Developing Distributed PV in Beijing: Deployment Potential and Economics

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The building sector consumed a total of 580 million tons-coal equivalent (Mtce) terminal energy in China in 2018 including 1,888 terawatt-hours (TWh) electricity, accounting for 20.2% of total terminal energy consumption in this country. As the capital of China, Beijing is striving to improve the air quality while ensuring power and heat supply due to heavy reliance on electricity intake from other energy-rich provinces. The distributed photovoltaic, as a flexible application of renewable energy systems in urban and rural regions, can contribute to the power supply for rapid urbanization and mitigate the negative environmental impact of fossil energy use. In the context of grid parity, this article provides a systematic analysis of solar resource potential, power generation economics and policy support for the rooftop photovoltaic (PV) system in Beijing. The deployment potential of rooftop PV is estimated to be 11.47 GW and the large-scale commercial rooftop PV is approaching grid parity. Furthermore, this article discusses the feasibility of large-scale distributed PV deployment in Beijing by considering distributed electricity trade envisioned the ongoing power market reform in China.

Keywords: rooftop PV, deployment potential, economics, environmental value, Beijing

INTRODUCTION

Solar PV and wind power are currently obtaining great opportunity for installation expansion and technological innovation around the world. Renewables are becoming an excellent option for many countries in the transition toward a secure, cost-effective and low-carbon energy supply system, while simultaneously combating climate change and local air pollution (IRENA, 2019). Current energy policies regard the development of renewables as a fundamental action plan to meet the immediate rise in energy demands expected in the coming decades. Moreover, solar PV is more universal and feasible for end-use sectors than clean energy such as hydropower, wind power, and biomass, because the rooftop PV can be installed on the demand side (IRENA, 2019). In this context, solar PV is one of the most promising options with an infinite sunlight resource and environmental sustainability to cover the evolving landscape for the integration of variable renewable power (Chitra and Himavathi, 2013; Bye et al., 2018).

The modularity of solar PV systems allows the universal deployment of modern energy across urban, rural, and suburban areas. Driven by the environmental policies and the sharp decline in renewable power costs, in particular the cost of PV falling by almost 75% between 2009 and 2018 (IRENA, 2018), the solar PV gains impressive growth with the installed capacity reaching 397 gigawatts (GW), comprising 17% of total renewable energy capacity and 5.78% of total power generating capacity (IEA, 2018). The power supply from distributed photovoltaic (DPV) and small solar devices, such as commercial park PV and solar home systems, is growing especially fast. New data from IRENA shows that about 25 million people obtain a higher level of
renewable energy services through solar home systems or connection to a solar mini-grid (IRENA, 2016). International experiences may provide insight that the successful applications of solar PV contribute energy supply and conservation in the building sector (Bansal and Goel, 2000; Radhi, 2010; Sadineni et al., 2012; Emziane and Al Ali, 2015).

Assessment of the deployment potential of rooftop PV systems has been an expansive area for research scholars. Taking advantages of developing geospatial technology and efficient computational methods, several methodologies based on Geographic Information System (GIS) techniques are more accurate than the constant value method (making a number of assumptions to calculate the utilisable rooftop area) and manual based selection (using remote sensing techniques such as high-resolution satellite images to evaluate the available rooftop areas) in evaluating the potential of building rooftop PV installation (Dehwah et al., 2018). Literature summarizes several generic GIS-based toolkits including Feature Analyst tool (Wiginton et al., 2010), Light Detection and Ranging (LiDAR) (Jacques et al., 2014; Gooding et al., 2015; Lingfors et al., 2017) and Digital Surface Model (DSM) (Buffat et al., 2018). An alternative to DSM is 3D building models created from aerial photos, as Google Maps demonstrates, which will be available in the foreseeable future. Digital Elevation Model (DEM) and DSM are both the branches of the Digital Terrain Model. DEM represents the topographic surface of the terrain. This article uses DEM supported by Platform for Geographical Situation Monitoring of China to identify the rooftop geometries and compute the PV installed potential in Beijing. Thus, the process of DEM assessments is further elaborated in the sections below.

The economic evaluation metrics of a power generation project comprise various technical indicators of engineering economics, including net present value (NPV), life-cycle costing, levelized cost of electricity (LCOE), internal rate of return (IRR) and payback period, etc. Short et al. (1995) presented a comprehensive and detailed review of economic evaluation modeling. NPV index, as a profitability indicator used in capital budgeting, refers to the present value of cash inflows minus the present value of cash outflows. Li and Liu (2018) integrated NPV analysis with a developed pixel-based method to estimate the revenue of potential building PV projects. IRR is defined as the discount rate when the NPV equals zero, that is, the total present value of inflows equals the total present value of outflows. IRR method integrates the project returns during its lifespan with its total investment and provides a benchmark metric to determine whether the project is worth investing (Zhao et al., 2017). This merits the attention that, when evaluating independent projects, NPV, and IRR yield the same decision. Unfortunately, NPV intrinsically necessitates an appropriate discount rate that is the focus of controversy. Thus, IRR analysis is generally preferred other than NPV. The LCOE methodology is extensively applied when mentioning generation competitiveness of various power technologies options or considering grid parities for emerging technologies (Branker et al., 2011; Congedo et al., 2013; Larsson et al., 2014). The rationale for LCOE analysis is to consider lifetime generation and costs to evaluate the tariff per unit of electricity by minimizing the biases between diverse generating technologies (Yuan et al., 2014). Therefore, this article applies the LCOE method and IRR analysis to appraise the rooftop PV system in Beijing.

The combustion of fossil fuels predominately causes deterioration of the atmospheric environment by releasing sulfur dioxide (SO₂), nitrogen oxides (NOₓ), particulate matter (PM), and carbon dioxide (CO₂). In China, the coal-fired power issued severe regional pollution. Beijing and its surrounding areas explicitly prohibit captive coal power plants for coal capping and air quality improvement (NDRC and NEA, 2017). The DPV deployment will contribute to this process. Jones and Gilbert (2018) used the life cycle assessment (LCA) to assess the greenhouse gases (GHG) emissions for PV generation at the aggregated distribution network scale. Wang et al. (2018) estimated the potential of life cycle CO₂ emissions reduction for three different patterns in Beijing. Allouhia et al. (2019) illustrated the environmental impact of PV systems by evaluating the potential of carbon emissions reduction, assuming that the energy generated by PV installations substitutes that by thermal power. The aforementioned literature conducted environmental impact analysis by employing a single factor of carbon emissions, which underestimates the environmental value without considering SO₂, NOₓ, and PM. Thus, this article will consider all of the emissions mitigation fees to explore the real environmental value of rooftop PV.

Compared with previous studies, this article contributes a more comprehensive and comprehensive analysis of the potential and value of photovoltaic development. This article employs DEM technology to explore the precise potential of rooftop PV deployment, reconciles LCOE and IRR theories to appraise the appealing economics, and further considers the environmental value through mitigating emissions from coal-fired power generating.

This study unfolds as follows. Section A Development Briefing of Beijing presents a brief overview of power development in Beijing. Section Methodology introduces the methodology of potential estimation and economic analysis. Section Results and Discussion illuminates the empirical results and discussion on rooftop PV development in Beijing. Finally, section Conclusion and policy implications concludes the article with implications. The abbreviation for manuscript is depicted in Appendix I, and supporting policies and governmental subsidies for DPV power are described in Appendix II.

**A DEVELOPMENT BRIEFING OF BEIJING**

Beijing, as the capital of China, covers 6,410 square kilometers with 27.1 million permanent residents. The capital city provides a massive daily energy consumption of 195,000 tce with daily GDP (Gross Domestic Product) of 767.5 million Chinese Yuan (CNY) in 2017. In order to optimize the energy structure and improve the environment, the government has formulated a large number of regulations to restrain the utilization of coal. Typically, from 2013, Beijing committed to phasing out all coal-fired generation fleets and installing alternative gas power plants. By the end of 2017, the energy mix of 71.33 Mtce in Beijing comprised coal (5.65%), petroleum (33.8%), natural gas (31.8%), external transmitted electricity (25.99%), and others (2.77%) (Beijing Municipal Bureau of Statistics, 2018). One of
the remarkable performances is that from 2000 to 2017, the daily average concentration of SO$_2$ has dropped from 71 to 8 mg/m$^3$.

The average concentration of Particulate Matters 2.5 (PM2.5) in Beijing drops from 104 µg/m$^3$ in 2010 to 50.9 µg/m$^3$ in 2018, ranking 8th in the global capital city in 2018 (AirVisual, 2018).

The improvement of environmental performance in Beijing benefits from the cleaner energy and power supply.

As shown in Figure 1, the total electric power consumption in Beijing has increased to 1,067 TWh by the end of 2017. The development process characterizes several following marked features: (a) the sharp growth in 2000 derives from the compression of the coal utilization in terminal energy consumption to mitigate the severe environmental pollution, with the proportion of coal in terminal energy consumption falling from 70% in 1978 to 43% in 2000 (Beijing Municipal Bureau of Statistics, 2017); (b) the power consumption of service industry exceeded that of secondary industry in 2011, indicating the strong growth of real economic in service industry; (c) residential power consumption remains a fairly rapid increasing, 44 times higher in 2017 than in 1986; (d) the rebound of electricity consumption growth in 2016 is partially driven by the clean heating policy of coal-to-electricity transformation. Simultaneously, in 2017, the household electricity consumption in Beijing reached 1004 kWh/p which is equivalent to the level in Germany, Korea and Italy in 2011 (IEA Statistics, 2018).

The solar PV resource in Beijing is pretty abundant. The annual solar radiation in Beijing is about 4,600–5,700 MJ/m$^2$, located in the Class-II resource areas of China$^1$. The annual average generation hours of DPV system may reach 1,214 h$^2$ in Beijing. PV systems can be classified into grid-connected and standalone systems based on their operational and functional requirements (Chitra and Himavathi, 2013).

### Table 1 | Beijing DPV power generation project award list.

| Time          | List | Number | Commercial Capacity (kW) | Number | Household Capacity (kW) |
|---------------|------|--------|--------------------------|--------|-------------------------|
| 2016.03.14    | 1    | 7      | 4319.4                   | 19     | 110.34                  |
| 2016.09.18    | 2    | 11     | 14446.52                 | 210    | 1758.875                |
| 2017.03.02    | 3    | 9      | 7986.3                   | 1207   | 10074.5                 |
| 2017.08.31    | 4    | 7      | 11038.1                  | 2045   | 16869.32                |
| 2018.03.02    | 5    | 37     | 12500.6                  | 2431   | 20342.375               |
| 2018.09.05    | 6    | 70     | 28265.92                 | 3884   | 34230                   |
| 2019.03.08    | 7    | 67     | 37343                    | 2337   | 23546.24                |
| Total         | 208  |        | 115909.84                | 12133  | 106931.65               |

Source: Compiled based on Award list of distributed photovoltaic power generation projects in Beijing (the 1–7th batches).

The article conducts a comparative economic evaluation of grid-connected and standalone rooftop PV systems for commerce and household.

Beijing pioneers in the full supply of clean electric power because there are no local coal-fired power plants. In 2017, the bulk of electric power was local gas power generation (34.7%) and renewable power generation (1.57%), as well as external electricity (63.7%) transmitted from vicinal provinces. By the end of 2018, the DPV installed capacity is 350 MW, occupying 87.5% of total solar PV installation, and the recently installed capacity accounts for 42.85% of the total. Until now, the government has issued seven award lists of DPV generation projects, which includes 141 commercial DPV projects and 9,796 household PV projects connected to the grid (shown in Table 1). The solar PV market gained momentum due to electricity generation planning and financial support policy. Beijing government explicitly pledged to 1,000 MW installed power generation.
capacity by 2020. The concentrated PV will be hardly increased because it covers additional land resources instead of building roof resources like DPV. Thus, for the overcrowded capital city, the DPV installation is a more probable choice for the rest of the deployment.

METHODOLOGY

We devised a three-stage approach to calculate the deployment potential and economics of rooftop PV in Beijing. The three research blocks comprise rooftop area assessment, PV generation economic appraisal and environmental value (depicted in Figure 2). In this article, the deployment potential of rooftop PV depends on the available roof of commercial and residential buildings, which is evaluated by DEM based on advanced digital and spatial techniques coupled with distinct building roof features. Then, the financial appraisal methods of engineering projects, including LCOE and Project Financial Evaluation, are employed to quantify the investment attraction. Finally, the environmental value assessment can provide insight into the positive impact on pollutant emission reduction in Beijing.

Digital Elevation Model

DEM realizes the digital simulation of terrain (i.e., the digital representation of terrain surface morphology) through limited terrain elevation data. It is an entity terrain model that represents terrain elevation in the form of a set of ordered numerical arrays. The technology map of DEM is presented in Figure 3.

DEM database supported by Platform for Geographical Situation Monitoring of China adopts a rapid extraction method of full digital human-computer interaction remote sensing to establish a spatial dataset for construction land and simultaneously make raster data of multiple scales. The high-quality DEM data with a spatial resolution of 30, 90 m and 1 km covers urban land use, rural residential area and other construction lands, etc. Then, the building area suitable for rooftop PV deployment is capable to be screened out from the massive land utilization data.

LCOE

LCOE refers to the tariff when the present value of the total revenues is equivalent to the present value of the total cost during the project lifespan. In this context, we employ the analytical approach proposed by Yuan et al. (2014) to evaluate the LCOE of rooftop PV systems in Beijing. The formula for calculation is shown as follows:

$$LCOE = \left( \sum_{n=0}^{N} \frac{Cost_n}{(1+r)^n} \right) / \left( \sum_{n=0}^{N} \frac{E_n}{(1+r)^n} \right)$$  \hspace{1cm} (1)
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FIGURE 3 | DEM technology map. Source: Platform for geographical situation monitoring of China.

\[
\text{LCOE} = \frac{C + \sum_{n=1}^{N} \left(\text{OPEX} + I\right) \times C + \text{TAX}_n + C_i + R}{\left(1+r\right)^{n}} + \frac{365-a}{365} \times H \times S \times \eta
\]

where \(E_n\) is the annual PV generation, \(C\) is the unit investment cost of the system, \(\text{OPEX}\) is the rate of operation and maintenance (O & M) cost, and \(I\) is the rate of insurance cost, \(\text{TAX}_n\) is annual tax, \(C_i\) is interest rate of the loan, \(R\) is roof renting cost, \(H\) is annual utilization hours, \(S\) is generating capacity, \(d\) is the annual degradation rate of PV system, \(\eta\) is the performance factor of the system, \(r\) is discount rate and \(a\) stands for the construction period.

**Project Financial Appraisal**

The financial appraisal analysis of engineering projects involves a comprehensive evaluation of profitability, solvency and financial viability through integrating investment, costs, revenues, taxes and profits under a certain system of accounting, tax and price (Fu and Quan, 1996). The source of funds and the repayment of loan funds will affect the cash flow, then affect the economic performance of an enterprise. Thus, the economic appraisal covers two assessments: (a) “full investment” financial analysis regards all funds as own funds to examine the economic effects within the scope of enterprises; (b) “proprietary funds” financial analysis considers all factors including financial conditions to investigate the profitability of enterprises. In this article, we appraise the economics of engineering projects, not the profitability of own investment. Thereby, the full investment assessment matches the purpose. IRR, as already noted, is a rational metric to determine whether the project is worthy of investment (Yuan et al., 2014). IRR is generally considered to reflect the investing efficiency. Thus, we employ full investment IRR as an economic indicator.

LCOE analysis and project financial appraisal share many common variables and parameters that can be integrated into four categories: technical and economic variables, taxes and charges, operation expenditure and financial variables (Figure 4). Table 2 reports a detailed description of the common parameters for LCOE and IRR estimation based on current PV investment market briefs (detailed in Yuan et al., 2014; Li et al., 2018).

**RESULTS AND DISCUSSION**

**Deployment Potential of Rooftop PV in Beijing**

The high-quality DEM data can categorize construction land area in Beijing into urban land, rural land, and industry and traffic land. In detail, the urban land includes commercial buildings, ancient buildings, office buildings (including government, hospital and education institutions), and urban residential buildings (including multi-family and detached house) with clear features and name identifications. The public facility consists of transportation, water conservancy and industrial land. This article identifies the commercial building, office building, and residential building as available blocks for the rooftop PV system.

The DEM data describes the land use of Beijing covers 16,411 km\(^2\) (square kilometer) and the share of the building area is 19.7%. The building area suitable for rooftop PV is estimated at 241 km\(^2\) in Beijing in 2018, accounting for 7.45% of the total building area. After estimating the rooftop areas available for PV installation, it also requires the information about land use for unit installation to calculate the deployment potential. The Ministry of Land and Resources (MLR) of China, now renamed the Ministry of Natural Resources (MNR), recommends that the average land use for the rooftop PV project is 21 m\(^2\)/kW in Beijing. Coupled with the estimated building roof area of...
241 km², the deployment potential of distributed PV in Beijing is determined to be 11.47 GW.

**LCOE Results**

By using the concise summaries of market findings, this article integrates the rooftop PV projects into six groups by generation capacity as the baseline levels of LCOE and IRR estimation. The distributed PV is defined as the station with generating capacity < 6 MW in China (NEA, 2013). The large-scale rooftop PV more than 1 MW is appreciated to installation in the commercial zones and office buildings, and the small-scale DPV can be installed in residential buildings (apartment buildings and detached houses). The smallest-scale rooftop PV occupies the highest initial unit investment cost, that is, 9,000 CNY/kWh in the current market. In addition, the 2 kW-scale PV project rarely obtains a loan due to the tiny investment scale. The annual utilization hours of DPV derives from the annual valid data extraction of previous years. Table 3 presents the baseline LCOE levels of rooftop PV projects in Beijing. The capacity of commercial rooftop PV is assumed as 6, 2, and 1 MW; for the residential rooftop PV projects, the capacity is set as 20, 10, and 2 kW. The unit investment costs decrease with the increase of installed capacity of DPV project. As mentioned above, the unit roof usage is set as 21 m²/kW and the annual utilization hours is configured as 1,214 h/year. The baseline LCOE for diverse scales of rooftop PV projects ranges between 0.57 and 0.79 CNY/kWh. The result explored by Yuan et al. (2014) revealed that the LCOE of DPV ranged between 1.16 and 1.29 CNY/kWh, which is substantially more than our estimation. This disparity is due to the sharp decline in PV modules and an additional reduction of operation and maintenance cost.

**IRR Appraisal**

In the baseline scenario of IRR, for convenience sake, we made some assumptions: (a) the roof owner and the PV investor are the same and thus the rules of on-site own consumption and on-grid redundant sale can be approved, and then the savings for commercial electricity bills are equivalent to the revenue of DPV project; (b) the shares of on-grid electricity for commercial and residential rooftop PV are 50% and 20%, respectively; (c) the benchmarking on-grid electricity for coal power is set to 0.36 CNY/kWh according to the market price in Hebei province (the district around Beijing), because there is no longer any coal power in Beijing; (d) the average commercial and residential electricity prices are 1 and 0.5 CNY/kWh, respectively. Table 4 reports the results of the baseline IRR of commercial and residential DPV in Beijing. We term 8% as the benchmarking IRR for the power industry (Beijing Municipal Commission of Development Reform, 2013; Yuan et al., 2014). Thus, the IRRs of residential rooftop PV yield of 10 and 2 kW installed capacity are less than industry reference profitability, implying the poor investment attraction even with government subsidies. For parts of the patch, feed-in-tariff (FIT) for renewable energy is equal to the benchmarking on-grid electricity price for coal power plus renewable energy price subsidy, and Beijing's subsidy for the first 5 years is additional (see Appendix II for details). Comparing

3https://www.sohu.com/a/158209384_752928
4http://www.hebei.gov.cn/hebei/11937442/10761139/13897734/index.html
5http://bj.bendibao.com/zffw/201374/109201.shtml
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TABLE 2 | Common parameters for economic analysis of rooftop PV.

| Common parameters                          | Value          |
|--------------------------------------------|----------------|
| **Technical and economic variables**       |                |
| Annual utilization hours (h)               | 1,300          |
| Annual degradation rate (%)                | 0.6            |
| Performance factor of the system (%)       | 75             |
| **Financial variables**                    |                |
| Unit investment costs (CNY/kW)             | 6,000–9,000    |
| Proprietary funds ratio (%)                | 80             |
| Loan investment rate (%)                   | 6              |
| Loan period (years)                        | 15             |
| Service period (years)                     | 25             |
| Residual rate of the project (%)           | 5              |
| Depreciation years                         | 15             |
| Discount rate (%)                          | 8              |
| **Operation expenditure**                  |                |
| Maintenance rate (%/decade)                | 8.56%          |
| Clean cost rate (%)                        | 1              |
| Insurance rate (%)                         | 0.25           |
| Roof rent (CNY/m²) (if valid)              | 2–4            |
| **Taxes and charges**                      |                |
| Income tax (%)                             | Full exemption of the first three operation years, and half exemption of the second three operation years, otherwise 15% |
| Value added tax (%)                        | 17% with 50% exemption |
| Land use tax (%)                           | 1.2% with 30% exemption of roof rent |
| Urban construction tax (%)                 | 5              |
| Education surcharge (%)                    | 1              |

TABLE 3 | Baseline LCOE levels of rooftop PV projects at various scales.

| PV project                     | Commercial rooftop PV | Residential rooftop PV |
|--------------------------------|-----------------------|-----------------------|
| Capacity (MW)                  | 6 MW                  | 2 MW                  |
| Own capital (%)                | 80%                   | 80%                   |
| Annual utilization hours (h/yr)| 1,214                 | 1,214                 |
| Roof usage (m²)               | 126,000               | 42,000                |
| LCOE (CNY/kWh)                | 0.57                  | 0.62                  |

TABLE 4 | IRR of commercial and residential rooftop PV in the baseline scenario.

| PV project                     | Commercial rooftop PV | Residential rooftop PV |
|--------------------------------|-----------------------|-----------------------|
| Capacity (kW)                  | 6 MW                  | 1 MW                  |
| Own capital (%)                | 80%                   | 80%                   |
| Annual utilization hours (h/yr)| 1,214                 | 1,214                 |
| Commercial/residential electricity price (CNY/kWh) | 0.36 | 0.36 |
| National subsidy (CNY/kWh)     | 0.1                   | 0.1                   |
| PV on-grid tariff (CNY/kWh)    | 0.46                  | 0.46                  |
| Local subsidy by Beijing (for 5 years) (CNY/kWh) | 0.3 | 0.3 |
| IRR                            | 14.4%                 | 12.9%                 |

TABLE 5 | Emissions factors and sewage tax for coal power and environmental value of DPV in Beijing.

| Sewage emissions   | CO₂ | SO₂ | NOₓ | PM |
|--------------------|-----|-----|-----|----|
| Emissions factors (g/kWh) | 987.23 | 1.37 | 4.07 | 0.11 |
| Sewage tax (CNY/t)   | 80  | 1,260 | 2,000 | 550 |
| Rooftop PV generation (GWh) | 13924.58 | 13924.58 |
| Emissions charge (million CNY) | 1099.74 | 24.04 |
| Environmental value (million CNY) | 1237.97 | 1237.97 |

Environmental Value Estimation

Although all the coal power plants have been eliminated, a large part of the power supply originates from the cross-regional transmission of coal power. This measure just shifts the pollution to other places rather than pollutants remission. Unlike the combustion of fossil fuels emitting various pollutants, the clean power generated by rooftop PV contributes to mitigating the environmental pressures. Lau et al. (2016) illustrated the emissions factors of different pollutants in China's regional power grids, and the sewage tax standard is the average charge of surrounding provinces (shown in Table 5) (Science Academy and Geography Institute of Henan Province, 2018). Then the total generation of rooftop PV could be 13924.58 GWh aligned with the deployment potential of 11.47 GW. Finally, the environmental value of rooftop PV in Beijing is estimated to be 1237.97 million CNY, which is a considerable social gain. Furthermore, DPV creates diverse implicit benefits, such as energy conservation, smart power and poverty alleviation, etc.

Sensitivity Analysis and Discussions

The initial investment of power project usually has a crucial impact on the LCOE, especially for the renewable energy stations due to the no-fuel-cost feature. The progress of grid parity for wind and solar power mainly derives from the device’s cost decline. In China, the lowest quotation for the DPV project is
At the end of October 2017, NDRC and NEA jointly issued the “notice on the implementation of a market-oriented trading pilot program for distributed power generation,” which put forward reform plans on the problems such as low degree of market-oriented trading, lagging public services and imperfect management system encountered in distributed power generation. Then in January 2018, NEA further clarified the market-oriented trading pilot requirements of distributed power generation in terms of detailed rules. Recently, NDRC announced the pilot list for market-oriented trading of distributed power generation including 26 programs with a total installed capacity 1.47 GW though not in the Beijing area. These distributed power programs as grid parity demonstration occupy a full-scale guaranteed acquisition and priority right for generating, which is pledged by long-term fixed-price electricity purchase contract (not <20 years) aligned with benchmarking tariff of coal power. The market-oriented transaction of DPV helps to form the mechanism of market-determined electricity price, construct the market transaction process and system, reflect the reasonable value of distributed power, realize the grid parity as soon as possible, and create a win-win situation for power enterprises and terminal consumers.

FiTs function in a similar way to a standardized, long-term power purchase agreement (PPA), usually signed with a utility or a network company and backed by the government, although the stability and consistency of the FiT depend on the durability of its supporting legislation. Full consumption of electricity production is the key prerequisite for realizing profitability. The long-term fixed-price electricity purchase contract would help rooftop PV projects weaken operation risk and then help cut down the loan threshold and interest rate, which is a strong incentive to deploy rooftop PV extensively in Beijing.

Furthermore, the pilots for DPV are exempted from policy cross-subsidies and transmission charges of the previous voltage level without being involved. In the policy context, the commercial DPV project in Beijing can be profitable without subsidies due to the high share of own-consumption or direct transaction with industrial and commercial consumers.

**CONCLUSION AND POLICY IMPLICATIONS**

The scope of this article is to estimate the deployment potential and economics of DPV in Beijing. The DEM identifies the roof area suitable for DPV installed in Beijing as 241 km², so the
deployment potential is estimated to be 11.47 GW according to the occupation standard of 21 m²/kW. Then, by employing the LCOE and project financial appraisal method, the rooftop PV can earn a profit under existing tariff and subsidy policy, except the 2 and 10 kW residential DPV projects. The reduction of initial investment cost and on-grid share both could improve the profitability of DPV. Moreover, if eliminating national subsidy but reserving local subsidy, the commercial rooftop PV still generates good returns, which reveals the feasibility of grid parity for large-scale DPV in Beijing.

Renewables are the rational choice to reconcile energy supply and environmental governance in Beijing. In the initial phase, DPV deployment in Beijing depends on the national and local preferential policies and financial incentives for promoting renewable energy, including FiT, tax breaks, on-grid priority, and pilot projects, etc. The favorable strength for DPV development in Beijing is to guarantee full-scale acquisition through the long-term fixed-price electricity purchase contract, which is in place to ensure stable market expectation and conducive to lowering the DPV project risks. Driven by policy stimulus and technology innovation, the rising profitability of DPV can motivate investors and even cause overheated investment without any guidance. DPV power generation project award list in Beijing and national DPV subsidy retreat can curb the excessive expansion momentum. Incidentally, excessive renewable subsidies will add to the public finance burden and drive up electricity prices. A sun-set mechanism in FiT and renewable subsidies will add to the public finance burden and drive up electricity prices. A sun-set mechanism in FiT and then integration with the market are the solution. Thus, in the development process, persistent adherence to progressive policies is crucial to readjust DPV deployment to rapidly evolving industrial landscape.

Aligned with ongoing power market reform, subsidy retreat indicates the upcoming grid parity of large-scale DPV. The pilots for nearby direct trading of DPV is gaining momentum without any subsidy in China. Meanwhile, to facilitate market-oriented transactions, the government issues a series of regulations involving reducing non-technical cost, equipping associated power network, and penalizing nonperformance. The non-technical cost dilemmas cover loan cost, land renting, and transmission-distribution price. From the perspective of policy innovation, China’s new policies include implementing a long-term PPA system, reducing transmission-distribution fees, exempting cross-subsidies, and implementing green certificate schemes, as well as emphasizing and clarifying past policies such as classified subsidy system, full-scale guaranteed acquisition system, and priority scheduling scheme. It can be concluded that full interact with a market-driven and policy guarantee is crucial to achieving the benign development of DPV. Beijing’s experience has a good reference for other cities to develop renewable energy.

**DATA AVAILABILITY STATEMENT**

The datasets generated for this study are available on request to the corresponding author.

**AUTHOR CONTRIBUTIONS**

XZ was responsible for the specific work of this paper. SF carried out some of the calculation work. HZ guided the work of this article. JY optimized the structure and tone of this article.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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APPENDIX I

Glossary table.

| Term     | Definition                              | Term     | Definition                             |
|----------|-----------------------------------------|----------|----------------------------------------|
| CNY      | Chinese Yuan                            | LCA      | Life cycle assessment                  |
| CfDs     | Contracts for Difference                | LiDAR    | Light Detection and Ranging            |
| CO₂      | Carbon dioxide                          | LCOE     | Levelized cost of electricity          |
| DPV      | Distributed photovoltaic                | MLR      | Ministry of Land and Resources         |
| DEM      | Digital Elevation Model                 | MNR      | Ministry of Natural Resources           |
| DSM      | Digital Surface Model                   | MW       | Megawatt                               |
| ERI      | Energy Research Institute               | NEA      | National Energy Agency                 |
| FIT      | Feed-in-tariff                          | NDRC     | National Development and Reform Council|
| GDP      | Gross Domestic Product                  | NPV      | Net present value                      |
| GW       | Gigawatt                                | NOx      | Nitrogen oxides                        |
| GIS      | Geographic Information System           | PV       | Photovoltaic                           |
| GHG      | Greenhouse gases                        | PM       | Particulate matter                     |
| IRENA    | International Renewable Energy Agency  | PPA      | Power purchase agreement               |
| IEA      | International Energy Agency             | SO₂      | Sulfur dioxide                         |
| IRR      | Internal rate of return                 | Mtce     | Million tons-coal equivalent           |
| kWh      | Kilowatt-hours                          | TWh      | Terawatt-hours                         |

APPENDIX II

Supporting policies and governmental subsidies for DPV power.

| Year       | Policy                                                      | Main content                                                                 | Source                                      |
|------------|-------------------------------------------------------------|------------------------------------------------------------------------------|---------------------------------------------|
| 2013       | Opinions on promoting the healthy development of the PV industry | Prioritized supporting commercial DPV, encouraging public and household PV | State Council                               |
| 2013       | Notice on exerting price leverage to promote the healthy development of the PV industry | DPV subsidy of 0.42 CNY/kWh                                               | National Development and Reform Commission (NDRC) |
| 2015       | Notice on the awarded funds of DPV power generation in Beijing | DPV subsidy of 0.3 CNY/kWh in the first 5 years                            | Beijing DRC                                |
| 2018.01    | Notice on price policy of PV power generation in 2018       | DPV subsidy of 0.37 CNY/kWh                                                 | NDRC                                       |
| 2018.06    | Notice on matters related to PV power generation in 2018    | DPV subsidy of 0.32 CNY/kWh                                                 | NDRC                                       |
| 2019.05    | Notice on Improving the Price Mechanism of PV Generation    | DPV subsidy; 0.1 CNY/kWh for a commercial project and 0.18 CNY/kWh for a residential project | NDRC                                       |