A Study on the Technology Diffusion of China’s Solar Photovoltaic Based on Bass and Generalized Bass Model

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ABSTRACT China's solar photovoltaic (PV) power generation has been developing rapidly and is in a priority position in the national energy strategy. In order to effectively coordinate the development scale, speed of solar PV and economic development, the Chinese government has constantly issued various solar PV development plans. However, as a new renewable energy generation technology, solar PV is still making technological innovation to achieve technological breakthroughs. In addition, external factors, such as resource potential and power grid consumption capacity, will influence its development. It is very important to explore the development path of solar PV in China and analyze the action mechanism of each influencing factor on the development path of solar PV. Based on the technology diffusion model, this study analyzes and predicts the technology diffusion trend of solar PV generation in China. The research finds: that 1) cost is still a big obstacle facing the large-scale development of PV generation at present; that 2) national economic operation, policy incentive intensity and other factors have limited influence on the development of solar PV generation; that 3) technological innovation and power grid absorption capacity are key factors affecting the development path of solar PV.

1. Introduction
In the past few decades, renewable energy technologies have been developing steadily and becoming mature, and their share in the energy structure has been increasing [1]. At the same time, among all the renewable energy sources, solar is considered as one of the renewable energy sources with the most potential for development, because of its abundant resource reserves, the characteristics of renewable, pollution-free, easy to widely distribute and flexible installation and other advantages [2]. Therefore, solar PV generation has extensive application space and huge development potential, which can provide technical solutions for China's and the world's future energy needs and promote sustainable development [3].

China is rich in solar resources, areas with an annual solar sunshine duration of more than 2,000 hours account for more than two-thirds of the country's total area [4]. After long-term development, China's solar PV generation industry has made unprecedented progress in the past ten years. Since 2015, China has become the world's largest market for solar PV generation, with 53 GW of new installed capacity and 130 GW of cumulative installed capacity in 2017, both ranking first in the world.
With the continuous upgrading of power generation technology, conversion efficiency is greatly improved and investment cost is greatly reduced, the development of PV generation tends to show a leap-forward development. Therefore, in order to make a more scientific development plan, it is necessary to study the development path of solar PV power generation in China, to analyze the key factors that influence its development, to find out the rule of influencing, especially the technological progress in it, and then put forward a more reasonable advice for the development of China's solar PV generation planning.

2. Literature Review
Technology diffusion model is widely used to predict the market demand of new technology, and can analyze the growth trend of new technology products in the early stage [5]. In 1969, Frank Bass firstly used Bass Model to describe the s-shaped curve of product technology diffusion [6]. The Bass model is also one of the most commonly used models to predict the proliferation of new products. Since the development trend of renewable energy is similar to that of emerging technology products, technology diffusion model has been widely used to analyze and predict the development trend of renewable energy [7]. Current research has shown that technology diffusion models can still fit its trends and predict the development potential of renewable energy from the perspective of historical data [8]. Up to now, a large number of literatures have applied technology diffusion model to analyze and predict the renewable energy diffusion trend [9]. Shi et al. used Logist model to predict the development of solar PV generation in China from 2010 to 2030 [10].

In order to incorporate other variables into the technology diffusion model, such as policy incentives and changes in external conditions, Frank Bass et al. introduced the impulse function and established the generalized Bass model in their subsequent studies [11]. Dalla et al. used the generalized Bass model to study the diffusion trend of solar PV generation technology [12]. Cong et al. used the generalized Bass model to predict China's solar potential in 2020 [8]. In general, technology diffusion model is a relatively mature method to study the development of renewable energy. The above studies show that the research on renewable energy through technology diffusion can effectively and accurately analyze its diffusion trend.

3. Methodology
In this paper, the Bass model can be represented by a first order differential equation:

$$z'(t) = m(p + q\frac{z(t)}{m})(1 - \frac{z(t)}{m}) \quad t \geq 0,$$

(1)

Where $z(t)$ represents the cumulative installed capacity of solar PV generation in $t$ period. $m$ represents the market potential and the theoretical maximum installed capacity of solar PV generation under the resource potential. $p$ is the innovator's coefficient, representing the influence of external information on technology diffusion, $q$ is the imitator's coefficient, representing the internal influence suffered by technology diffusion. $z'(t)$ is the number of new solar PV installations per year.

Meanwhile, we use the generalized bass model and introduce the impulse function to reflect the market mix strategy. The generalized Buss model can be expressed by the following formula:

$$z'(t) = m(p + q\frac{z(t)}{m})(1 - \frac{z(t)}{m})x(t) \quad t \geq 0,$$

(2)

Here, $x(t)$ is the introduced impulse function, which represents the external perturbation. Equation (2) is the modified Riccati function, when $z(0)=0$, $z(t)=0$, $t<0$, the solution to equation (2) is expressed as:

$$z(t) = m\frac{1-e^{-(p+q)\int_0^t x(t)dt}}{1+q\frac{e^{-(p+q)\int_0^t x(t)dt}}{p}}, 0 \leq t \leq \infty$$

(3)

In equation (3), $m$ means the resource potential of the technology diffusion as same as the above. The
impulse function also has different forms, including exponential impulse and rectangular impulse. The exponential impulse can be expressed by the following formula:

\[ x(t) = 1 + c_1 e^{\alpha (t-a_1)} I_{[t\geq a_1]} \]  

\[ (4) \]

\( a_1 \) represents the moment when the external disturbance begins to have an impact, which is realized by the indicator function \( I_{[t\geq a_1]} \). The effect of rectangle impulse is continuous and does not change with time, which can be expressed as follows:

\[ x(t) = 1 + c_2 I_{[a_2 \leq t \leq b_2]} \]  

\[ (5) \]

In the function (5), \( I_{[a_2 \leq t \leq b_2]} \) is also a reference function of 0 or 1, when \( a_2 \leq t \leq b_2 \), the value of the indicator function is 1, indicating that the effect of impulse exists; otherwise, the value of the indicator function is 0, indicating that there is no impulse. \( a_2 \) is the beginning of the impulse, \( b_2 \) is the end of the impulse, \( c_2 \) represents the effect of rectangular impulse.

We should consider different types of impulse, which requires the impulse function \( x(t) \) to reflect both rectangular impulse and exponential impulse. The impulse function under mixed disturbance is proposed, and the mathematical model is expressed as follows:

\[ x(t) = 1 + c_1 e^{\alpha (t-a_1)} I_{[t\geq a_1]} + c_2 I_{[a_2 \leq t \leq b_2]} \]  

\[ (6) \]

4. Results and Discussion

4.1. Diffusion analysis of solar PV generation technology in China under resource constraint

The results obtained can represent the diffusion trend under the remaining resource constraints (In this paper, the cumulative installed capacity of solar PV can’t exceed resource potential \( m \)). Figure 1 and Table 1 show the results of Bass model.

According to the calculation results, the maximum exploitable capacity of PV generation in China is 1357 GW. And the innovation coefficient \( p \) in the model is far less than the imitation coefficient \( q \), indicating that the technology diffusion in this stage mainly relies on the imitation behavior. In addition, the parameters were obtained by the least square method, and then the model was used for fitting, resulting in a good effect and a correlation coefficient of 0.998.

| Parameter | Estimated value | correlation coefficient |
|-----------|----------------|------------------------|
| \( m \)   | 1.35×10^6      |                        |
| \( p \)   | 1.41×10^-6     | 0.998                  |
| \( q \)   | 0.56           |                        |

However, in some early literatures, it is predicted that the potential cumulative installed capacity of solar PV generation will reach 287.68 GW by 2050. The maximum cumulative installed capacity (installed potential) predicted in this paper is much higher than the results predicted in these studies on the development of solar PV generation in China.
4.2. Analysis on the diffusion of PV generation technology in China under the influence of policies and external conditions

As mentioned above, diffusion trend of solar PV generation will be affected by policies and other external conditions. Thus, it is necessary to forecast the trend of technology diffusion through establishing the generalized bass model based on the impulse function. The following section will show the trend of technology diffusion of solar PV generation and analyze the effect of the impulse. The results obtained by the generalized Bass model are shown in Table 2.

Table 2: Parameter results of generalized Bass model with various impulse functions

| Parameter | Rectangular impulse | Exponential impulse | Mix impulse |
|-----------|---------------------|---------------------|-------------|
| m         | 289999.99           | 235190.63           | 235158.42   |
| p         | 2.25×10⁻⁴           | 2.49×10⁻⁸           | 2.33×10⁻⁷   |
| q         | 0.87                | 1.08                | 1.08        |
| a₁        | 7.41                | 14.31               | 14.31       |
| b₁        | 12.87               | -0.64               | -0.64       |
| c₁        | 0.99                | -1.12               | -1.12       |
| a₂        |                     | 7.98                |             |
| b₂        |                     | 12.89               |             |
| c₂        |                     | -1.36               |             |

4.2.1. The analysis of rectangular impulse

As shown in Table 2, according to the results, the impulse occurred in 2000+a₁ (7.41) ≈ 2007, and it was a positive impact c₁ (0.99) > 0. The impact of the impulse on diffusion lasts to 2000+b₁ (12.87) ≈ 2013. Considering the development history of China's solar PV generation, the Chinese government issued more than 10 supporting documents to support the development of solar PV generation, for example, “The Dispatch of Power Generation Saving (Trial)” published in 2007.

Therefore, this series of policy incentives is likely to be the main reason for the rectangular impulse from 2007 to 2013. This shows that incentive policies do indeed have an impact on the technology diffusion of solar PV. The Figure 2 shows the diffusion trend is in accord with the classic s-shaped curve. It can be seen solar PV technology will witness a fast diffusion in our country during 2018-2025, and then gradually meets the resource limit of 289 GW.

![Figure 2: The results of the generalized Bass model with rectangular impulse](image)

4.2.2. The analysis of exponential impulse

Table 2 and Figure 3 show the results of generalized Bass model combined with exponential impact. It can be seen from that China's solar PV generation had negative (c₁(-1.12) < 0) exponential impulse in 2000+a₁ (14.31) ≈ 2014. However, because of the rapid growth of PV, the difficult problems began to emerge more and more seriously in around 2014, resulting in a nationwide abandonment of solar PV.

At the same time, compared with the trend under the rectangular impulse, the technology diffusion will develop faster before 2020, enter the flat period earlier, and shows the classic S-shaped curve.
4.2.3. The analysis of mix impulse Finally, we use mixed impulse to study China’s solar PV technology diffusion (see Figure 4). In the mixed impulse there are two impulses, one is the rectangular impulse in $2000 + a_1 (7.98) \approx 2008$, the effect of which continues. The other one is the exponential impulse occurring in $2000 + a_2 (14.31) \approx 2014$, which is a negative impact. Under the mixed impulse model, it can be considered as the result of the superposition of the single rectangular impulse and the single exponential impulse.

5. Conclusions
In this study, the Bass model and the generalized Bass model are used to analyze the diffusion of solar PV generation technology in China, and the diffusion trend of solar PV generation technology is analyzed.

First, the results show that with the resources constraint and the upper limit of the potential of solar PV generation in our country, solar PV generation is forecasted to maintain rapid growth during 2018-2030. Second, it was found that solar PV industry treated as the renewable energy is easily affected by policy and external conditions. Third, the cost is still a difficult problem faced by the large-scale development of current PV. The technological progress is the most critical factors affecting the development of PV generation. Therefore, our government should vigorously encourage solar PV enterprises to improve the industry standard and develop the new technology.

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