36]. Stable policies and market incentives can reduce political interference, harmonize federal and state-level regulations, simplify approval processes, and foster steady PV industry growth[37]. Furthermore, to address transmission and distribution capacity limitations, investment in grid infrastructure, improvement of grid connection standards, and smart dispatch systems are essential[38]. Finally, addressing land-use planning, ecological concerns, and community acceptance through improved land-use planning and environmental assessment mechanisms, as well as innovative models like agrivoltaics, can enhance public acceptance[39].

5. CONCLUSIONS

This study quantitatively classified the key constraints on future PV development in 11 countries or regions from the perspective of land, capital, and policy, providing an initial overview of the limiting factors and differences in PV deployment worldwide. The results indicate that Japan, South Korea, the European Union, Brazil, China, and the United States are land-constrained, Egypt and South Africa are capital-constrained, Thailand and India are land and capital-constrained, and Australia is policy-constrained. Accordingly, countries or regions should adopt targeted strategies based on their constraints: land-constrained areas should focus on optimized land use and continuous development of high-efficiency PV technologies; capital-constrained regions need to diversify financing channels; land and capital-constrained countries must balance policy and resource allocation; and policy-constrained markets should strengthen long-term planning. The findings provide a scientific basis for global energy structure optimization and land-use management, as well as important guidance for the spatial planning and policy formulation of future low-carbon energy systems.

Despite some limitations, such as the model's assumption that future trends mirror historical patterns—potentially restricting its ability to capture structural changes and nonlinear shocks in socio-economic systems—and the lack of a fully comprehensive and multidimensional set of indicators for classifying PV development constraints, these do not undermine the conclusions that future electricity demand and PV land requirements will continue to grow, and that PV deployment in different countries is constrained to varying degrees by land, capital, and policy. Moreover, although the study further subdivided regions at the provincial level, significant heterogeneity exists within provinces in terms of resource endowments and development conditions. Therefore, the conclusions are more applicable to macro-level national and regional strategic planning rather than specific project siting. For guiding the implementation of new PV projects, finer-scale assessments are needed in future studies. Long-term electricity demand forecasting should integrate multi-source drivers such as population growth, economic development, and climate change, and constraint classification should incorporate a more comprehensive multi-indicator evaluation system, including factors like grid infrastructure and social acceptance.

ACKNOWLEDGEMENT

This research received financial support from the National Natural Science Fund of China (42271266).

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