Evaluation of generation efficiency for solar power plants in China based on stochastic data

Xian-Peng Chen, Tianjin University, Phone +86-13141199887, E-mail: chenxianpeng@tju.edu.cn
Bai-Chen Xie, Tianjin University, Phone +86-13312188917, E-mail: xiebaichen@tju.edu.cn

Overview

As China has become the world's largest producer and consumer of energy, its renewable energy development is of great significance to the governance of global energy and campaign against climate change. With the promotion of China's energy supply and consumption revolution strategy, the proportion of renewable energy sources, such as wind power and solar power, promises to exceed 50% in power mix by 2025. Efficiency analysis of renewable energy generation becomes a vital reference for policy design, it also benefits China in achieving carbon peaking and carbon neutrality goals on time.

Different from thermal power sector, the production technology of renewable energy is not compatible with deterministic efficiency evaluation approach. Accurate measurement of input data is almost impossible as it is dominated by natural resource inputs with high volatility, such as solar or wind. Therefore, this study employs the central limit theorem to configure solar energy input as a stochastic distribution and constructs a stochastic production possibility set. A chance constrained data envelopment analysis (DEA) model combined with the direction distance function is developed to measure the efficiency of solar power plants in Qinghai, China, in order to investigate the driving force of natural resources behind the change of renewable energy generation efficiency. The study also combines incomplete price information on inputs and outputs to measure the operation performance under the orientation of profit maximization. The results will help reveal the sources of inefficiency in solar power plants, thereafter to improve productivity and operation, and provide decision supports for government on long-term planning of renewable energy development.

Methods

A lot of researches have proved that DEA is suitable for measuring the efficiency of power generation sector. However, conventional DEA models have been criticized for their inability to handle stochastic data set. Lots of efforts have been made to handle the randomness in either input or output data. Chance constrained DEA has gained popularity within the management science framework because randomness in performance can be handled under appropriate assumptions on the special distribution.

In order to compare the efficiency ranking and reference benchmark under different measures, this study combines chance constrained DEA with directional distance function to propose the following stochastic production possibility set:

$$T=\left\{\left(\tilde{x},y\right):\sum_{r=1}^{s}\mu_r y_{rj}-\sum_{i=1}^{m}\nu_i\tilde{x}_{ij}+\mu_0\geq 0,\sum_{r=1}^{s}\mu_r g_r^y-\sum_{i=1}^{m}\nu_i g_i^x=1,\mu,\nu\geq 0,\ j=1,\cdots,n\right\}$$

where ν_i and μ_r are optimal weights for stochastic input $\tilde{x}_{ij}$ and deterministic output y_{rj}, $\left(\mathbf{g}^x,\mathbf{g}^y\right)$ is the direction vector.

By defining the upper bound U and lower bound L of the price ratio, this study implements a measure of profit efficiency by constructing an assurance region for incomplete price information with the following constraints:

$$L\leq\frac{\nu_a}{\nu_b}\leq U\quad L'\leq\frac{\mu_a}{\mu_b}\leq U'$$

The chance constrained programming needs to be transformed into a deterministic formulation for software solution, which implies restrictions on the distribution of stochastic data. In this study, the annual solar energy consumption following a normal distribution is derived by cumulating the short-time solar radiation resources fitted to a Beta distribution through central limit theorem under Lyapunov condition.

Results

Compared to the results of the deterministic DEA model, there are remarkable differences in that of chance constrained model which incorporates solar consumption as an input. The efficiency of most plants show a decreasing trend, which leads to a significant shift in best practice frontier. This suggests that the technical efficiency of solar power plants is to some extent inconsistent with local solar resource endowments.

Notably, the technical efficiency of solar power plants in Qinghai is much closer under the exogenous directional distance function over the study period, with solar consumption instead of other technical factors being the major contributor to the efficiency gap. The endogenous directional distance function likewise suggests that saving solar energy inputs is an optimal path to improve technical efficiency.

Moreover, the gap among decision-making units in profit efficiency performance is further magnified when price information is included. From the perspective of profit improvement for power plants, even though almost zero-cost natural resource inputs do not increase the cost of power generation, their contribution to increasing corporate revenues is often overlooked.

Conclusions

Given the characteristics of renewable energy generation, the stochastic DEA approach allows for more objective and instructive efficiency evaluation results as it uncovers the potential bias caused by neglecting natural resource inputs. The introduction of central limit theorem making it possible to deal with massive amounts of geographical and meteorological data under various distribution assumptions.

In general, the inefficient utilization of solar resources indicates a new direction for efficiency improvement of China’s power plants. The improvement measures could be undertaken in two aspects: examining the root causes of the inefficient utilization of solar resources by photovoltaic units from a technical perspective, or scaling up production to make better use of the excellent local insolation conditions.

Considering that the current reference pricing policy does not guide operation improvement sufficiently, the introduction of power market transactions may be a beneficial attempt to narrow the profit gap. It is necessary for government to give policy incentives to motivate well-performing plants fully exploit their technical potential.

References

Cooper, W.W., Huang, Z., Lelas, V. et al. Chance constrained programming formulations for stochastic characterizations of efficiency and dominance in DEA. Journal of Productivity Analysis, 1998, 9: 53–79.

Cook, W.D., Zhu, J. CAR-DEA: Context-dependent assurance regions in DEA. Operations Research, 2008, 56(1): 69-78.

Azadeh, A., Ghaderi, S.F., Maghsoudi, A. Location optimization of solar plants by an integrated hierarchical DEA PCA approach. Energy Policy, 2008, 36(10): 3993-4004.

Valenzuela, J.M., Qi, Y. Framing energy efficiency and renewable energy policies: An international comparison between Mexico and China. Energy Policy, 2012, 51: 128-137.

Lo, K. A critical review of China's rapidly developing renewable energy and energy efficiency policies. Renewable and Sustainable Energy Reviews, 2014, 29: 508-516.

Duan, N., Guo, J.-P., Xie, B.-C. Is there a difference between the energy and CO2 emission performance for China’s thermal power industry? A bootstrapped directional distance function approach. Applied Energy, 2016, 162: 1552-1563.

Petersen, N.C. Directional distance functions in DEA with optimal endogenous directions. Operations Research, 2018, 66(4): 1068–1085.

Parmeter, C.F., Zelenyuk, V. Combining the virtues of stochastic frontier and data envelopment analysis. Operations Research, 2019, 67(6): 1628-1658.

Lin, B.-Q., Chen, Y.-F. Does electricity price matter for innovation in renewable energy technologies in China?. Energy Economics, 2019, 78: 259-266.

She, Z.-Y., Meng, G., Xie, B.-C. et al. The effectiveness of the unbundling reform in China’s power system from a dynamic efficiency perspective. Applied Energy, 2020, 264: 114717.

Mohsin, M., Hanif, I., Taghizadeh-Hesary, F. et al. Nexus between energy efficiency and electricity reforms: a DEA-based way forward for clean power development. Energy Policy, 2021, 149: 112052.

Yu, B.-L., Fang, D.-B., Meng, J.-X. Analysis of the generation efficiency of disaggregated renewable energy and its spatial heterogeneity influencing factors: A case study of China. Energy, 2021, 234: 121295.