Assessing the regional grid-parity potential of utility-scale photovoltaic in China

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Abstract. Chinese government announced to phase out photovoltaic (PV) generation subsidies in following years, which made analysis of economic feasibility of grid-parity crucial. We present an expression of levelized cost of electricity (LCOE) consistent with Chinese situation, which takes comprehensive life cycle cost, region-specific capital cost, and tax effect into consideration. Based on LCOE calculation, we make regional grid-parity estimation by comparing utility-scale PV LCOE to government benchmark price. Results show a constant progress to achieve grid-parity for utility-scale PV in China. By 2030, most regions will achieve grid-parity of large scale PV projects. More than half of the regions will achieve grid-parity before 2022. Policy suggestions are: (1) Policy should be made to improve developers’ access to low-cost financing; (2) To reduce investment cost, favourable mechanisms related to the profit sharing between land owner and developer could be developed. Local government could also support PV by lowering land tax and fees; (3) Government should plan to construct cross-regional transmission line for PV. In this way, northwest power could be transmitted to middle or eastern China and achieve remote grid-parity.

1. Introduction

1.1. Research background
Increasing attention to sustainable energy has led to rapid expansion of PV generation all over the world[1–4]. Compared to traditional energy, PV technology has not yet mature, which resulted in higher cost and longer payback period[4,5]. Chinese government formulated a series of policies and regulations to encourage the development of PV including generous subsidies. Under the strong support, at the end of 2019, PV capacity in China has reached a total amount of 204.3GW, with a yearly growth rate of 17.3%. With the sharp decline in PV investment cost, Chinese subsidies have fallen several times. In 2019, National Development and Reform Commission posted an announcement named “promoting wind and PV generation without subsidies”[6]. In official interpretation following this announcement made by National Energy Administration, it is stated clearly that PV generation subsidies will be phased out in early 14th plan period, which is in 2021 or 2022[7]. Against this background, analysis of economic feasibility of grid-parity for PV is crucial.

1.2. The LCOE of PV
The LCOE method, which estimates the cost of lifetime generated energy, is used as a benchmarking tool to assess the cost-effectiveness of different energy generation technologies[8]. It is widely used to estimate power generation cost of PV[2,3,5,9–16]. In some studies, LCOE of PV was compared with
varies other power technologies in different locations[5,10,13,14]. Another common use was to compare PV LCOE with electricity price to assess its competitiveness and to measure grid-parity[2,3,5,9,11,12,15,16]. This is because LCOE could be interpreted as the minimum price per kWh that an electricity generating plant would have to obtain in order to break-even on its investment over the entire life cycle of the facility[5]. The latter use is in accordance with our purpose. However, we have noticed discrepancies of LCOE calculations among studies, which have led to variances in results. There are three main domains of discrepancies:

1) Cost: earlier studies’ make their own choice to take initial investment cost, routine operation and maintenance expenditures (opex), debt cost, and decommissioning cost into account.

2) Discount rate: region-specific or uniform.

3) Tax: a few studies take tax effect into consideration, including corporate income taxes, VAT et.

Constitution of cost affects LCOE directly. Investment and opex are commonly considered, while whether to include debt cost or decommissioning cost depends on the author’s understanding of LCOE concept. Meanwhile, LCOE variation was found to a large extent determined by discount rate, which stands for capital cost and varies greatly among regions[13,17]. Bobinaite and Tarvydas’s study revealed that LCOE calculations should take into account tax effects[9], and tax reductions are important factors to consider[2]. Based on the widely accepted concept that “LCOE is the constant dollar electricity price that would be required over the life of the plant to cover all operating expenses, payment of debt and accrued interest on initial project expenses, and the payment of an acceptable return to investors”[18], we present an expression of LCOE consistent with Chinese situation, which takes comprehensive life cycle cost, region-specific capital cost, and tax effect into consideration. Based on LCOE calculation, we make regional grid-parity estimation by comparing utility-scale PV LCOE to government benchmark price, which is a representative of regional selling-side electricity price.

2. Methodology and data

The LCOE is given by:

$$ LCOE = (1 + V) \left\{ \sum_{t} \left[ I_0 + O_t (1 - TR_t) + D_t (1 - TR_t) - Dep_t TR_t - VR_t \right] \left( \frac{1}{1 + r} \right)^t \right\}^{-1} $$

Where

- $V$ = Value Added Tax (VAT) rate
- $t$ = year $t$
- $I_0$ = Investment cost, VAT included. It only occurs in year 0.
- $O_t$ = Opex in year $t$, denoted as a fraction of $I_0$
- $TR_t$ = tax rate in year $t$
- $D_t$ = decommissioning cost in year $t$, denoted as a fraction of $I_0$. It only occurs in the final year.
- $Dep_t$ = depreciation in year $t$
- $VR_t$ = Initial investment VAT refund, whose total value denoted as a fraction of $I_0$
- $r$ = discount rate, cost of capital
- $E_t$ = energy yield in year $t$

We use Weighted Average Cost of Capital (WACC) as discount rate in our calculation. WACC is also the choice of many other studies[5,13,19], since it is a standard result in corporate finance. Using WACC as discount rate, debt holder is assumed as financial investor. Therefore, life cycle cost in our LCOE expression excludes debt cost. Despite initial investment cost, all the other cost excludes VAT. To make LCOE comparable with government benchmark price, which includes VAT, we put $(1 + V)$ as a multiplier. According to Chinese tax law, output tax generated during construction will be refunded during operation. Thus, VR is considered a cash inflow and subtracted in our expression. Income tax effect is considered in our calculation by subtracting tax part from opex, decommissioning cost, and depreciation, because they creates tax shield. In the same time, tax part in energy yield is also subtracted, because revenue is taxable. Debt tax shield is already incorporated in WACC:

$$ WACC = w_{debt} \cdot r_{debt} \cdot (1 - TR) + w_{equity} \cdot r_{equity} $$

(2)
is the portion of debt or equity capital. \( r \) is the required rate of return of debt or equity capital. Since China has a vast territory, the level of economic and social development and deepening of capital market varies among regions[20]. We use different WACC for eastern China, middle China, western China, and northeast China respectively. PV plant in China has tax cut in earlier stage of operation, so income tax rate varies from year to year.

Investment cost is the sum of PV module cost plus balance-of-system (BOS) cost[21]. We use learning curve to project PV module cost and BOS cost in the future[22]:

\[
C_w = C_{2019} \left( \frac{P_w}{P_{2019}} \right)^b
\]

(3)

The learning rate (LR) is the relative cost reduction from a doubling of cumulative production. It is used for calculating \( b \):

\[
LR = 1 - 2^b
\]

(4)

Module price is more influenced by global industry situation than country-specific factors[23,24]. So, \( P_{m} \) \( P_{2019} \) is cumulative global installed PV capacity in year \( m \) and 2019 for module. Although BOS price is affected by more complicated and country-specific factors such as land cost, we also base our calculation of BOS price on the same bases in the interest of simplicity. It is believed that price dropping of BOS will be slower than module[4]. We also take this viewpoint into consideration.

Energy yield is given by:

\[
E_t = PR_t \cdot GHI
\]

(5)

Where

\( PR_t = \) Performance ratio in year \( t \), \( PR = n_{sh}n_{IAM}n_{deg}n_{inv}n_{soil}n_{mismatch}n_{inverter} \), it considers all the loses including nearby shadows, incident angle modifier, module degradation, temperature, soiling, mismatch, wiring, maximum power point, and inverter losses. \( n_{deg} = (1-d)^{n_{deg,t-1}} \), where \( d \) is annual degradation rate.

\( GHI = \) Global Horizontal Irradiance

Table 1 is the list of parameter values used to calculate LCOE.
Table 1. Input parameter values to calculate LCOE.

| Parameter                             | Value                  | Unit    | Source            |
|---------------------------------------|------------------------|---------|-------------------|
| Lifetime ($T$)                        | 25                     | years   | [25]              |
|                                       | module: 2.1 BOS: 3.1 for small scale plant (20MW), 2.2 for large scale plant (100MW). We added 0.6 for Beijing, Tianjin, and Shanghai, which are municipalities with expensive land. |
| Investment cost in 2019 ($C_{2019}$) | 2.1 module: 2.1 BOS: 3.1 for small scale plant (20MW), 2.2 for large scale plant (100MW). We added 0.6 for Beijing, Tianjin, and Shanghai, which are municipalities with expensive land. |
| Cumulative global capacity ($P_n$)    | a sequence of number   | MW      | [26]              |
| Learning rate ($LR$)                  | module: 23 BOS: 7      | percent | [21]              |
| Opex ($O_t$)                          | 1.5                    | percent | [10]              |
| Decommissioning cost ($D_T$)          | 5                      | percent | [25]              |
| Tax rate ($TR_t$)                     | operating year 1-3: 0  | percent | [27]              |
|                                       | operating year 4-6: 12.5 |
|                                       | operating year 7-25: 25|
| Depreciation method                   | 15 year's straight-line depreciation method | expert interview |
| VAT refund                            | 9                      | percent | expert interview   |
| Initial performance ratio ($PR_0$)    | 0.8                    | percent | [2]               |
| Annual degradation rate ($d$)         | 0.5                    | percent | [25]              |
| Global horizontal irradiance ($GHI$)  | region-specific, average value for each region. To account for site selection, we add 5% on average value | kWh/m2/a | NASA^a |
| Weighted average cost of capital ($WACC$) | Eastern China: 5.94 |
|                                       | Central China: 6.12    |
|                                       | Western China: 5.88    |
|                                       | Northeast China: 6.53  |
| Electricity benchmark price           | region-specific       | yuan/kWh|                  |

^a These data were obtained from the NASA Langley Research Center (LaRC) POWER Project funded through the NASA Earth Science/Applied Science Program.

3. Results and policy suggestions

![Figure 1](image.png)

Figure 1. Time to achieve grid-parity for large-scale PV in each region (a); Time to achieve grid-parity for small-scale PV in each region (b).

Results are shown in figure 1. The main result is a constant progress to achieve grid-parity for utility-scale PV in China. Grid-parity for large-scale PV has already occurred in some part of China. LCOE of PV in 2020 is below government benchmark price in Hainan, Guangdong, Shandong, western Sichuan.
Hebei, Jiangsu, and Qinghai province. This is verified by the first batch of grid-parity PV projects that will complete construction before 2020. The total capacity of the first batch is 14.78 GW, including 2.380 MW in Guangdong (the largest portion), 1310MW in Hebei, 1090MW in Jiangsu, 910 MW in Shandong. These four provinces have relatively good solar radiation resource, low capital cost, and high electricity price. However, there is no projects in the first batch located in Hainan, Qinghai and western Sichuan. These parts of China are rich in solar resource, but is relatively backward in social-economic development, underpopulated, and with narrow industrial base. Meanwhile, insufficient construction of transmission lines also creates barrier to power consumption. The second and third highest portion in the first grid-parity batch is Shaanxi and Guangxi. First batch projects in Shaanxi distribute all in the most north part of this province, and that in Guangxi distribute all in the south coastal part of this province. Solar radiation in these parts are 10% higher than the average level of each province, which is the main reason contributes to grid-parity. Before the early 14th plan period (2022), 19 regions among 33 regions will achieve grid-parity. Before 2030, 27 regions will achieve grid-parity. Those remain backward are Chongqing, Guizhou for their poor solar and Ningxia, eastern Inner Mongolia for their low electricity price.

Small scale projects show obviously worse economics than large scale projects. Only 7 regions will achieve grid-parity in 2030. Among them are Hainan, Guangdong, Shandong, western Sichuan, Hebei, Qinghai, and Jiangsu. The same as large-scale plants, problems in power consumption will create severe obstacle for small-scale plants in Hainan, western Sichuan, and Qinghai. The results show that economic difference roots in scale is hard to overcome. Large-scale will remain the main feature for grid-parity utility-scale PV plants in the near future. This is in accordance with the results of first batch of grid-parity PV plants, whose average capacity is 112 MW (exclusive of 47 projects in Liaoning, which has unusual small capacity (25MW average)).

The result is lagged behind Chinese government’s target. We performed sensitivity analysis for crucial parameters including WACC and BOS cost. Sensitivity results shows that if WACC falls by 10%, in the early 14th plan period, 24 regions will achieve grid-parity. It also shows that if BOS cost falls by 10%, 24 regions will reach grid-parity in the same period.

Based on our findings, we have three policy suggestions. First, capital cost affects economics of power plant to a large extent. Thus, policy should be made to improve developers’ access to low-cost financing. Second, land cost as a main uncertain factor that constitutes BOS cost should be paid attention. Favorable mechanisms related to the profit sharing between land owner and developer could be developed. Local government could also support PV by lowering land tax and fees. Third, northwest regions have advantageous solar resource, but local consumption is limited by backward economy condition. What’s more, regional electricity price is brought down by local richness of fossil fuel. It is a better choice to transmit northwest power to the rest part China and achieve remote grid-parity. Central government should plan to construct cross-regional transmission line for PV.

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