博士論文

The Impact of Renewable Energy Policies on Solar Photovoltaic Energy : Comparison of China, Germany, Japan, and the United States of America

再生可能エネルギー促進政策の太陽光発電への影響分析:
中国、ドイツ、日本、アメリカ合衆国の比較

北九州市立大学国際環境工学研究科

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The Impact of Renewable Energy Policies on Solar Photovoltaic Energy : Comparison of China, Germany, Japan, and the United States of America

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Preface

With the reduction in the cost of solar PV systems, it has led to an increasing interest in the application of PV energy in various countries around the world. Consequently, different types of energy policies have been introduced to promote the expansion of PV energy development. These support policies have been very effective in the development of PV energy, especially in the four largest PV markets in the world, China, Germany, Japan and the United States. Therefore, it is important to study the effect of energy policies on PV energy. In this study, firstly, a technological learning analysis for the cost reduction effects of PV policies in four countries, China, Germany, Japan, and the United States, was carried out. After that, residential PV systems and large PV plants are modeled in the context of different policies in each country to examine the impact of PV policies on the economics of PV systems. Finally, the performance and impact of PV policies in each country are comparative, and policy implications are proposed.

ACKNOWLEDGEMENTS

Five years have gone by in a flash. The picture of the first I arrived at the University of Kitakyushu also be visible before the eyes. I will never forget the experience of studying under Prof. Weijun Gao. It was with his support and many others that I was able to complete this thesis.

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Finally, I would like to thank my family, whose love, support and encouragement made it possible for me to complete this thesis.

THE IMPACT OF RENEWABLE ENERGY POLICIES ON SOLAR PHOTOVOLTAIC ENERGY: COMPARISON OF CHINA, GERMANY, JAPAN, AND THE UNITED STATES OF AMERICA

ABSTRACT

The rapid growth in energy demand and concerns about climate change, coupled with the depletion of fossil fuels, have led countries around the world to expect a cleaner, efficient and reliable approach to alternative energy consumption. Photovoltaic (PV) energy has received increasing attention as a clean and low-emission renewable energy. Various ambitious policies have also been introduced to promote PV energy in countries around the world, especially in the four largest PV markets in the world, China, Germany, Japan, and the United States. The effectiveness and stability of PV support policies greatly impact the deployment of PV energy. Currently, countries are constantly pushing for PV policy reform. In this study, the relationship between photovoltaic (PV) incentive policies, technological innovation and market development are demonstrated between China, Germany, Japan, and the United States of America (USA). First, this study presents a technical learning analysis of PV products in four countries based on different PV policy contexts. After that, a techno-economic analysis of residential PV systems and large-scale PV power plants in each of the four countries is conducted. Finally, the PV policy impacts of each country are compared and policy implications are proposed. It is hoped that the effect of PV policy can be enhanced and PV energy development can be promoted.

In chapter one, research background and significance of PV energy development and energy policy is demonstrated. In addition, current status of PV development is investigated and policies to support PV energy are presented. Then the purpose of the study is proposed.

In chapter two, a detailed analysis of the rise of solar PV technology in China, Germany, Japan, and the USA are presented. The effects of different incentive policies implemented over the past decades on PV development in these four leading countries are demonstrated. At different development periods, some special external factors may have guided the introduced policy, and the type of policy implemented may vary across different countries. Therefore, the trajectory of the PV incentive policy from three aspects: R&D, industry and market are traced systematically.

In chapter three, the methodological research and established the mathematical mode are presented. First, the research motivation of the study is described. Then, the model for technology learning and the one-factor learning curve and two-factor learning curve analysis of PV policy

performance are presented. In addition, a simulation model of the PV system and the techno-economic analysis methods used in the subsequent chapters are provided.

In chapter four, a technology learning model based on the one-factor learning curve and two-factor learning curve approaches for PV energy was developed and the impact of different policy periods on the production cost reduction of PV systems was analyzed, taking into account the public R&D investment and the installed PV capacity. Based on a technical learning approach, the effects of the policies in the four countries were analyzed and compared in different periods. This contributes to our understanding of the strengths and weaknesses of energy policies in their implementation.

In chapter five, a techno-economic analysis of residential PV systems and large PV plants in typical cities in four countries was carried out. Under different climatic and geographic conditions and based on different policy conditions, residential PV systems and large grid-connected PV plant were simulated using SAM and PVsyst software for four selected cities. Detailed technical and economic analysis were determined based on the energy production injected into the grid by the PV systems. This study can provide insight into the economics of current residential PV systems and large-scale PV plants in the context of different PV policies. At present, PV policy remains an important guarantee to improve the feasibility of PV investments. Our techno-economic analysis of typical cities in four countries shows that the PV policies implemented in different countries play a decisive role in the economics of PV systems. It contributes to the energy policy reform and promotes the development of PV energy.

In chapter six, first, a comparative study of the results of the technical learning and the results of the techno-economic analysis of the PV plants in the four countries was carried out. The performance of energy policies to drive PV technology development is compared by countries. Second, the results of the technical and economic analysis of residential PV systems and large PV plants in the four countries were compared. Finally, the future PV development strategies of the four countries were overviewed, and then policy implication were made for PV industry development and demand-pull policies and supply-side promotion policies.

In chapter seven, conclusion and prospect have been presented.

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Chapter 1. Research background and Purpose

1.1. Background

1.1.1. Current status and bottleneck of international energy development

(1) Primary energy

Since the creation of mankind, energy has been a necessary material basis for production and life. There are different ways to classify energy sources. According to the form of energy use, there are primary energy and secondary energy. Primary energy is obtained directly from nature and used directly without changing its form, such as coal, oil, natural gas, fuel wood, solar energy, wind energy, geothermal energy, etc.; secondary energy refers to primary energy converted into another form of energy by processing, such as electricity, coke, various petroleum products (gasoline, diesel, kerosene, etc.). According to whether the energy can be regenerated in nature, it can be divided into renewable and non-renewable energy. Solar energy, wind energy, water energy, biomass energy and other energy that can be constantly replenished from nature belong to renewable energy; while coal, oil, natural gas and other fossil energy and nuclear fuel belong to non-renewable energy.

Energy supports human survival and economic development. However, with the sustained and rapid development of the world economy, the problems of energy shortage (Keleş and Bilgen 2012), environmental pollution and ecological deterioration are gradually deepening, and the contradiction of energy supply is becoming increasingly prominent. At present, the world's energy consumption is still dominated by fossil resources.

Global energy consumption has continued to grow. According to the statistics released by BP (Figure 1-1), In 2019, global primary energy consumption will total 583.9 EJ (1 EJ = 1018 J), an increase of 7.7 EJ from 2018 (576.2 EJ), slowing to an average annual growth rate of 1.3%, below the average of the last decade (1.6%) and less than half of the growth rate in 2018 (2.8%). In terms of energy type, fossil energy, consisting of oil, natural gas and coal, accounted for 84.3% of the global primary energy consumption composition in 2019.

Compared to 2018, oil still accounts for the largest energy consumption in 2019, but its share in global energy decreases to 33%. Driven by a sharp decline in OECD (Organization for Economic Cooperation and Development) demand, coal consumption declined for the fourth time in the last six years, falling by 0.5% in 2019 and it is at lowest level in sixteen years. Nonetheless, coal generation still accounts for more than 36% of global electricity, making it the largest single source of electricity generation (BP 2020).

The proportion of oil consumption in primary energy consumption has been stable with a slight decline. As the largest primary energy consumption in the world, oil consumption continued to grow, while its share has basically remained stable in the past few years. The annual growth rate of oil consumption in 2019 was only 0.83%, which was consistently lower than the level of primary energy growth (BP 2020).

Natural gas consumption was 141.5 EJ, share 24.2% of primary energy consumption; hydropower consumption was 37.6 EJ, 6.4% of primary energy consumption, unchanged compared to 2018. Nuclear energy consumption was 24.9 EJ, accounting for 4.3% of primary energy consumption; and other renewable energy sources such as wind and solar were consumed accounting for 5% of primary energy consumption. Thus, global primary energy consumption growth was driven by renewables and natural gas, growing by more than three-quarters, and for the first time, renewables surpassed nuclear in the share of electricity generation. It is evident that global energy is transitioning to a sustainable, green and low-carbon path.

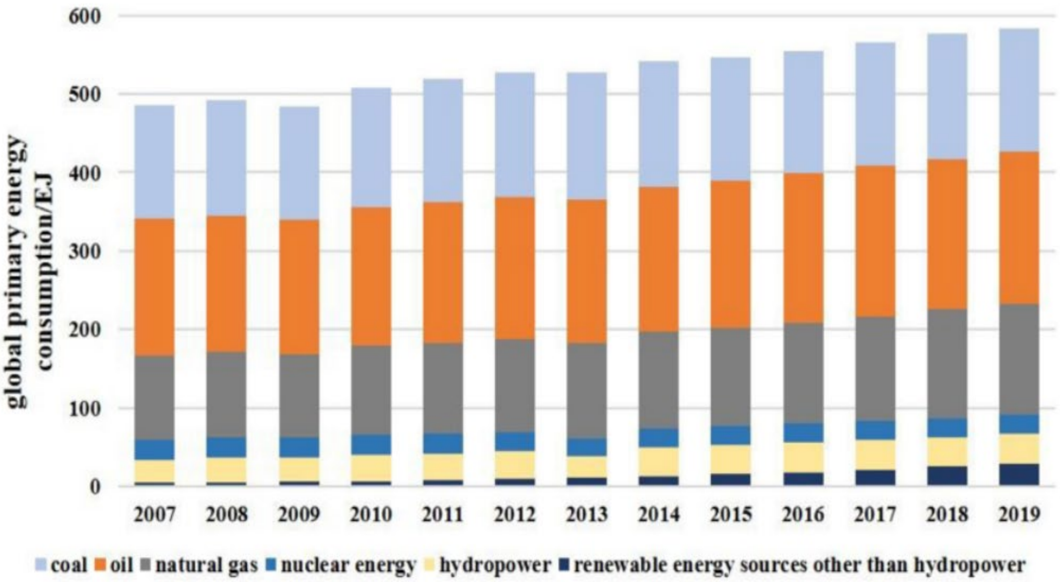

Figure 1-1 Changes in global primary energy consumption (Source: BP 2020).

The entire energy structure varies from country to country. The global energy structure shows a trend of more primary energy and less renewable energy, but renewable energy as a whole shows a growing trend. And renewable energy includes wind, solar, biomass, geothermal, hydrogen energy and other sources of renewable energy (REN21 2018).

Prior to COVID-19, the energy sector was undergoing profound changes, with the following key developments: global primary energy consumption grew slowing to 1.3%, with all fuels except nuclear growing at a slower rate than the average of the past decade; global oil production decreased slightly and consumption was below the historical average; natural gas proved reserves grew slightly, production grew by 3.4% and consumption grew at a slower rate of 2.0%, but its share in primary energy remained at a record high; coal's share 24.2% in global primary energy remained at a record high. The share of primary energy is still at a record high, despite a 2.0% slowdown in consumption growth; the share of coal in global primary energy fell to 27%, but remains the dominant source of energy for electricity generation; renewable energy consumption achieved record growth, led by wind and solar energy, accounting for 41% of the total primary energy Renewable energy consumption, led by wind and solar, achieved record growth, accounting for 41% of the total increase in primary energy consumption and, for the first time, surpassing nuclear power in the share of electricity generation; carbon emissions growth slowed but remained high.

2019-2020 is a special period. COVID-19 has seriously disrupted global economic activity, especially in the energy sector. Under the situation of great blockade, all parties have paid huge economic and social costs. From a certain point of view, the interruption of daily life caused by the blockade shows a glimpse of a clean and low-carbon world. For example, the air quality of many of the world's most polluted cities has improved, and the sky has become clearer.

The International Energy Agency (IEA) estimates that global CO^{2} emissions could fall by 2.6 billion tons in 2021. In fact, such a decline has come at a huge cost. These seemingly optimistic ecological benefits are at risk of being lost as the economy recovers and normal life resumes (IEA 2020).

Slower growth in energy demand and a shift in the fuel mix from coal to natural gas and renewables have contributed to a marked slowdown in the growth of carbon emissions. Emissions increased by 0.5%, which is slower than the 10-year average, but it only partially dislodged the unusually strong growth of 2.1% in 2018 (Gaetan, Sinead, and Manoel 2018).

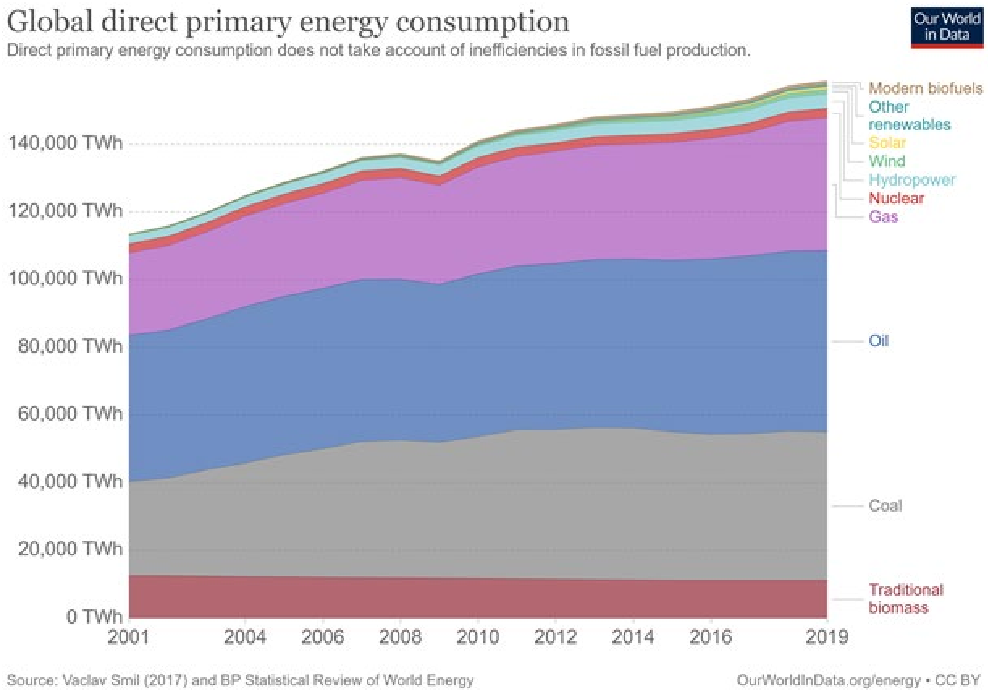

Figure 1-2 Shares of primary energy in 2019 (Source: Our World in Data 2020).

Table 1-1 Fuel shares of primary energy and contributions to growth in 2019 (IEA 2020)

Energy source	Consumption (exajoules)	Annual change (exajoules)	Share of primary energy	Percentage point change in share from 2018
Oil	193.0	1.6	33.1%	-0.2%
Gas	141.5	2.8	24.2%	0.2%
Coal	157.9	-0.9	27.0%	-0.5%
Renewables	29.0	3.2	5.0%	0.5%
Hydro	37.6	0.3	5.0%	-0.0%
Nuclear	24.9	0.8	6.4%	0.1%
Total	583.9	7.7		

(2) Renewable energy

Many countries promote their energy transition through the development of renewable energy represented by wind, solar and biomass, and vigorously promote the deployment of renewable energy as an important measure to address climatic changes, while focusing on promoting the development of wind, solar and other renewable energy is also a major initiative to promote energy production and the consumption revolution and achieve energy transition. Therefore, many countries proposed that the core element of energy strategy transformation is to vigorously promote the deployment of renewable energy, the world's mainstream research institutions such as the United Nations Intergovernmental Panel on Climate Change (IPCC), the International Renewable Energy Agency (IRENA) and the International Energy Agency (IEA) and other research institutions also pointed out that the response to climate change and to complete the objectives of the climate change agreement The most critical and important measure to address climate change and meet the goals of the climate change agreement is the development of renewable energy. Specifically, the Paris Agreement issued by the United Nations Climate Change Conference is an important document in the international response to climate change, and more than 90% of the signatory members of the agreement have set targets for the future development of renewable energy in their countries. Meanwhile, developed countries such as the United States, the United Kingdom, Japan and the European Union have chosen to increase the deployment of renewable energy as an important means of reducing greenhouse gas emissions.

Many countries regard renewable energy as the strategic commanding height of a new generation of energy technology, and made high targets for renewable energy as part of their policies (Sen and Ganguly 2017). With the development of national policies and the maturity of renewable energy technologies, the experience of low-carbon development is very important (Kankam and Boon 2009). At present, the international energy situation is in a stage of new changes and adjustments (Nfah, Ngundam, and Tchinda 2007). The basic trend of the global energy transition is to realize the transition of the fossil energy system into a low-carbon energy system, and finally enter the era of sustainable energy mainly based on renewable energy (Dizdaroglu 2017).

Renewable energy consumption, which includes biofuels and all traded renewable electricity apart from hydro continued to grow strongly, contributing its largest increase in energy terms on record. This accounted for over 40% of the global growth in primary energy last year, which is larger than any other fuel. As a result, renewable energy increased its share in the energy mix from 4.5% in 2018 to 5% in 2020.

By energy source, wind generation provided the largest contribution to growth (1.4 EJ) followed closely by solar (1.2 EJ). Other sources of renewable electricity, such as biomass and geothermal, grew by 0.3 EJ, while biofuels consumption increased by 0.2 EJ, or 100,000 barrels of oil equivalent per day.

China's use of renewables grew by more than any other country, although its increase of 0.8 EJ was below the strong rate of growth seen in 2017 and 2018. Solar provided half of China's growth, followed by wind (around 40%). The US (0.3 EJ) and Japan (0.2 EJ) were the next largest individual contributors to growth.

Hydroelectric consumption rose by 0.8%, below its 10-year average of 1.9% p.a. Growth was led by China (0.6 EJ), Turkey (0.3 EJ) and India (0.2 EJ). The US and Vietnam saw the biggest declines (both -0.2 EJ).

Nuclear consumption increased by 3.2%, its fastest growth since 2004 and well above the 10-year average of -0.7% p.a. As in 2018, China recorded the largest increment of any country and, last year, it was also its biggest increase ever (0.5 EJ). Japan also posted notable growth of 0.15 EJ (33%) as it continued to recover from the impact of the Fukushima incident in 2011 .

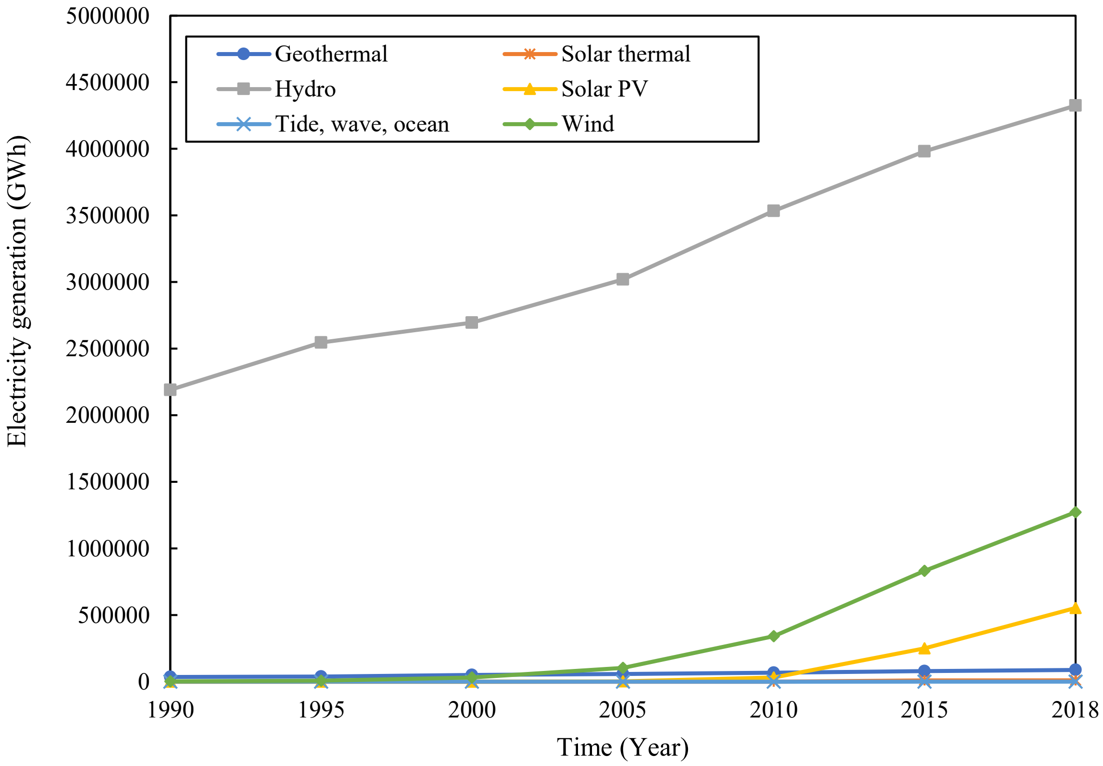

Figure 1-3 Renewable electricity generation by source (non-combustible)

Table 1-2 Renewables share of primary energy in key countries and regions

Region	Share in 2019	Percentage point change from 2018
US	6.2%	0.4%
Other North America	4.0%	0.7%
Brazil	16.3%	1.2%
Other S. & Cent America	4.3%	0.7%
EU	11.0%	1.0%
Other Europe	4.3%	0.7%
CIS	0.1%	0.0%
Middle East	0.3%	0.1%
Africa	2.0%	0.5%
OECD Asia	5.0%	0.9%
China	4.7%	0.4%
Other Asia	2.9%	0.4%
World	5.0%	0.5%

1.1.2.The bottleneck of energy development

(1) Depletion of fossil fuels

The world's demand for energy is growing rapidly as a result of population explosion and industrialization (Tripanagnostopoulos et al. 2002). Since the dawn of the industrial revolution, fossil fuels have been the driving force behind the industrialized world and its economic growth. According to the Statistical Review of World Energy, the primary direct energy consumption of the fossil fuels from insignificant levels in 1800 to an output of nearly 140,000 TWh in 2019. At present, about 85% of all primary energy in the world is derived from fossil fuels with oil accounting for 33.06%, coal for 27.04% and natural gas for 24.23%. Global fossil fuel consumption is on the rise, and new reserves are becoming harder to find. Those that are discovered are significantly smaller than the ones that have been found in the past. Oil reserves are a good example: 16 of the 20 largest oil fields in the world have reached peak level production – they're simply too small to keep up with global demand. Global proved oil reserves were 1734 billion barrels at the end of 2019, down 2 billion barrels versus 2018. The global R/P ratio shows that oil reserves in 2019 accounted for 50 years of current production (IEA 2020).

(2) Environmental deterioration

The main reason for climate change is the greenhouse gases released from the burning of fossil fuels. Almost 80% of greenhouse gases come from generation and consumption of electrical energy. World primary energy demand will increase almost 60% between 2002 and 2030; this is a 1.7% average annual increase, which further increases greenhouse gases leading to consideration climate degradation with global warming phenomena (Moosavian et al. 2013). Global warming is a serious issue that threatens human and other species' survival. The energy crisis is an obstacle to the economic growth in many countries (Tripanagnostopoulos et al. 2002).

(3) Bottleneck of renewable energy development

Despite the progress in renewable energy development over the past decades, more renewable energy deployment is required to meet international climate goals. Policymakers can play a key role in driving the energy transition that support policy could increase renewable energy deployment and integration. Supportive policies for renewable energy are primarily designed to stimulate growth in production and installed capacity. Well-designed policies can lead to increased deployment and lower costs. Policy support can facilitate renewable energy market creation and expansion, as well as technology development; they provide the security needed for renewable energy investments - all of which help reduce costs and improve competitiveness.

Awareness and capacity barriers relate to a lack of sufficient information and knowledge about renewables and their performance as well as a lack of skilled personnel and training programs. Developing countries often struggle with limitations in capacity and training and therefore the lack of a qualified and skilled workforce and an insufficient local value chain (Renewable and Agency 2017).

Cost barriers refer to the investment costs of renewable energy technologies. With adequate resources, some renewable energy technologies are already cost competitive with other fuel energy sources. Of all renewable energy technologies, utility-scale solar PV has seen the fastest rate of cost reduction. Although renewable energy costs have fallen as deployment of various renewable energy technologies has accelerated, they remain high for some technologies. Lack of economies of scale can also lead to higher system costs, especially in the early stages of market growth.

Market barriers include inconsistent pricing structures that lead to renewable energy disadvantages, asymmetric price information, fossil fuel and nuclear subsidies, and the failure to incorporate social and environmental costs. Low prices for fossil fuels can likewise lead to slow deployment, especially for renewable energy heating, cooling and transport. Trade barriers, such as import tariffs, also make imported renewable energy products more expensive. Public acceptance and environmental barriers pose limitations that make renewable energy projects unsuitable for specific locations. Lack of public acceptance alone can lead to increased costs, delays, and even cancellation of projects. Local planning and zoning regulations and environmental features may further hinder renewable energy deployment in certain areas (Tolnov and Rudolph 2020).

Regulatory and policy barriers include poor policy design, policy discontinuity, perverse or divisive incentives, unfavorable or inconsistent policies, unclear agreements (e.g., power purchase agreements, feed-in tariffs, or self-consumption subsidy), and lack of transparency. Uncertainty and inconsistency in goals and policies, including retroactive changes, significantly hinder renewable energy expansion, as unclear support programs or procedures reduce investor and developer confidence.

1.1.3. The significance of the support policy for renewable energy development

Support for renewable energy development is rising worldwide, while renewable energy targets are becoming more ambitious. Many factors are driving the rapid growth of renewable energy, not the least of which are: mitigating climate change; reducing local air pollution; enhancing energy security; maximizing return on investment; creating local economic value and jobs; and increasing access to reliable and sustainable energy.

Climate change mitigation has been one of the main reasons for calling for an increase in the share of renewable energy in the energy mix. Among the 194 countries that are parties under the Paris Agreement, 145 countries mention renewable energy actions for climate change mitigation and adaptation, and 109 countries have set renewable energy targets that include quantified targets. Most countries focus their renewable energy targets on electricity generation, but some focus on end uses, such as transportation and building heating and cooling. By 2030, it is estimated that 1.3 TW or more of installed renewable energy capacity will be added globally. However, national renewable energy targets are often less ambitious than those in national energy plans and strategies. They do not capture the cost-efficiency potential of renewable energy, which leaves a lot of room for strengthening the renewable energy component. As people continue to migrate to urban areas, the goal of reducing local air pollution and its associated costs and health impacts is increasingly driving the development of renewable energy.

Investment in renewable energy is climbing worldwide as the cost of renewable energy declines. The increased investor interest is due in part to supportive government policies and rapidly maturing technologies. Beginning in 2017, investment in new renewable energy generation capacity far outpaced investment in fossil fuel generation capacity, with developing and emerging countries surpassing developed countries in renewable energy investment. Emerging economies are increasingly committed to the energy transition as capital and operating costs decline and renewable energy deployment strategies expand in popularity.

Despite the progress in renewable energy development over the past decades, more renewable energy deployment is needed to meet international climate goals. Policymakers can play a key role in driving the energy transition by developing policies that support increased renewable energy deployment and integration. Supportive policies for renewable energy are primarily designed to stimulate growth in production and installed capacity. Well-designed policies can lead to increased deployment and lower costs. Policy support can facilitate renewable energy market creation and expansion, as well as technology development; they provide the security needed for renewable energy investments - all of which help reduce costs and improve competitiveness.

1.2. Solar PV Energy and Energy Policy

1.2.1. The advantages and development status of solar PV energy

(1) The advantages of solar PV energy

Abundant solar energy is an inexhaustible, pollution-free, cheap and freely available energy. Among them, PV power generation is the fastest growing and the most potential energy development field in recent years. PV is vitally important because they are eco-friendly (Bergene and Løvvik 1995). The application and development of solar energy is the most promising choice and reasons can be listed as follows:

- Solar energy is the richest renewable energy source, nearly 1.8×1014 kW is absorbed by the earth in forms like heat and light without any expense (Nfah et al. 2007).
- The utilization of solar energy does less harm to the earth's environment and it is renewable, cheap and environmental friendly (Chow 2003).
- It is convenient and effective for village systems, industrial operations and houses to use solar systems, since it is easily affordable and applicable (Kannan and Vakeesan 2016).

From the production of the first crystalline silicon solar cell in Bell Labs to the large-scale application in national defense and civil use, PV energy has developed rapidly in recent years, and several megawatt PV power plants have been built in the world. PV system is mainly composed of solar cells, batteries, controllers and inverters. PV system can be divided into independent solar PV system and grid connected solar PV power generation system: independent solar PV system means that solar PV system is not connected to the grid, and the typical feature is that battery is required to store energy. Grid connected solar PV system means that solar PV system is connected to the grid, become a supplement to the grid(IRENA 2019).

1.2.2. The development status of solar PV energy

1) World

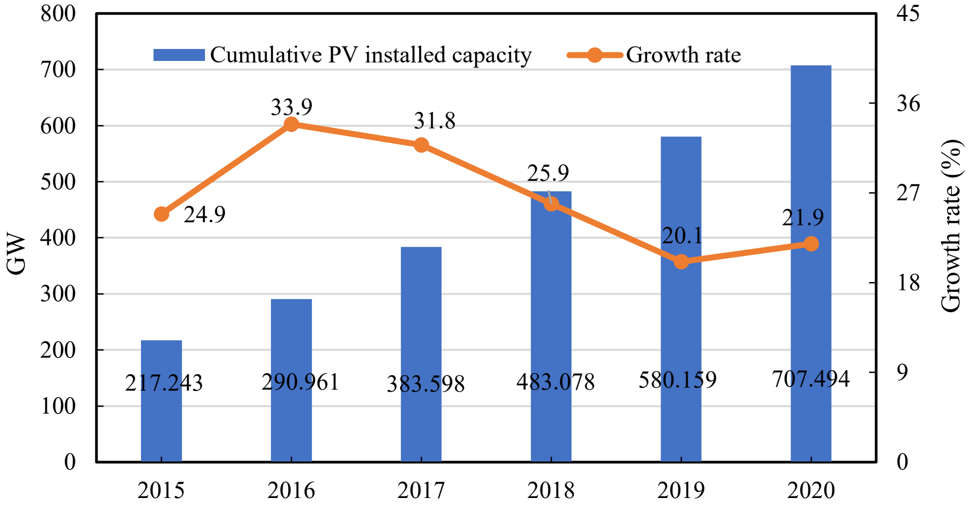

Figure 1-4 Global PV total installed capacity

(Source: IEA 2020).

According to the data of IEA, the cumulative installed capacity of global PV is maintaining a stable upward trend from 2015 to 2020. In 2020, the cumulative installed capacity of global PV energy is 707.5 GW, with a yearly growth rate of 21.9% (IEA 2020).

According to the regional distribution of global PV power generation, Asia is the main market of PV power generation. In 2019, the installed PV capacity in Asia is 330GW, accounting for 56.9% of the global PV installed capacity; Followed by Europe, the installed PV capacity is 138GW, accounting for 23.8% of the global PV installed capacity (Figure 1-5) (IEA 2020).

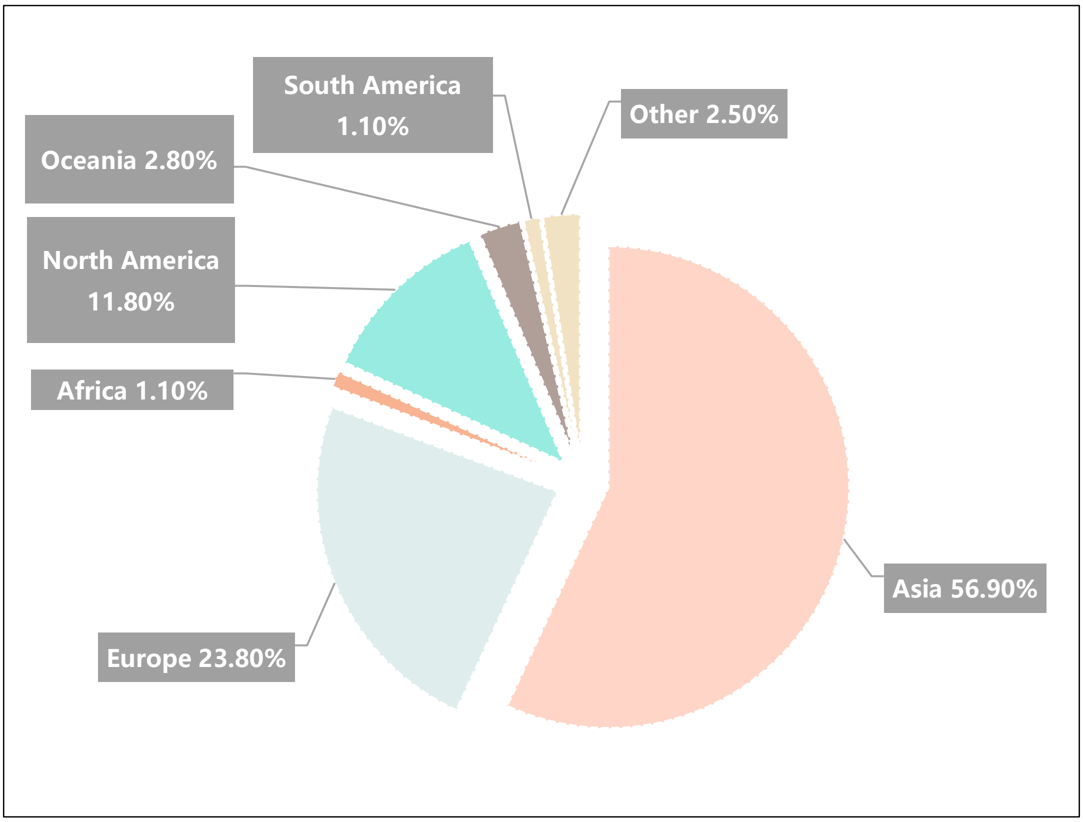

Figure 1-5 Regional distribution of global PV power generation in 2019 (by installed capacity) *(Source: IRENA 2020).*

In recent years, the average annual production of solar PV products in the world has increased significantly. Research and production of solar cells is taking place on a large scale in Europe, the Americas and Asia. In the early 21st century, the U.S. and Japan competed to introduce R&D programs for solar technology in order to compete for dominance of the world PV market. Greater incentives are given in terms of solar power prices, taxes, and development funds. At the same time, with government support, some high-level research institutions in Europe have also accelerated the pace of research. Europe, the United States, Japan and other countries have also formulated long-term energy development strategies and made long-term plans for the development of solar energy. After that, the rise of China's PV industry shocked the world (Huang et al. 2016). Especially after 2014, China has the world's largest PV market and PV product capacity. Figure 1-6 shows the PV installed capacity of China, United states of America, Japan and Germany.

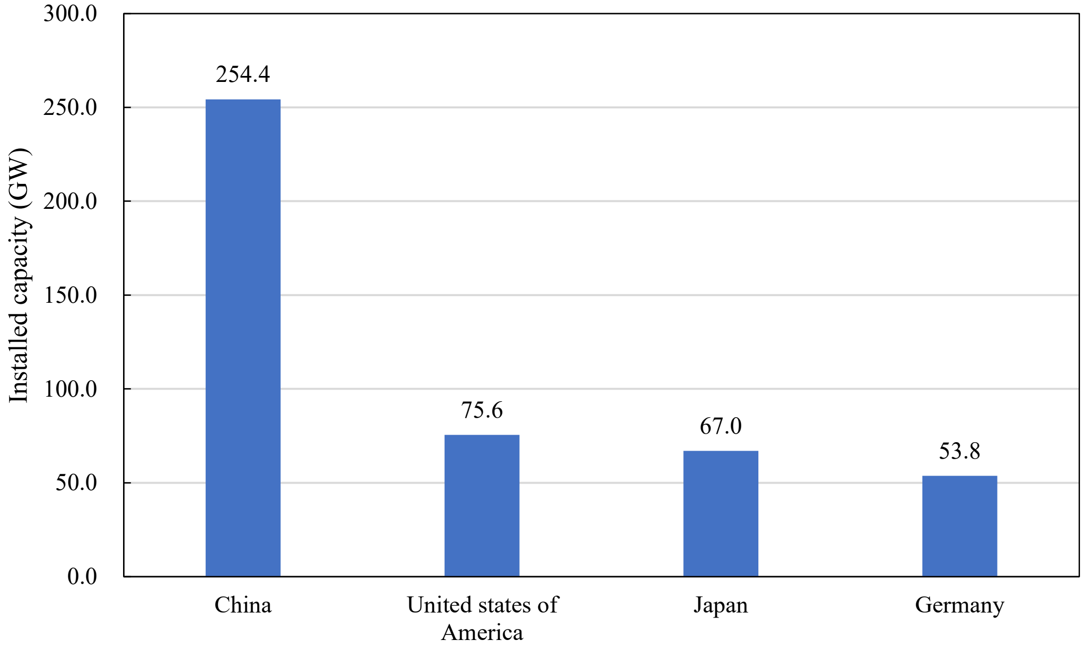

Figure 1-6 The PV installed capacity of China, United states of America, Japan and Germany in 2020 *(Source: IRENA 2020).*

Driven by technological advances, economies of scale, increasing supply chain competition, and growing developer experience, the cost of renewable energy generation has fallen significantly over the past decade. According to cost data collected by IRENA for 17,000 projects in 2019, the costs of solar photovoltaic (PV), concentrated solar thermal (CSP), onshore wind and offshore wind have declined by 82%, 47%, 39% and 29%, respectively. In 2019, 56% of new operational grid-connected large-scale renewable generation capacity will be less than the cheapest fossil-fueled generation. Between 2010 and 2019, the cost of solar photovoltaic generation has fallen by 82% (REN21 2018). The main reason for the cost decline since 2010 has been the decline in panel prices and system package costs, with the former falling by 90%. These factors have reduced the total installed cost of solar PV by about four-fifths over the past decade (Gaetan et al. 2018).

Despite the Covid-19 pandemic, solar PV is poised for steady growth in 2020 , thanks to strong growth in the utility-scale sector offsetting a modest contraction in the distributed market. Major markets such as the U.S., China and the EU will help solar PV add an average of more than 125 GW of capacity per year between 2021-2025 (REN21 2019). A smooth transition in China's renewable energy policy, a faster recovery in distributed solar PV and policy clarity in emerging markets such as the ASEAN region, the Middle East and Africa could lead to more rapid growth in PV energy.

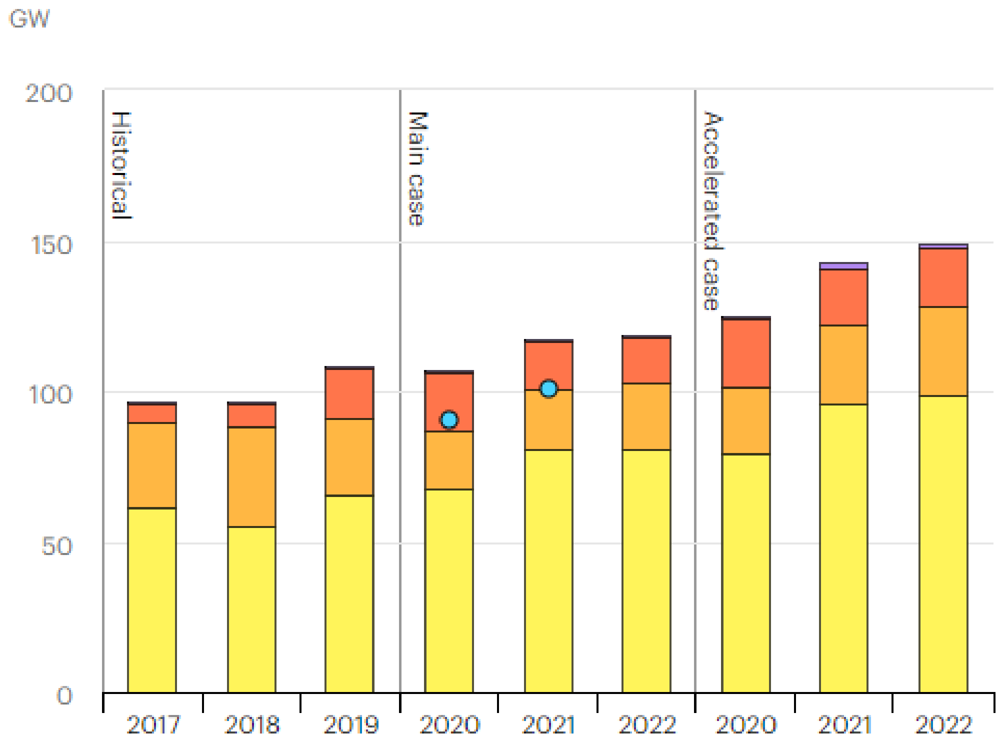

Figure 1-7 Solar PV net capacity additions by application segment, 2017-2022

(Source: IRENA 2020).

2) China

Before 2010, China's cumulative installed solar power capacity was only 1 million kilowatts, and the proportion of solar power generation was very low. Since then, the solar power generation has gradually increased. In the eight years from 2012 to 2020, the installed solar power capacity has increased rapidly, reaching 248 times of 2012 in 2020 (Li and Taeihagh 2020) (Fig. 1-8).

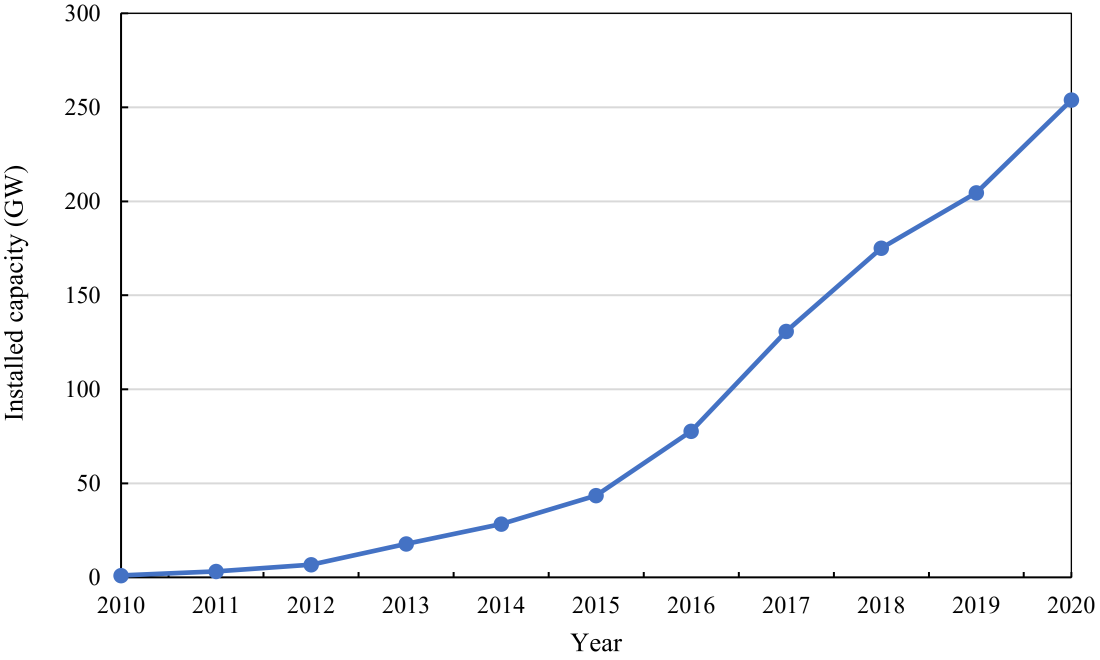

Figure 1-8 The cumulative PV installed capacity of China in 2010-2020 *(Source: IRENA 2020).*

Over the past decade, China has increased installed PV capacity from 80 MW in 2006 to more than 204 GW by 2019, and surpassed Germany as the world's largest PV market in 2015. The key subsidy policy that has led to this surge in China is the zonal feed-in tariff (FIT). Under the zonal feed-in tariff policy, China is divided into three different resource zones based on solar radiation resources, each with its own feed-in tariff tier. However, the first adjustment of the zonal feed-in tariff policy was made about three years after its enactment. This lagging policy adjustment and the over-subsidization of PV generation has resulted in more PV capacity than the grid can absorb. This has also resulted in a large deficit in the government's renewable energy subsidy budget. The study of renewable energy support policies is critical to the future health and sustainability of PV energy in China (Shubbak 2019).

3) Germany

Over the past two decades, the German PV market has developed into one of the most mature PV markets in the world. Since the enactment of the EEG in 2000, the development of PV energy has been a success in Germany. With more than 2 million PV systems, the share of total electricity consumption produced in 2019 is around 8%. Germany's PV installed capacity reaches 54GW in 2020 (Figure 1-9). The majority of new PV energy installation in Germany (more than 80% in number; 21% in capacity) are smaller than 10kW, that making Germany by far the largest market for residential PV system in Europe. Germany's potential rooftop area could accommodate about 200 GW of PV installed capacity.

Germany is expected to continue to lead the global rooftop PV market in the coming years. The German government is aiming for 2 to 2.5 GW of new PV installations per year in Germany over the next few years.

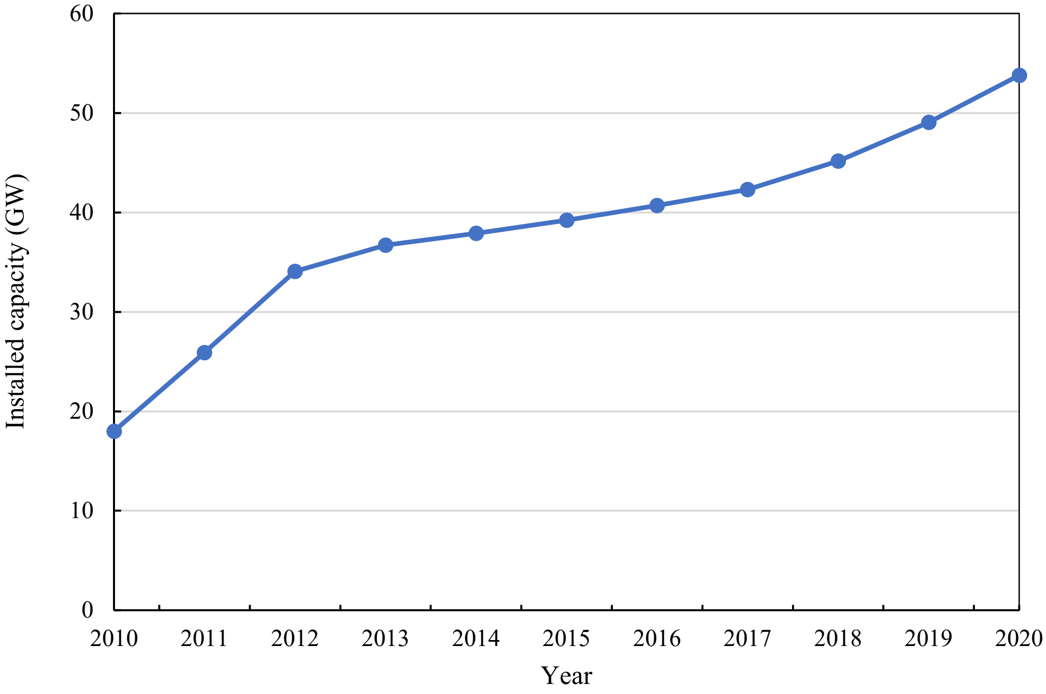

Figure 1-9 The cumulative PV installed capacity of Germany in 2010-2020

(Source: IRENA 2020).

4) Japan

Solar PV energy in Japan has been expanding since the late 1990s. With a long history of PV support policies, Japan has a leading manufacturer of PV and a large domestic PV market, 85% of which is residential rooftop PV systems. Since the Fukushima Daiichi disaster in 2011, the development of renewable energy in Japan has become an important national energy goal. In 2012, Japan launched the Feed-in Tariff Act (Huenteler, Schmidt, and Kanie 2012). In 2013 and 2014, Japan was the second largest global market for solar PV growth, adding a record 6.97 GW and 9.74 GW, respectively. By the end of 2020, the cumulative PV installed capacity reached 68 GW, behind the US and China (Figure 1-10). The total PV installed capacity is estimated to be sufficient to supply nearly 7.6% of the annual electricity demand in 2019.

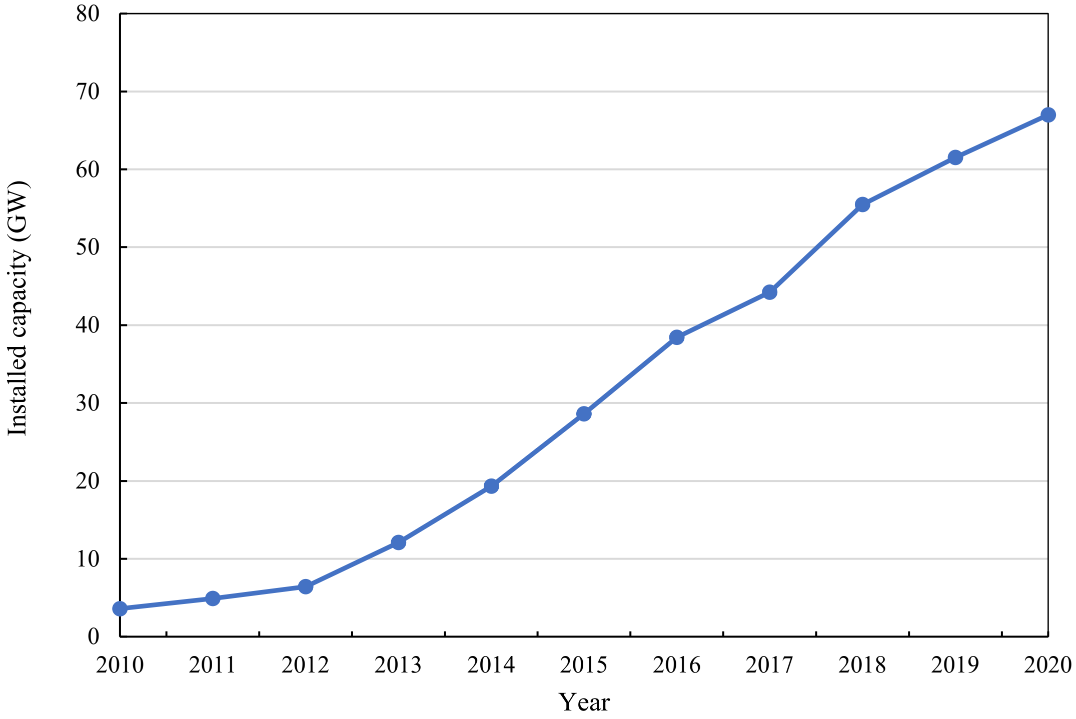

Figure 1-10 The cumulative PV installed capacity of Japan in 2010-2020

(Source: IRENA 2020).

5) the United States of America

In 2005, the U.S. government introduced the Energy Policy Act of 2005 (ITC) to promote the development of the PV market by providing a 30% investment tax credit for those who invest in PV systems. The ITC has proven to be one of the most important federal policy acts to stimulate PV development in the United States. The Act, supplemented by accelerated depreciation, increased the tax credit by approximately 26%; thus, for many investors, reducing system costs by approximately 56% over a six-year period. Since ITC implementation, the residential and commercial ITC has helped the solar PV market grow significantly, averaging 50% annual growth over the last decade alone. U.S. solar PV capacity grows from 0.34 GW in 2008 to 97.2 GW by 2020. More than 3% of U.S. electricity comes from solar energy.

1.2.3. Framework of renewable energy policy

In general, the renewable energy policy can be differentiated into market-pull policies and technology-push policies. The main objective of technology-push policies is to increase the incentive for companies to engage in technological innovation by reducing the negative impact of the imperfect disreputability of innovation benefits, leading to the development of renewable energy technologies or the improvement of existing technologies. Market-pull policies aim to increase the demand for renewable energies by internalizing negative externalities or reducing market barriers (Bobinait, Galinis, and Lekavi 2021). The following discussion highlights the fact that both approaches are crucial in the context of renewable energies and technological change.

1.2.3.1 Market-pull policies

Market-pull policies aim to increase the use of renewable energy by creating a demand for renewable energy. It is generally accepted in the environmental economics literature that market-pull policies not only promote the use of technologies, but also induce innovation. Market-based approaches encourage firms to innovate through the setting of market signals and incentives, which still gives them the flexibility to choose the least costly option (David,Popp;Richard,G.Newell;Adam n.d.). Market-pull policies to increase renewable energy deployment typically have various formulas that focus on the deployment and diffusion of the renewable. For example, the introduction of a carbon tax is a non-technical, price-driven approach where the quantity is determined by limits on emissions allocation, while the creation of a carbon tax is technology neutral and the price of carbon is determined by the market. Feed-in tariffs is a technology-specific, price-driven approach, while renewable portfolio standards are a technology-specific, amount-driven policy measure (Moosavian et al. 2013). Similarly, public funding can help mobilize and generate commercial investment in renewable energy projects, directly or indirectly, by reducing investment risk through loans, guarantees, or long-term commitments to direct public investment.

In theory, indirect, technology-neutral policies such as pricing carbon through taxes or emission trading schemes (ETS) result in cost-efficient mitigation measures, provided no further market failures exist (Fischer and Newell 2008). Establishing a carbon price through a technology-neutral, market-based approach like the ETS provides dynamic incentives for low carbon innovation, which is thus, in theory, superior to a command-and-control measure in spurring innovation (Vollebergh 2011).

Although the debate is on-going about the contribution of renewable energy support schemes to emission reduction and the effect of additional technology-specific policies on the cost-effectiveness of emission trading, many authors highlight that direct, technology-specific support policies for renewable energies, like feed-in-tariffs, are necessary complements in the light of the knowledge about market distortions and path dependency in socio-technical systems (Vollebergh 2011).

Technology-specific policies aim at increasing the specific demand for renewable energy technologies. Quantity-driven policies allow the market price to be determined by market transactions between actors while ensuring that utility operators generate or sell a predetermined amount of electricity from renewable energy sources (Liu and Lin 2019). The price is determined by the market and operating firms have a certain choice about which technology is used. Price-driven policies provide financial incentives for capacity expansion and direct generation. Additionally, voluntary programs can be implemented which depend on the consumers' and producers' willingness-to-pay for or invest in renewable energy (Liu and Lin 2019).

1.2.3.2 Technology-push policies

In addition to the benefits that market-pull measures provide, technology-push policies, such as public research and development (R&D) funding as well as fiscal measures that incentivize private R&D, are important in order to internalize the benefits from innovations in climate-friendly technologies. Without adequate policy support, especially in the early stages of innovation, companies tend to underinvest in clean energy technologies, as they cannot exclude spillovers to competitors who have borne none of the development costs. Further, they tend to be risk averse if technology success is uncertain and the time span until market maturity is expected to be lengthy (Rodríguez-urrego and Rodríguez-urrego 2022).

1.2.3.3 Policy mix of market-pull and technology-push policies

The development of renewable energy technologies, which ranges from basic research, applied R&D, demonstration to commercialization of new technologies, products or processes, requires policy support of different intensities and directions. Renewable energy development requires technology-driven policies for public funding and fundamental and applied R&D in the early stages, and market-pull policies for full commercialization in the later stages. The national innovation system and the policy mix implemented are important determinants of the technological change process. In addition, specific policies for the respective technology development stages and technology-specific diffusion approaches are needed to enhance the development of less mature technologies.

Tables 1-4 show the main policies and strategies currently adopted by major countries around the world to support renewable energy development. The policy effects of PV energy studied in this paper encompass the final effects on PV development after the mix of policies and the implementation of these policies.

Table 1-3 Strategies and selected policies for the promotion of renewable energy (Groba and Breitschopf 2013)

Market-pull policies				
		Technology-specific (direct)		Non-technology-specific (indirect)
		Price–driven	Quantity-driven	
Market-based	Investment incentives	● Investment subsidies ● Tax credits ● Supportive tax policy ● Tenders (price)	● Tendering systems for investment grants (quantity) ● Quotas (capacity)	● Environmental taxes ● Emission trading
	Generation incentives	● Feed-in tariffs ● Premium feed-in tariffs	● Energy portfolio standards (quotas) in combination with tradable green certificates ● Tendering systems for long-term contracts	

Command-and-control		● Technology and performance standards ● Authorization procedures	
Voluntary	Investment Promotion	● Shareholder programs ● Contribution programs	● Voluntary agreements
	Generation promotion	● Green tariffs	
Technology-push policies			

	● Public R&D spending (direct funding, grants, prices) ● Tax credits to invest in R&D ● Capacity enhancement for knowledge exchange ● Support for education and training ● Financing demonstration or pilot projects ● Market engagement/incentive programs/public procurement ● Strategic development policies ● Technology exhibitions/fairs ● Network creation/building

Sources: (Groba 2013).

2

1.3.Research structure and logical framework

1.3.1. Research purpose and core content

Solar PV technology has experienced rapid growth, driven by advanced technologies and diversified energy policies. With the increasing application of PV energy in countries around the world, the PV industry has become a strategic emerging industry. PV energy has become an important part of the world's energy system, and countries have made the PV energy sector a key area of economic development and technological innovation a high point of energy strategy implementation. Government policies are proving to be the key to developing PV energy. To achieve the development goals of PV energy, policy guidance and promotion are crucial. An in-depth analysis of the impact mechanism and effects of different policy on PV energy development, and a systematic sorting and analysis can provide scientific references for policy makers. The overall purpose of this study is to assess the implementation performance of PV policies in four PV leading countries through quantitative models to propose policy implications for promoting PV energy development and technological progress.

The research objectives and logic of the article are shown in Figures 1-16 below. This study examines the significant role of PV energy policy in driving PV energy development based on energy challenges and PV energy development. Using the top four countries in the world by installed PV capacity (China, Germany, Japan, and the United States) as study cases, the impact of energy policy on PV product price reduction is determined using a technology learning approach. After that, the impact of current energy policies on the economics of residential PV systems and large PV plants is analyzed using a techno-economic analysis. Finally, a comparative analysis of four countries' cases is presented, and policy implications are suggested. It is hoped that it could be helpful for the promotion of PV energy development.

1.3.2. Chapter content overview and related instructions

The chapter titles and the basic structure of the article are shown in Figure 1-11. A purpose of each chapter is shown in Figure 1-12.

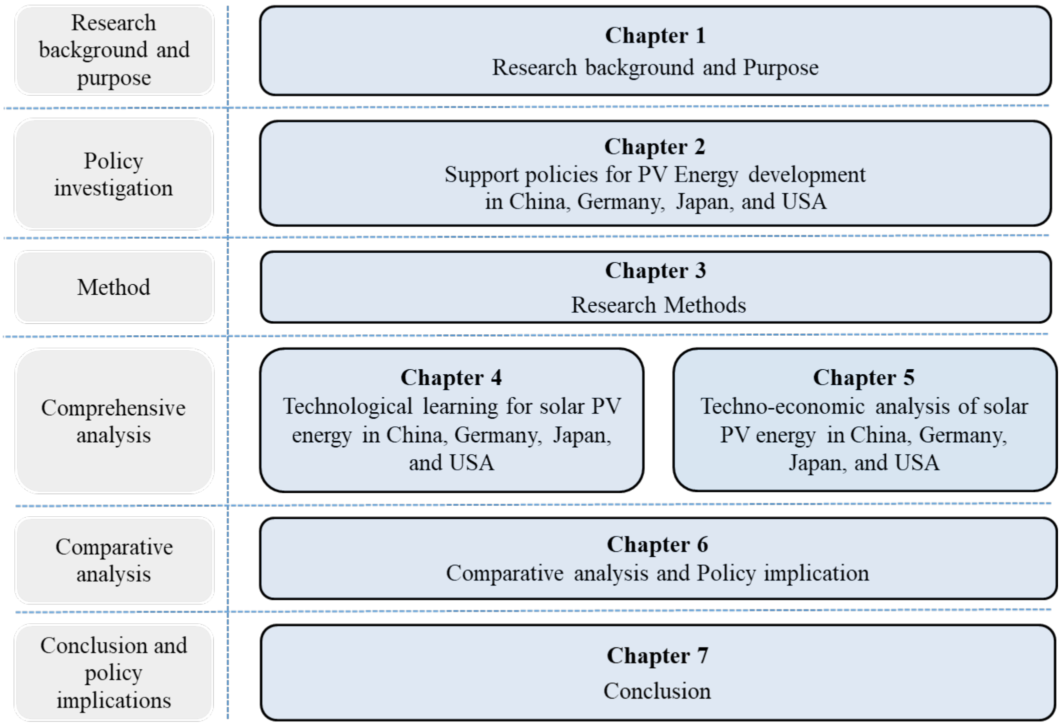

Figure 1-11 The title of chapters and the basic structure

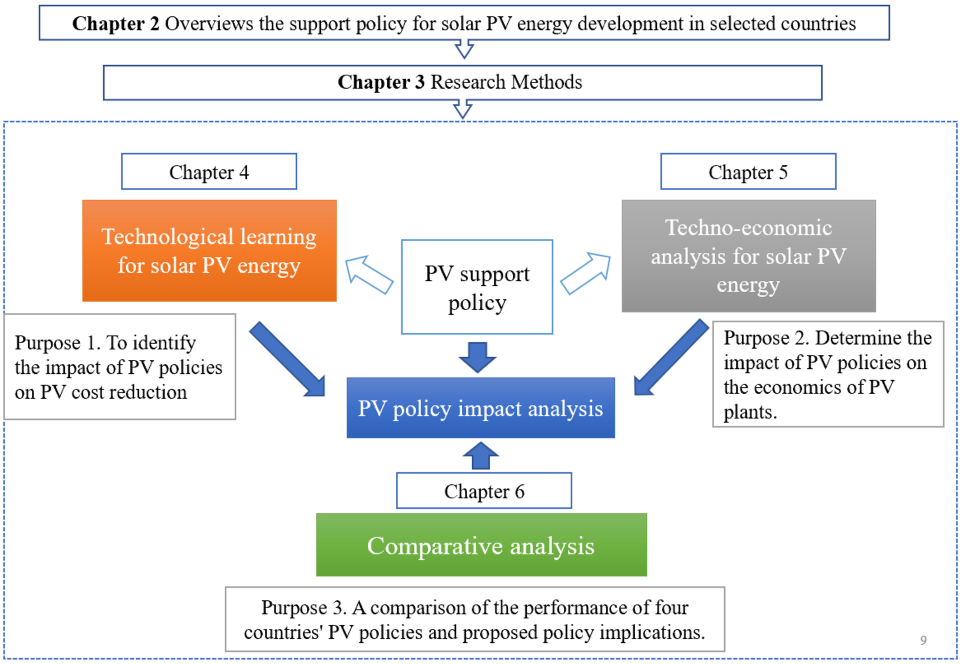

Figure 1-12 Research purpose of each chapter

In Chapter 1, Research Background and Purpose of the Study:

With the rapid growth of energy demand, concerns about climate change, high prices of fossil fuels and the depletion of fossil fuels, PV energy has been playing an active role in the development of renewable energy. And energy policy, as the main actor driving the development of PV energy, has been the focus of scholars' interest in research. In view of the current energy issues, this chapter discusses the significance of PV energy for future energy development. In addition, the current status of PV energy is investigated and the main categories of energy policies applied to drive PV energy development are presented. The limitations and barriers of PV energy policies are also discussed.

In Chapter 2, Support policies for PV Energy development in China, Germany, Japan, and USA:

This chapter presents a detailed analysis of the rise of solar PV technology in China, Germany, Japan, and the USA. The effects of different incentive policies implemented over the past decades on PV development in these four leading countries are demonstrated. At different development periods, some special external factors may have guided the policy introduced, and the type of policy implemented is vary across different countries. Therefore, the trajectory of the PV incentive policy from three aspects: R&D, industry and market are traced systematically.

In Chapter 3, Research method of the study:

This chapter presents the methodological research and established the mathematical model. First, the research motivation of the study is described. Then, the model for technology learning and the single-factor learning curve and two-factor learning curve analysis of PV policy performance are presented. In addition, a simulation model of the PV system and the techno-economic analysis methods used in the subsequent chapters are provided.

In Chapter 4, Technology Learning Curves for Solar PV Energy Policy in China, Germany, Japan and USA:

This chapter proposed a one factor learning curve (OFLC) and two factor learning curve(TFLC) method of the PV energy taking the public R&D investment and PV installed capacity into consideration, and the effect of different policy periods on the PV production cost in the PV system was compared and analyzed. A literature review of one-factor learning curves and two-factor learning curves for technology learning is presented, and the basic concepts of learning curve models are introduced. The reduction of PV product cost is correlated with PV installed capacity and R&D investment. After that, a technology learning model based on the one-factor learning curve was developed for four countries during different policy implementation periods. The effectiveness of different policies was found by analyzing the learning rates of LBDs in different periods.

In Chapter 5, Techno-economic evaluation of solar PV energy in China, Germany, Japan and USA:

A techno-economic analysis of residential PV systems and large PV plants in typical cities in four countries are carried out. Under different climatic and geographic conditions and based on different policy conditions, residential PV systems and large grid-connected PV plant are simulated using SAM and PVsyst software for four selected cities. Detailed technical and economic analysis is determined based on the energy production injected into the grid by the PV systems. In addition, I select the city with the highest energy production among all the case cities in the four countries as the location for large-scale PV plants, the economics of PV plants are investigation.

In Chapter 6, Comparative analysis and policy implication:

First, the effect of technology learning is compared in four countries at different periods. The incentive effects of different PV policies on PV energy development are evaluated in this context. Second, the impact of the incentive policies on residential PV systems and large-scale PV plants in the four countries is evaluated based on the results of the techno-economic analysis. Finally, the future PV development strategies of the four countries were overviewed, and then policy implication are made for PV industry development and demand-pull policies and supply-side promotion policies.

In Chapter 7, Conclusion:

This part summarizes the research of previous chapters. And based on the conclusions, the future development of PV energy and the prospect of further research are put forward.

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Chapter 2. Support policies and PV technology development in China, Germany, Japan and the USA

2.1.Introduction

Since the 1970s, due to the limited supply of fossil energy and increasing pressure regarding environmental protection, numerous countries worldwide have begun to exploit and utilize renewable energy. Among all renewable energy sources, solar photovoltaic (PV) technology has a huge potential in alleviating pollution, reducing CO2 emissions and addressing energy demand pressures (Sen and Ganguly 2017). Therefore, promoting solar PV technology has become a vital part of sustainable development strategie worldwide. In the last few decades, driven by advanced technology and improved regulations, solar PV technology has experienced grown rapidly (Sovacool and Gilbert 2013).

The first PV device was invented by Bell Labs in the United States of America (USA) in 1954 and mainly applied to space satellites (Hart and Birson 2016). From the 1960s to the 1990s, the United States took the lead in PV technology. Platzer et al. (Platzer 2016) pointed out that the introduced incentive policies were the key factors to affecting the PV deployment and that they helped to initiate the early niche markets in the United States. Since the 1990s, Japan and Germany have become the leading countries in solar PV development. Jacobsson et al.(Jacobsson, Sandén, and Bångens 2004) examined the development of solar cells in Germany from 1958 to 2000 and emphasized the importance of market formation policies for PV technology development to maintain technological variety. Watanabe et al. (Watanabe, Wakabayashi, and Miyazawa 2000) demonstrated the government's incentive policy creating a “virtuous cycle” between R&D, market growth and price reduction on the basis of an empirical analysis of Japan’s firm-level PV R&D. After 2000, the German PV market grew rapidly and the country was the leader during this period. Blankenberg et al. (Blankenberg and Dewald 2013) discussed the evolution of PV technology in Germany and explained that the trigger of this development were demand-side policy instruments of feed-in tariff (FiT). In the following years, the successful expansion of the German PV market promoted the diffusion of FiT to other countries; the Chinese PV industry has been significantly affected by the German PV market since 2000. Zhang et al. (Zhang and Sims 2016) indicated that the main drivers of PV technology transferred from the global innovation system to China were global market changes, formation of policy, international mobilization of talent, and flexibility offered by Chinese manufacturing. After 2011, China’s PV market also began to growth rapidly. Zhang et al. (Zhang and He 2013) pointed out that China relied on the FiT scheme to stimulate local PV market development, which helped the domestic PV industry to overcome the difficulties caused by anti-dumping actions in USA and Europe. Muhammad-sukki et al. (Muhammad-Sukki et al. 2014) indicated that Japan through the FiT scheme, achieved rapid growth in the domestic PV market after the Fukushima disaster. These studies show that policy instruments have been the key factor driving the global development of PV technologies.

Hoppmann et al. (Hoppmann, Huenteler, and Girod 2014) used the innovation system approach to analyze the evolution of the FiT, and explained how this policy affected PV development in Germany. The authors confirmed that the policy issues were driven by unforeseen technological developments induced by previous policy interventions. Huang et al. (Huang et al. 2016) focused on understanding the rapid rise of the Chinese PV industry and concluded that the rise of the Chinese PV industry can be explained by the interaction of three factors: the change in Chinese institutions, technology transfer, and its large European selling market. Hart and Birson et al. (Hart and Birson 2016) traced the history of PV deployment in the USA and found that solar PV with federal subsidies alone, was economically viable. Those studies have determined the importance of policy impact on PV development in the fields of R&D, industry, and market development by examiningPV development process in each country.

A comparative study of several countries can also contribute to determining the advantages of PV policies and the results of their implementation. Chowdhury et al. (Chowdhury et al. 2014) showed the impact of policies on the diffusion of PV technology in Germany and Japan and identified that the policies implemented during different periods are the key factors that affected the diffusion of PV in both countries. Grau et al. (Grau, Huo, and Neuhoff 2012) surveyed policies and industrial actors in Germany and China and concluded that incentive policy in the field of PV R&D is weak in Germany. Quitzow (Quitzow 2015) showed that there were a set of dynamic and mutual interdependencies between Germany and China, which promoted the development and diffusion of PV technology in those countries. Strupeit et al. (Strupeit and Palm 2015) investigated organizational configurations related to the deployment of customer-oriented PV systems in Germany, Japan and the USA. Their research showedhow the business models in the three countries successfully removed typical barriers to PV adoption. Solangi et al. (Solangi et al. 2011) provided a comprehensive review of solar PV technology in terms of the efficiency of photovoltaic materials in five leading countries and discussed the driving policies, funding, and R&D activities to comprehend the reasons behind the success of the leading countries in adopting PV technologies. The authors found that the FiT, Renewable Portfolio Standard (RPS) are the most beneficial energy policies implemented by several countries worldwide.

In this chapter, a detailed analysis of the rise of solar PV technology in China, Germany, Japan, and the USA are presented. The effects of different incentive policies implemented over the past decades on PV development in these four leading countries is demonstrated. At different development periods, some special external factors may have guided the introduced policy, and the type of policy implemented may vary across different countries. Therefore, the trajectory of the PV incentive policy from three aspects: R&D, industry and market is systematically traced. The industry refers to the entire supply chain of PV product manufacturing, and the main indicators include the output of PV technology products. The market refers to the PV energy market scale, and the main indicators include the installation capacity of solar PV energy. The role of policy instruments and international factors is investigated. Thereafter, different policies are identified and how they have driven PV development in China, Germany, Japan, and the USA are examined.

2.2.Data Source Mining and Methodology

2.2.1.Data source

In this chapter, research data were obtained from publicly available sources and secondary literature, such as academic and professional journals, reports, and websites. This study adopted databases and keyword searches to identify articles related to PV technology and incentive policies. Relevant literature reviews of PV development mainly used multiple databases such as Web of Science and Scopus. We also obtain data from different sources of information to guarantee validity. The first source was the annual report from the International Energy Agency (IEA), Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE), and REN21. The cost and price data of PV production and PV installed capacity from these reports were used to analyze different fields in the PV industry. The second source was the IEA's online data services and policy database, and it was used for policy investigation. Other sources were scientific, technical, conference articles, press releases, policy documents, and technical and government reports. We conducted a systematic literature review and used several literature systems to retrieve relevant publications; finally, we identified a combination of keywords as follows: "solar PV development or diffusion", "solar PV R&D or industry or market", and "China or Germany or Japan or the United States".

2.2.2.Methodology

A case study approach is used in this chapter, and conducteds an in-depth study of one or more cases (based on the research question) by obtaining reliable historical data (Yin, 2009). In this paper, how policy influencing PV development in different periods is traced by four countries as study cases. The research structure of this study is presented in Figure 1. First, I trace the evolution of PV incentive policies in China, Germany, Japan and the USA. Detailed data were obtained via data mining by investigating PV development in three fields: PV R&D activities, PV industry and PV market. The purpose of this investigation is to clearly identify key incentive policies related to different fields in the PV development process, such as renewable energy targets, R&D funds, net-metering, and feed-in tariffs. These policies can be divided into two main categories, supply-push policies and demand-pull policies (Fabrizio, Poczter, and Zelner 2017; Nemet 2009; Nuñez-jimenez et al. 2019). The main difference between of those policies is that supply (technology) push policies are aimed at providing R&D and manufacturing support to industry, while demand-pull policies are aimed at stimulating the market demand for a certain technology (Hansen et al. 2017; Samant, Thakur-Wernz, and Hatfield 2020). Second, I analyze the role of the push and pull policies in the three fields of PV by investigating on PV R&D activities, PV industry development, and PV market development. We examine the supply-push policies and analyze their impact on PV R&D and industry. The main indicators are public funds for PV R&D, PV module cost reduction, and production share changes. Then, I analyze the impact of demand-push policies on PV market development, in which the main indicator is the change in PV market scale and market share. The three fields of PV technology are relevant under the expectation of internationalization. Global dynamics across the four countries are also accounted for.

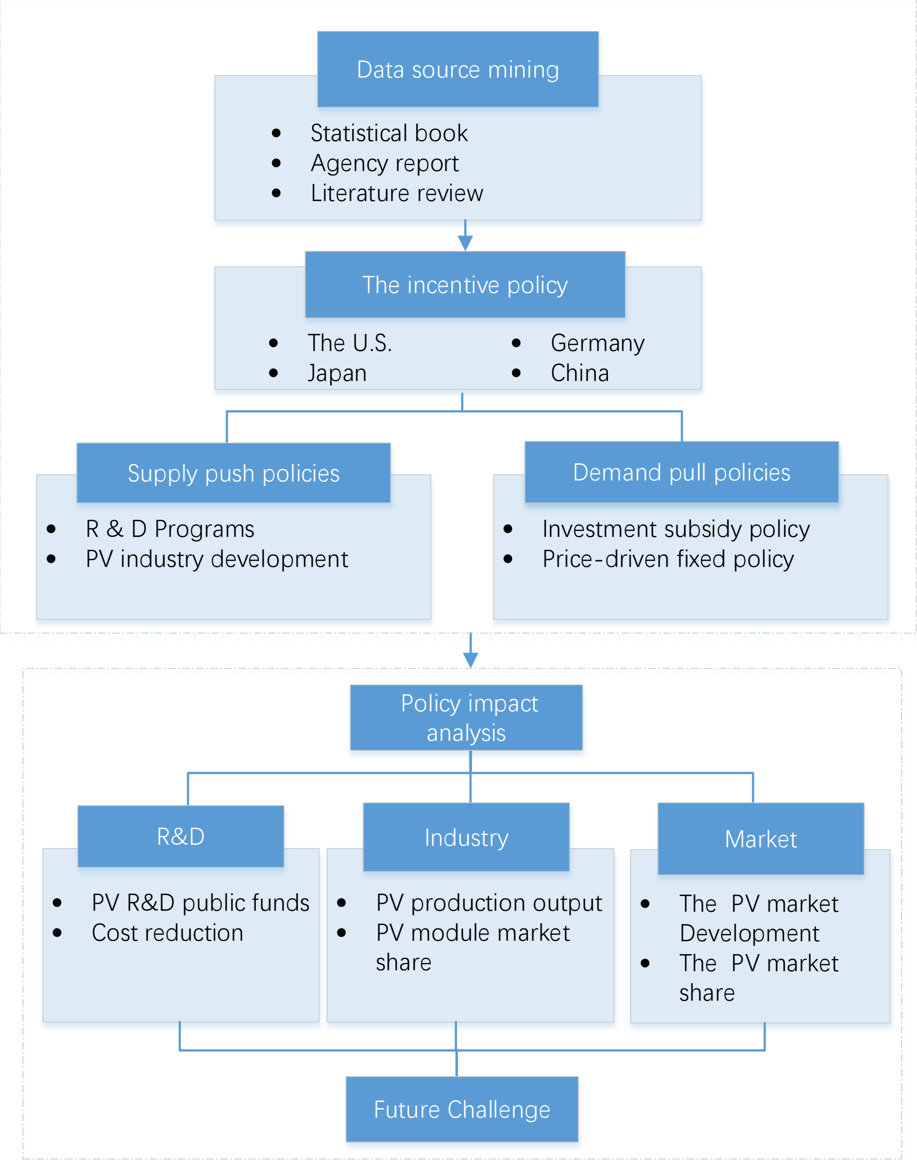


Figure 2-1 Research structure

2.3.Investigation of PV incentive policy in China, Germany, Japan, and the USA

2.3.1.Investigation of PV incentive policies in China, Germany, Japan, and USA before 2000

Table 1 shows the history footprint of incentive policies for solar PV technology development in

China, Germany, Japan, and the USA. Supply-push policies and demand-pull policies have played important roles during the different periods of development. In the USA, the 1973 oil crisis triggered a serious push to develop PV terrestrial applications. The Electrical Research and Development Association (ERDA) purchased almost 2000 kW of capacity between 1977 and 1980 (Hart and Birson 2016). The Department of Energy (DOE) began operations in 1977, which directed the USA's Solar Energy Technologies Program (SETP) through its Office of Solar Energy Technologies (Clark 2018). The "Public Utility Regulatory Policy Act of 1978" provided tax credits for residents who invested in solar energy in an attempt to initiate a small niche PV market. The demand from these sources stimulated the establishment of PV module factories during the late 1970s (Hirsh 2007). In 1977, the Solar Energy Research Institute (SERI) began operating as a laboratory dedicated to the R&D of renewable energy. Furthermore, the PV R&D program expanded significantly, reaching USD 157 million in 1980 (U.S.DOE. 2010). In 1991, SERI designated a national laboratory to renewable energy and subsequently renamed it the National Renewable Energy Laboratory (NREL). The NREL and Sandia National Laboratories (Sandia) are dedicated to solar PV R&D. The reduced PV investment costs through R&D breakthroughs and manufacturing process improvements as well as incentives facilitated growth of more niche markets (Norberg-Bohm 2000). However, dropping oil and gas prices have considerably exacerbated the cost reduction challenge and diminished public interest in solar energy.

Table 2-1 The PV incentive policies in China, Germany, Japan and the USA

Year	The USA	Germany	Japan	China
1974			Sunshine Program*	
1977		Energy Research and Technology Program*		
1978	Solar Photovoltaic Energy Research, Development and Demonstration Act*; Energy Tax Act of 1978**			
1980			The New Energy and Development Organization (NEDO) established*	
1981		Fraunhofer ISE established*		
1990	National Renewable Energy Laboratory (NREL) established*			
1991		1.000 roofs program**; Electricity Feed-in Law**		

1992	Energy Policy Act 1992 (ITC) **		Net-metering(billing) Program**	
1993			New Sunshine Program*	
1994			Monitoring program for residential PV systems**	
1996		Way Paving Program*; Green tariffs**		
1997			Subsidy for R&D for New and Renewable Energy*	
1998			Promotion for the Local Introduction of New Energy**	
2000		Feed-in Tariff Law (EEG) **		
2001			The new 5-year plan for PV Power Generation Technology R&D*	10th Five Year Plan*
2003			New Monitoring program for residential PV systems**; Renewable Portfolio Standard**	
2004		EEG Amended**		
2005	Energy Policy Act 2005 (ITC) **			
2006	Solar America*	Funding for Solar Power Development Center*	PV Roadmap toward 2030**	Catalog of Chinese high-technology products for export*; Renewable Energy Law**
2008	Solar America Initiative*; Extension ITC**	EEG Amended**		
2009			R&D for High Performance PV Generation System*; Subsidy for Residential PV systems**; Feed-in Tariff Law**	The “Golden Sun” demonstration project**
2010		The Innovation Alliance PV; EEG Amended**		The BIPV subsidy program**
2011				973 Program*;863 Program*; Solar PV feed-in tariff**
2012			New Feed-in Tariff Law**	The new "Golden Sun" demonstration project**

2013				Feed-in tariff support for solar PV**; PV electricity grant**
2014		EEG Amended**	NEDO PV Challenges*	
2015	Extension ITC**			The Top Runner Program**

Note: The sign with a "*" in the upper right hand corner refers to supply-push policies. The sign with a "**" in the upper right hand corner refers to demand-pull policies.

In Germany, the Federal Ministry of Economics and Technology (BMWi) was responsible for applied energy research as well as market promotion (Jan Frederik Braun 2019). In 1977, the government beginning introduced the an "Energy Research and Technology Program" to for facilitating the budget distribution of the budget to the various sectors of PV R&D. In 1990, the German government started a "1000 Rooftops Program" (Mints, 2012). This program was an important attempt to promote the PV market, and it intended to obtain experience in PV system installation and encourage investment in solar energy (NIR, 2018). With thire successful experience in the "1000 Rooftops Program", the government expanded the program to the "100,000 Rooftops Program" in 1999 (ERGE, HOFFMANN, and KIEFER 2001). These demonstrations created a niche market for solar PVs (Hoppmann et al. 2014). At the same time, the "Feed-in Tariff (FiT) Law", which was implemented in 1999 was further enhancing German PV market formation (IEA. 2000). With the start of the 4th Federal Program on Energy Research and Energy Technology in 1996, "Way Paving Program Photovoltaic 2005" program was formulated (Hongxing and Yutong 2007). This long-term program focused on cost reduciton in PVs and their grid-independent system applications. Public R&D funds and demonstration programs encouraged private firms to enter the market as well, such as large electronic or chemical companies, and to invest in PVs. However, the high cost of solar energy limited PV market development, which was not large enough to justify investments in new production facilities. The German PV firms bought U.S. firms and expanded their production in USA and the production of solar cells in Germany dropped to nearly nil (Jacobsson et al. 2004).

In Japan, the Ministry of Economy, Trade and Industry (MITI) has been actively driving promotion measures and policies for R&D for renewable energy in Japan. After the first oil crisis, the Japanese government was aware of the importance of energy security and energy independence (Watanabe 1999). In 1974, MITI implemented a "New Energy Technology Research and Development Plan" to provide a substantial amount of renewable energy by 2000 (Kimura 2006). The New Energy and Development Organization (NEDO) was established in 1980 as the central actor responsible for new energy development (Yamazaki 2016). The NEDO took a four-year demonstration project from 1986 to 1990, which provided a niche market to PV manufactures in the country. Sharp, Sanyo and Kyocera continued to implement the program and became the leading companies in solar PV manufacturing in

Japan. These firms established the Japan Photovoltaic Energy Association (JPEA) in 1987, this was a PV industry coalition group that aimed to promote the utilization of solar PV technology(Kimura 2006). In 1992, the first demand-pull policy called "Net-Metering (Billing) Program" for PV market development was introduced. This program was initiated by 10 domestic electrical enterprises (Suwa and Jupesta 2012). In the following year, a specific guideline related to grid connection for solar PV called "Monitoring Program for Residential PV Systems" was implemented by the government (Kaizuka 2012). In 1993, the "Sunshine Program" merged with the "Moonlight Program" and the "R&D Project on Environmental Technology" in the form of the "New Sunshine Project" was implemented, which focused on promoting comprehensive and long-term R&D for PV technology (Tatsuta 1996). Most PV R&D activities were performed by PV manufacturers, including basic research (IEA, 2017).

In China, the State Scientific and Technological Commission was set up by the China Optics and Electronics Technology Centre in 1980s, which began research of monocrystalline silicon solar cells and polysilicon silicon solar cells (Wang et al. 2018). In the 1990s, apart from importing PV technology, R&D activities were carried out only in a few PV companies and some Chinese universities (Zhao et al. 2013).

2.3.2.PV incentive policy in China, Germany, Japan, and the USA after 2000

Consistent public funding for PV R&D has helped the USA become the technology leader in the solar PV industry. Until 2006, the DOE was appropriated USD 5.8 billion for solar research (U.S.DOE, 2006). The "U.S. Photovoltaics Industry Roadmap", which was refined in December 2000 and updated in 2004, unifies the long-term (2000-2020) strategies and goals for the PV industry in the country (Farris and Industries 2003; IEA. 2018). The production targets of the U.S. PV industry roadmap reveal that 70% of the production capacities are aimed for export. This series of efforts by the policy instruments facilitated expansion of the PV industry in the USA (IEA. 2003, 2011). In 2005, the "Energy Policy Act 2005（ITC）" was introduced to promote PV market development, which provided a 30 % investment tax credit to those who invested in PV systems. The ITC has proven to be one of the most important federal policy mechanisms to incentivize PV development in the USA. This Act was complemented by accelerated depreciation, which added approximatedly 26% to the tax benefit; thus, reducing the system cost by approximatedly 56% over a six-year period for many investors (IEA, 2009; Stegman and Davis, 2016). The residential and commercial ITC has helped the solar PV market to grow significantly since it was implemented, with an average annual growth of 50% over the last decade alone (IEA, 2004). The ITC Act 2005 was implemented until the end of 2007. Thereafter, the ITC Act was extended in 2008 and 2015 to ensure continued growth of the PV market. In 2007, the Solar America Initiative (SAI) funded up to USD 13.7 million for 11 university-led projects that focused on the development of advanced solar PV technology manufacturing processes and products (IEA, 2011). During 2009-2011, public funds for PV R&D exceeded USD 400 million in the USA. In 2011, the "SunShot Initiative" was introduced by the Solar Energy Technologies Office (SETO) of the DOE, which aimed to reduce the total cost of PV solar energy systems by 75% by 2020 (U.S. DOE. 2015). As solar PV technology made rapidly progressed closer to the 2020 targets, the SETO committed to reaching new cost targets for the upcoming decade, supporting greater energy affordability by reducing the cost of solar electricity by an additional 50% between 2020 and 2030. The SunShot 2030 targets were 0.05 USD/kWh for residential PV, 0.04 USD/kWh for commercial PV systmes, and 0.03 USD/kWh for utility-scale PV systems (U.S. DOE, 2017).

In Germany, the "100,000 Rooftops Program" and the EEG (FiT) scheme became an opportunity for rapid growth in the PV market since 2000. (Dewald and Fromhold-Eisebith 2015). The FiT scheme has driven the rapid growth of the market, which has grown consistently the government targets; the growing PV market has become an opportunity for new companies to enter the PV industry (Ito 2011). Therefore, the government of Germany reformulated the R&D program emphasizing not only cost reduction but also on the consequent utilization of the R&D results in PV production. Since autumn 2002, the Federal Ministry of Environment (BMU) has been responsible within the federal government for promoting renewable energy development (Altenhöfer-Pflaum 2003). In 2006, in addition to BMU grants, the Federal Ministry of Education and Research (BMBF) also provided funding for the development of PV technologies (Agency et al. 2007). In 2010, the BMU and BMBF initiated an Innovation Alliance for PV technology. Under this scheme, the R&D projects were funded to support a significant reduction in PV production costs for enhancing the competitiveness of the German PV industry. The BMU and BMBF allocated EUR 100 million to support this initiative. The German PV industry agreed to raise an additional EUR 500 million to accompany the Innovation Alliance (IEA. 2010). To streamline the German energy policies, the responsibility for all energy-related activities was concentrated within BMWi since the end of 2013 (Wehrmann 2018). The EEG has accelerated the growth of PV market, which has been consistent and has surpassed the government targets. Therefore, the government further fundamentally revised the EEG in 2014 (Wirth 2017).

In Japan, a new R&D program called "the new 5-year plan for PV power generation technology R&D", was initiated in 2001. This program focused on four areas: advanced solar cell technologies; comprehensive introduction of common basic PV technologies; innovative next-generation PV power technologies, and advanced manufacturing technology of PV systems. In 2006, the new 5-year plan was completed, and then a 4-year plan was launched based on "PV Roadmap toward 2030 (PV2030)" plan (Kosuke 2007). The "R&D for high performance PV generation system for the future" and "R&D on innovative solar cells" were initiated in 2009; these plans aimed to make a breakthrough in next-generation solar cells were governed by the Ministry of Education, Culture, Sports, Science, and

Technology (MEXT) and were promoted by the Japan Science and Technology Agency (JST). A new guidance for technology development based on the "NEDO PV Challenges," formulated in 2014 for technology development, set a target to realize a power generation cost of 14 JPY/kWh by 2020 and 7 JPY/kWh by 2030 (Hahn 2014). Under the new framework of technological research, NEDO shifted its direction from "strategies to promote dissemination of PV power generation" to "strategies to support the society after penetration of PV power" (IEA, 2014a). On the demand-pull policy side, parallel to a new monitoring program for residential PV systems, the government introduced another renewable energy policy known as the "Renewable Portfolio Standard (RPS)" in 2003 (Ito 2015). In addition, the FiT scheme for residential PV was adopted in November 2009 (Ogimoto et al. 2013). It was estimated that more than 90% of the PV installations were carried out in residential buildings (IEA, 2012b). With the start of the new FiT Act in 2012, the Japanese PV market entered a new growth phase (Kimura 2017). For residential PV installations, tariffs with 42 JPY/kWh were paid for 10 years. The non-residential sector had a 40 JPY/kWh paid for 20 years (IEA. 2018). The FiT policy has thus, driven the rapid growth of PV market in Japan.

In China, the Ministry of Science and Technology (MOST) supports PV R&D in universities and research institutions, and provides assistance to enterprises for realizing each of the central government's "Five-Year Plan" (Huang et al. 2016). In the Plan for New Energy and Renewable Energy Industry Development in the 10th Five-Year (2001–2005) plan, renewable energy was viewed as a significant choice to optimize the Chinese energy structure. The public PV R&D funding increased to USD 6 million per year for the 11th Five-Year Plan (2006–2010). Addtionally, three most significant national research programs that have included are "National Basic Research Program of China (973 Program)," the "National High Technology Research and Development Program of China (863 Program)," and the "Plan of National Key Science and Technology." These three national research programs were regarded as guidelines for the development of key national strategic technologies in China for renewable energy (Huang et al. 2016). During the12th Five-Year Plan (2011-2015), the support for PV fields covered the entire manufacturing chain. The average annual investment in R&D from MOST was approximately USD 75 million during this period. In 2006, China began to enact the "Renewable Energy Law." The law was a national framework for promoting renewable energy development. This proved to be a huge driving force for the Chinese PV industry. From 2004, China's PV production invreased remarkably (Zhang and He 2013). Benefiting from the assistance of the "Catalog of Chinese High-Technology Products for Export" in the form of tax rebates, free land for factories and low-interest government loans, Chinese solar PV product suppliers expanded their production lines rapidly, especially for PV cells and modules (Jia, Sun, and Koh 2016). Since 2009, the government has attached importance to the domestic PV market and adopted a range of policies to support its development, such as special funds for renewable energy, feed-in tariff subsidies, preferential income tax for high and new technology enterprises, financial aid for PV applications, and demonstration projects. "Rooftop Subsidy Program" and "Golden Sun Demonstration Program" were initiated by the MOST and the National Energy Administration (NEA) (Zhao, Wan, and Yang 2015). In July 2011, the National Development and Reform Commission (NDRC) announced a nationwide FiT policy for the development of solar PV energy (Anon 2016). In August 2013, the NDRC issued a "notice on the role of price lever in promoting the healthy development of the PV industry". PV power generation was categorized into either distributed or centralized systems (IEA, 2012c). Concerning centralized power generation, the whole country was further divided into three regions based on the solar resource distribution. In particular, the FiT is be guaranteed for 20 years. Thus, the FiT policy has driven the rapid growth of the PV market in China. In 2015, "a Top Runner Program" was introduced to encourage Chinese PV companies to invest in PV R&D (IEC, 2018). With the expansion of the domestic PV market, the PV product capacity in China continues to grow. Until now, the Chinese PV product output and market scale still ranks first worldwide.

2.4.Sensitive analysis of impacts on PV development in China, Germany, Japan and the USA

Based on the investigation of PV incentive policies mentioned above, their impacts were analyzed from three perspectives. Further, the linkages and interactions between the three fields were also considered.

2.4.1.PV R&D activities

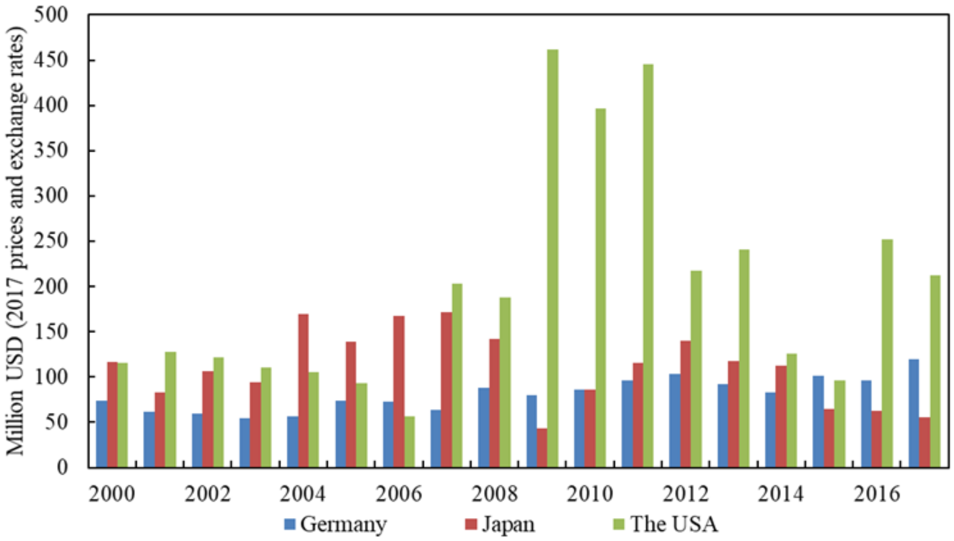


Figure 2-2 Public funds for photovoltaic(PV) R&D in Germany, Japan, and the USA in Million USD; 2017 prices and exchange rates (Data source: The online IEA data service and IEA,

PVPS, National Survey Report of PV Power Applications)

Figure 2-2 shows a graphical representation of the public funds for PV R&D in Germany, Japan, and the USA from 2000 to 2017. Supply-side push policies have played a major role in promoting PV R&D activities. The most direct manifestation was the investment in public funding. The USA has maintained a high level of investment in PV R&D. In particular, a significant investment in public funds was made from 2008 to 2013. In this period, the SAI was launched to promote close collaboration between universities and industries to accelerate the commercialization of PV technologies, which would ensure that research results can be quickly implemented in manufacturing processes and deliver market ready-products. Until now, the USA is the only country that has invested the most public funds in PV R&D. Japan invested a large amount of government funds for PV R&D during the early 2000s. This could be attributed to implementation of a new five-year R&D plan for PV to the improve the performance and economics of PV power. From 2009, the “R&D for a high performance PV generation system” was started. R&D investment in Japan increased annually from 2009 to 2012. Annual PV R&D funds have remained constant for Germany since 2000. This can be attributed to the stable implementation of the federal government’s Energy Research Program. In China, in addition to the import of technology, the R&D activity comprised the emergence of only a few PV companies before 2000. Since 2006, China has initiated several national R&D programs; the public PV R&D funding increased to a modest USD 6 million per year for the 11th Five-Year Plan (2006–2010). During the 12th Five-Year Plan (2011-2015), the average annual investment for R&D was approximately USD 75 million, with the supported fields covering entire manufacturing chain (IEA, 2014b).

2.4.2.PV R&D activities and product cost reduction

Figure 3 depicts the dramatic change in PV module prices from 2000 to 2016 in the four countries. The PV module prices were influenced by PV R&D activities and the PV industry’s production status. The USA and Japan retained a price advantage regarding the PV module compared with other countries until 2008. Furthermore, before 2010, PV module average prices in the USA were lower than in other countries. This can be explained by the large-scale investment in PV R&D activities over a long period. Beginning in 2008, module prices in the four countries declined rapidly. This is partly due to advances in PV technology and partly due to the expansion of the global PV production capacity. In Japan, the decline in module prices has been slow because of thier high domestic production costs (Myojo and Ohashi 2018). In Germany, the expansion of the PV industry in eastern Germany (after 2006) has contributed to a decline in the module prices (Brachert, Matthias; Hornych 2010). PV industrial research collaborations managed to get support from nationally funded R&D collaboration programs. In China, before 2010, even though the production in the PV industry was large-scale, average module prices were still higher than those in the USA and Germany. This can be explained by the lack of systematic investment in PV R&D in China, considering that the other three countries invest much more public funding in PV R&D than China. From 2012, Chinese PV products were enforced by anti-dumping duties and anti-subsidy countervailing duties in both the USA and the Europe. Most Chinese manufacturers have increase R&D investment to improve product competitiveness to reduce costs (Zhao et al. 2013). Chinese PV module costs have decreased rapidly as well. In 2010, the PV module price reductions in Germany and China caught up with those in the USA and Japan (Zhang and Sims 2016). Until now, German and Chinese PV modules have maintained their price advantage among the four countries; China has the lowest module price compared with the other countries. As a developing country, China's PV industry development trajectory is completely different from that of other developed countries. It is important to note that China's PV development has not experienced a long basic technology R&D period, and improvements to technology were only achieved via learning-by-doing strategies. For a long time, most of the technology was imported, mainly from western countries. To summarize, we can state that compared with the USA, Germany and Japan, China lacked a long-term PV R&D program and invested less public R&D funds. Addtionally, in China, the PV R&D activities and policies focused on the production-oriented to reduce costs, while in Germany, Japan and the USA, the focus was more on technology improvement.

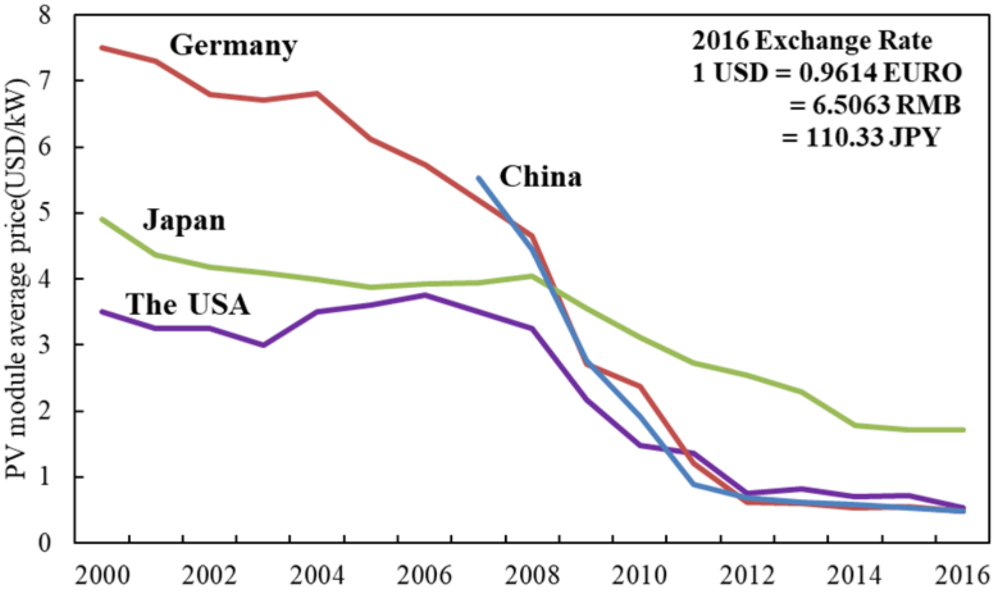


Figure 2-3 Photovoltaic (PV) module average price in China, Germany, Japan and the USA from 2000 to 2016, 2017 prices and exchange rates (Data source: IEA. PVPS. National Survey Report of PV Power Applications)

Figure 2-3 shows the trends in average PV module prices with an increase in the cumulative public R&D funding. The USA, Germany and Japan maintained long-term PV R&D programs and invested considerable public funds. The USA has the highest public investment for PV R&D compared with the other two countries. As a result, it gained an early advantage in terms of PV module cost reduction, with Japan following closely behind. Compared with these two countries, Germany's PV R&D investments are less and have fewer links between institutions, academia, and the PV industry. After 2006, the industrial research collaborations were supported by nationally funded R&D collaboration programs, which contributed to cost reduction. Even though the German cumulative PV R&D investment was lower than that of the other two countries, the PV module cost reductions have been effective. The three countries' success could be attributed to their long-term stable coordinated public investment in PV technology innovation. And another crucial point is that the policies implement by these countries provide a high level of collaboration between the PV industry, academia and research institute.

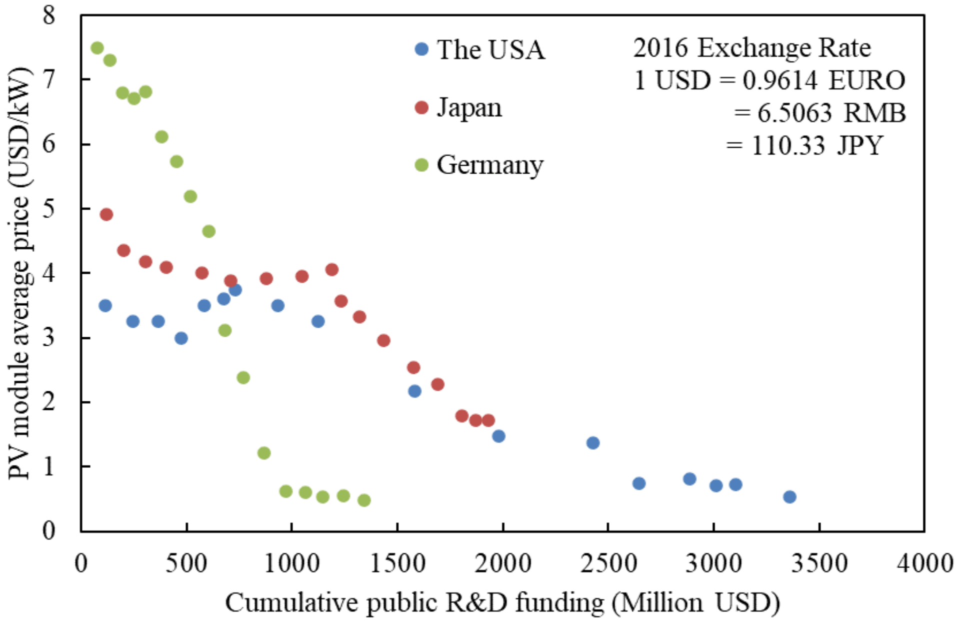
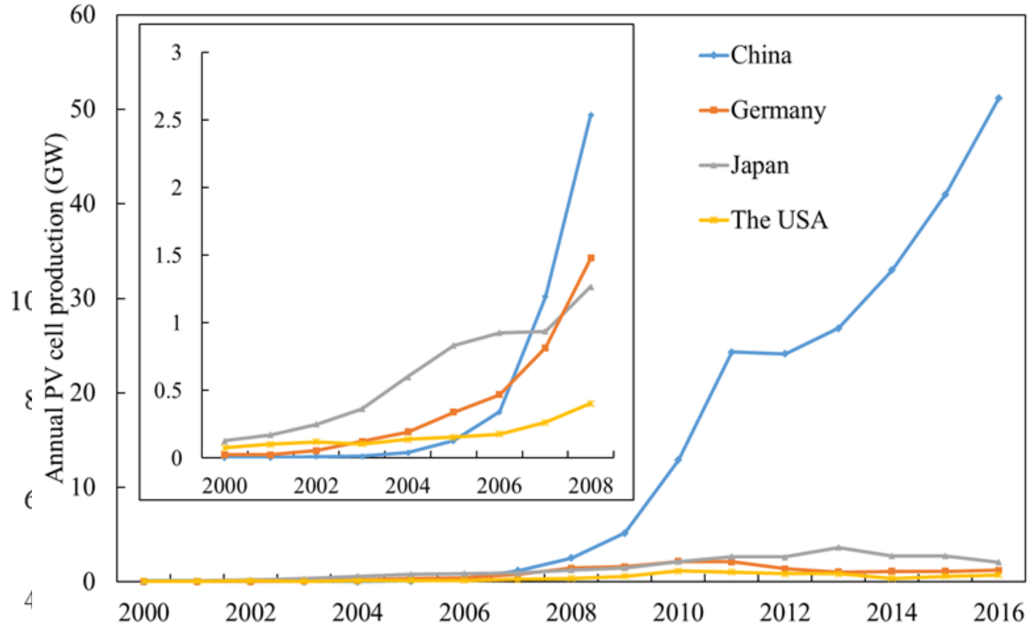


Figure 2-4 Trends in average photovoltaic (PV) module prices with increase of cumulative public R&D funding (Data source: IEA. PVPS. National Survey Report of PV Power Applications)

2.4.3.PV Industry

Figure 2-5 shows the annual PV cell production in China, Japan, Germany, and the USA from 2000 to 2016. Figure 2-6 shows the PV production share of the four countries and the rest of world from 2000 to 2016. Due to the massive R&D investment before 2000, the USA and Japanese PV modules achieved technology and price advantages and occupied most of the PV production market (Yu, Popiolek, and Geoffron 2015). The PV industry in Japan experienced a period of robust growth, leading to Japan being the leader in the PV industry worldwide. Since 1999, Japan has ranked first in PV production worldwide. Japan dominated the PV cell and module markets and contributed to more than 40% of the world's PV production capacity until 2006 (Kimura 2006). Due to the establishment of the PV industry in East Germany, the PV production share in Germany increased rapidly since 2005 (Blankenberg and Dewald 2013). From 2005 to 2007, Germany and Japan occupied more than 50% of the market for PV products. Then, the rise of China's PV industry shocked the world. China's current PV productions is higher than that of any other country. The highly profitable PV market in Europe has attracted many Chinese companies to enter the PV manufacturing sector. German PV companies have played an important role in the rise of China's PV industry. To find a large PV equipment market, German companies helped China to install PV production lines thereby increasing China's competitiveness. High-tech capabilities and knowledge were embedded in the production line, and the Chinese PV industry obtained technology for large-scale production (Quitzow 2015). On the other hand, Chinese PV manufacturers benefited directly from the investment support measures offered by the Chinese central government (Zhao et al. 2013). As the PV industry is one of the strategic emerging industries, the Chinese government has substantially subsidized the PV manufacturing sector along with related research grants, tax rebates, loans, and lands. Among the four countries, China is the only country that implements supply-push policies for promoted PV production (Jia et al. 2016), and thus, the Chinese PV industry quickly gained competitive advantage over other countries. China's involvement has greatly affected the structure of the global PV industry. Over time, China has started to dominate the worldwide PV production, and the production of Japan, Germany and the USA decreased immediately. In 2011, China's PV products accounted for more than 66% of the global production. Subsequently, the USA and the European Union launched anti-dumping and countervailing duties on Chinese PV products, forcing Chinese PV companies to struggle (Zou et al. 2017). The restriction on exports caused a decline in Chinese PV cell production in 2012. Therefore, the Chinese government drafted market incentives to improve domestic PV market development. Thereafter, the Chinese domestic market has expanded significantly, and the Chinese PV industry continued to grow. Currently, China's PV production share accounts for more than 70% of the world's production (IEA, 2018). China is the leading country in PV production.

Figure 2-5 Annual photovoltaic(PV) cell production in China, Japan, Germany and the USA from 2000 to 2016 (Data source: IEA. PVPS. National Survey Report of PV Power Applications)



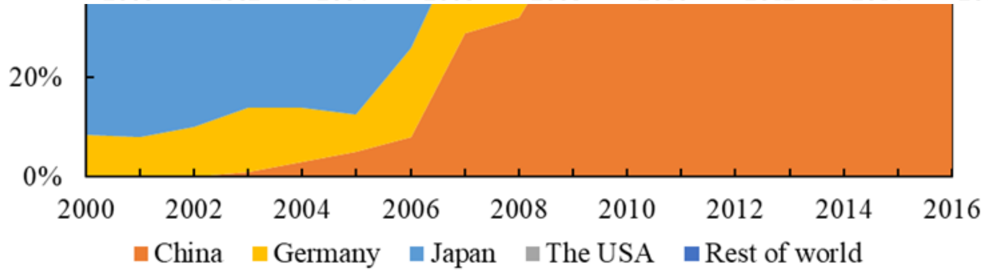


Figure 2-6 The photovoltaic(PV) production share by countries 2000 -2016
(Data source: IEA data service and Fraunhofer ISE)

2.4.4.PV market

Figure 2-7 shows the development of PV market in China, Germany, Japan and the USA from 1990 to 2017. From 2001 to 2009, the USA once again became a major player in the global PV development process, with an average PV market growth rate of approximately 60% per annum, the fastest growth of roughly being approximately 100% in 2003 (Haley and Schuler 2013). In 2000, the PV total installed capacity was 138MW, but the number increased to 1642 MW by the end of 2009. The ITC has contributed to the tremendous growth of the PV market since its implementation. In 2010, compared with 2009, the PV market in the USA grew by 92%. The PV installed capacity exceeded 40 GW from 2010 to 2016, with an average annual growth rate of over 70% (SEIA 2018). In Germany, from 2000, the subsidy program of “100,000 rooftops program” became an opportunity for rapid growth in PV market. The residential PV market continuously increased under stable conditions and modified the “Renewable Energy Sources Act (EEG) program” in the form of a FiT. Since 2008, Germany has proven to be the world’s largest PV market, with its cumulative installed capacity was increased to 34 GW at the end of 2012. In Japan, the annual installed capacity was approximately 290 MW in 2005. The installed capacity grew by more than 200% in 2008, reaching a cumulative capacity of 4.9 GW in 2011. The FiT policy has driven the rapid growth of the PV market in Japan, and the cumulative PV installed capacity increased from 4.9 GW in 2011 to 42.7 GW in 2016.

By the end of 2009, the cumulative PV installed capacity in China was only 300 MW. By 2012, 455 projects with a total capacity of 2872 MW were approved under the Golden Sun demonstration program. The cumulative PV installed capacity reached 3 GW in 2011. In 2015, the NEA proposed the implementation of the “Top-Runner program” for PV power generation. At the end of 2017, 43 projects and 26 GW in total have been approved (Nie, Wang, and Chen 2018). The PV cumulative installed capacity increased from 3.5 GW in 2011 to 77 GW in 2016. In 2017, China added 52.83 GW of new PV installed capacity, accounting for over half of all PVs installed worldwide that year.

Figure 2-8 shows the changes in the PV market worldwide from 2000 to 2017. In 2000, the PV market in Germany and Japan shared nearly 60% of the world’s PV market. In Japan, the subsidy program for PV deployment ended in 2005. Thus, the expansion of the PV market in Japan was caught during stagnation. Japan lost its position as the world leader of the PV market share in 2005 and Germany began to rule the world PV market. The German PV market accounted for more than 60% of the world PV installed capacity. In 2012, a new EEG was implemented and the growth of the German PV market slowed down. In the USA, Congress passed the “Energy Policy Act (ITC)” in 2005 and the PV market has grown rapidly across the country. In China, the Chinese government introduced the first significant measures in 2009, which is “the Golden Sun demonstration program,” to promote the development of domestic PV market. The market grew by over 300% in 2010 and 500% in 2011 (Zhang and Sims 2016). In 2011, China began implementing the FiT scheme, followed by Japan in the following year; corresponding to this scheme, the PV markets in China and Japan expanded significantly. The Chinese PV market ranked first worldwide and accounted for more than 50% of the world PV market in 2017.

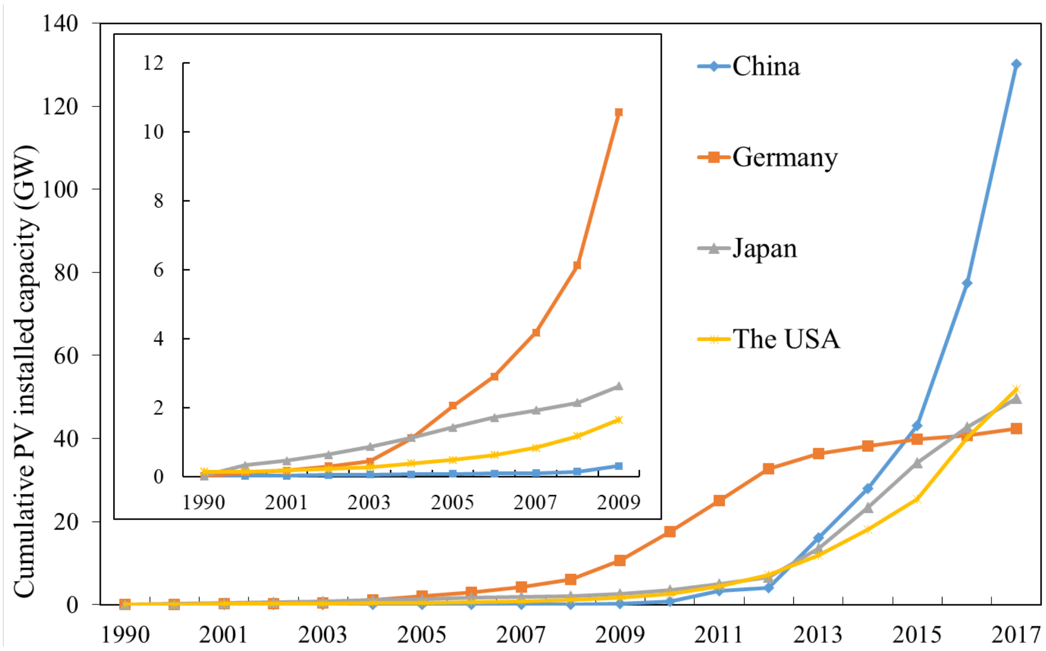


Figure 2-7 The photovoltaic(PV) market development in China, Germany, Japan and the USA from 1990 to 2017 (Data source: IEA. PVPS. National Survey Report of PV Power Applications)

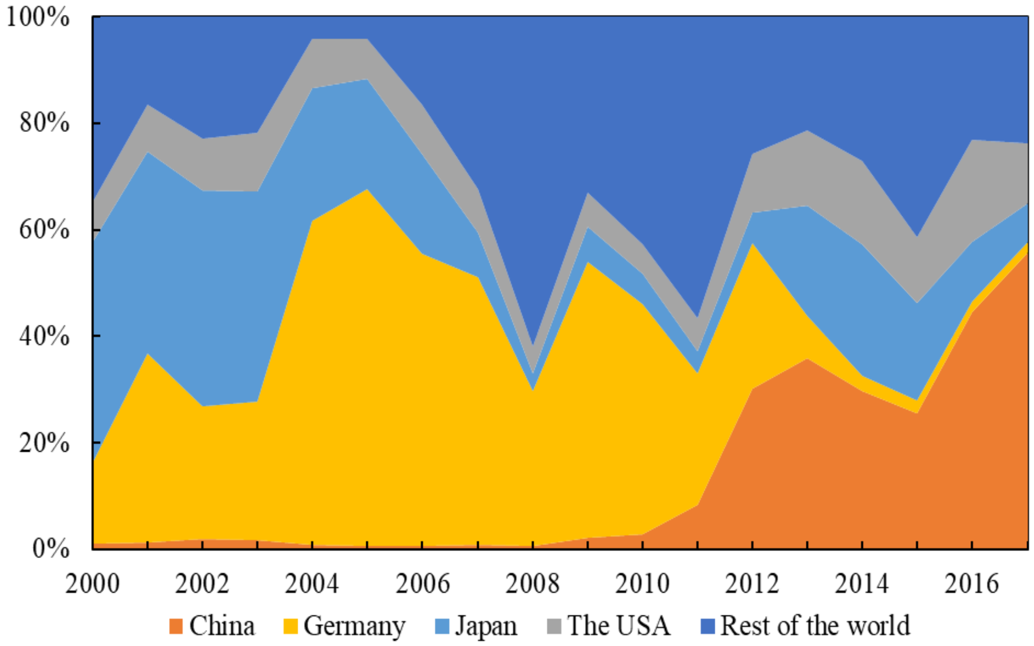


Figure 2-8 Photovoltaic (PV) market share by countries 2000 -2017 (Data source: IEA. PVPS. National Survey Report of PV Power Applications)

2.4.5.PV industry and market

Figure 2-9 shows the relationship between PV production and the PV market share in the four countries. The governments in all the four countries have used policy regulations to promote PV market development. The expansion of the PV market in Japan provided a boost for the Japanese PV industry, and the Japanese PV products occupied more than 40% of the global PV production market until 2006. Due to the rise of the photovoltaic industry in East Germany, Germany started producing more PV products than Japan. Subsequently, PV products in China have increased dramatically. China's PV module production accounted for more than 70% in 2017.

In terms of PV installed capacity, until 2012, Germany was the leader. With the start of the FiT in 2012, the Japanese PV market has entered a new phase of growth and Japan maintained an increased PV installed capacity of more than 7000MW per year. After 2014, the USA also maintained a capacity of more than 7000MW per year. Regarding the PV products, the Chinese PV market was delayed until 2013. The PV cumulative capacity in China was only 300MW at the end of 2009, and the domestic PV market accounted for less than 5% of the PV production (IEC, 2018). More than 90% of the PV products in China were export to the USA and Europe. From 2012, demand-side pull policies have boosted China's PV market development. Since 2015, PV installed capacity in China maintained rapid growth, accounting for nearly more than 50% of the global PV installed capacity. Japan has been an importer of PV modules since 2013 and the USA has been an importer since 2011. The gap between PV module production and domestic PV installed capacity has continued to widen. The overcapacity of China's PV industry has expanded along with the increasing imbalance between production and demand in the international market. Although the government expected to reduce this imbalance by tapping into the domestic market in 2013, the results were not ideal, and China's PV production capacity remains significantly over the capacity.

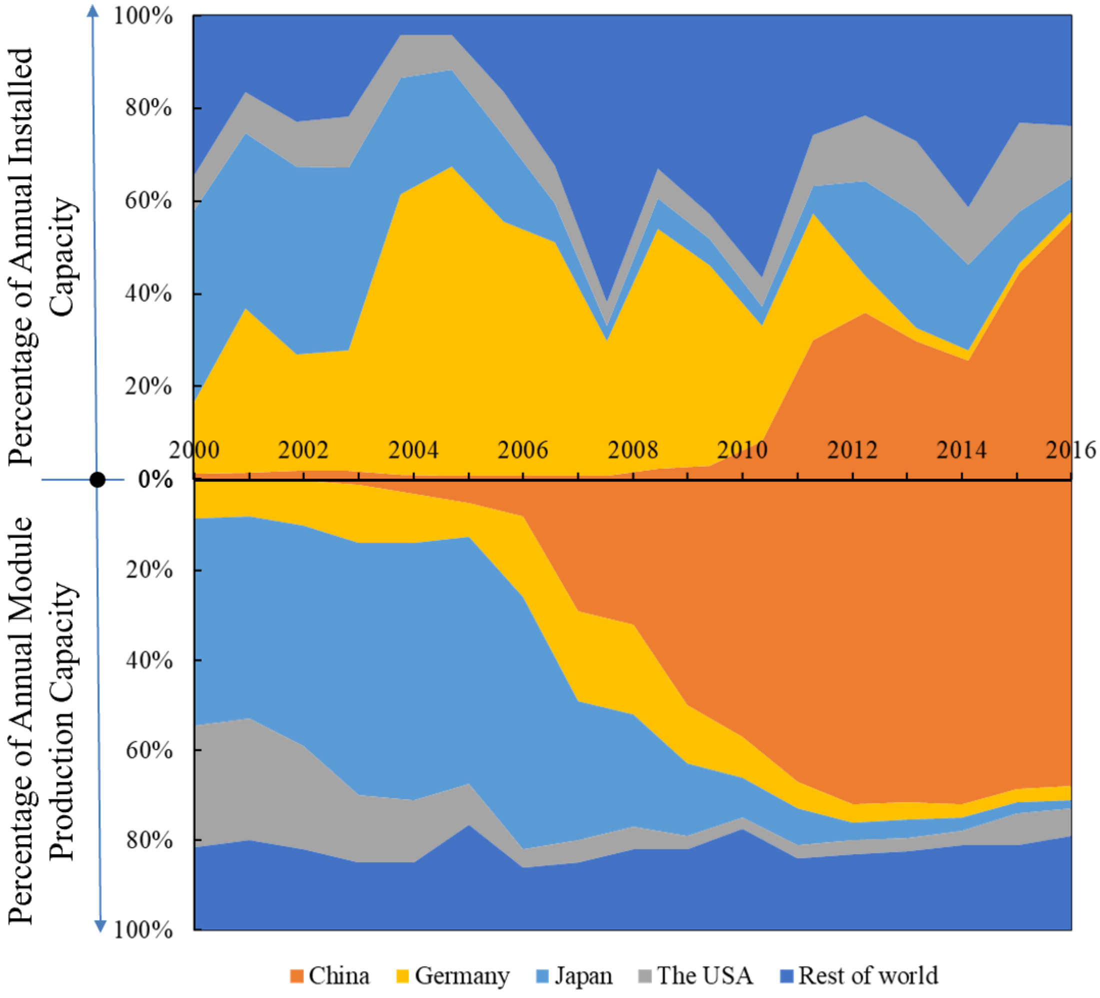


Figure 2-9 Share of annual photovoltaic (PV) module production and installed capacity (Data source: EPI data base; IEA. PVPS. National Survey Report of PV Power Applications)

2.4.6.Key incentive policies and PV market development

As shown in Figure 2-10, all four countries implemented investment subsidies to push the PV market expanded in the early stage of PV development, including rooftop programs in Germany, subsidy programs in Japan, the Golden Sun program in China and the Energy Policy Act 1992 in the USA.

Except for the USA, all other three countries launched national-scale FiT schemes. Figure 10 shows the annual PV market and incentive policy in China, Germany, Japan, and the USA from 1990 to 2016. We find that the FiT policy significantly affected the global PV market development. Germany introduced the FiT scheme in 1991, which drove the formation of the German PV market. The PV market continuously increased under a stable “EEG” in 2000. Since 2008, Germany has been the largest PV market. However, with the expansion of PV deployment, the cost of electricity borne by consumers has increased dramatically. In response to these challenges, a new EEG was implemented in 2010, which included specific measures such as limited market development, limited additional costs for consumers, and reduced profitability. The EEG was amended in 2012, which introduced a monthly adapted digression rate limited to 52 GW of the total installed PV capacity. In 2014, the government further fundamentally revised the EEG. The annual PV installed capacity decreased from 8200 MW in 2012 to 1200 MW in 2014, 1300 MW in 2015, and 1500 MW in 2016. The PV market expansion in Germany has been relatively stable.

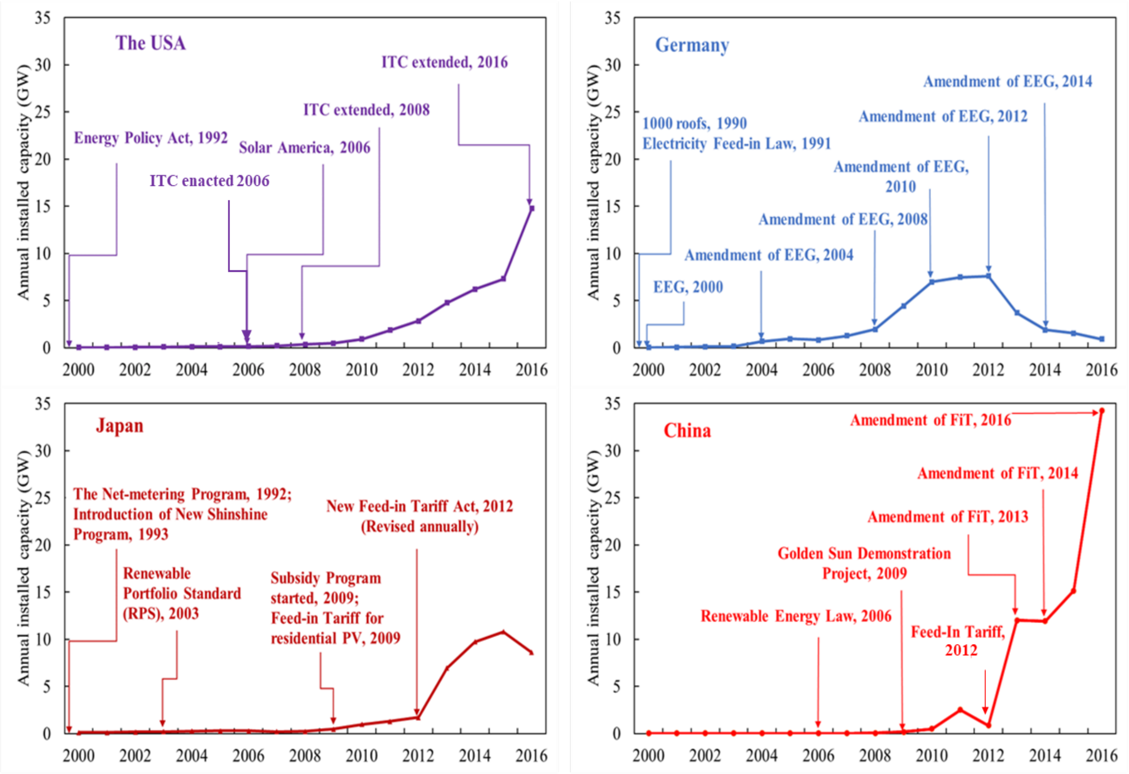


Figure 2-10 Annual photovoltaic (PV) market development and incentive policy in China, Germany, Japan and the United States (Data source: IEA policy database)

With the reduction of the initial investment in PV energy in recent years, the FiT has replaced the investment incentive policy to become an essential energy policy. The success of the FiT in Germany proves that this Act is a highly effective policy framework for accelerating the deployment of PV energy. China and Japan have begun to follow the German approach. Japan implemented FITs in 2012 and offered the most attractive tariffs of 0.36 USD/kWh (Kimura 2017). China started implementing FITs in 2011 and had the lowest financial incentives of 0.146 to 0.163 USD/kWh (Zhang and Chang 2016). Since 2013, China has ranked first in the worldwide PV market and Japan was the world's second-largest market for solar PV growth in 2013 and 2014. The feed-in tariff helps Germany, Japan and China to occupy three of the world's top four positions in PV the market. In the USA, the ITC has proven to be one of the most important federal policy mechanisms for driving PV energy deployment since 2005. The residential and commercial ITC have helped the solar PV market to grow significantly since it was implemented in 2006, with an average annual installed capacity growth rate of 50% over the last decade alone. However, this support mechanism also has certain limitations. The ITC is geared toward investment only and does not improve the long-term operating performance of PV power plants. Several states in the USA implemented the FiT scheme on a local scale, which is also a great push for PV deployment (Office of Energy Efficiency & Renewable Energy 2019). Therefore, the FiT has proven to be more effective than tax and investment incentive policies in PV development.

2.5.Conclusion

Solar PV technology is an inevitable choice for countries around the world to ensure energy security and promote greenhouse gas emission reductions. PV technology has made tremendous progress over the past few decades, with strong support from governments. Governments in various countries have designed different kinds of incentive policies based on the characteristics of different market development phases, including supply push policies for R&D and industry and demand pull policies for market development.

This chapter provides an overview of solar PV development in the top four leading countries and highlightes the policy instruments that influenced PV development processes. It inspected PV development processes from three perspectives: PV R&D, industry and market development. These four cases highlight the significant role of government policy in supporting PV development.

The main findings of this study can be concluded as follows:

(1) The success of PV technology development in the USA, Germany and Japan in the early stages could be attributed to the long-term stable coordinated public funds received in PV technology innovation, and another crucial point is that those policies provide a high level of collaboration between industry, academia and research institutes.

(2) As a developing country, China has improved PV technology achieved via learning-by-doing strategies and not technological innovation. The technology mainly transfers from Western countries. High-tech capabilities and knowledge are embedded in the production line, which is an import from western countries, mainly from Germany. China lacked a long-term PV R&D program, and invested less public R&D funds than the other three developed countries. In China, R&D activities and policies

focus on prodcution oriented to reduce costs. In Germany, Japan and the USA, which focus is more on technology improvements.

(3) In those four countries, China was the only country with production push policies. The Chinese government has substantially subsidized the PV manufacturing sector with producer subsidies, research grants, tax rebates, loans and lower price lands. The incentive policy supports enable China to establish a complete PV industry supply chain. Large-scale production also promotes cost reduction.

(4) Although China's PV industry was the largest player worldwide, the overcapacity of China's PV industry has expanded along with the increasing imbalance between production and demand in the international market. In Japan and the United States, a large party of PV modules relies on imports, mainly from China.

(5) The tax and investment subsidy policy is more in line with the implementation of PV development to reduce the investment threshold. The cases of the four countries all prove that investment subsidies could help the PV market to realize rapid formation. However, the subsidy is not assessed on the basis of the quantities of power generated, which adds a lot of uncertainty to the subsequent power supply. This confirms that tax and investment incentives should be used as supplementary support instruments but not as the major policy.

(6) Except for the USA, all of the other three countries launched a nationwide FiT scheme. The success of PV development in three countries has proved that FiT is a highly effective policy framework for accelerating the deployment of solar PV energy. The FiT could provide price certainty and offer long-term contracts to PV energy producers, and encourages the transmission of all the PV electricity generated to the grid. With the reduction of the initial investment in PV energy in recent years, FiT has replaced the investment incentive policy to become an essential energy policy.

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Chapter 3. Research Methods

3.1. Motivation

The main issue in developing new energy technologies is how to achieve start-up investments in new energy technologies, which are already amortized in traditional energy technologies, making them more profitable and competitive, becomes particularly important. In order to promote the development of new technologies, support policies must be developed. Major countries around the world have enacted and implemented policies to support PV energy investments, in terms of technological innovation and market promotion.

By reviewing the PV policy and the impact of PV policy on PV industry and market in Chapter 2, it is found that the cost of PV products has decreased to a large extent under the influence of various policies. However, under the existing energy system, the current price of PV power is still not enough to gain economic advantages, especially for residential PV systems, which still need to rely on policy support for a long time to come. According to the development strategy of each country, the large-scale popularization of PV power generation is inevitable, but most of the current studies are still based on the current energy supply and demand. Considering future cost changes will help to get a clearer picture of the potential of PV energy applications and development under more stringent environmental conditions. This study will examine the economic potential, impact analysis and development forecasts of PV based on energy policy at both technical and economic perspective. It is hoped that it will provide new ideas for incentive policy and PV energy promotion, and provide theoretical references for the study of practical applications of PV energy systems.

Therefore, the effects of energy policies must be studied in order to achieve the goal of renewable energy penetration in the most efficient way. Learning curves were used to analyze the impact of capacity increases on the cost of installed technologies. With this, it is possible to understand whether the implementation of the policy makes more sense in terms of cost reduction or whether it is worth a large-scale public investment. Furthermore, learning curves can yield different results for different analysis objectives, guiding governments or organizations to support more aspects that are more beneficial to the development of emerging energy sources, such as more support for markets or R&D.

After obtaining the policy performance through the learning curve, a techno-economic analysis of residential PV systems and large-scale PV plants is performed by combining the current PV policies of each country. Techno-economic analysis is a method widely used to estimate the performance and cost of renewable energy systems before they are built. The main purpose of the method is to provide potential investors and users with a basis for investment decisions and guidance on the performance of the technology to improve the overall value of the system (Acharya 2017). In this paper, this approach is using to analyze the impact of renewable energy policies on the economics of the PV energy. Finally, we hope to examine the future trends and potential of PV power system development through sensitivity analysis of policy indicators and system costs. By comparing the economics of PV systems between the four countries, we can see the strength of policy support for PV systems and the effectiveness of the policies in each country. The methodology of the article is mainly as follows.

3.2. Methodology of technological learning

3.2.1. Overview of the technological learning

Technological learning is a concept that allows the reduction of unit production costs to be evaluated as cumulative production increases (Tang 2018). It is assumed that the performance of the technology will improve with the accumulation of technological experience. More specifically, for every doubling of cumulative production, the unit production cost decreases by a certain value, which is called the learning rate. Several technology learning mechanisms have been identified that can justify the observed decrease in unit production cost (Kahouli-Brahmi 2008). Technological learning can be categorized into five forms: learning-by-doing, learning-by-researching (Klaassen et al. 2005), learning-by-using, learning-by-interacting and economies of scale (Wright and Corporation 1936)(Cohen et al. 2017)(Messner 1998)(Junginger, Faaij, and Turkenburg 2005).

Learning-by-doing focuses on estimating the learning rate on the basis of learning from accumulated capacity, for a one-factor learning curve (OFLC). Wright first defined the concept of learning rate as the reduction in unit cost when cumulative production doubles. The reduction in cost is due to improvements in the processes and management procedures used to produce a given product as cumulative production increases. OFLC is the most widely used method for estimating the learning rate. Technology learning curves have been used in various fields over the past decades, and in recent years it has also been widely used for renewable energy cost analysis and policy effect analysis (Arrow 1962) . Nemet estimated the learning curve from increase of accumulated production of photovoltaic power generation, and from empirical analysis of distribution promotion by government policy (Nemet 2006).

Due to the fact that OFLC depends only on the increase in installed capacity, it can be concluded that its analyzed policy is only a demand-pull policy to increase installed capacity by increasing demand. In many cases, price reductions are achieved through R&D policies, but the OFLC does not specifically reflect the effects of the implementation of R&D policies. The OFLC model has been developed to the two-factor learning curve (TFLC) model that considers not only accumulated installed capacity but also learning by researching. The cumulative installed capacity or production of a certain technology in the so-called one-factor learning curve, as well as the cumulative R&D expenditures or knowledge stock with regard to that technology in TFLC. The TFLC was originally introduced by Kouvaritakis for the use of input data from the POLES energy model as independent variables for the learning curve estimation equation which is the first experiment to estimate TFLC (Hong, Chung, and Woo 2015). It has extended the application of all energy technologies from the already commercialized thermal power generation to the future fuel cell technology. The learning curve is a widely used technique with a variety of different indicators of technological performance and experience. The performance indicators are mainly the capital costs, investment costs, production costs and the prices. The experience performance indicators are the cumulative installed capacity or the cumulative production or the R&D investment (Figure 3-1).

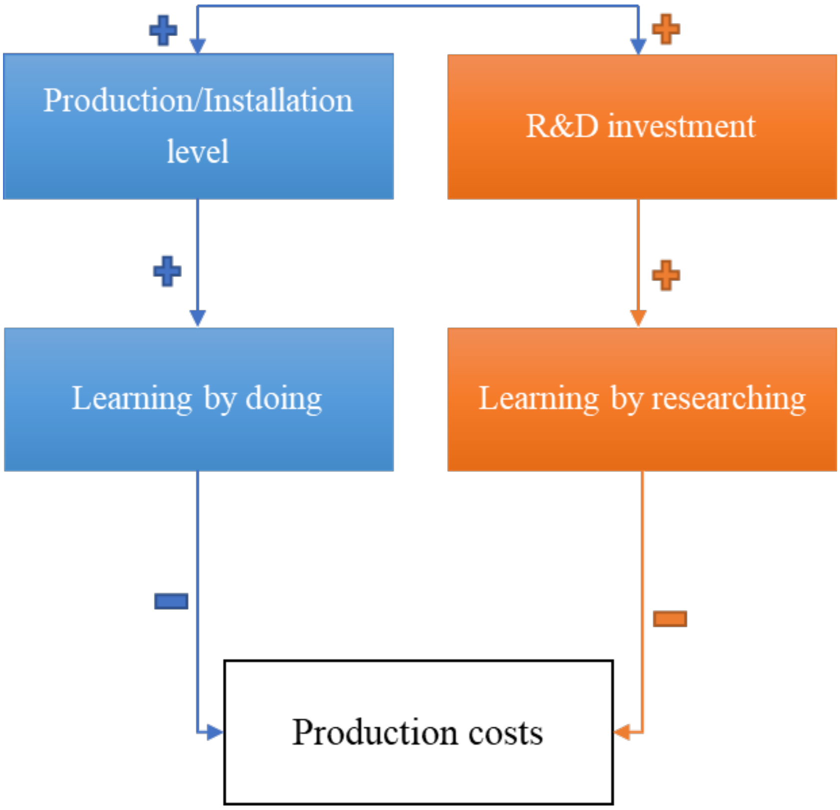

Figure 3-1 Relationships between R&D, production growth and production cost.

Most studies of learning curves for PV energy have focused on the cost of PV modules, again using a OFLC model that relates the cost per watt to the cumulative installed capacity. Several OFLC studies suggest learning rates of around 20%, Rubin overviews the learning rates for different technologies and confirm it (Rubin et al. 2015). His review article also mentions about TFLC analysis for solar PV energy, which a learning- by-doing rate of 17% and a learning-by-researching rate of 10%. And Kobos et al. using worldwide data for solar PV from 1975 to 2000, report rates of 18.4% for learning-by-doing and 14.3% for learning-by-researching (Kobos, Erickson, and Drennen 2006).

3.2.2. One-factor learning curve (OFLC) model

1) Learning-by-doing

Technological learning concepts are simulated through the learning curve model, which explains the relationship between cost decrease and output growth. This type of learning curve is the so-called one-factor learning curve (OFLC) (Ferioli, Schoots, and van der Zwaan 2009) . The usual form to express the OFLC is by using a power function:

$$UC_t = c \times CUM_t^{-a} \qquad (3\text{-}1)$$

Where CUM means the cumulative production or installed capacity of the technology, UC means the unit cost of the production or of installed capacity, and a means the LI (learning index). LI is a negative value, and a higher absolute value means a higher learning effect. c means the initial cost data, and t means the given time.

Since the cost function is an exponential form, learning elasticity a can be converted to a linear function in log scale as shown in Eq.(3-2)(Yu, Van Sark, and Alsema 2011)

$$logUC_t = logC_0 - a \times logCUM_t \qquad (3\text{-}2)$$

The LI is converted into terms of the PR (progress ratio) and LR (learning rate).

$$PR = 2^{-a} \qquad (3\text{-}3)$$

The equation means progress ratio (PR) defined as the relative cost reduction when the cumulative production is doubled.

$$LDR = 1 - PR = 1 - 2^{-a} \qquad (3\text{-}4)$$

LDR in Eq. (3-4) is more explicit than PR in showing the cost reduction when the cumulative production is doubled.

Then, the slope of the linear function becomes LI and can be easily calculated. Although the learning rate can be easily calculated in OFLC, it is limited in reflecting a supplier-oriented policy like R&D investment since it takes into account the change of unit cost based only on the cumulative production or installed capacity.

2) Learning-by-searching (LBS)

Public R&D spending and deployment incentives are two main types of government subsidies to solar PV energy. Defined as the cost reduction induced by the R&D activities and production accumulation, technological learning is widely applied in the literature. In order to evaluate the performance of incentive policies in the four countries, the forms of “learning-by-searching” and “learning-by-doing” by technological learning are used. Although the PV installed capacity was used usually as an explanatory variable in the learning curve model, the cumulative public R&D funds instead in consideration of the fact that PV R&D activities are the subject. The technological improvement can be achieved through R&D activities. This process is referred to as “learning-by searching”. To evaluate the effectiveness of PV R&D activities in terms of how PV cost reduction, estimate the learning rate in three countries. The LBS can be described by eq. (3-5):

$$P_n = \mathrm{k} \times KS_y^{\alpha} \qquad (3\text{-}5)$$

P_n is the product price in year y; k is a normalization parameter with respect to initial conditions; KS_y^{α} is the knowledge stock (here: approximated through R&D investments, USD). Knowledge stock is calculated eq. (3-6):

$$KS_y = (1-b)KS_{y-1} + RD_y \tag{3-6}$$

Here, b is the knowledge depreciation factor and RD_y is the annual R&D investment in year y. Knowledge depreciation is important when considering the effects of LBS. In this study, a depreciation rate of 5% to analyzed R&D knowledge stocks. And α is the learning index related to LSR (learning-by-searching rate).

$$LSR = 1 - 2^{\alpha} \tag{3-7}$$

LSR is the relative unit cost reduction when the cumulative PV R&D investment is doubled. The general performance of government R&D policies can be measured by using LBR. A learning curve-based method is then constructed to analyze the performance of current government PV R&D policies. LBR rates are estimated to measure these PV R&D policy general effects.

3.2.3. Two-factor learning curve (TFLC) model

Considering the effects of cumulative R&D expenditures the TFLC has been extended by integrating the knowledge stock (KS) as an additional variable:

$$UC_t = C_0 \times CUM_t^{-a} \times KS_t^{-b} \tag{3-8}$$

KS_t^{-b} is the knowledge stock. Knowledge stock is calculated eq. (7):

$$KS_t = (1-\varepsilon)KS_{t-1} + RD_{t-RDlag} \tag{3-9}$$

Here, ε is the knowledge depreciation factor and RD_t is the annual R&D investment in year t. Knowledge depreciation is important when considering the effects of learning-by-researching. And b is the learning index related to LSR (learning-by-searching rate).

Eq. (5) is similar to the Cobbe Douglas production function, and it can be converted to a log scale for estimation through linear regression.

$$logUC_t = logC_0 - \alpha \times \log CUM_t - b \times logKS_t \tag{3-10}$$

Eq. (7) uses the least square method for estimation. The data are validated using serial correlation and multicollinearity. When error terms in a regression equation from different time periods or cross-sectional observations are corrected, the error term must be serially correlated.

Multicollinearity occurs when two or more explanatory variables in a multiple regression have a high degree of linearity. It means that multicollinearity is an undesirable situation where the explanatory variables are highly correlated with each other. However, multicollinearity is a matter of degree, so there is no irrefutable test to show that it is or is not a problem (Hong et al. 2015). In Eq. (3-11), KS represents the stock of knowledge and indicates the amount of internal knowledge directly used in production activities, which is essential to promote future technological development. It implies accumulated technological knowledge or accumulated R&D investments. In general, industrial growth in the current year is not the result of capital investment in the current year, but a reflection of the capital stock in the past. The concept of knowledge stock can be used in the same way as capital stock. In other words, most of the technological innovations of the current year are the result of the knowledge and experience accumulated over the years. National and governmental R&D policies play an important role in technological progress. Therefore, the technological innovation capacity can be expressed in terms of the country's knowledge and experience. Time lag and depreciation rate must be considered if one is to realistically reflect such knowledge stock. Klaassen et al. (2005) analyzed the R&D knowledge stock using a 5% depreciation rate when examining the impact of wind energy R&D on innovation in a number of countries (Klaassen et al. 2005). Some researchers have indicated that the appropriate time lag for adding R&D investments to the knowledge stock is 2-3 years (Nemet 2009). In Eq. (3-8) (3-9), a means LDI (learning-by-doing index) and b means LSI (learning-by-searching index). ε means depreciation rate of knowledge stock, and represents how much knowledge stock of power is reflected ($0< \varepsilon <1$). $RD_{t-RDlag}$ means R&D investment contributing to knowledge stock with a time lag, ε means that the past R&D investment gradually depreciates.

As OFLC adopts the concept of LR (learning rate), TFLC also defines LDR (learning-by-doing rate) and LSR (learning-by-searching rate) for application as Eq. (3-11)(3-12). (Hong et al. 2015)

$$LDR = 1 - PR = 1 - 2^{-a} \qquad (3\text{-}11)$$

$$LSR = 1 - PR = 1 - 2^{-b} \qquad (3\text{-}12)$$

While the concept of a TFLC is theoretically appealing, many scholars have noted two significant problems with this approach. The first is the availability of actual data. Reliable data on public and private sector R&D expenditures are difficult to collect, and the quality of available data cannot be determined. Using these data to estimate the KS is approximate at best and sensitive to the assumed rate of knowledge depreciation.

The second major drawback is the high degree of covariance between these two variables. That is, both R&D investment and cumulative production or capacity may respond to the same drivers and/or directly affect each other. For example, an increase in product may stimulate R&D expenditures to further improve the product. In addition, from a policy perspective, there is a clear distinction between government-funded R&D and private sector R&D. Because these funding sources may have different effects on the cost and performance of a specific technology (Holmes 2010). As a result, OFLC is still widely used to evaluate policy effects and cost reductions.

3.3. Methodology of the techno-economic analysis

3.3.1. Model establishes

3.3.1.1 Devices of PV systems and PV BESS system

A solar photovoltaic (PV) system consists of one or more solar panels with inverters and other electrical and mechanical hardware that use solar power to generate electricity. It includes a solar array and a balance of system components. Photovoltaic modules convert sunlight into electricity. An inverter that converts DC power to AC power. The support structure keeps the PV module facing the sun. PV systems can be classified in several ways, such as grid-connected systems, stand-alone systems, building-integrated systems, rack-mounted systems, residential systems, utility systems, distributed systems, centralized systems, rooftop systems, ground-mounted systems , tracking systems, and fixed-tilt systems. In this paper, PV systems is divided into two areas: residential PV systems and large-scale PV plants. Solar PV systems consist of PV arrays, inverters, and support structures, as shown in Figure 3-1.

- Solar Panels: The current solar module manufacturing industry produces various types of photovoltaic panels depending on the materials used. However, crystalline solar panels are typically used for residential PV systems and large PV plant installations.
- Inverters: It is used to convert direct current (DC) to alternating current (AC). The size of the inverter is selected according to the class of the PV plant.
- Mounting structures: Structures are needed to position the PV panels, inverters and some other accessories. The mounting of the PV panels is a key issue to be ensuring that they are mounted at the best angle according to the specifications of the site.
- Grid connection: Includes substations and their components, such as transformers, net meters, protection devices, etc.
- Cables: DC cables are used to connect the PV array with inverter and AC

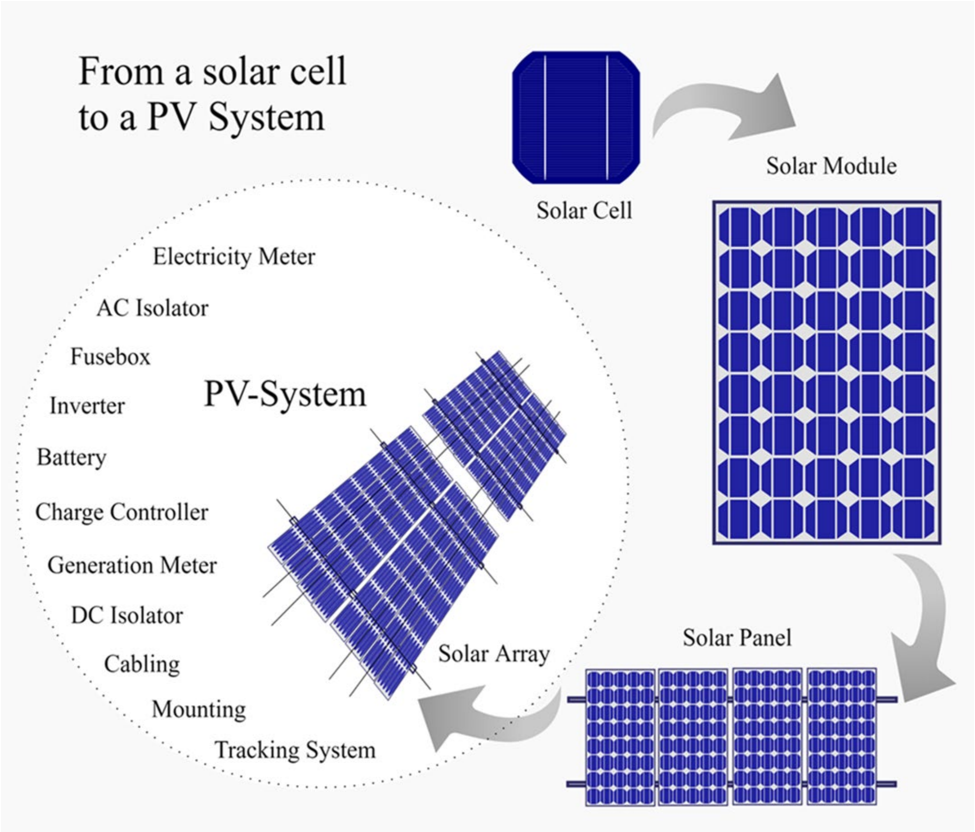

Figure 3-2 From a solar cell to a PV system (Making et al. 2018)

(1) The output of PV arrays

The output of PV arrays depends on the time, location, tilt angle, orientation of the PV module, and the environmental conditions such as temperature and solar irradiance. The PV modules operate at output power, which is the catalogue value under STC (1 kW/m2 irradiance, 25 °C ambient temperature and 1.5 air mass). This paper calculates the output of the PV system based on irradiation and temperature data on different locations, the energy losses of the system that occur during the energy conversion are also considered. The PV power outputs can be estimated using the following equations:

The power outputs from PV at t-time can be estimated using the following equations (Radhakrishnan and Srinivasan 2016; Rocchetta, Li, and Zio 2015):

$$V_{pv}^{t} = V_{oc} + \eta_v \times T_{cell}^{t} \tag{3-13}$$

$$I_{pv}^{t} = RI(t) \times \left(I_{sc} + \eta_i \times (T_{cell}^{t} - 25)\right) \tag{3-14}$$

where V_{pv}^{t} is the circuit voltage of single cell, V. V_{oc} is the open circuit voltage, V. η_v is the voltage temperature coefficient, mV/°C. I_{pv}^{t} is the circuit current of single cell, A. $RI(t)$ is the random irradiance, W/m^2. I_{sc} is the short circuit current, A. η_i is the current temperature coefficient, mA/°C. T_{cell}^t is the cell temperature, °C, which can be calculated using the following expression:

$$T_{cell}^t = T_{ao} + RI(t) \times \left(\frac{T_{nominal} - 20}{0.8}\right) \tag{3-15}$$

where T_{ao} is ambient operating temperature, °C, $T_{nominal}$ is the nominal operating cell temperature, which is approximately 48 °C (Afzali, Keynia, and Rashidinejad 2019).

Therefore, the output power of the PV system is given as

$$E_{PV}^t = N_{cell} \times V_{pv}^t \times I_{pv}^t \times FF \tag{3-16}$$

where E_{PV} is the electricity generated by the PV system at t-time, W. N_{cell} is the number of solar cells, FF is fill factor, which can be obtained as follow:

$$FF = \frac{V_{\mathrm{pvmax}} \times I_{pvmax}}{V_{oc} \times I_{sc}} \tag{3-17}$$

where $V_{\max}$ is the voltage at maximum power, V. I_{max} is the current at maximum power;

The output power of the PV system depends on the operating temperature and solar irradiance, which may vary naturally through the day.

(2) Inverter

A solar inverter or PV inverter, is a type of electrical converter which converts the variable direct current (DC) output of a photovoltaic (PV) solar panel into a utility frequency alternating current (AC) that can be fed into a commercial electrical grid or used by a local, off-grid electrical network. It is a critical balance of system (BOS)–component in a PV system, allowing the use of ordinary AC-powered equipment. Solar power inverters have special functions adapted for use with photovoltaic arrays, including maximum power point tracking and anti-islanding protection (Wikipedia 2021).
Solar inverters may be classified into three broad types (Staff 2010):

Stand-alone inverters, used in isolated systems where the inverter draws its DC energy from batteries charged by photovoltaic arrays. Many stand-alone inverters also incorporate integral battery chargers to replenish the battery from an AC source, when available. Normally these do not interface in any way with the utility grid, and as such, are not required to have anti-islanding protection.

Grid-tie inverters, which match phase with a utility-supplied sine wave. Grid-tie inverters are designed to shut down automatically upon loss of utility supply, for safety reasons. They do not provide backup power during utility outages.

Battery backup inverters, are special inverters which are designed to draw energy from a battery, manage the battery charge via an onboard charger, and export excess energy to the utility grid. These inverters are capable of supplying AC energy to selected loads during a utility outage, and are required to have anti-islanding protection.

Intelligent hybrid inverters, manage photovoltaic array, battery storage and utility grid, which are all coupled directly to the unit. These modern all-in-one systems are usually highly versatile and can be used for grid-tie, stand-alone or backup applications but their primary function is self-consumption with the use of storage.

The inverter output model considerate the inverter's DC-to-AC power conversion efficiency, and calculates the inverter input power for each hourly time step by dividing the total DC power output of the array by the number of inverters in the system. The inverter output model considerate the inverter's DC-to-AC power conversion efficiency, calculates the maximum DC input power from the rated efficiency and rated maximum AC output power values:

$$P_{dc} = \frac{P_{ac}}{\eta_{inv}} \qquad (3\text{-}18)$$

Where P_{dc} is net DC power output of the PV array; P_{ac} is inverter AC output power; η_{inv} is the Inverter efficiency.

(3) Battery energy storage system (BESS)

For the purpose of peak shaving or increasing the self-consumption rate of PV generation, BESS should charge the energy input from the PV system during off-peak demand and discharge it to inject energy into the load during peak power demand. It can contribute to smoothing the fluctuations of the grid with typical mountain and valley shapes. At the same time, the BESS system can significantly reduce the electricity bills of customers. Peak shaving is a technique used to reduce electricity consumption during periods of maximum demand for electric facilities (Ananda-Rao et al. 2015). Load balancing, on the other hand, is known as a method to reduce the large fluctuations that can occur in electricity demand by storing excess electricity during periods of low demand for use during times of high demand (Rahimi et al. 2013) .

Furthermore, in applications combined with PV systems, BESS is used to address the intermittency and instability of PV power and to provide a continuous supply like current conventional systems. It is well known that PV power has an unpredictable stochastic behavior and is weather dependent. Therefore, it is difficult to obtain a stable and continuous supply of electricity from PV to meet the 24-hour load demand. These drawbacks can be overcome by integrating BESS with PV systems.

Lithium-ion batteries are used in PV battery system models. Lithium-ion batteries have many advantages over other high quality rechargeable battery technologies (NiCd or NiMH). They have one of the highest energy densities of any battery technology available today. In addition, lithium-ion battery cells can deliver large amounts of current for high-power applications, which makes lithium-ion batteries relatively low-maintenance and does not require periodic cycling to maintain their battery life. Lithium-ion batteries do not have a memory effect, a harmful process where repeated partial discharge/charge cycles cause the battery to "remember" a lower capacity. This is an advantage over NiCd and NiMH batteries, which both have this effect. Lithium-ion batteries have a very low self-discharge rate of about 1.5-2% per month (UNIVERSITY OF WASHINGTON 2020).

The state of charge (SOC) of a battery bank is be described as follows:

$$\mathrm{SOC(t+1)=SOC(t)+\frac{P_{ch}(t)i_{ch}(t)\eta_{ch}}{E_{mb}}-\frac{P_{dch}(t)i_{dch}}{E_{mb}\eta_{dch}}-\frac{P_{sfd}(t)}{E_{mb}}} \tag{3-19}$$

Where SOC is the state of charge of battery(%), E_{mb} is the maximum battery usable energy during an entire roundtrip (kWh), t is the time iteration for almost all of the parameters in the equation (h), 1 ≤t≤8760, P_{ch} is the battery charging power (W), i_{ch} is the battery charging duration (h), assumed as 1 or 0, η_{ch} is the battery charging efficiency (%), P_{dch} is the battery discharging power (W), i_{dch} is the battery discharging duration (h), assumed as 1 or 0, η_{dch} is the battery discharging efficiency (%), and P_{sfd} is the battery self-discharging power (W).

The battery could not be charged and discharged at the same time. In order to avoid overcharging and over-discharging, some limitations are imposed on the minimum and maximum of the SOC:

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \tag{3-20}$$

Where SOC_{min} is the minimum of SOC, assumed as 0.2, SOC_{max} is the maximum of SOC, assumed as 1.

3.3.2.Residential PV and battery system model

(1) Yearly energy flows

Power generation from PV system has priority in meeting the local household electricity demand, excess generation can be directly sold to the public grid or stored in the battery system (Lim et al. 2020). Depending on the application scenario, the battery as a balancing tool is charged while the considerably surplus PV generated, maximizing self-consumption level. Then the battery will come into discharge condition to provide additional power to reduce the imported power from the public grid. The public grid can supply power to cover demand over the period when the PV generation is insufficient or unavailable (Schopfer, Tiefenbeck, and Staake 2018).

For a yearly simulation, the main variable of interest is the total volume of self-consumption, which is commonly expressed as a SSR (the self-sufficiency rate) or a SCR (the self-consumption rate) (Quoilin et al. 2016). The SSR is defined as the ratio between the self-consumed energy and the total yearly energy demand:

$$SSR=\frac{E_{sc}}{E_{load}}=\frac{\sum_{i=1}^{N}(P_{dis,i}+P_{SC,i})*\eta_{inv}}{\sum_{i=1}^{N}P_{load,i}} \tag{3-21}$$

where E refers to an annual energy flow and P to an instantaneous power. N is the number of time steps in one year and $P_{SC,i}$ is the PV generation directly self-consumption.

The SCR is defined in a similar manner (Quoilin et al. 2016). Note that the reference is the annual energy produced by the PV array before the inverter:

$$SCR = \frac{E_{sc}}{E_{PV}} = \frac{\sum_{i=1}^{N}(P_{dis,i}+P_{SC,i})*\eta_{inv}}{\sum_{i=1}^{N} P_{PV,i}} \tag{3-22}$$

(2) Electricity exchanged with the grid in on-grid PV system

In this study, the time step of the simulation is one hour due to the time step of the available weather and load data and the relatively long simulation period. Load balance is the core part of any renewable energy-based system. To ensure the electricity demand of the consumer at each time step, the PV system load balance equation is subject to:

$$E_{pv} + E_{gird} = E_{load} + E_{fit} \tag{3-23}$$

Where E_{pv} is the PV energy production (kWh), E_{gird} is grid injection (kWh), E_{load} is the household load demand (kWh), E_{fit} is the energy feed-in to the grid (kWh).

(3) Electricity exchanged with the gird in on grid PV and battery system

In this study, the time step of the simulation is one hour due to the time step of the available weather and load data and the relatively long simulation period. Load balance is the core part of any renewable energy-based system (Lazzeroni, Moretti, and Fondazione 2020). To ensure the electricity demand of the consumer at each time step, the PV and battery system load balance equation is subject to:

$$E_{pv} + E_{gird} + E_{dis} = E_{load} + E_{ch} + E_{fit} \tag{3-24}$$

Where E_{pv} is the PV energy production (kWh), E_{gird} is grid injection (kWh), E_{dis} is the battery discharge (kWh), E_{load} is the household load demand (kWh), E_{ch} is the battery charge (kWh), E_{fit} is the energy feed-in to the grid (kWh).

3.3.3. Economical model

The PV battery system economic assessment includes the Levelized Cost of Electricity (LCOE) and the Net Present Value (NPV) and the Internal Rate of Return (IRR) as criteria for the evaluation of the profitability of a PV investment. The following paragraphs provide details about such economic performance analyses.

3.3.3.1 The levelized cost of electricity (LCOE)

The LCOE represents the total project lifecycle costs, measured in USD per kilowatt-hour

(USD/kWh) (Sheha, Mohammadi, and Powell 2021). Through calculations, it is possible to compare the impact of different technologies on financial feasibility, project size, production capacity and capital costs. Grid parity is defined as the situation where the LCOE for alternative energy production the same as the cost of purchasing power from grid.

$$LCOE = \frac{\sum_{t=0}^{T} C_t/(1+d)^t}{\sum_{t=0}^{T} E_t/(1+d)^t} \qquad (3\text{-}25)$$

Where C_t is the annal project cash flow including; installation, operation and maintenance, financial costs and fees; E_t is the electricity generated by the system in year 't'; d is the nominal discount rate, T is the project lifetime. In this study, cash flow analyses were conducted with a discount rate of 4%.

In this chapter, the LCOE has been compared to the current electricity tariff, which the future inflation in the prices is ignore. The LCOE also depends on investment and operating costs and greatly affected by investment subsidy policies.

3.3.3.2 Discounted cash flow model

In this chapter, I established a discounted cash flow model to calculate the Discounted Payback Period (DPP) and the Internal rate of return (IRR) for different scale PV plants and examine their changes from each year. The longer the DPP means the higher risk of the investment. IRR should be greater than the initial discount rate to make a project profit (Duman and Güler 2020). In this study, the discounted cash flow is applied to calculate the profitability of PV plants in different scales under the different FIT fixed purchase prices and initial investment cost. The cash flows are calculated as follows:

The cash flows, C_t^*, by summing all the costs Ci and all the profits Pi related to the generic t th year:

$$C_t^* = \sum_i P_{i,t} - \sum_i C_{i,t} = F \times E_{t,1} + C_{kWh,t} \times E_{t,2} - u \times C_0 \qquad (3\text{-}26)$$

where $E_{t,1}$ is the energy generated by the PV system and uploaded to the grid in kWh in year t;

F is the economic value of the electricity generated according to the FIT;

$C_{kWh,t}$ is the energy price per kWh in year t;

$E_{t,2}$ is the share of energy generated by the PV system and used for self-consumption in kWh in year t;

u is the operation and maintenance (O&M) cost per year, estimated as a percentage of initial investment cost.

C_0 is initial investment cost of PV installation;

The net cash flows C_t are then discounted using the classical expression for discounted cash flows, which is calculated as follows:

$$C_t = C_t^*/(1+i)^t \qquad (3\text{-}27)$$

where i is the discount factor, assumed equal to 4% (IEA 2015). The classic methods for calculating

PBP as follows:

$$\sum_{t=1}^{PBP} C_t^* - C_0 = 0 \qquad (3\text{-}28)$$

where T is the project lifetime.

3.3.3.4 Net Present Value (NPV) and Internal Rate of Return (IRR)

A discount cash flow analysis has been used in this study (Dusonchet and Telaretti 2015); the NPV was calculated for different economic scenarios involving a range of electricity prices, solar PV degradation rates and inverter and battery replacement costs to reproduce the annual cash flow for the lifetime of the solar PV system. The NPV was calculated using equation:

$$NPV = \sum_{t=0}^{T} \frac{C_t}{(1+d)^t} \qquad (3\text{-}29)$$

Where, C_t is the cash flow, t is the number of years, d is the nominal discount rate, T is the project lifetime. In this study, cash flow analyses were conducted with a discount rate of 4%. The discount rate is the primary factor affecting the NPV calculation. For residential solar projects, the discount rate should be the same as or higher than the target for the return on investors.

The IRR is one of the most useful tools for measuring profitability and is the most commonly used method to calculate the rate of return. It is calculated using Equation:

$$NPV = \sum_{t}^{N} \frac{C_n}{(1+IRR)^t} = 0 \qquad (3\text{-}30)$$

3.3.4. Simulation tool

A key step in assessing the technical and economic viability of a PV plant is to simulate the expected energy output of the PV plant. Accurately estimating the energy output requires the use of information such as weather data (irradiance, temperature, wind speed and relative humidity) for the location of the PV plant, as well as the size of the PV plant and the technical specifications of the plant components.

In recent years, simulation software tools have been very useful for the performance evaluation of PV plants. There are several simulation tools to evaluate the performance of solar PV plants to support system designers and developers. Some tools such as PVsyst, SAM, and PVGIS have been used by a large number of researchers for energy forecasting and modeling(Ahmed et al. 2021)(Ahmed, Mohamed, and Al-sulaiman 2017). Others use SAM for economic analysis (Branker, Pathak, and Pearce 2011)(Kobashi et al. 2020). Nevertheless, all simulation software is used for one purpose, which is to provide useful information for the technical and economic analysis of PV plants. In this paper, PVsyst and SAM were selected for simulation because they are widely used by scholars.

PVsyst is widely used as simulation software in the field of PV power research and is often used by researchers to estimate energy yield and economics and to optimize the design of solar power plants.

PVsyst integrates extensive knowledge of PV technology, meteorological irradiation resources and data on PV system components. Thus, PVsyst can help calculate PV system component performance and help refine system design.

Besides PVsyst, SAM is also used as a simulation tool by several scholars to evaluate the technical and economic feasibility of different types of renewable energy sources. Mirzania using the SAM as a simulation tool to conduct techno-economic analyses to investigates how integrated solar and battery storage system would be financially viable in UK (Mirzania, Balta-Ozkan, and Ford 2020). Kobashi conduct a techno-economic analysis of a city-scale energy system with roof-top PV, batteries, and EVs for Kyoto City in Japan (Kobashi et al. 2020).

3.3.4.1 Simulation using System Advisor Model (SAM)

SAM was developed by the National Renewable Energy Laboratory (NREL) in collaboration with Sandia National Laboratories in 2005 specifically for the analysis of solar technologies. This study used SAM to compare the technical and economic performance of models using residential PV systems from different geographic locations operating under different policy-economic conditions (Gilman 2015). Figure 3-3 illustrates the use of SAM as a simulation tool in this study to outline the techno-economic analysis process for residential PV generation and electricity storage. The inputs to the model include weather data and solar radiation at the project location, economic parameters and system technical parameters.

3.3.4.2 Simulation using PV syst

PVsyst has utilized extensive knowledge of PV technology, meteorological irradiation resource data and components of PV systems. Therefore, PVsyst can help refine the design of large PV plants. Figure shows the simulation procedure of PVsyst software. The following are the data to be entered into the simulation software (Ahmed et al. 2021).

1. specify the location
2. enter the weather data (solar irradiance, wind speed and ambient temperature)
3. define the orientation of the PV module (tilt angle and azimuth)
4. select the PV system components, such as PV modules and inverters
5. Select the grid-connected system requirements required by the user
6. Adjust the value of the PV system loss type.

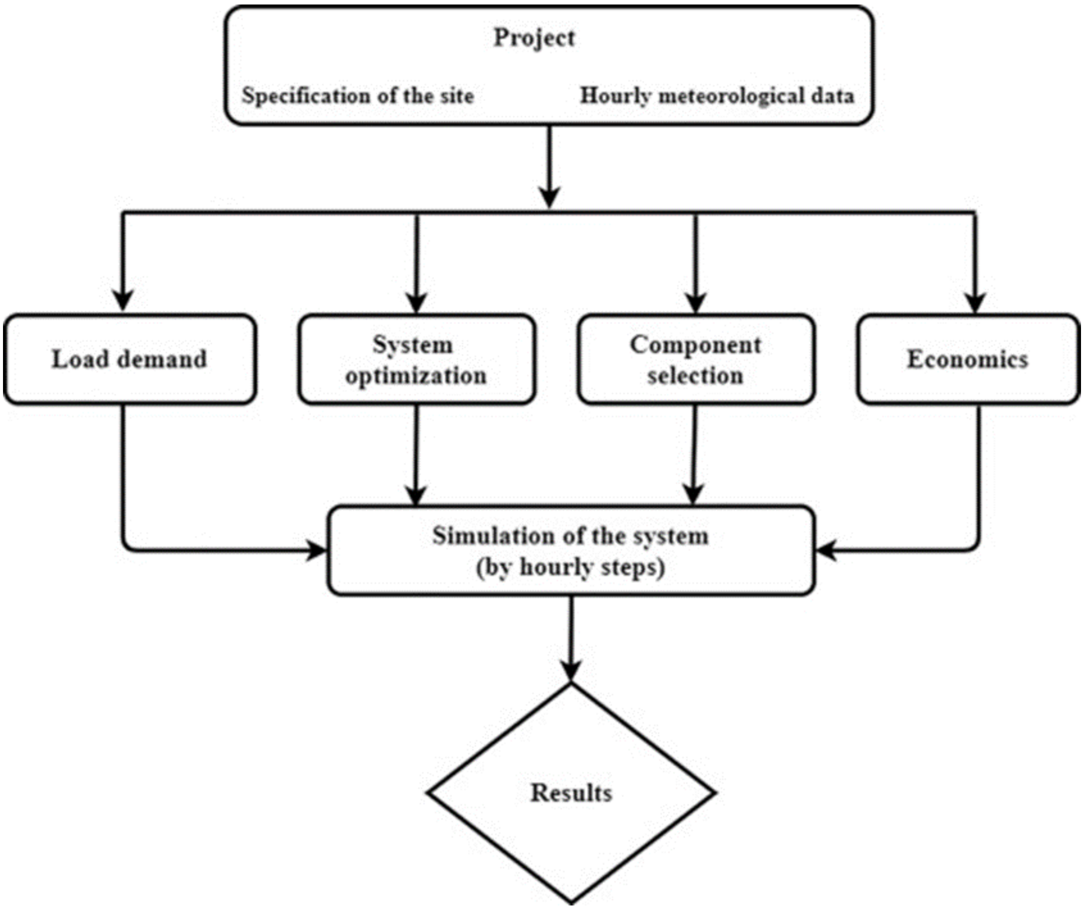

Figure 3-3 Simulation framework in PVsyst software (Ahmed et al. 2021)

3.3.4.3 Performance coefficients

The International Electrotechnical Commission has established the IEC 61724 standard, which has been followed by several countries around the world (IEC 1998). Several recent studies have been conducted to evaluate the performance of grid-connected PV systems according to the IEC 61724 standard (Ahmed et al. 2021)(Litjens, Worrell, and van Sark 2018). In order to calculate the performance of all forms of PV technologies, IEC 61724 provides a common standard for comparing the performance of PV plants in different locations. A summary of IEC 61724 performance parameters is given in the table

Table 3-1 IEC 61724 performance parameters

Parameter	Definition	Equation	Unit
Reference yield (Y_r)	The ratio of the total solar radiation H_t (kWh/m2) absorbed by the solar module plane and the	$Y_r = H_t / G_o$	kWh/kW/day

	reference solar radiation G_o (1 kW/m2) is called reference yield. Its value represents the available peak sun hours for a solar plant in a day for any location. The Y_r is highly dependent on field orientation and weather conditions of the location		
Array yield (Y_a)	The ratio between the energy generated E_{dc} (kWh) from the PV array for a specific period and the nominal power P_o (kWp) of the PV array under STC.	Y_a = E_{dc} / P_o	kWh/kW/day
Final yield (Y_f)	The final yield $Y_f$is defined as the total system useful AC energy E_{ac} (kWh) over a fixed time period divided by the nominal power P_o (kWp) of the installed plant.	Y_f = E_{ac} / Po	kWh/kW/day
Performance ratio (PR)	Ratio of the final yield (Y_f) to the reference yield (Y_r).	PR = Y_f/Y_r	%
Capacity factor (CF)	Ratio of the annual energy output of the PV system to the amount of Energy the PV system could be generated if the PV plant operated with its full rated power for 24 h a day over a year	**CF** = E_{ac} / (P_o*8760)	%
System production	The useful energy produced by the PV plant in a specific period.	E_{ac}	kWh

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Chapter 4. Technological learning for solar PV energy in China, Germany, Japan, and the USA

4.1. Introduction

The rapid spread of solar PV installations around the world has been accompanied by a significant reduction in the costs of solar PV energy systems. The success of solar PV technology is seen by many as its large-scale deployment worldwide, however in reality one of the more beneficial solutions for promoting solar PV energy generation consists in the further reduction of the cost of solar PV products. Therefore, cost reduction is the key to the further spread of PV energy development. Policy makers, investors and society should more fully consider ways to reduce costs and its social impact.

Many governments around the world have adopted different energy policies to reduce the cost of renewable energy and thus help increase the adoption of renewable energy. Governments have enacted bills, provided economic incentives and increased R&D budgets to promote renewable energy. For predicting future global warming trends and greenhouse gas emission levels, the experts have developed energy-environment-economy models to simulate these impacts. However, these models are extremely sensitive to assumptions about the improvement and deployment of new technologies.

Technological changes are usually considered the most important factor in estimating these new technological trends. Therefore, the technological learning concept has recently been widely used and plays a key role in the simulation process. The concept of learning curves is the basis for the EU's "push" and "pull" policy approach, in which policy interventions are designed to encourage energy technologies to follow the trends modeled by their development curves (Wiesenthal et al. 2012). Typically, the technological learning concept is represented by a learning curve model that explains the relationship between cost reduction and production growth. The learning curve model is based on the observed fact that as technological experience accumulates, usually through cumulative production as a reference, technology improves with experience. The approach assumes that as technology experience is earned through production and deployment, the cost of the technology will decrease. Empirical evidence indeed suggests that there is a strong negative correlation between experience and cost for various power generation technologies, with costs decreasing at a certain rate for each doubling of technological capability. Based on assumptions about the future deployment of an energy technology, this model can be used to predict future changes in the cost of a power generation technology, e.g., future costs can be calculated from past learning rates assumed to maintain a stable rate in the future. In the last two decades, learning curve methods have been increasingly used in energy modeling to predict future cost development by representing the correlation between technology costs and their cumulative deployment (Coulomb and Neuhoff 2006)(de La Tour, Glachant, and Ménière 2013)(Samadi 2017)(Elshurafa et al. 2018)(Zhou and Gu 2019). Learning curves can be used to estimate the production costs resulting from a reduction in unit costs cumulative production increases. Explanations supporting learning curve concepts indicate various types of learning, i.e., learning by doing, learning by research, learning by use, and learning by interaction (Fig. 1-1).

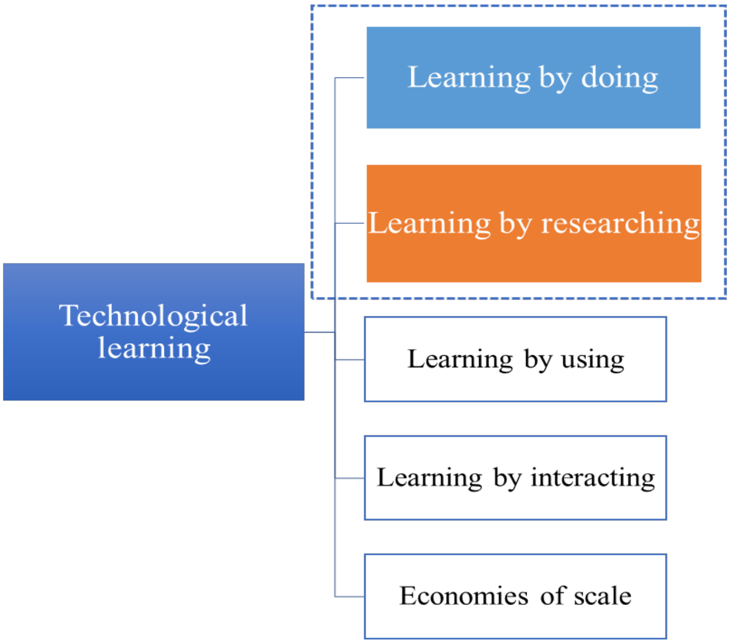


Figure 4-1 The mechanisms of technological learning

The purpose of renewable energy policy is to achieve a reduction in technology costs by increasing the deployment of new energy sources. Thus, the new technology will increase its cost competitiveness in the market. Historical observations of technology cost developments and an understanding of the mechanisms behind these developments, such as R&D, learning by doing, and economies of scale, are critical when trying to understand possible pathways to technology cost reduction and how these relate to expectations (Wiesenthal et al. 2012). The use of learning concepts in models as a conceptual tool has been widely accepted and many studies have applied it to evaluate the effectiveness of different components of energy policy, such as demand pull policies and technology push policies (Tang 2018)(Yu, Van Sark, and Alsema 2011)(Hong, Chung, and Woo 2015).

In this chapter, we have attempted to conduct a learning rate analysis on PV cost reduction by using a learning curve model on the cumulative investment in PV R&D policy and the cumulative installation of PV systems since 2000. Using learning rates, we compare the impact of demand pull and technology-push policies on the cost reduction of PV products in China, Germany, Japan, and the United States, and then compare the effects of policy implementation. Using the results of the learning curve analysis, we evaluate the effect of the policy by projecting the cost of PV products in 2030.

4.2. Literature review and theoretical framework

4.2.1.One-factor learning curve (OFLC)

Wright first defined the concept of learning rate as the reduction in unit cost when cumulative production doubles (Wright and Corporation 1936). The reduction in cost is due to improvements in the processes and management procedures used to produce a given product as cumulative production increases. One-factor learning curve (OFLC) is the most widely used method for estimating the learning rate. Technology learning curves have been used in various fields over the past decades, and in recent years it has also been widely used for renewable energy cost analysis and policy effect analysis (Arrow 1962) . Nemet estimated the learning curve from increase of accumulated production of photovoltaic power generation, and from empirical analysis of distribution promotion by government policy (Nemet 2006).There are lots of studies to be applied by GDP deflator in learning curve analysis in order to limit the impact of other factors, for example, inflation and qualitative improvement. T. Tang examines the drivers of technological change in the US wind industry from perspectives of technological learning, collaboration, and energy policies (Tang 2018).

Technological learning concepts are simulated through the learning curve model, which explains the relationship between cost decrease and output growth. This type of learning curve is the so-called one-factor learning curve (OFLC) (Ferioli, Schoots, and van der Zwaan 2009) . The usual form to express the OFLC is by using a power function:

$$UC_t = c \times CUM_t^{-a} \tag{1}$$

Where CUM means the cumulative production or installed capacity of the technology, UC means the unit cost of the production or of installed capacity, and a means the LI (learning index). LI is a negative value, and a higher absolute value means a higher learning effect. c means the initial cost data, and t means the given time.

Since the cost function is an exponential form, learning elasticity a can be converted to a linear function in log scale as shown in Eq.(2)(Yu et al. 2011)

$$logUC_t = logC_0 - a \times logCUM_t \tag{2}$$

The LI is converted into terms of the PR (progress ratio) and LR (learning rate).

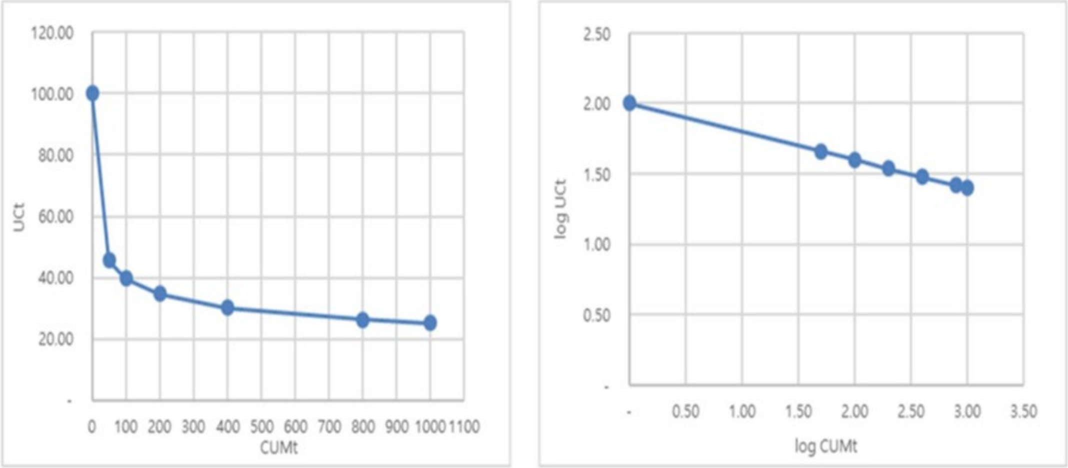
$$PR = 2^{-a} \tag{3}$$

The equation means progress ratio (PR) defined as the relative cost reduction when the cumulative production is doubled.

$$LDR = 1 - PR = 1 - 2^{-a} \tag{4}$$

LDR in Eq. (3) is more explicit than PR in showing the cost reduction when the cumulative production is doubled.

Then, the slope of the linear function as shown in Fig. 1-1(b) becomes LI and can be easily calculated. Although the learning rate can be easily calculated in OFLC, it is limited in reflecting a supplier-oriented policy like R&D investment since it takes into account the change of unit cost based only on the cumulative production or installed capacity.



(a) Linear scale learning curve from eq. (1) (b) Log-log scale learning curve from eq. (2)

Figure 4-2 Examples of linear scale and log-log scale learning curves (Modified from (Kahouli-Brahmi 2008)).

4.2.2.Two-factor learning curve (TFLC)

Due to the fact that OFLC depends only on the increase in installed capacity, it can be concluded that its analyzed policy is only a demand-pull policy to increase installed capacity by increasing demand. In many cases, price reductions are achieved through R&D policies, but the OFLC does not specifically reflect the effects of the implementation of R&D policies. TFLC generally adds learning-by-searching to the learning-by-doing which is considered in OFLC. Therefore, using TFLC is beneficial in that it can reflect the effect of supplier-oriented R&D investment among the main government policies mentioned above (Bosetti et al. 2011). Considering the effects of cumulative R&D expenditures the TFLC has been extended by integrating the knowledge stock (KS) as an additional variable:

$$UC_t = C_0 \times CUM_t^{-a} \times KS_t^{-b} \tag{5}$$

KS_t^{-b} is the knowledge stock. Knowledge stock is calculated eq. (7):

$$KS_t = (1-\varepsilon)KS_{t-1} + RD_{t-RDlag} \tag{6}$$

Here, ε is the knowledge depreciation factor and RD_t is the annual R&D investment in year t. Knowledge depreciation is important when considering the effects of learning-by-researching. And b is the learning index related to LSR (learning-by-searching rate).

Eq. (5) is similar to the Cobbe Douglas production function, and it can be converted to a log scale for estimation through linear regression.

$$logUC_t = logC_0 - \alpha \times \log CUM_t - b \times logKS_t \tag{7}$$

As OFLC adopts the concept of LR (learning rate), TFLC also defines LDR (learning-by-doing rate) and LSR (learning-by-searching rate) for application as Eq. (8). (Hong et al. 2015)

$$LDR = 1 - PR = 1 - 2^{-a} \tag{8}$$

$$LSR = 1 - PR = 1 - 2^{-b} \tag{9}$$

While the concept of a TFLC is theoretically appealing, many scholars have noted two significant problems with this approach. The first is the availability of actual data. Reliable data on public and private sector R&D expenditures are difficult to collect, and the quality of available data cannot be determined. Using these data to estimate the KS is approximate at best and sensitive to the assumed rate of knowledge depreciation.

The second major drawback is the high degree of covariance between these two variables. That is, both R&D investment and cumulative production or capacity may respond to the same drivers and/or directly affect each other. For example, an increase in product may stimulate R&D expenditures to further improve the product. In addition, from a policy perspective, there is a clear distinction between government-funded R&D and private sector R&D. Because these funding sources may have different effects on the cost and performance of a specific technology (Holmes 2010). As a result, OFLC is still widely used to evaluate policy effects and cost reductions.

4.3. Methods and data collection

4.3.1. Research model

OFLC benefits from the relative ease of access to data. Investment costs and installation capacity are typically easy to collection compared to other underlying cost drivers, so reliable learning curves can be identified for economic modeling purposes.

Therefore, I mainly adopt the OFLC to analyze the implementation effects of PV policies in selected countries. After identifying the effects of policy implementation in different periods, then I investigated the effects of R&D policies on PV energy learning rates using a TFLC. OFLC estimates cost reduction through the cumulative production installation, while TFLC is the theoretical model required to estimate cost reduction through cumulative production and knowledge stock (Fig. 8).

As described above, the research concept of this chapter as showing in Figure 4-3.

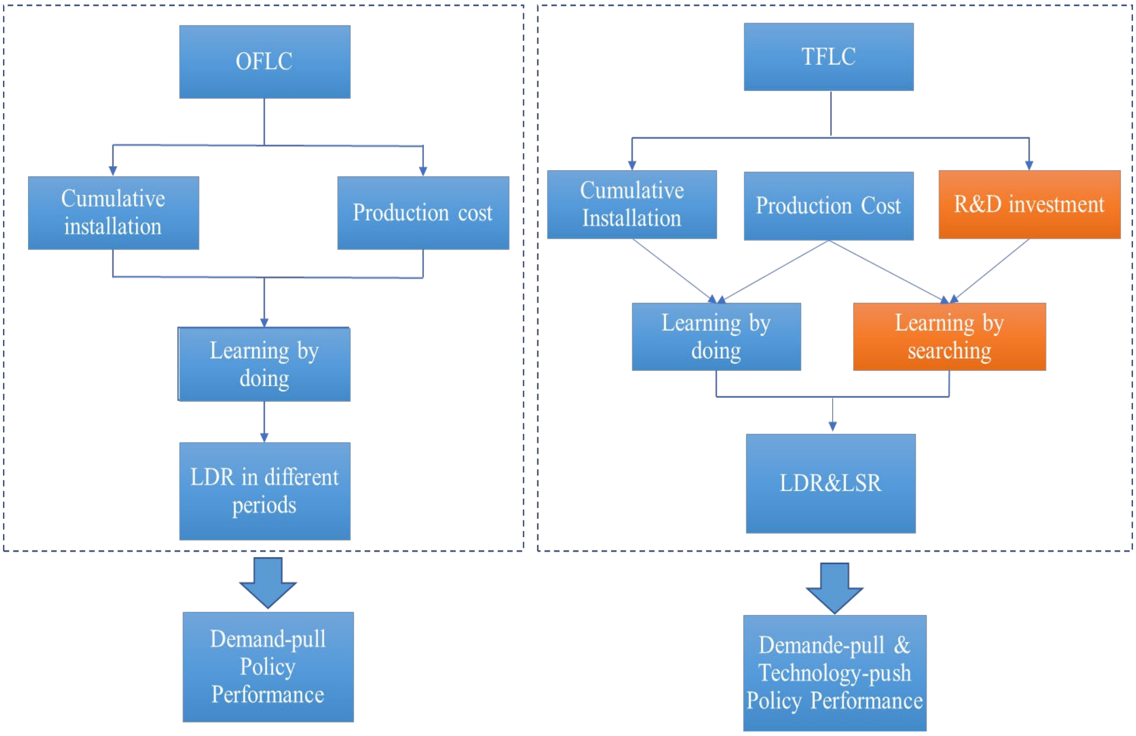


Figure 4-3 Research concept of chapter 4

4.3.2. Analysis period

The concept of learning quantifies an observed relationship without being able to analytically decompose the share caused by individual drivers - i.e., learning by search, learning by doing, economies of scale, etc. However, the contribution of each underlying cost reduction factor may change over time, depending on the stage of the innovation process. These different periods in the historical cost development of the technology may lead to the calculation of different learning rates, thus which will differ from the learning rates for the entire data set. This means that the learning rate may change over time.

Therefore, in this chapter, in order to study the impact of different policies on the learning rate of PV technologies. I divide the analysis of learning rates into different time periods according to the period of policy implementation and analyze the changes in learning rates under the impact of different policies.

In China, PV products were added to the Catalog of Chinese high technology products for export in 2006, therefore, the PV product manufacturers were fully supported by the Chinese government (Zhang and He 2013). At the same time, China Renewable Energy Law was implemented. Although the majority of Chinese PV products were exported by this time, the government attached more and more attention to the development of the domestic renewable energy market, and a series of PV demonstration projects, such as the Golden Sun Project, were implemented on a large scale starting in

2008 (Zou et al. 2017). During this period, China's PV policy was dominated by supply-side push policy. In 2011, the implementation of the FIT policy became a milestone in the development of the PV market in China. China's PV market began to experience explosive growth. Therefore, we divide China's Learning by doing into two periods. The first period is 2007-2011, during which the government's support policies for the PV industry were mainly based on supply-side push policies. The second period is after 2012, when the FIT was implemented on a large scale and the Chinese local PV market started to expand.

Germany was the first country to introduce the FIT, which has been in implementation since 2000. The FIT Act has been amended a several times, and is still the core of the German PV market development (Hoppmann, Huenteler, and Girod 2014). Currently, the FIT is still the core of driving the development of the German PV market. Therefore, in order to study the policy effects of the FIT, the overall effects from the beginning of 2000 to 2019 was studied, without a period division.

Japan implemented the Renewable Portfolio Standard and various investment subsidies for PV stimulation before the introduction of the FIT Act in 2012. After 2012, the FIT Act became the core new energy support policy in Japan (Li, Xu, and Shiroyama 2019). Therefore, we divided the learning curve in Japan into two periods, before 2012 and after 2012.

The United States before 2005, photovoltaic development mainly relies on local policy support. After 2006, the ITC began to be formally implemented, after which the policy has long driven the rapid development of the U.S. PV market (Office of Energy Efficiency & Renewable Energy 2019). The U.S. PV policy development period is divided into before and after 2006.

4.3.3. Data source

In this chapter, research data come from both publicly available sources, and the secondary literature, including academic and professional, journals, reports, and websites. This study adopted databases and keyword searches to identify PV technology and incentive policy related articles. Relevant literature reviews of PV development mainly use multiple databases like Web of Science and Scopus. We obtain data from different sources of information to guarantee the validity. The first source is annual report from the International Energy Agency (IEA), Fraunhofer Institute for Manufacturing Engineering and Automation (Fraunhofer IPA), and REN21. The cost and price data of PV production and PV installed capacity from these reports are used to analyze the fields of the PV industry. The second source was the IEA's online data services and policy data base, which used to policy investigation. Data on R&D investments are sparse, especially in the private sector. the IEA's RD&D statistics database provides information on public investments in RD&D in its member countries. Although there are some associated uncertainties stemming from data gaps and differences in the extent to which individual member countries include regional funding, institutional budgets, and support for demonstration activities in their data submissions to the IEA. However, this dataset is a very useful source for capturing public investment in R&D. The other source is scientific articles, technical articles, conference articles, press releases, policy documents, technical reports.

In the learning curve, considering the accuracy of the two independent variable inputs, scholars usually use the GDP deflator to collate the cost data to limit the change in the quality of the analysis by inflation. With this in consideration, we deflate the cost data based on GDP deflator from 2000 to 2019 (Hong et al. 2015). In this study, we are using exchange rate: 1 RMB=0.1449 USD; 1 Euro=1.212 USD; 1 JPY= 0.0095 USD.

Table 4-1 GDP deflator in four countries (The World Bank Group 2021)

GDP deflator (2015=100)				
Periods	**China**	**Germany**	**Japan**	**USA**
2000		82.64	110.9878	74.5608
2001		83.7	109.7619	76.19623
2002		84.86	108.1613	77.40147
2003		85.99	106.4123	78.83889
2004		86.94	105.241	80.9614
2005		87.3	104.1492	83.48331
2006		87.64	103.2292	86.00968
2007	76.19657	89.19	102.4761	88.32014
2008	82.13635	90	101.471	90.03808
2009	81.96425	91.66	100.8507	90.72449
2010	87.60452	92.25	98.9394	91.78166
2011	94.67918	93.24	97.28283	93.69889
2012	96.88636	94.63	96.54197	95.49589
2013	98.98237	96.5	96.22032	97.17176
2014	100.0029	98.29	97.89966	98.96927
2015	100	100	100	100
2016	101.4073	101.18	100.2704	101.0353
2017	105.6996	102.24	100.041	102.9385
2018	109.3988	104.4177	99.94304	105.446
2019	110.8073	106.707	100.5342	107.4937

4.4.Results

4.4.1. Results of OFLC analysis

This study applied two methods to estimate the learning effect of photovoltaic technology. Let us first observe the result of OFLC, which is the most widely used estimation method. As described above, OFLC estimates the cost only with cumulative PV installed capacity.

4.4.1.1 China

Figures 4-4 show the evolution of PV costs and market installed capacity in China. Following the enactment of the Renewable Energy Law in 2006, a series of PV demonstration projects began to be implemented and the prices of PV products in China rapidly decreased. The reduction in PV product prices is also related to the rapid maturation of the PV industry. After the cost was reduced to a certain level and the conditions for large-scale deployment were available, the PV market in China expanded rapidly.

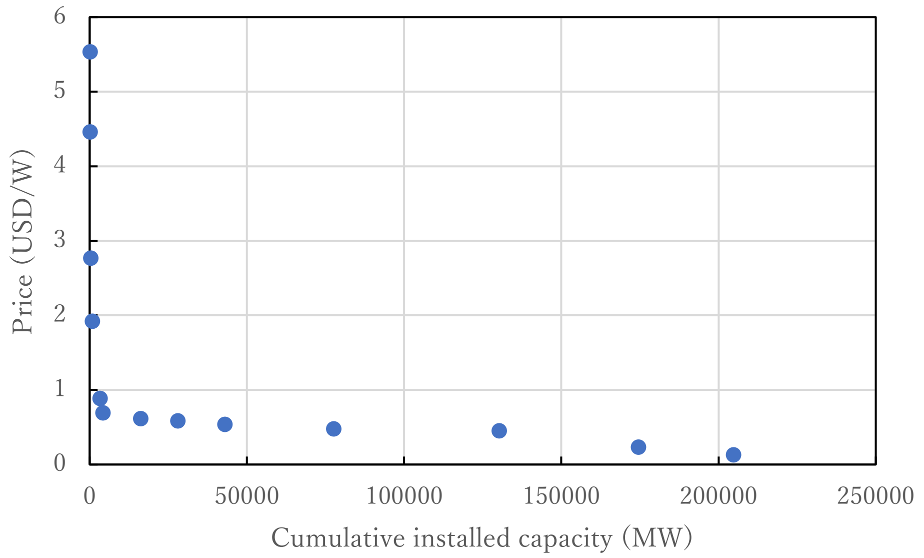


Figure 4-4 Changes in cumulative installed PV capacity and product prices from 2007 to 2019

Based on the results in Figure 4-5, we obtained learning curve plots of log C (unit cost) and log CUM (cumulative PV installed) based on time periods, as shown in Figures 4-5. The results of the regression analysis of log CUM and log UC are shown in Table 4-2. The R^2-value, which indicates the accuracy of the estimation equation, was 0.995 and p-value was 0.000 meaning the statistically significant level. For the period 2000-2011, the coefficient a of log CUM is expressed as -0.5378; therefore, the learning rate is 33.51%, which means that the unit price of PV power decreases by 33.51% when the cumulative PV installation doubles. However, the R^2 is 0.9945, which means that the derived learning curve model explains 99.45% of the empirical data. The learning rate during the FIT program period (2012-2019) is 30.98%, which means that the learning rate is also at high leavel and have a good learning effect, and the R^2 is 0.686, which means that the learning curve model explains 68.6% of the empirical data.

From 2007-2011, the learning rate is 33.51%, which is higher than the 30.98% after the implementation of the FIT policy from 2012. Thus, we can see that China's industrial promotion policy has a huge impact on PV costs, and the market drives the policy. This result shows that the learning effect during China's industrial promotion policy is very strong and very clear in terms of R^2 values.

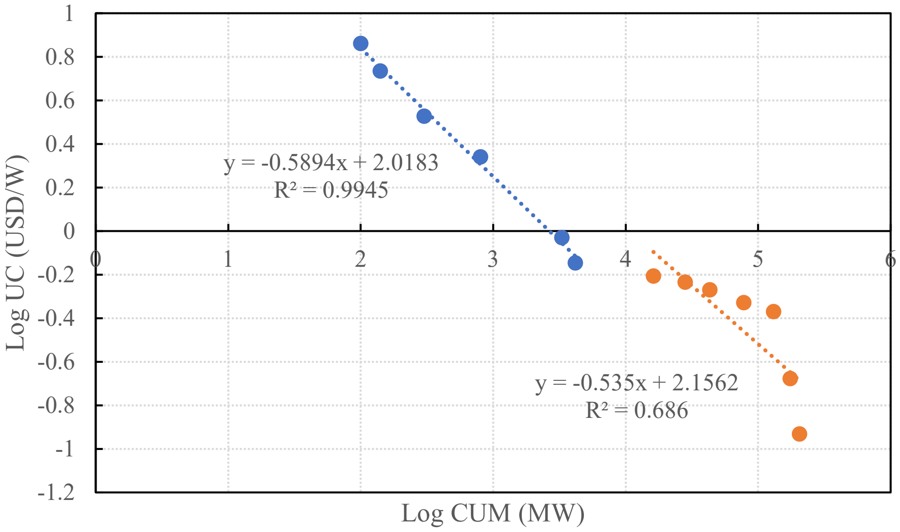


Figure 4-5 OFCL for LBD in different periods

Table 4-2 The analysis results of OFLC in different periods

Country	Time Period	*a*	Learning Rate	R^2	P-value	Performance Measure	Experience Measure
China	2007-2012	-0.538	33.51%	0.995	0.000	Module Price (USD/W)	Cumulative Installed Capacity
China	2013-2019	-0.535	30.98%	0.686	0.000	Module Price (USD/W)	Cumulative Installed Capacity

After analyzing the learning rates for different periods, the learning rate was analyzed for the overall period from 2000 to 2019. The R^2-value, which indicates the accuracy of the estimation equation, was 0.932 and p-value was 0.000 meaning the statistically significant level (Fig. 4-6). Using Eq. (4), a learning rate of 25.78% were estimated. That means the cost of PV production decreases 25.78% as the cumulative PV installed capacity.

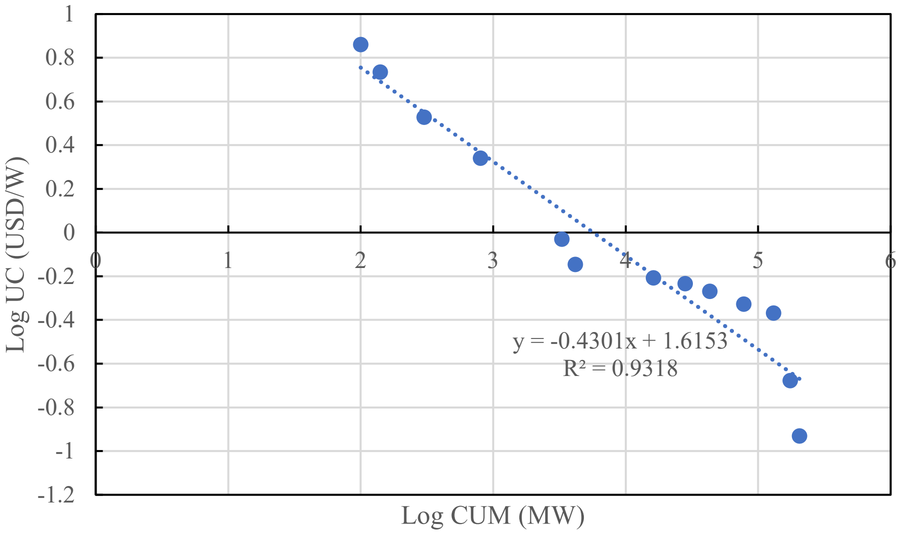


Figure 4-6 OFLC for LBD from 2000 to 2019.

Table 4-3 The analysis results of OFLC from 2000 to 2019.

Country	Period	*a*	Learning Rate	R^2	P-value	Performance Measure	Experience Measure
China	2007-2019	-0.430	25.78%	0.932	0.000	Module Price (USD/W)	Cumulative Installed Capacity

4.4.1.2 Germany

Figures 4-7 show the evolution of PV costs and market installed capacity in Germany. Following the introducing of the EEG (FIT) in 2000, the price of PV products has steadily declined as the market has expanded. The high subsidy price of FIT has attracted investors to invest in PV energy market. However, it is also because of the high price of FIT let to PV product prices fall slowly. The EEG underwent a major revision in 2012 to introduce a market-based competitive bidding mechanism, which ensures that the FIT policy promotes market expansion while also accelerating cost reductions.

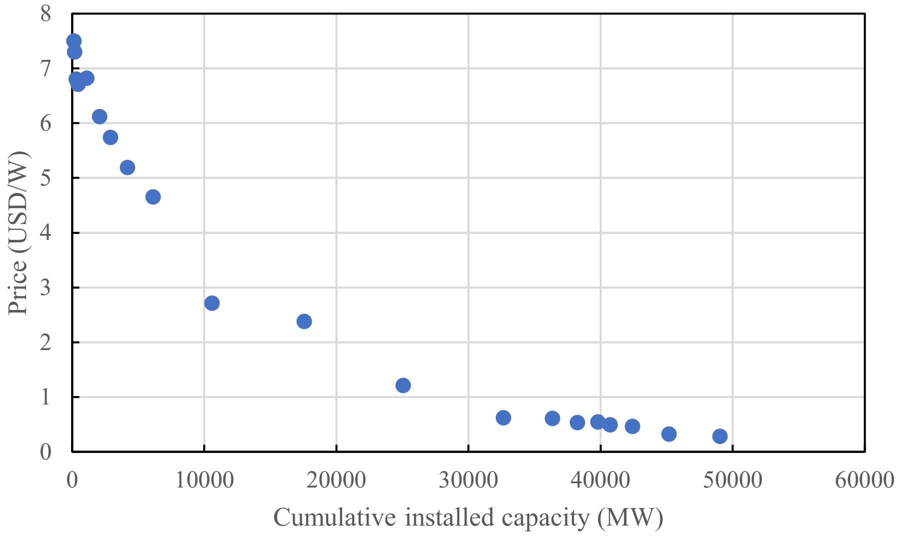


Figure 4-7 Changes in cumulative installed PV capacity and product prices from 2007 to 2019

Figure 4-8 shows the learning curve plots for log C (unit cost) and log CUM (cumulative PV installations) for Germany based on time periods. For the years 2000-2011, the coefficient a of the log CUM is expressed as -0.341; thus, the learning rate is 21.03%, which implies that the unit price of PV product decreases by 21.03% when the cumulative PV installation doubles. The results of the regression analysis of log CUM and log UC are shown in Table 4-4. The R^2 value indicating the accuracy of the estimated equations is 0.693 and the p-value is 0.000, implying statistical significance. The learning rate of the amended FIT at the period from 2013 to 2019 is 85.4%, which indicates a significant contribution to the price reduction of PV products after the FIT introduced a series of revisions such as market bidding measures. The R^2 is 0.939, which implies that the learning curve model explains 93.9% of the empirical data.

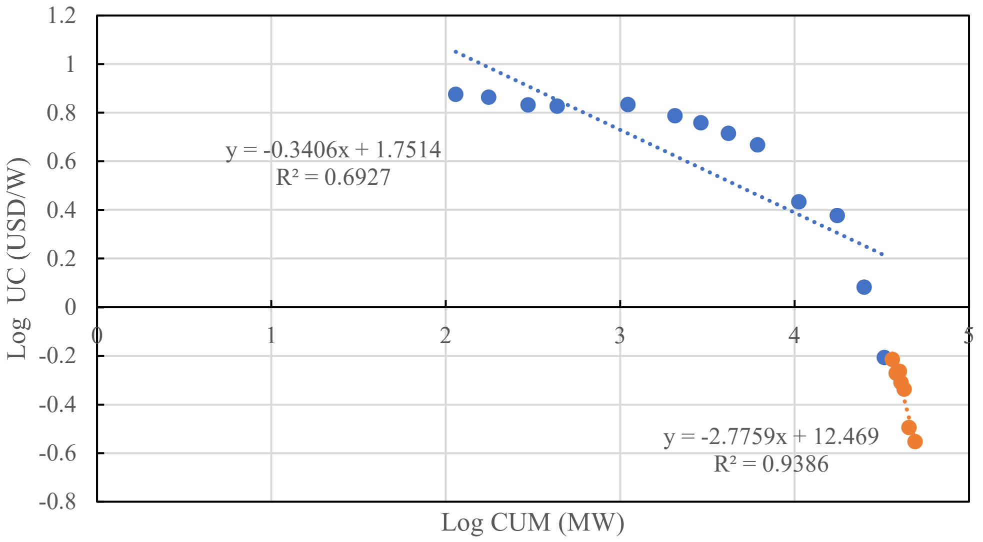


Figure 4-8 OFLC for LBD in different periods

Table 4-4 The results of OFLC for LBD from 2000 to 2019

Country	Time Period	*a*	Learning Rate	R^2	P-value	Performance Measure	Experience Measure
Germany	2000-2012	-0.341	21.03%	0.693	0.000	Module Price (USD/W)	Cumulative Installed Capacity
Germany	2013-2019	-2.776	85.40%	0.939	0.000	Module Price (USD/W)	Cumulative Installed Capacity

After analyzing the learning rates for different periods, the learning rates were analyzed for the entire period from 2000 to 2019. Figure 4-9 and Table 4-5 shows the learning curve in Germany from 2000 to 2019. The R^2 value for estimating the equation accuracy was 0.791 and the p-value was 0.000, indicating statistical significance. The learning rate was calculated and then learned to be 31.12%. This represents a 31.12% reduction in the cost of PV production when the cumulative installed PV capacity doubles.

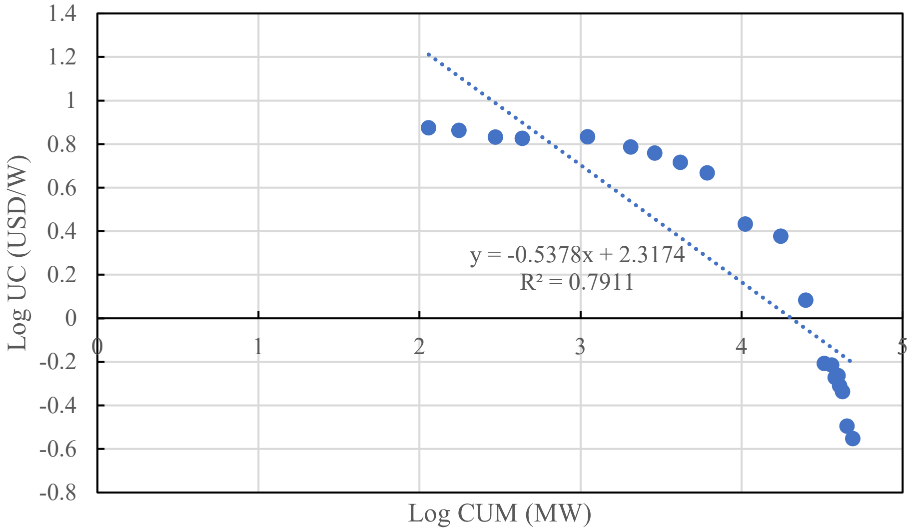


Figure 4-9 OFLC for LBD from 2000 to 2019

Table 4-5 The result of OFLC analysis from 2000 to 2019

Country	Time Period	*a*	Learning Rate	R^2	P-value	Performance Measure	Experience Measure
Germany	2000-2019	-0.538	31.12%	0.791	0.000	Module Price (USD/W)	Cumulative Installed Capacity

4.4.1.3 Japan

Figure 4-10 shows the evolution of PV costs and installed market capacity in Japan. Until 2012, support for PV market development in Japan was focused on the residential side. This led to a small PV market and a slow price decline. After 2012, the implementation of the FIT has greatly contributed to the development of the PV market, and with the expansion of the market, it has also reduced the prices of PV products.

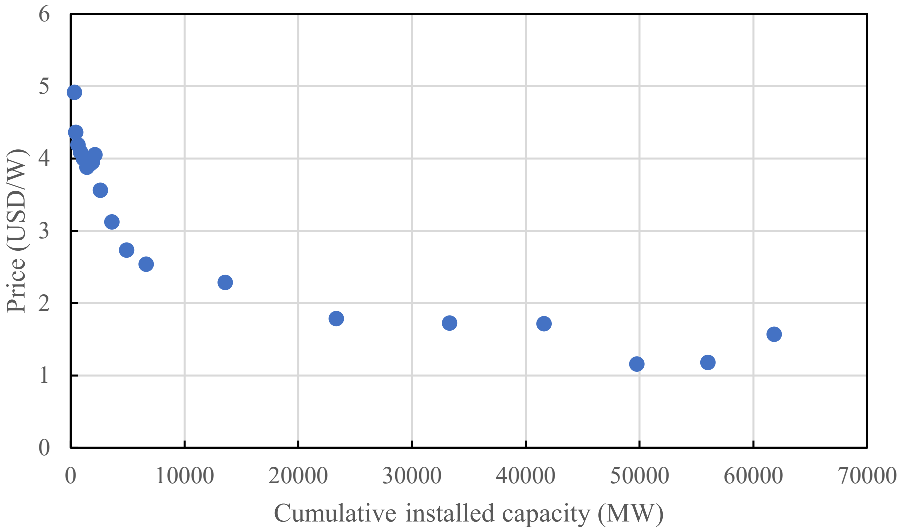


Figure 4-10 Changes in cumulative installed PV capacity and product prices from 2000 to 2019.

Figures 4-11 show the learning curve plots for log UC (unit cost) and log CUM (cumulative PV installations) for Japan based on time periods. For 2000-2011, the coefficient a of log CUM is expressed as -0.1662; thus, the learning rate is 10.88%, which implies that the unit price of PV product decreases by 10.88% when the cumulative PV installation doubles. The results of the regression analysis for log CUM and log UC are shown in Table 4-6. The R^2 value indicating the accuracy of the estimated equations is 0.799 and the p-value is 0.000, implying that the analysis is statistically significant. The learning rate between 2013 and 2019, after the implementation of the FIT, is 19.50%, indicating a significant contribution to the price reduction of PV products after the implementation of the FIT Act. The R^2 is 0.774, implying that the learning curve model explains 77.4% of the empirical data.

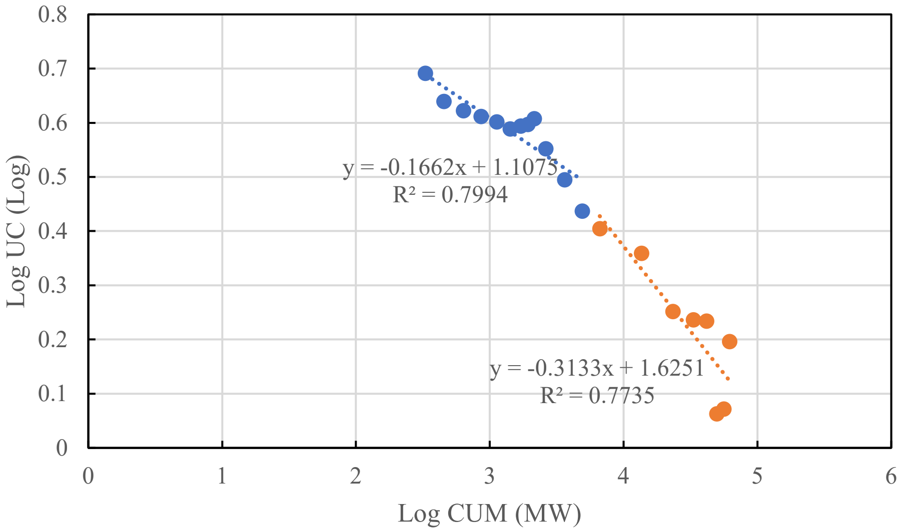


Figure 4-11 OFCL for LBD in different periods

Table 4-6 The analysis results of OFLC in different periods

Country	Time Period	*a*	Learning Rate	R^2	P-value	Performance Measure	Experience Measure
Japan	2000-2011	-0.166	10.88%	0.799	0.000	Module Price (USD/W)	Cumulative Installed Capacity
Japan	2012-2019	-0.313	19.50%	0.774	0.000	Module Price (USD/W)	Cumulative Installed Capacity

After analyzing the learning rates in Japan for different periods, the learning rates for the entire period from 2000 to 2019 were analyzed. Figure 4-12 and Table 4-7 show the learning curve for Japan from 2000 to 2019. The R^2 value for the accuracy of the estimated equation is 0.937 and the p-value is 0.000, indicating statistical significance. The learning rate is calculated to be 16.49%. That means when the cumulative installed PV capacity doubles, the PV production cost will decrease by 16.49%.

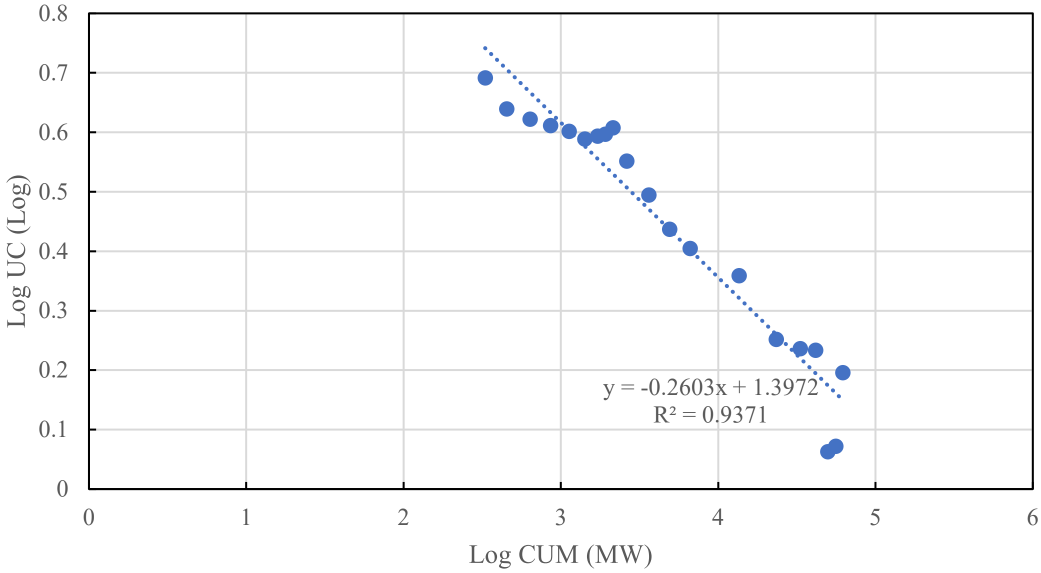


Figure 4-12 OFCL for LBD from 2000 to 2019

Table 4-7 The analysis results of OFLC from 2000 to 2019

Country	Time Period	*a*	Learning Rate	R^2	P-value	Performance Measure	Experience Measure
Japan	2000-2019	-0.260	16.49%	0.937	0.000	Module Price (USD/W)	Cumulative Installed Capacity

4.4.1.4 USA

Figure 4-13 shows the evolution of PV costs and market installed capacity in the US. Prior to 2006, the price of PV products in the U.S. did not drop significantly and stayed within a certain range. Because of the lack of incentives, the U.S. PV market grew at a slow pace. After 2006, the implementation of the ITC act promoted investment in PV and, as the market expanded, reduced the price of PV products.

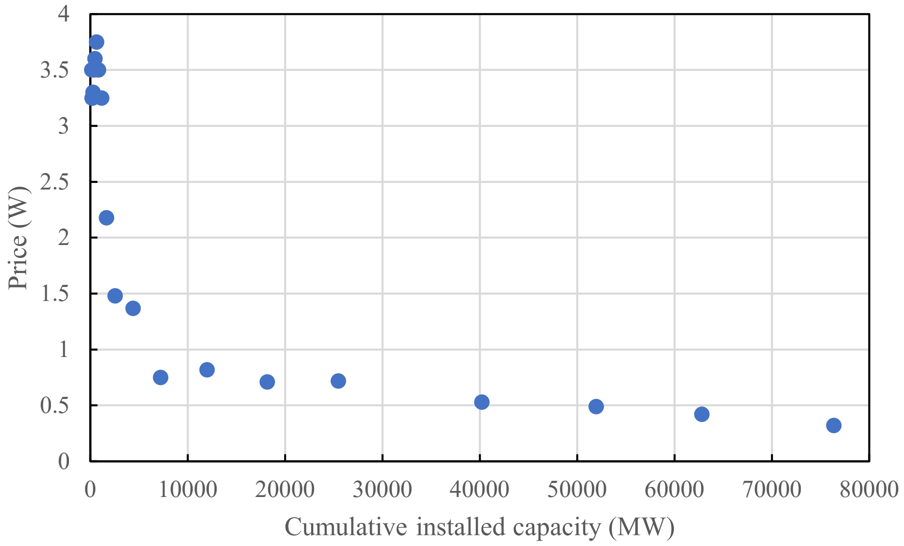


Figure 4-13 Changes in cumulative installed PV capacity and product prices from 2007 to 2019

Figure 4-14 shows a time period-based learning curve plot of log UC (unit cost) and log CUM (cumulative PV installations) for the United States. For the period 2000-2006, the coefficient a of log CUM is expressed as 0.072; the learning rate is negative, which means that the unit price of PV product did not decrease when the cumulative PV installation doubled during this period. The results of the regression analysis for log CUM and log UC are presented in Table 4-8. the R^2 value indicating the accuracy of the estimated equation is 0.516. the learning rate from 2007 to 2019 after ITC implementation is 27.49%, indicating that ITC implementation has contributed significantly to the price reduction of PV products. the R^2 is 0.947, indicating that the value is statistically significant, implying that the learning curve model explains 94.7% of the experience data.

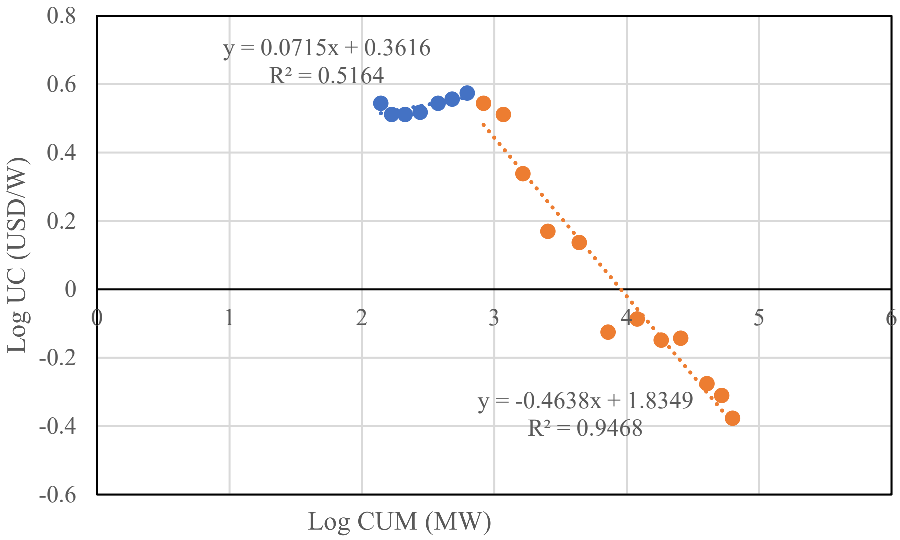


Figure 4-14 OFLC for LBD in different periods

Table 4-8 The results of OFLC for LBD in different periods

Country	Time Period	*a*	Learning Rate	R^2	P-value	Performance Measure	Experience Measure
USA	2000-2006	0.072	-5.08%	0.516	0.000	Module Price (USD/W)	Cumulative Installed Capacity
USA	2007-2019	-0.464	27.49%	0.947	0.000	Module Price (USD/W)	Cumulative Installed Capacity

Figure 4-15 and Table 4-9 show the learning curve for the United States from 2000 to 2019. The R^2 value for the accuracy of the estimated equation is 0.933 and the p-value is 0.000, indicating that the result is statistically significant. The learning rate was calculated to be 23.79%. This means that the PV production cost will decrease by 23.79% when the cumulative installed PV capacity is doubled.

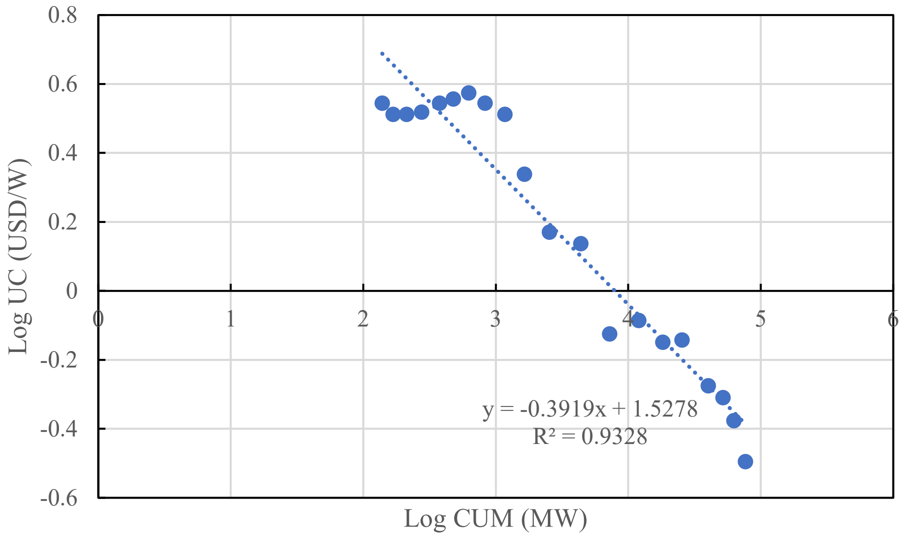


Figure 4-15 OFLC for LBD from 2000 to 2019

Table 4-9 The results of OFLC from 2000 to 2019

Country	Time Period	*a*	Learning Rate	R^2	P-value	Performance Measure	Experience Measure
USA	2000-2019	-0.392	23.79%	0.933	0.000	Module Price (USD/W)	Cumulative Installed Capacity

4.4.2.Results of TFLC analysis

4.4.2.1 China

In China, three most significant national research programs have included: “National Basic Research Program of China (973 Program)”, the “National High Technology Research and Development Program of China (863 Program)”, and the “Plan of National Key Science and Technology”. These three national R&D programs were regarded as guidelines for the development of national strategic key technologies. However, the use of funds for these public R&D projects is not publicly available, so we lack data on this. In addition, R&D and cost reduction efforts in Chinese PV are mainly carried out by private PV companies, so country-wide statistical values are difficult to obtain, and therefore we did not analyze the two-factor learning curve for China.

5.1.2.2 Germany

Table 4-10 The result of TFLC in Germany from 2000 to 2019

	Learning Index	**PR**	**Learning rate**	**P-value**	**R^2**
LBS	-0.337	0.7916	20.83%	0.041	0.753
LBD	-0.317	0.8362	19.72%	0.000	

As shown in Table 4-10, the TFLC model has an LBS coefficient of -0.337 for cumulative installed capacity from 2009 to 2016, an LBS rate of 20.83% for cumulative effective R&D expenditures, a time delay of 2 years, a decay coefficient of 2%, and an adjusted R^2 of 0.7916. The fitted results for the learning rate are influenced by the choice of model variables. The one-factor model did not consider the contribution of R&D, so it overestimated the LBD. For the TFLC analysis in Germany that considers both cumulative installed capacity and cumulative R&D investment, we obtain an LBD rate of 19.72% and an LBS rate of 20.83%. The R^2 for linear regression analysis is 0.753, the P-value for LBS is 0.041, the p-values for LBD is 0.000, all within 0.05 , which indicated that the analysis was statistically significant and tested for multicollinearity.

Based on the above analysis results we can find that after considering both cumulative R&D investment and cumulative installed capacity on PV product cost, the Learning Index of LBS is -0.337 and the LBS rate is 20.83%, and the Learning Index of LBD is -0.317 and the LBD is 19.72%, which indicates that every doubling of cumulative PV installed capacity reduces the PV product cost by 19.72%, while every doubling of R&D investment leads to a 20.83% reduction in product cost.

The results of the analysis demonstrate that, in addition to demand-side driving policies, Germany's R&D policies play an important role in cost reduction. This can be attributed to Germany's Energy Research and Technology Program, which has been implemented since 1977, and in 2018, the seventh Energy Research and Technology Program started to be implemented, and the long-term stable R&D policy has played an important role in the reduction of PV costs. At the same time, the expanding PV market, stimulated by the FIT policy, has also made an important contribution to the reduction of PV product costs.

5.1.2.3 Japan

Table 4-11 The result of TFLC in Japan from 2000 to 2019

	Learning Index	**PR**	**Learning rate**	**P-value**	**R^2**
LBS	-0.059	0.9599	4%	0.043	0.755
LBD	-0.125	0.917	8.30%	0.000	

As shown in Table 4-11, the TFLC model has an LBS coefficient of -0.059 for cumulative installed capacity from 2009 to 2016, an LBS rate of 4% for cumulative effective R&D expenditures, a time delay of 2 years, a decay coefficient of 2%, and an adjusted R^2 of 0.755. The results for the learning rate are influenced by the choice of model variables. The one-factor model did not consider the contribution of R&D, so it overestimated the LBD. For the TFLC analysis in Japan that considers both cumulative installed capacity and cumulative R&D investment, we obtain an LBD rate of 4% and an LBS rate of 8.3%. The R^2 for linear regression analysis is 0.755, the P-value for LBS is 0.043, the p-values for LBD is 0.000, all within 0.05 , which indicated that the analysis was statistically significant and tested for multicollinearity.

Based on the above analysis results we can find that after considering both cumulative R&D investment and cumulative installed capacity on PV product cost, the Learning Index of LBS is -0.059 and the LBS rate is 4%, and the Learning Index of LBD is -0.125 and the LBD is 8.3%, which indicates that every doubling of cumulative PV installed capacity reduces the PV product cost by 4%, while every doubling of R&D investment leads to a 8.3% reduction in product cost.

The analysis shows that the main driver of PV price reduction in Japan is the LBD, which is mainly attributed to the investment demand-side pull policy. Since the 1990s, Japan has been implementing net-metering and various residential PV system investment subsidies, which have accelerated the development of the Japanese PV market. After 2012, the implementation of the FIT Act accelerated the price reduction of PV products. In contrast, Japan's R&D policy focuses on the development of new technologies and innovation, and the cost reduction effect is not significant.

5.1.2.4 USA

Table 4-12 The result of TFLC in USA from 2000 to 2019

	Learning Index	**PR**	**Learning rate**	**P-value**	**R^2**
LBS	-0.122	0.9189	8.10%	0.040	0.868
LBD	-0.258	0.8362	16.38%	0.000	

As shown in Table 4-12, the TFLC model has an LBS coefficient of -0.122 for cumulative installed capacity from 2009 to 2016, an LBS rate of 8.1% for cumulative effective R&D expenditures, a time delay of 2 years, a decay coefficient of 2%, and an adjusted R^2 of 0.868. The results for the learning rate are influenced by the choice of model variables. The one-factor model did not consider the contribution of R&D, so it overestimated the LBD. For the TFLC analysis in USA that considers both cumulative installed capacity and cumulative R&D investment, we obtain an LBD rate of 8.1% and an LBS rate of 16.38%. The R^2 for linear regression analysis is 0.868, the P-value for LBS is 0.040, the p-values for LBD is 0.000, all within 0.05 , which indicated that the analysis was statistically significant and tested for multicollinearity.

Based on the above analysis results we can find that after considering both cumulative R&D investment and cumulative installed capacity on PV product cost, the Learning Index of LBS is -0.122 and the LBS rate is 8.1%, and the Learning Index of LBD is -0.258 and the LBD is 16.38%, which indicates that every doubling of cumulative PV installed capacity reduces the PV product cost by 16.38%, while every doubling of R&D investment leads to a 8.1% reduction in product cost.

The results of TFLC's analysis show that LBD has a greater impact on price reductions for U.S. PV products. The U.S. has invested significant public funds in R&D of PV technologies, however, these investments are more focused on innovation of new technologies. As a result, the LBS rate is not high. In contrast, the U.S. has long lacked a country-wide demand-side pull policy, and therefore had a huge impact on the PV market after the ITC began to be implemented in 2006. The analysis shows that the growth in installations has contributed significantly to cost reductions.

4.5. Conclusion

This chapter estimates the decrease in PV product cost in four countries, China, Germany, Japan, and the United States, based on a learning curve model for technology learning. The traditional OFLC (considering only cumulative PV installation) and TFLC (considering cumulative installation and cumulative R&D investment) models were used. In the OFLC analysis, we divided the period of analysis by policy to assess the impact of different policies on PV product reduction. The summary of this chapter is as follows:

OFLC's analysis shows that before 2012, China's PV industry promotion policy and investment subsidy policy contributed significantly to cost reduction, with an LBD rate of 33.51% from 2007 to 2012. After 2012, the implementation of the FIT policy contributed to the explosive growth of China's PV market. After the implementation of the FIT policy, the LBD rate was 30.08%. This shows that different types of stimulus policies have achieved good cost reduction effects, and in comparison, the effect of industry-driven policies is more effective.

The EEG (FIT) act has been in effect in Germany since 2000. The results of the analysis from 2000 to 2012 show that the LBD rate was 21.03% during this period and the price of PV products was also reduced along with the market expansion. After 2012, the implementation of the revised EEG Act, which introduced a series of bidding policies, led to an exponential decrease in the price of PV products in Germany, with the LBD even reaching 85.40%. Therefore, it can be seen that the market bidding mechanism of FIT has a huge impact on cost reduction.

From the results of OFLC analysis in Japan, we can understand that investment subsidies and RPS policies do not have good effects on PV product cost reduction. From 2000 to 2011, the LBD rate was only 10.88%, and the price of PV products even increased during the period of time. After the implementation of FIT Act in 2012, the price of Japanese PV products also decreased along with the market expansion, and the LBD rate reached 20%.

During the period 2000-2006, the OFLC learning rate in the US was negative, which means that the expansion of the market had no impact on the unit price of PV during this period. This is mainly due to the fact that the US did not have a country-wide support policy for PV energy during this period. It was not until the implementation of the ITC in 2006 that the learning effect of PV in the U.S. began to materialize, and during this period the LBD rate reached 27.49%, with significant PV cost reductions.

The OFLC analysis for a single period shows that China's LBD rate from 2007 to 2019 is 23.59%, Germany's LBD rate from 2000 to 2019 is 31.12%, Japan's LBD rate is 16.49%, and the U.S.'s LBD rate is 23.79%. Germany's LBD rate is at the highest value. This could indicate that Germany's demand-side pull policy has a better effect on cost reduction of PV production.

The results of the TFLC analysis showed that the LBS rate in Germany was 20.83% and the LBD rate was 19.72%. Japan's LBS rate was 4% and LBD rate was 8.3%. The LBS rate in the U.S. was 8.10% and the LBD rate was 16.38%. Germany had the best learning effect of R&D investment and market expansion on PV costs during this period, followed by the U.S., and Japan had the lowest learning effect.

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Chapter 5. Techno-economic analysis of solar PV energy in China, Germany, Japan, and the USA

5.1.Introduction

To achieve energy security goals and reduce greenhouse gas emissions, countries around the world have introduced different policy tools to promote renewable energy installations, such as feed-in tariffs (FITs), capital investment subsidies (CIS), and investment tax support policies (ITCs). In particular, in China, Germany, Japan, and the United States, four governments have been promoting renewable energy sources, including photovoltaic (PV) energy, since the 20th century in order to ensure energy supply security and reduce CO2 emissions. These policies have significantly increased the amount of renewable energy installed in the four countries. As a result, governments have become more ambitious about renewable energy development.

In 2019, the world PV energy installation capacity has reached 586 GW. China's PV installation capacity is 205.5 GW, ranking first in the world. Germany PV installed capacity is 49.2GW, ranking the fourth in the world. Japan's installed capacity of solar PV capacity reached 63GW, ranking third in the world, the United States has PV installation capacity of 60.6GW ranks second in the world (IRENA. 2020). Four countries from the central government to local governments, all targeted at residential PV systems and large-scale PV power plant support policy of diversification.

In this context, investors in residential PV systems could receive a positive return on their investment (Muhammad-Sukki et al. 2014). This ensures the rapid growth of the PV market in four countries. However, the explosive growth of PV energy has led to a series of problems, such as substantial net demand changes and the high renewable energy tax burden (METI 2019). The increase in PV penetration has affected the stability of the grid. The daily or seasonal balancing of supply and demand has become a huge challenge. As a result, governments in four countries has been reducing subsidies for PV system each year and considering eliminating the subsidy policy (METI. 2020).

With the continued reduction or even elimination of support policies, the development of PV energy tends to slow down. The growth rate of PV energy introduction reduced year after year in recent year (METI 2020). However, continued reliance on the FIT to facilitate reinvestment is not a sustainable approach to expanding the introduction of PV energy. For mitigation of this reduction, governments are trying to achieve renewable energy goals by implementing innovative policy solutions. These policies could improve the utilization and flexibility of PV power generation by introducing battery system into the residential and increase the stability of the grid.

Residential PV battery systems can inject the produced electricity into the grid at feed-in tariffs and store the PV produced electricity for self-consumption to meet the electricity demand. Especially for end-users with inconsistent production and demand times, adding a battery system can improve the self-consumption of PV energy (Schopfer, Tiefenbeck, and Staake 2018). The self-consumption of PV energy is beneficial to both the end-user and the grid side when the generation cost of the battery system can be lower than the retail price.

The cost of lithium-ion batteries has begun to decrease significantly and has been projected to decline by a similar cost to that of PV modules. In fact, battery system costs have declined significantly globally and the feasibility of PV and battery system without the FIT has been demonstrated in many regions, but it is unclear what conditions an installation is feasible.

In the literature, an increasing number of researches analyze the feasibility of residential PV systems under different incentive policies between different countries with varying investment costs, solar irradiation, and electricity tariffs. La Monaca and Ryan (La Monaca and Ryan 2017) presented an economic analysis of rooftop PV in Ireland. A System Advisory Model (SAM) was used in the simulation and proved that the incentive policies reduced the current payback period in Ireland. Quoilin et al. (Quoilin et al. 2016) analyzed the self-consumption and economic performances of residential PV-battery systems in cases of European countries, concluded that self-consumption and economic profitability were a function of the PV system and battery sizes, residential PV battery profitability and future uptake depend mainly on the indirect subsidies for self-consumption provided by the structure of retail prices. Sow et al. (Sow et al. 2019) presented the results of a comparative economic analysis of residential solar PV systems throughout the provinces of Canada in 2013 and 2016 under the change of supporting policies and support policies. Bakhshi et al. (Bakhshi and Sadeh 2017) analyzed the changes in economic indicators such as IRR, NPV and payback period (PBP) of PV energy in Iran under the proposed a new dynamic FIT strategy and indicated that the PV energy is feasible in Iran. Can Duman et al. (Duman and Güler 2020) performed an economic analysis and sensitivity analysis for grid-connected residential PVs in Turkey under the FIT and recommended increase the PV support policies.

Regarding political boundary conditions, a number of articles assess how electricity retail tariffs, interest rates, and subsidy schemes affect the economic viability of grid-connected residential PBS, and others evaluate the role of feed-in tariffs in near- and post-grid parity markets. Several studies compare the profitability of PBS in different climatic regions and weather conditions within or between countries. Moien et al. (Omar and Mahmoud 2018) mainly analyzed the expansion plan for residential combined PV, battery and heat pump applications, that may steadily increase in residential sector in Japan, results clarified the optimal installation capacity over a twenty-year period considering the changing condition of investment cost, incentive policy and electricity market. Simultaneously

As residential PV system is considered as a beneficiary of policy support, it is timely to examine the economic value currently available to homeowners who might consider installing solar, and how the asset owners' financial gains could be affected under different policy schemes. Such analysis may also inform any deliberations regarding whether and how to implement policy support schemes. The economic benefits of the PBS investment depend on the location of the end-user and its behavior as customer. In fact, the PV energy production depend on the global solar radiation that varies in different countries, while the electricity demand is influenced by customer behavior. A residential customer that consumes large amounts of electricity during daytime could obtain the return on investment into a PV and battery system much faster than a residential with the same annual demand that uses electricity primarily in the evening hours. The results indicate that PV alone is profitable, with an optimum installed capacity around 200% of the peak load. However, the only scenario in which a battery is profitable is the one in which it costs decreases down to 200 USD/kWh (Sii 2013).

Figure 5-1 shows the cumulative installed of battery systems in major countries in the world until end of 2019. In Japan, the battery system used in conjunction with renewable energy systems reach 1.2 GWh, and the installed capacity of residential battery systems reaches 2.4 GWh.

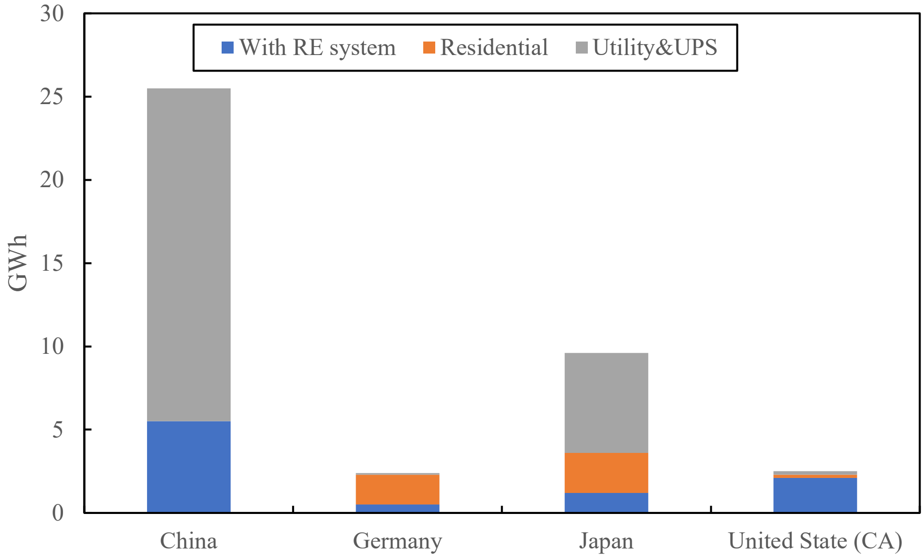

Figure 5-1 The cumulative installed of battery systems in major countries until 2019

Table 5-1 PV system average initial investment cost by country in 2019 (USD/W).

	China	**Germany**	**Japan**	**USA**
Residential sector	810	1588	2170	1680

Date source: IRENA. 1 RMB=0.1449 USD; 1 Euro=1.2 USD; 1 JPY= 0.0095 USD; 2020 Exchange rate.

In 2014, the world average price of lithium-ion battery was about 400 USD/kWh. Compared with the price of 1300 USD/kWh in 2006, it has been significantly reduced. In Japan, both solar power generation and storage batteries are considerably more expensive than the world standard due to strong demand for high quality and hindering the creation of a competitive market due to excessive economic support. Storage batteries were still expensive to use for system stabilization of variable output renewable energy until a few years ago, but the price of lithium-ion batteries has dropped sharply with the spread of electric vehicles. In 2015, the price of household batteries in Japan was 2030 USD/kWh. The Japanese battery strategy aims to reach 830 USD/kWh and large-scale batteries to 212 USD/kWh in 2020.

Based on the real-measured load data of typical residential users, this chapter establishes a virtual model of residential PBS system to analyze the technical and economic performance in the locations of four cities in selected countries. At the same time, according to the current different policy conditions, the impact of policy on the economic feasibility of PV system and PBS in various regions is analyzed. In addition, for large-scale PV plants, we used PV syst software in combination with existing policies to evaluate the technical and economic viability of PV plants in four cities with the best light conditions in four countries.

5.2.Methods

5.2.1.PV system model

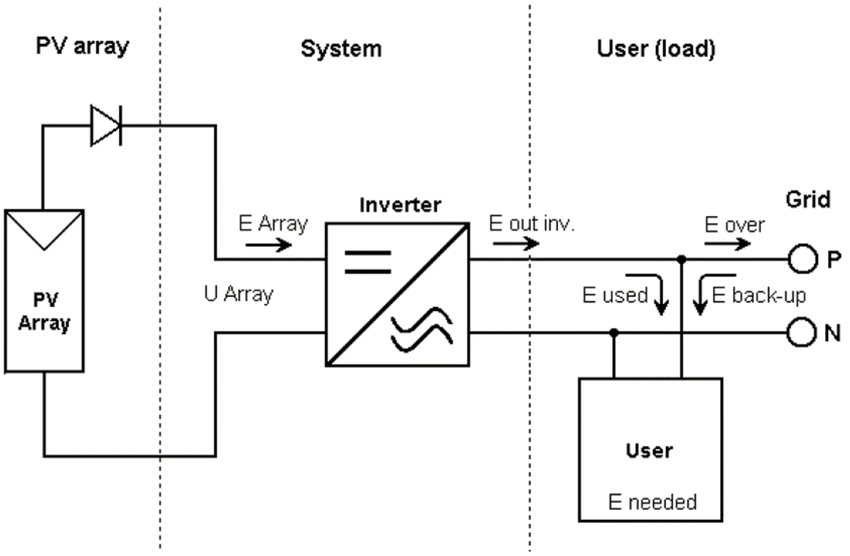

Figure 5-2 The schematic layout of the grid-connected residential PV system (Source: PV Syst)

Figure 5-2 shows the schematic layout of the grid-connected residential PV system in this paper. The main components of the grid-connected system are following

•Solar Panels (modules)

•Inverters

•Mounting structures

•Grid connection

•Cables

In this PV system, if excess power is produced, it can be supplied to the grid. In USA, it could by Net-metering inject into grid and then use it when there is less power generation of system. In Japan, Germany and China, the excess PV energy is injecting into grid and gain the profit through the Feed-in Tariff.

5.2.2.Simulation tool

SAM was developed by the National Renewable Energy Laboratory (NREL) in collaboration with Sandia National Laboratories in 2005 specifically for the analysis of solar technologies. This study used SAM and MATLAB to compare the technical and economic performance of models using residential PV systems from different geographic locations operating under different policy-economic conditions (Gilman 2015). The inputs to the model include weather data and solar radiation at the project location, economic parameters and system technical parameters. PVsyst has utilized extensive knowledge of PV technology, meteorological irradiation resource data and components of PV systems. Therefore, PVsyst can help refine the design of large-scale PV plants.

5.2.3.PV and battery system models

Figure 5-3 illustrates the schematic layout of the grid-connected residential PV BESS, which consists of a DC-coupled PV and battery system. Power generation from PV system has priority in meeting the local household electricity demand, excess generation can be directly sold to the public grid or stored in the battery system (Lim et al. 2020). Depending on the application scenario, the battery as a balancing tool is charged while the considerably surplus PV generated, maximizing self-consumption level. Then the battery will come into discharge condition to provide additional power to reduce the imported power from the public grid. The public grid can supply power to cover demand over the period when the PV generation is insufficient or unavailable (Schopfer et al. 2018).

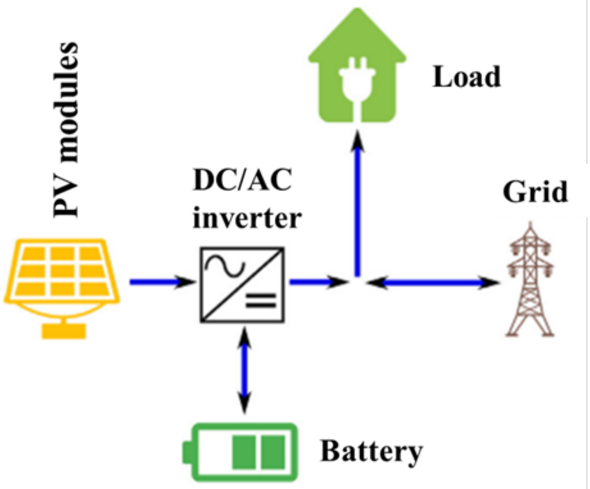

Figure 5-3 The schematic layout of the grid-connected residential PV-battery system (Schopfer et al. 2018)

(1) Energy balance

In this study, the time step of the simulation is one hour due to the time step of the available weather and load data and the relatively long simulation period. Load balance is the core part of any renewable energy-based system (Lazzeroni, Moretti, and Fondazione 2020). To ensure the electricity demand of the consumer at each time step, the load balance equation of PV system and PV and battery system is subject to:

$$E_{pv} + E_{gird} = E_{load} + E_{fit} \tag{5-1}$$

$$E_{pv} + E_{gird} + E_{dis} = E_{load} + E_{ch} + E_{fit} \tag{5-2}$$

Where E_{pv} is the PV energy production (kWh), E_{gird} is grid injection (kWh), E_{dis} is the battery discharge (kWh), E_{load} is the household load demand (kWh), E_{ch} is the battery charge (kWh), E_{fit} is the energy feed-in to the grid (kWh).

(2) Battery system

The lithium-ion battery is selected as the energy storage system (Merei et al. 2016). The state of charge (SOC) of a battery bank is be described as follows:

$$SOC(t+1) = SOC(t) + \frac{P_{ch}(t) i_{ch}(t) \eta_{ch}}{E_{mb}} - \frac{P_{dch}(t) i_{dch}}{E_{mb}\eta_{dch}} - \frac{P_{sfd}(t)}{E_{mb}} \tag{5-3}$$

Where SOC is the state of charge of battery (%), E_{mb} is the maximum battery usable energy during an entire roundtrip (kWh), t is the time iteration for almost all of the parameters in the equation (h), $1 \leqslant t \leq 8760$, P_{ch} is the battery charging power (W), i_{ch} is the battery charging duration (h), assumed as 1 or 0, η_{ch} is the battery charging efficiency (%), P_{dch} is the battery discharging power (W), i_{dch} is the battery discharging duration (h), assumed as 1 or 0, η_{dch} is the battery discharging efficiency (%), and P_{sfd} is the battery self-discharging power (W).

The battery could not be charged and discharged at the same time. In order to avoid overcharging and over-discharging, some limitations are imposed on the minimum and maximum of the SOC:

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \tag{5-4}$$

Where SOC_{min} is the minimum of SOC, assumed as 0.2, SOC_{max} is the maximum of SOC, assumed as 1.

5.2.4.Economical model

The PV system and the PV BESS economic assessment includes the Levelized Cost of Electricity (LCOE) and the Net Present Value (NPV) and the Internal Rate of Return (IRR) as criteria for the evaluation of the profitability of a PV investment. The following paragraphs provide details about such economic performance analyses.

(1) The levelized cost of electricity (LCOE)

The LCOE represents the total project lifecycle costs, measured in cent USD per kilowatt-hour (cent/kWh). Through calculations, it is possible to compare the impact of different technologies on financial feasibility, project size, production capacity and capital costs. Grid parity is defined as the situation where the LCOE for alternative energy production the same as the cost of purchasing power from grid.

$$LCOE = \frac{\sum_{t=0}^{T} C_t/(1+d)^t}{\sum_{t=0}^{T} E_t/(1+d)^t} \qquad (5\text{-}5)$$

Where C_t is the annal project cash flow including; installation, operation and maintenance, financial costs and fees; E_t is the electricity generated by the system in year 't';

In this paper, the LCOE has been compared to the current electric bill, which ignores the future inflation in the prices. The LCOE also depends on investment and operating costs and greatly affected by investment subsidy policies.

(2) Net Present Value (NPV) and Internal Rate of Return (IRR)

A discount cash flow analysis has been used in this study (Dusonchet and Telaretti 2015); the NPV was calculated for different economic scenarios involving a range of electricity prices, solar PV degradation rates and inverter and battery replacement costs to reproduce the annual cash flow for the lifetime of the solar PV system. The NPV was calculated using equation:

$$NPV = \sum_{t=0}^{T} \frac{C_t}{(1+d)^t} \qquad (5\text{-}6)$$

Where, C_t is the cash flow, t is the number of years, d is the nominal discount rate, T is the project lifetime. In this study, cash flow analyses were conducted with a discount rate of 4%. The discount rate is the primary factor affecting the NPV calculation. For residential solar projects, the discount rate should be the same as or higher than the target for the return on investors.

The IRR is one of the most useful tools for measuring profitability and is the most used method to calculate the rate of return. It is calculated using Equation:

$$NPV = \sum_{t}^{T} \frac{C_t}{(1+IRR)^t} = 0 \qquad (5\text{-}7)$$

5.2.5. Simulation parameters

Table 5-2 PV module specification

Specification of the module	
Manufacturer	Longi Solar
Module No.	LR4-60 HPH 350 M
Type	Si-mono
Reference conditions	

Gref	1000W/m2
Tref	20℃
Isc	11.020A
Voc	40.50V
Max Power Point	
Impp	10.530A
Vmpp	30.30V
Efficiency	
Cells	21.21%
Module	18.77%
Sizes	
Length	1776mm
Width	1052mm
Area	1.868m2

Table 5-3 PV inverter specification

Specification of the inverter	
Manufacturer	SMA
Model	SB5.0-1SP-US-40 [240V]
Nominal PV power	5.05kW
Maximum PV power	5.207kW
Maximum PV Current	14.26A
Minimum MPP voltage	220V
Maximum MPP Voltage	480V
Maximum efficiency	96.90%

Nowadays, most common installation capacity of the residential PV system in worldwide is mainly between 4.0 kW to 5.5 kW, due to the limited roof area and limited weigh bearing capacity of the building. In this study, the applied PV production profile is a simulation profile of a 5 kW PV system on a residential house in four selected countries. The proposed solar module for the 5 kW residential PV system and PV BESS is the Longi Solar LR4-60 HPH 350 M Si-mono PV with a rating of 350W

(Table 5-2). The inverter used for this plant is SB5.0-1SP-US-40 made by SMA. The selected SMA inverter has a rated power of 5.05 kW. Table 5-3 lists the technical specifications of invertor. The PV battery model is used lithium-ion based battery systems. For clarity of the analysis, only lithium-ion based systems are considered with their respective parameters. Other PV system parameters include the inverter efficiency, degradation, operation and maintenance costs, battery parameter and economic parameters are shown in Table 5-4. The parameters have been chosen according to typical parameter which can be found in various government statistical reports and official website.

Table 5-4 List of simulation parameters.

Category	**Assumption**
PV system parameters	
Energy yield	1000kWh/kWp
Nameplate DC capacity	4.902kW
Total AC capacity	5.050kW
Total inverter DC capacity	5.207
Number of modules	14
Number of strings	2
Total module area	24.8m^2
Inverter efficiency	96.9 %
Module degradation	0.05%
Lifetime	25years
Investment cost	Table 5-1
Battery system parameters	
Depth of discharge DoD	80%
Charge/discharge efficiency	95%
Lifetime	10 years
Cycle life	6000
Battery degradation	0.40%
Investment cost	400-900 USD/kWh
Economic parameters	
Operation and maintenance costs	2%
Discount rate	4%
Electricity inflation rate	2%
Project lifetime	25 years

5.3. Description of the case studies

5.3.1.Study scenarios

Four typical cities in China, Germany, Japan and the United States were selected as case studies based on the distribution of national grids or power companies. Three different study scenarios in each case were considered, with PV systems in the "No support policies" and "With support policies" cases; PV and battery systems and with investment support policies (Table 5-5). Each technology combination is analyzed in the case of no increase in the average electricity price.

Table 5-5 Study scenario

	Policies
PV system	
Scenario 1	National and local wide support policies
Scenario 2	No support policies
PV and battery system	
Scenario 3	With support policies

5.3.2. China

5.3.2.1 Research location

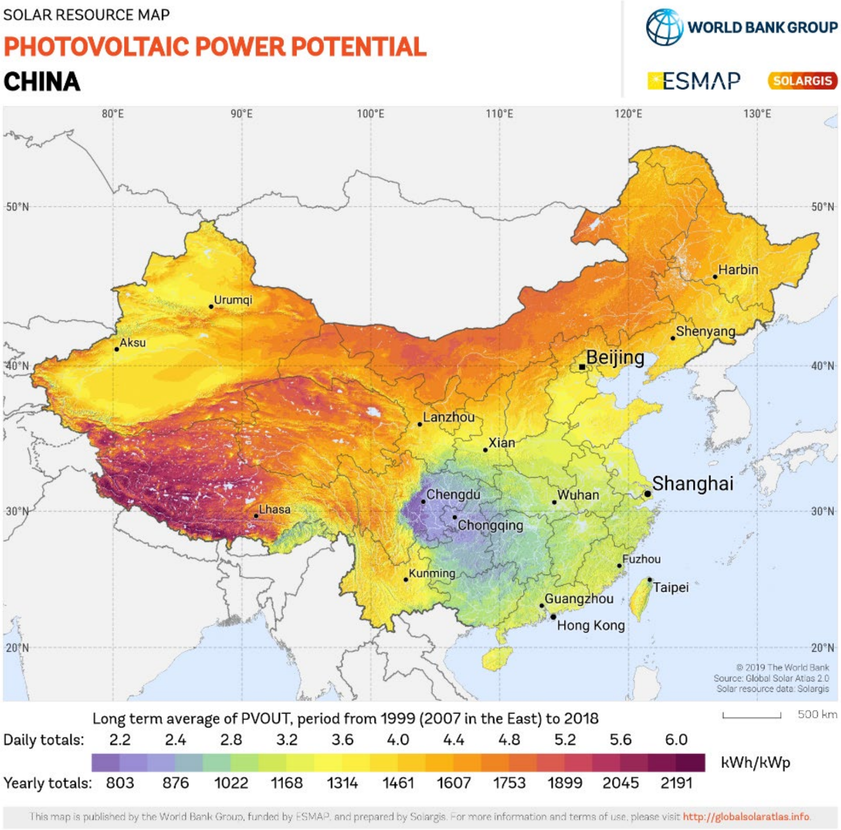

Figure 5-4 Solar PV power potential in China (Sources: Solar GIS)

China, which covers 9.6 million square kilometers, is a vast country with diverse climatic conditions. Under solar resource map of solar GIS, the long-term average of PV output is from 803kWh/kW to 2191 kWh/kW (Figure 5-4). According to the national electricity grid company of China, the country is divided into four major gird regions: Northwest, Central China, East China, Northeast China, and Southern China. To study the most important impact parameters in those grid regions, four representative cities, Beijing, Shanghai, Guangzhou and Lanzhou were chosen to represent the four major electricity grid company. Figure 5-5 shows the geographical location of the four cities, and Table 5-6 gives their coordinate information.

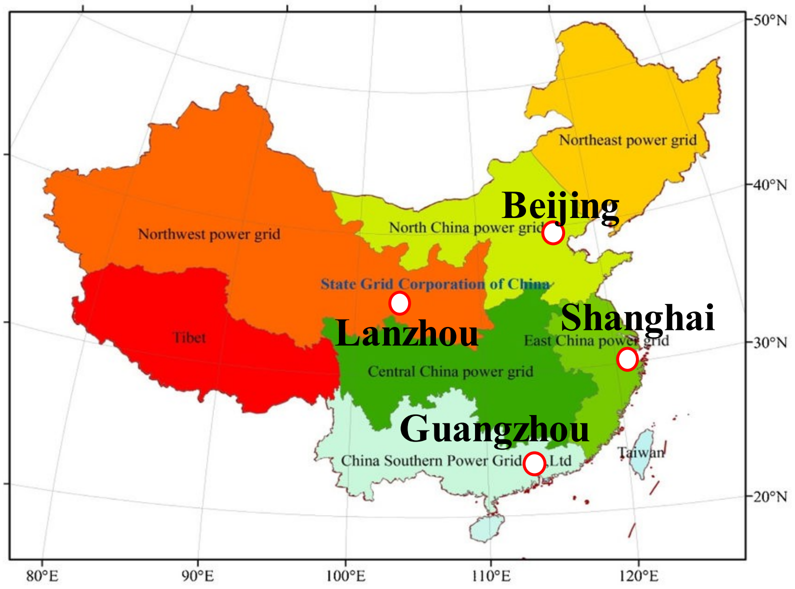

Figure 5-5 Geographical location of the various power grids in China

Table 5-6 Geographical location of study cities and the gird information

City	**Beijing**	**Shanghai**	**Guangzhou**	**Lanzhou**
Latitude (°N)	39.9075	31.2222	23.1167	36.057
Longitude (°E)	116.3972	121.4581	113.25	103.8399
Altitude (m)	39	9	31	1531
Power gird	North China	East China	China Southern	Northwest

5.3.2.2 Climatic data for the cities under study

The solar radiation data used in this study were obtained from NREL's Surface Meteorology and

Solar Energy Database. Figures 5-6 show the global monthly average solar radiation for the proposed locations. The highest values of monthly solar radiation in Beijing, Shanghai, Guangzhou and Lanzhou occur in May and the lowest in December, the lowest values in Shanghai occur in January and the highest in July, the highest irradiance in Guangzhou occurs in July and the lowest in February, and the highest irradiance in Lanzhou occurs in June and the lowest in December. Solar irradiance in Beijing and Lanzhou is higher from May to July because of the similar climatic conditions in these two cities. For the same reason, solar irradiance in Shanghai and Guangzhou is also high from May to August.

The ambient temperature data are important for determining the actual output power of the PV modules. Figure 5-7 shows the monthly average ambient temperature data for the proposed sites obtained from METEONORM V7.0 software. The minimum and maximum ambient temperatures in Beijing, Shanghai, Guangzhou, and Lanzhou were -3.4°C, 3.7°C, 13.5°C, and -4.4°C in January, and 27°C, 30.1°C, 29.9°C, and 22.5°C in July, respectively. Figure 5-8 shows the monthly average wind speed in Beijing, Shanghai, Guangzhou, and Lanzhou.

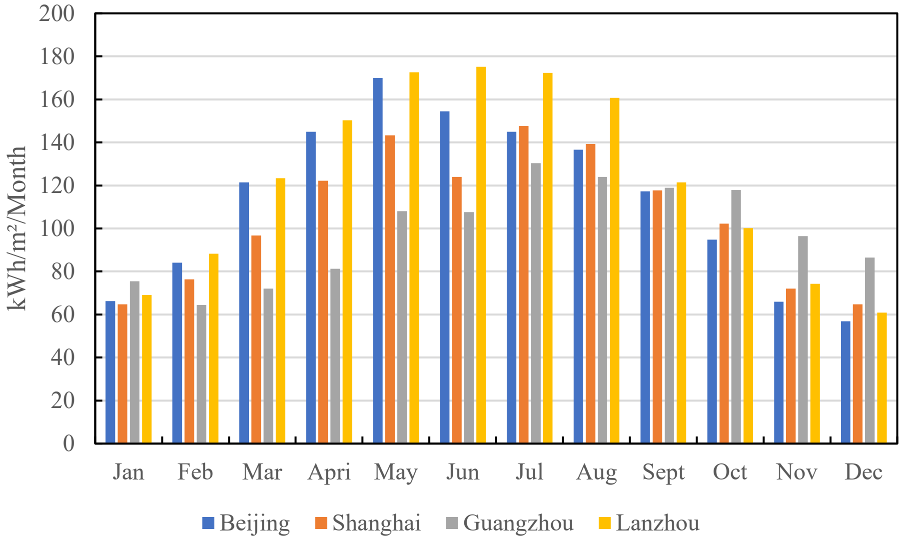

Figure 5-6 Monthly average global solar radiation for the proposed cities

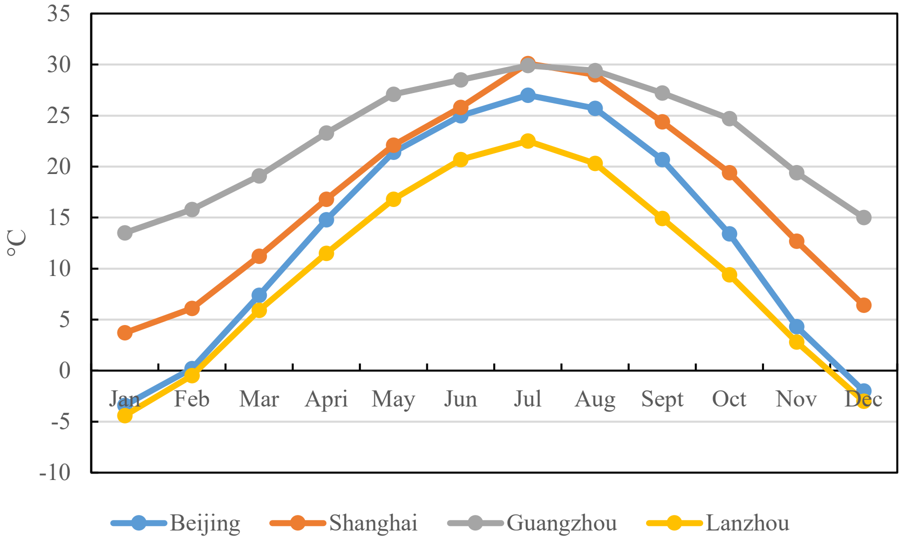

Figure 5-7 Monthly average temperature for the proposed cities

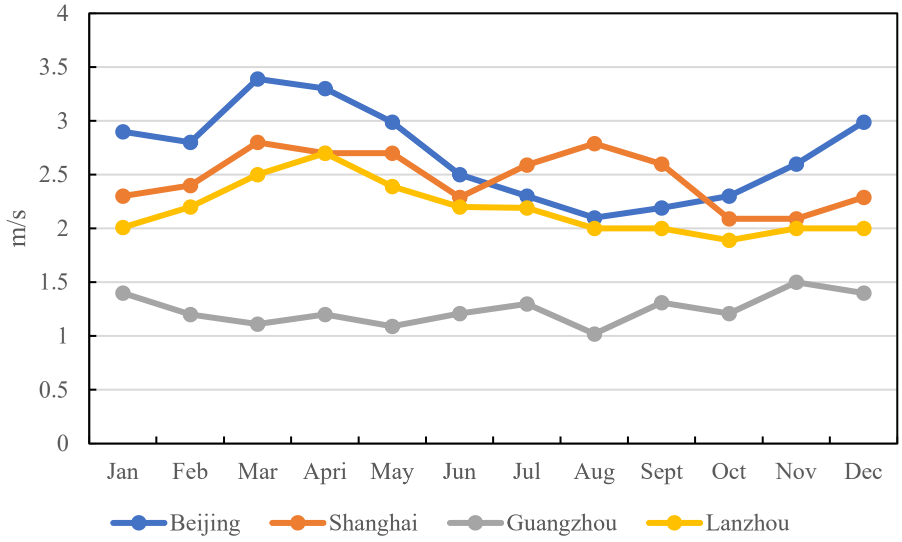

Figure 5-8 The monthly average wind speed for the proposed cities

5.3.2.3 Annual residential load profile

Figure 5-9 and 5-10 illustrates the typical load profile of Chinese households for different seasons, which is calculated based on the annual electricity consumption provided by authoritative statistical reports and the load characteristics of Chinese households using the built-in model provided by SAM software (30 Day Shrink 2020)(Khanna and Berkeley 2016)(Zhang and Lahr 2018). Low demand occurs between 07:00 and 18:00, when most people have gone to work or school, resulting in low electricity consumption. On the other hand, peak load demand occurs at night between 18:00 and 22:00 hours. This is mainly because all the family members go home in the evening and start their own recreational activities, resulting in high electricity consumption. The lowest electricity consumption in the four regions occurs in the spring and fall, and the highest electricity consumption occurs in the summer.

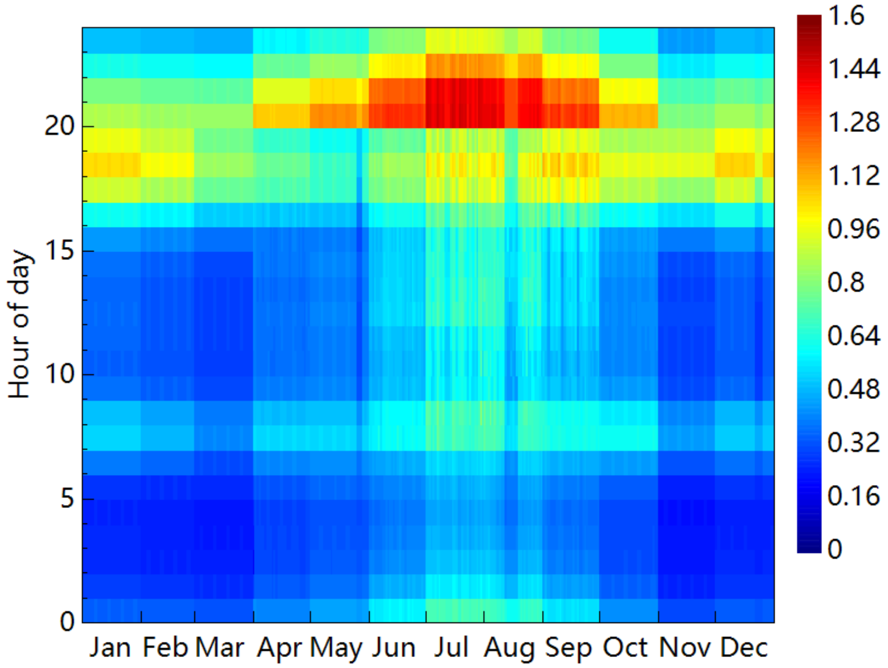

Figure 5-9 Heat map of annual household electricity load in China

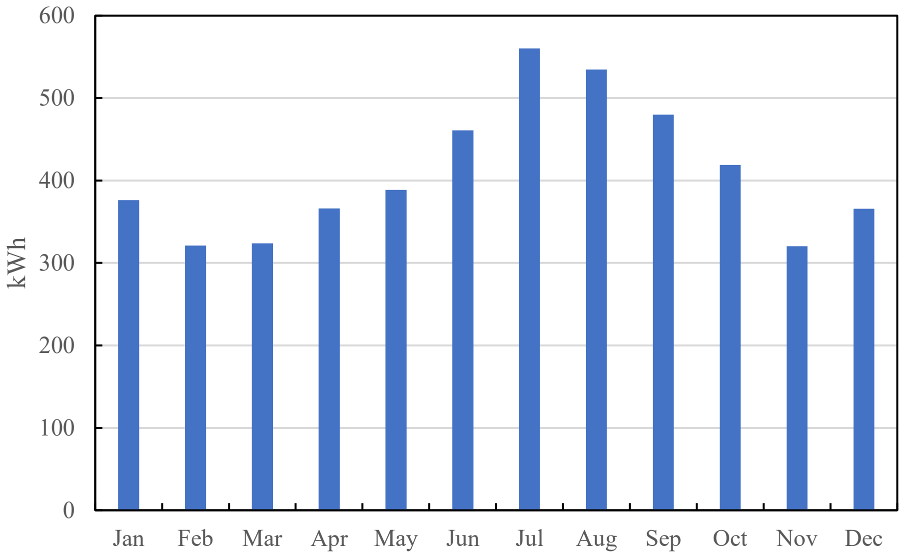

Figure 5-10 Monthly load characteristics in China

5.3.2.4 Electricity tariffs in study cities

Table 5-7 describes the electricity price of regional residents, which we used to calculate the income from self-consumed electricity. These electricity prices vary according to the geographic location where the PV system is installed. The current electricity price in the country highly depends on the consumption level, time of use, region and time of year. The average prices are between 0.88

USD/kWh to 0.13 USD/kWh for residential consumers. In addition, the FIT is also described in Table.

Table 5-7 The average electricity tariff and FIT price in selected cities.

Region	**Major electricity company**	**City**	**FIT (cent/kWh)**	**Average Tariff (cent/kWh)**
North	North China power grid	Beijing	1.1594	8.8407
East	East China power grid	Shanghai	1.1594	11.3045
Southern	China Southern power grid	Guangzhou	1.1594	13.6234
Northwest	Northwest power grid	Lanzhou	1.1594	11.7393

5.3.3. Germany

5.3.3.1 Research location

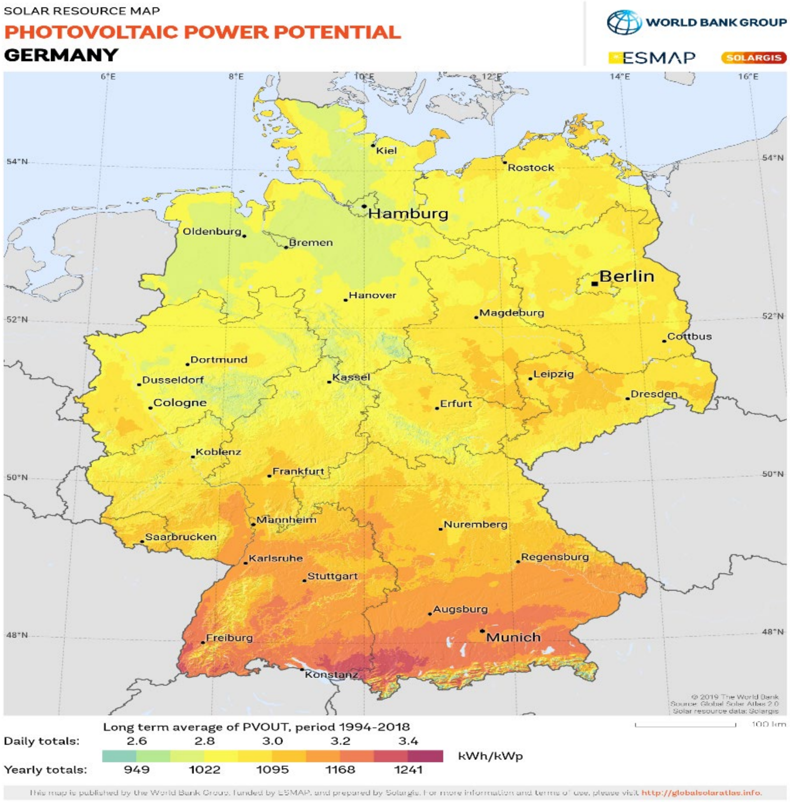

Figure 5-11 Solar PV power potential in Germany (Sources: Solar GIS)

Germany has a temperate maritime climate with most of the country having a cool temperate climate. (Figure 5-11) The northwestern and northern parts of the country are heavily influenced by the maritime climate and receive rainfall all year round, where winters are relatively mild and summers are cool. The eastern region has a continental climate with long, cold winters and hot summers. According to the solar resource map of the Solar GIS, long-term averages of PV production range from 949 kWh/kW to 1241 kWh/kW. PV in Germany is uploaded to four major power transmission companies, Amprion in the west, 50Hertz in the east, TenneT in the center, and TransnetBW in the south. To study the impact parameters of these power transmission companies, four representative cities, Dortmund in the east, Stuttgart in the south, Munich in the south-central region, and Berlin in the northwest, were selected. Figure 5-12 shows the geographical locations of these four cities, and Table 5-8 gives their coordinate information.

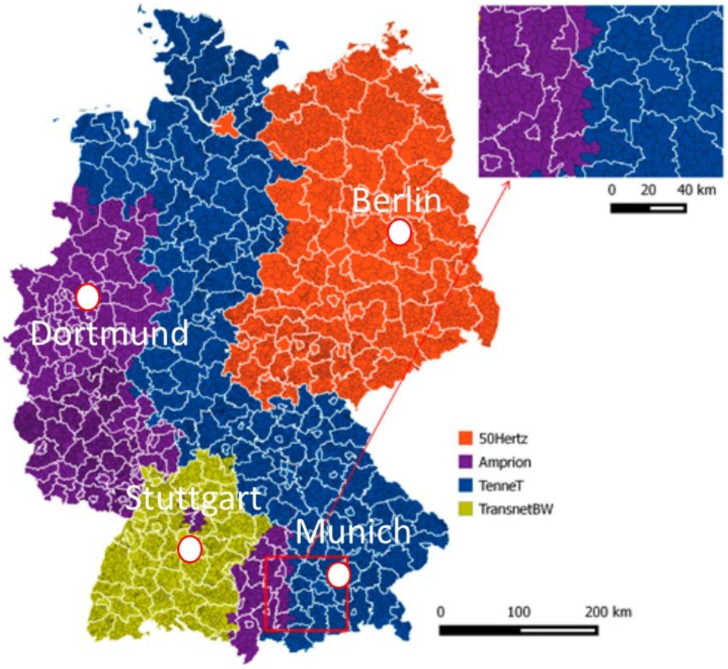

Figure 5-12 Geographical location of the transmission system operators (TSOs) in Germany

Table 5-8 Geographical coordinates of the study cities

	Dortmund	Berlin	Stuttgart	Munich
Latitude (°N)	51.5149	52.5244	48.7823	48.1374
Longitude (°E)	7.466	13.4105	9.177	11.5755
Altitude (m)	93	52	259	536
Latitude (°N)	Amprion	50Hertz	TransnetBW	TenneT

5.3.3.2 Climatic data for the cities under study

The solar radiation data used in this study are from METEONORM V7.0. Figures 5-13 show the global monthly average solar radiation for the proposed locations throughout the year. The highest monthly solar radiation values occur in July in Dortmund and Munich, and the highest in May in Berlin and Stuttgart. The lowest monthly radiation for all four cities occurs in December.

The ambient temperature data is important to determine the actual output power of the PV modules. Figure 5-14 show the monthly average ambient temperature data for the proposed sites obtained from METEONORM V7.0 software. The minimum ambient temperatures for the four cities were 3.1°C, -0.2°C, 1.1°C, and -1.1°C in January and the maximum ambient temperatures were 19.1°C, 19.6°C, 19.2°C, and 18.9°C in July, respectively. Figures 5-15 show the monthly average wind speeds in Dortmund, Berlin, Stuttgart and Munich.

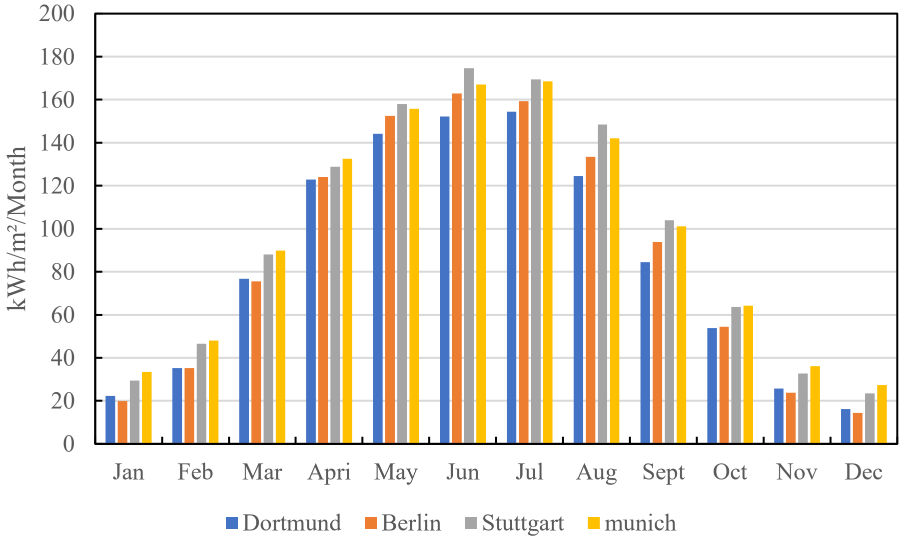

Figure 5-13 Monthly average global solar radiation in study cities

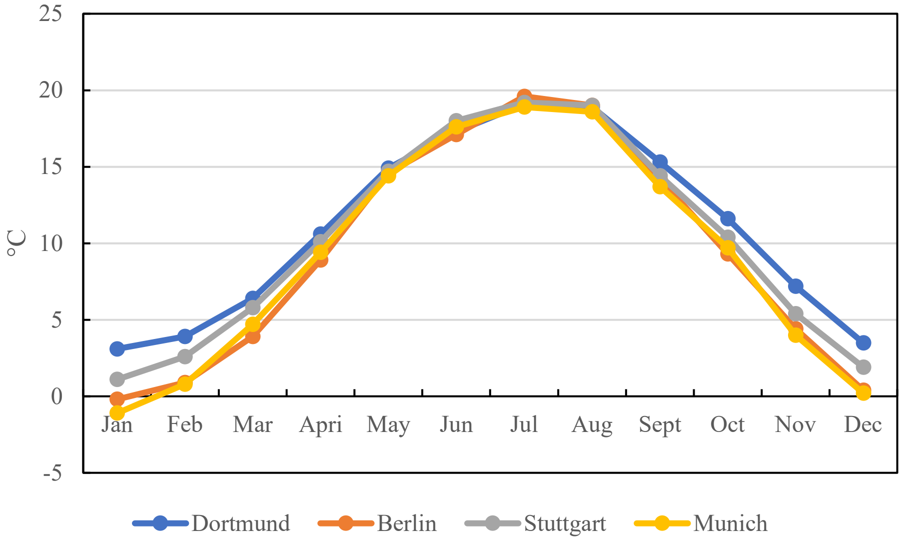

Figure 5-14 Monthly average temperature in study cities

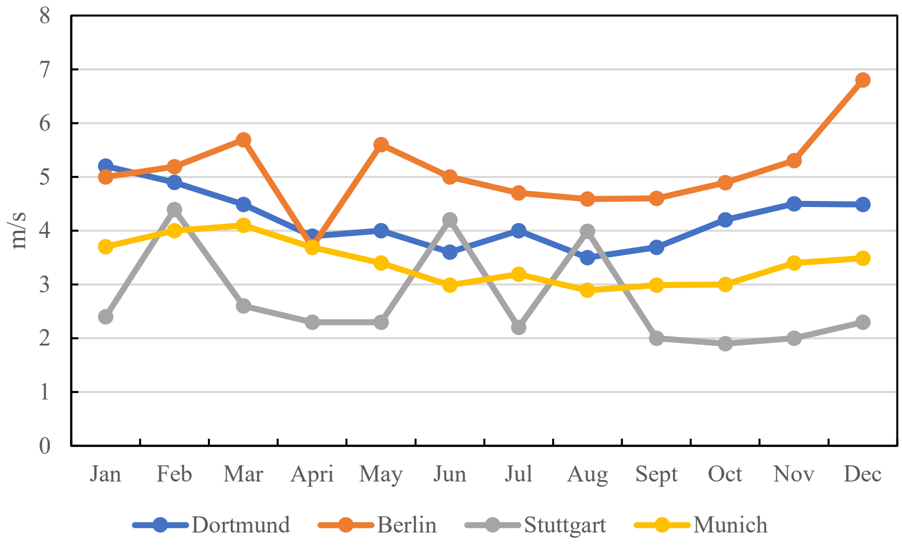

Figure 5-15 Monthly average wind speed in study cities

5.3.2.3 Annual residential load profile

Figure 5-16 shows the typical load profile of a German household for a year, which is calculated based on the annual electricity consumption provided by authoritative statistical reports and the load characteristics of German households, using the built-in model provided by SAM software (Clean Energy Wire 2019)(Schlomann et al. n.d.). Low demand occurs between 07:00 and 16:00 in spring and autumn, when most people have already left for work or school, resulting in low electricity consumption. On the other hand, peak load demand occurs in the evening between 18:00 and 22:00 when all the family members go home in the evening and start their recreational activities, resulting in high electricity consumption. The peak load time is longer in summer this is mainly due to the cooling equipment that may be used. The lowest electricity consumption in the four regions occurs in the spring and fall, while the highest electricity consumption occurs in the summer.

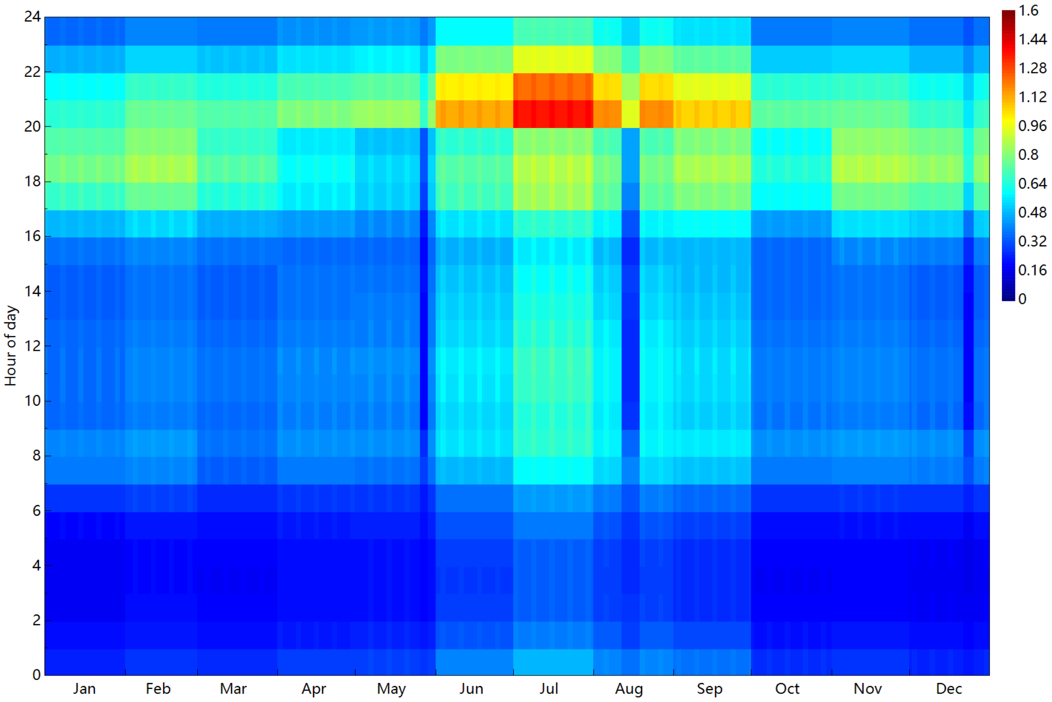

Figure 5-16 Daily average load profiles in a year for the study regions

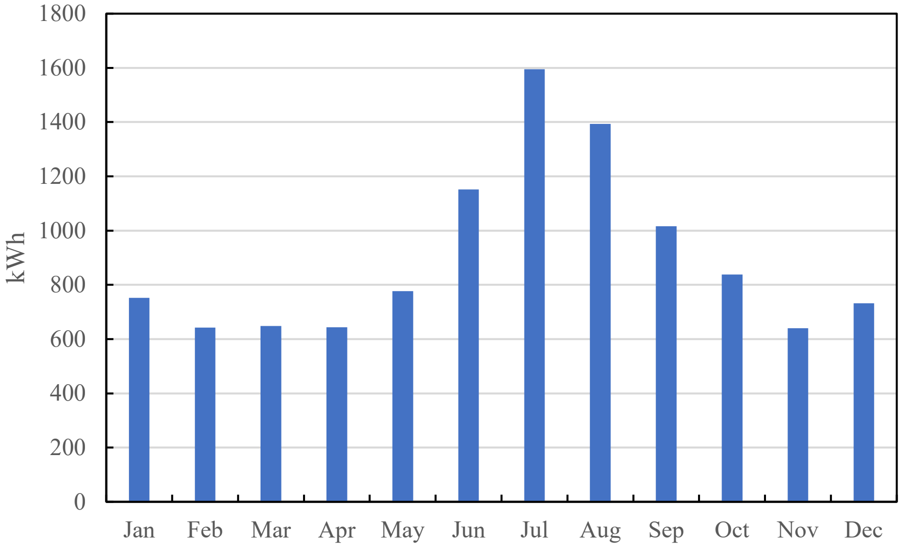

Figure 5-17 Monthly load characteristics of household in Germany

5.3.3.4 Electricity tariffs in selected cities

Table 5-9 describes the residential electricity prices in the city, which we use to calculate the income from PV energy self-consumption and purchased electricity from the grid. These tariffs vary depending on the geographical location where the PV storage system is installed. The current electricity prices are highly dependent on the level of consumption, time of use, region and time of day (summer and winter time). The average price for residential customers ranges from \$0.345/kWh to \$0.31/kWh. In addition, Table 5-9 describes the average price of FIP in Germany in the year 2000.

Table 5-9 The electricity tariff and average FIP price in selected cities in 2020.

Region	**Major electricity company**	**City**	**FIT (cent/kWh)**	**Average Tariff (cent/kWh)**
North	Amprion	Berlin	11.8	32.1
East	50Hertz	Stuttgart	11.8	31.1
Southern	TransnetBW	Dortmund	11.8	32.3
Northeast	TenneT	Munich	11.8	34.5

5.3.4. Japan

5.3.4.1 Research location

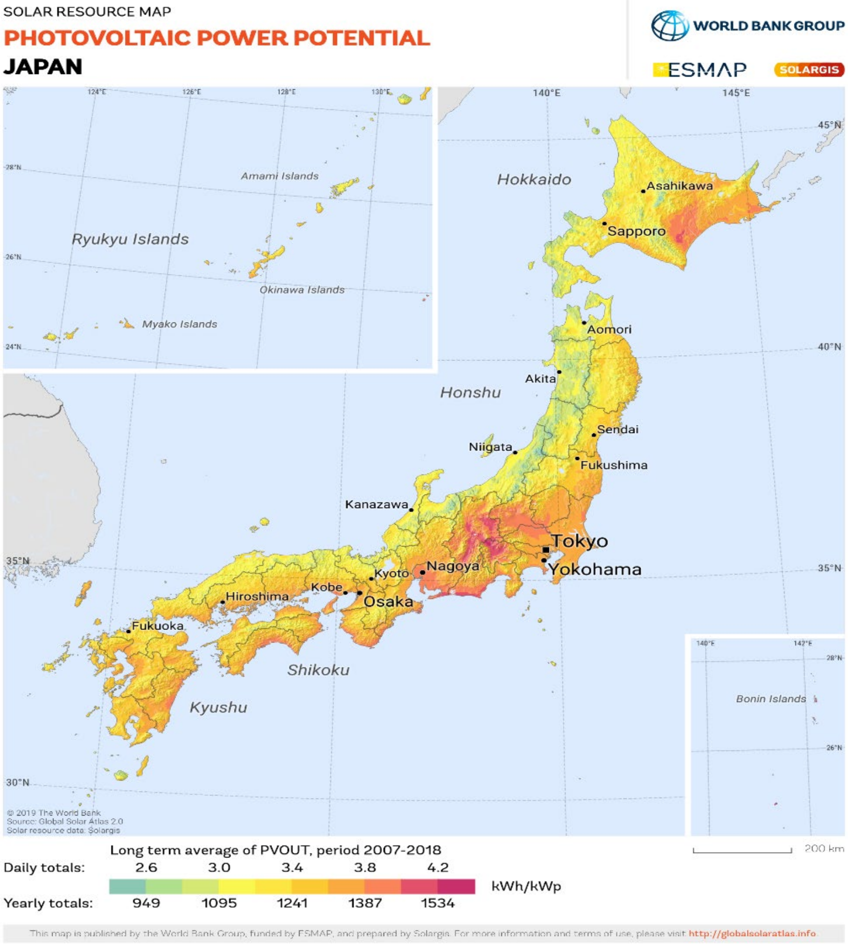

Figure 5-18 Solar PV power potential in Japan (Sources: Solar GIS)

Japan has a temperate continental humid climate in Hokkaido and Tohoku; Honshu, Shikoku, Kyushu, and Ryukyu Islands have a subtropical humid climate, and the temperature difference between the north and south is significant due to the rather large latitude across Japan. Based on the areas under the jurisdiction of Japan's nine major power companies, we selected four typical cities across Japan as research locations. The basic electricity tariff and the feed-in electricity tariff after FIT are different for each city. Regarding the division of regional electricity prices, we took into account the official Japanese division method since 1905, dividing Japan into eight regions, and then selecting eight cities as the main research locations based on the locations of major Japanese power companies. At the same time, the different solar radiation and climatic conditions in different regions also change the performance of the PV system (Kobashi et al. 2020). Because Okinawa is far away from the Japanese mainland, we did not take Okinawa into consideration due to its geographical particularity. Figure 5-19 shows the location of four cities in study regions.

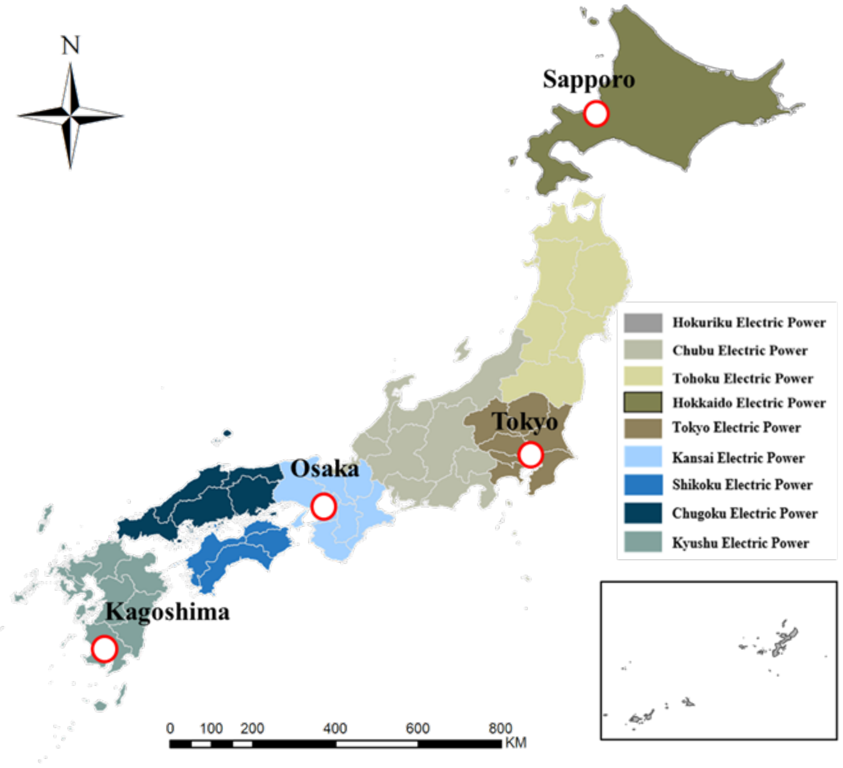

Figure 5-19 Japan Electric Power Company's grid distribution and selected cities

Table 5-10 Geographical coordinates of the study cities

	Tokyo	**Osaka**	**Sapporo**	**Kagoshima**
Latitude (°N)	35.6895	34.6937	43.0667	31.5667
Longitude (°E)	139.6917	135.5022	141.35	130.55

Altitude (m)	52	14	29	14
Grid company	Tokyo	Kansai	Hokkaido	Kyushu

5.3.4.2 Climatic data for the study cities

The climate data used in this study are from Meteonorm 7.2. the annual solar radiation and average atmospheric ambient temperature of the selected cities are shown in Figures 5-20 and 5-21. the highest solar radiation months in all four cities are July and August, and the lowest solar radiation month is December. Kagoshima has the highest total annual solar radiation, Osaka ranks second, and Tokyo is the lowest.

Ambient temperature data are essential for evaluating the efficiency and power output of PV panels. The lowest month of ambient temperature for all four cities is in January, and the highest score occurs in August for all four cities. Figure 5-22 shows the average wind speed data for the selected sites, with Sapporo having the highest average wind speed and Kagoshima the lowest.

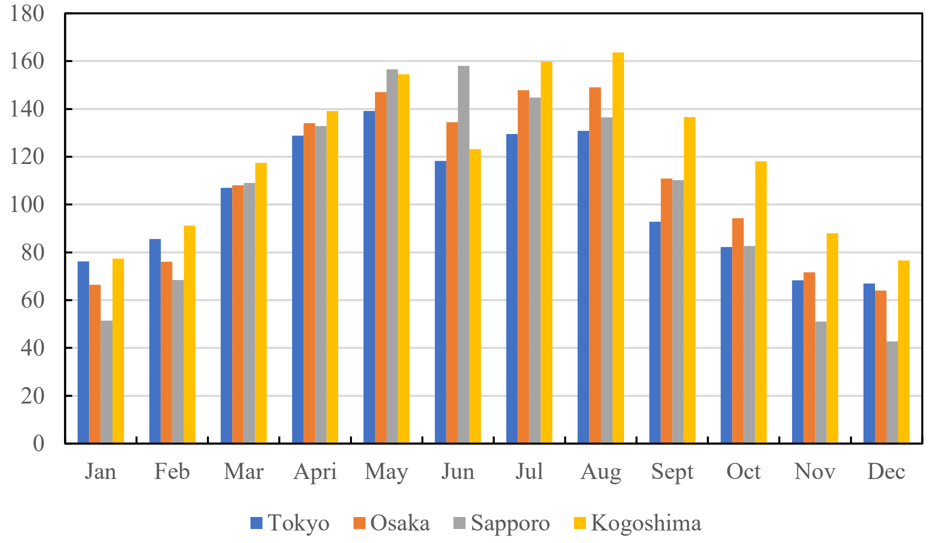

Figure 5-20 Monthly average global solar radiation in study cities

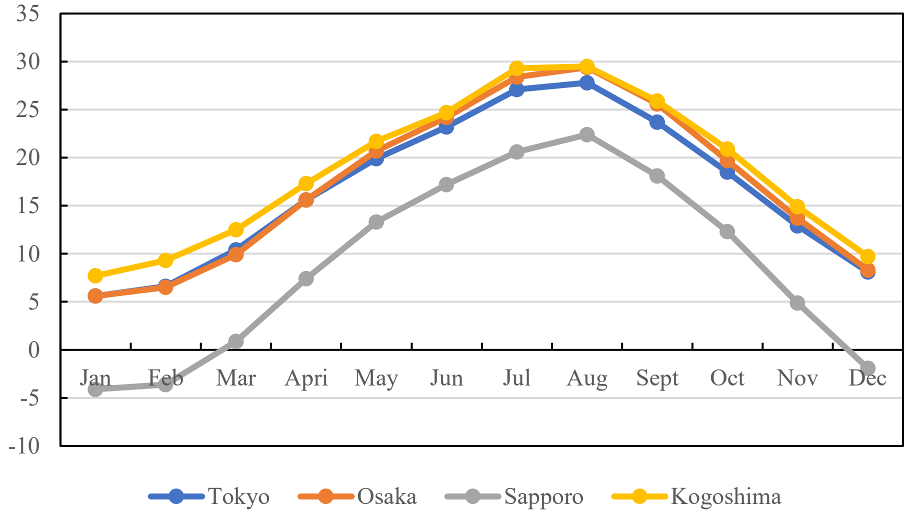

Figure 5-21 Monthly average temperature in study cities

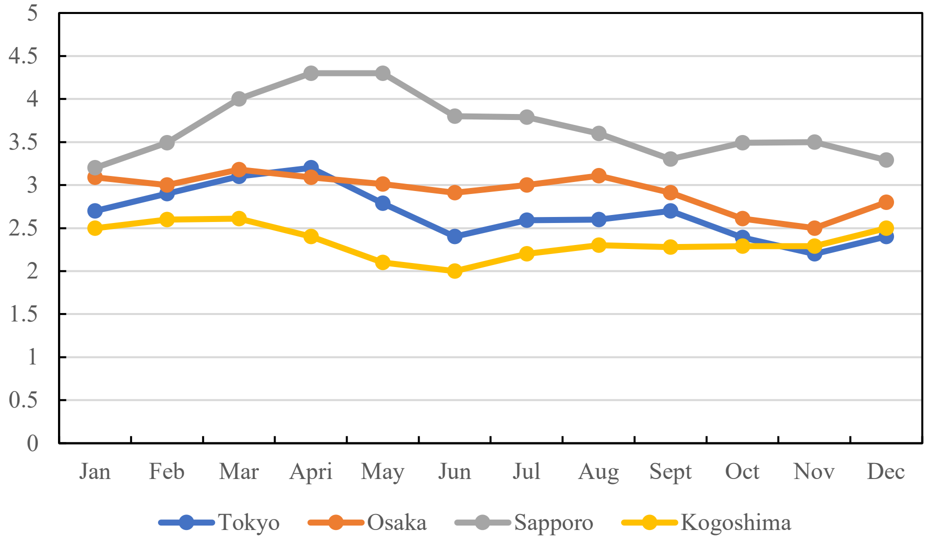

Figure 5-22 Monthly average wind speed in study cities

5.3.4.3 Annual residential load profile

Realistic time series of domestic electricity demand and PV production throughout the year should be used to evaluate the potential for self-consumption and the levelized cost of a residential battery storage system. This is necessary to account for the match between solar generation and household consumption at each moment of the day.

The electricity loads in this chapter composed of approximately 200 residential households in Japan, and local climate information were obtained from on-site physical meters over 1 year (Figure 5-23 and 5-24). The daily peak electricity loads of the household mainly occur in the early morning and the evening, which is a common habit in Japan households.

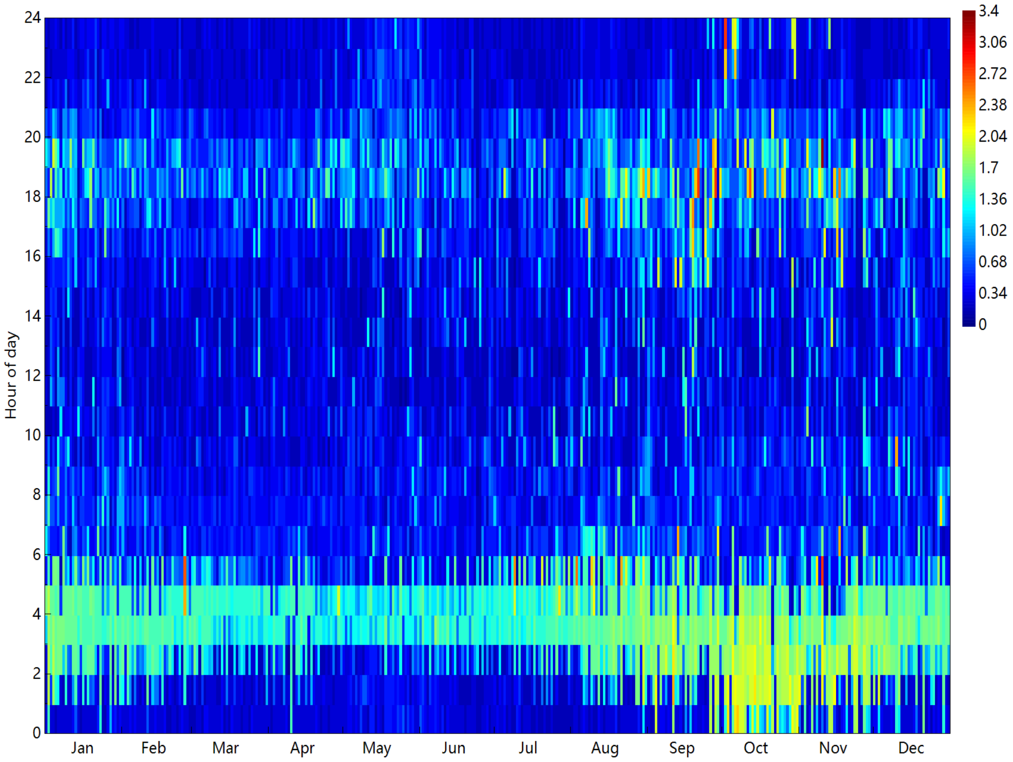

Figure 5-23 Heat map of annual household electricity load in Japan

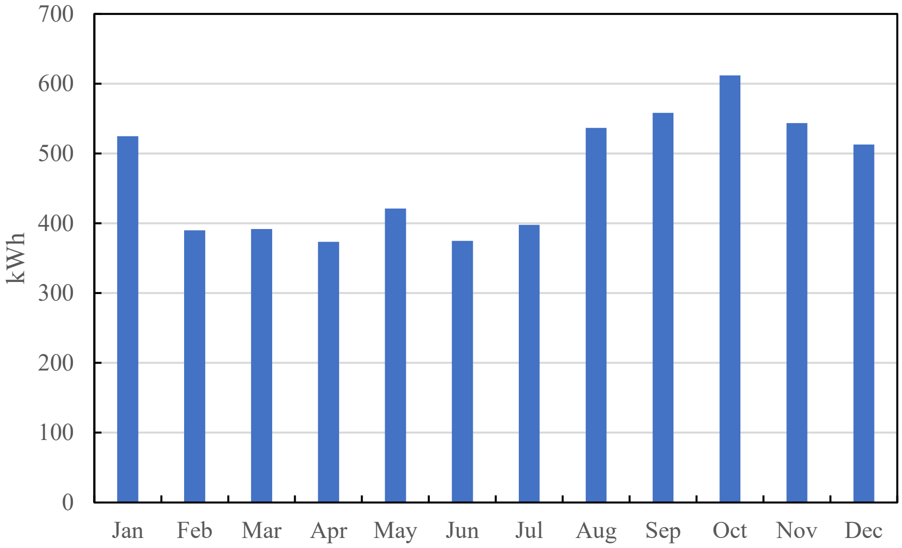

Figure 5-24 Monthly load characteristics of household in Japan

5.3.4.4 The electricity tariff and average FIT price

Table 5-11 describes the electricity price of regional residents, which we used to calculate the income from self-consumed electricity. These electricity prices vary according to the geographic location where the PV energy storage system is installed. The current electricity price in the country highly depends on the consumption level, time of use, region and time of year (summer and winter times). The average prices are between 0.28 USD/kWh to 0.22 USD/kWh for residential consumers. In addition, the nine electric power companies' purchase prices for feed-in energy after the FIT are also described in Table 5-11.

Table 5-11 The electricity tariff and Surplus price after FIT in selected cities.

Region	**Major electricity company**	**City**	**FIT (cent/kWh)**	**Average Tariff (cent/kWh)**
Hokkaido	Hokkaido Electric Power Company	Sapporo	20	28
Kanto	Tokyo Electric Power Company	Tokyo	20	25
Kansai	Kansai Electric Power Company	Osaka	20	22
Kyushu	Kyushu Electric Power Company	Fukuoka	20	23

5.3.5.U.S.A.

5.3.5.1 Research location

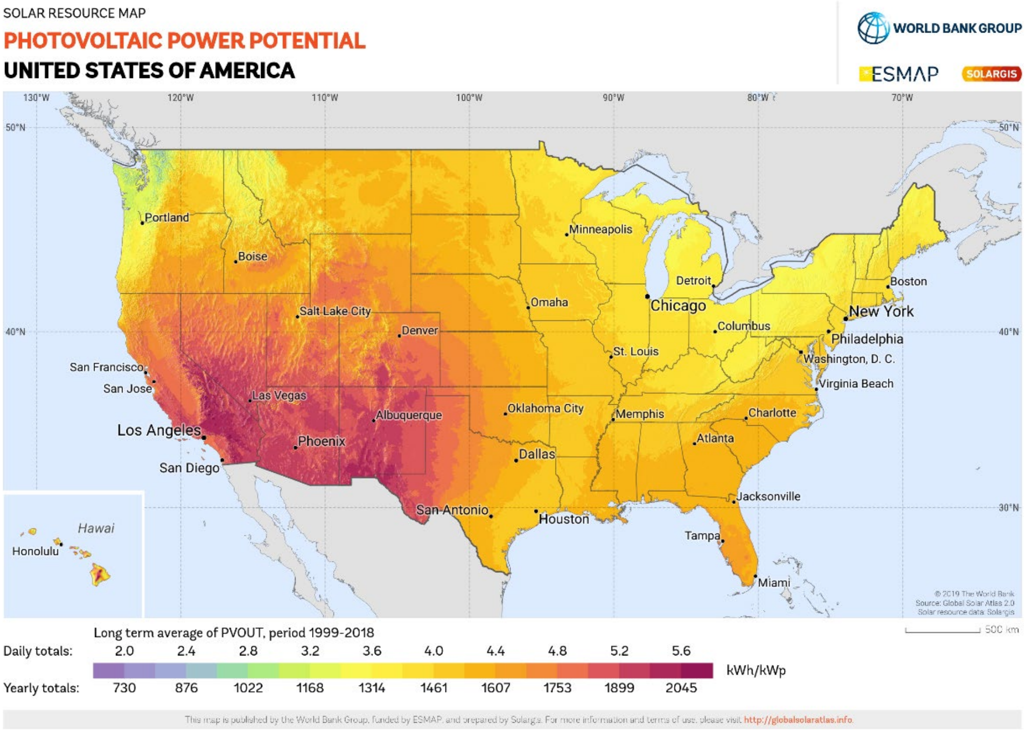

Figure 5-25 Solar PV power potential in the USA (Sources: Solar GIS)

The United States is a vast country with complex topography and is subject to different air currents, and the climate varies greatly from place to place (Figure 5-25). The northeastern coast and the Great Lakes region have a temperate continental climate with cooler temperatures, while the southeast has a subtropical monsoonal humid climate with warm and humid conditions. The northern Pacific coast has a temperate maritime climate zone with warm winters and cool summers. According to the solar resource map of Solar GIS, the long-term average of photovoltaic power generation is 730 kWh/kW to 2045 kWh/kW. electric power grid in the United States is divided into three grid interconnection companies, namely West interconnect, Eastern interconnect. Larger electricity networks are created through the interconnection of local grids, which are linked for commercial and reliability purposes. At the highest level, the network covering the lower 48 states is comprised of three major interconnections, functioning predominantly independently of one another with limited exchanges of power between them. Based on the grid distribution and geographic location, we selected four representative cities, Portland in the northwest, Los Angeles in the southwest, Houston in the south-central region, and New York in the northwest. Figure 5-26 shows the geographical locations of these four cities, and Table 5-11 gives their coordinate information.

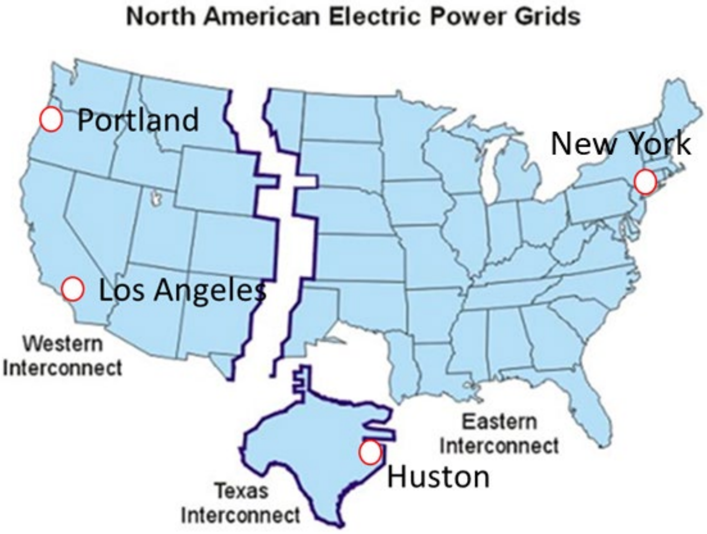

Figure 5-26 Geographical location of North American Electric Power Grid Interconnect and selected cities

Table 5-12 Geographical coordinates of the study cities

	Los Angeles	New York	Houston	Portland
Latitude (°N)	34.0522	40.7143	29.7633	45.5235
Longitude (°E)	-118.244	-74.006	-95.3633	-122.676
Altitude (m)	91	46	33	26
Interconnect company	Western	Eastern	Texas	Western

5.3.5.2 Climatic data for the study cities

The climate data used in this study are from Meteonorm 7.2. The annual solar radiation and mean ambient atmospheric temperature for the selected cities are shown in Figures 5-27 and 5-28. The months with the highest solar radiation in all four cities are June and July, and the months with the lowest solar radiation are December and January. Los Angeles has the highest total annual solar radiation, with Houston ranking second and Portland the lowest.

Ambient temperature data is critical for evaluating the efficiency and power output of PV panels. The lowest ambient temperatures in New York and Houston occur in January, with the highest scores occurring in July and August, while Los Angeles has temperatures above 10 degrees throughout the year, with the highest occurring in July August and September, with an average temperature of around 22 degrees. Figure 5-29 shows the average wind speed data for the selected locations, with the highest average wind speeds in New York and Houston and the lowest in Los Angeles.

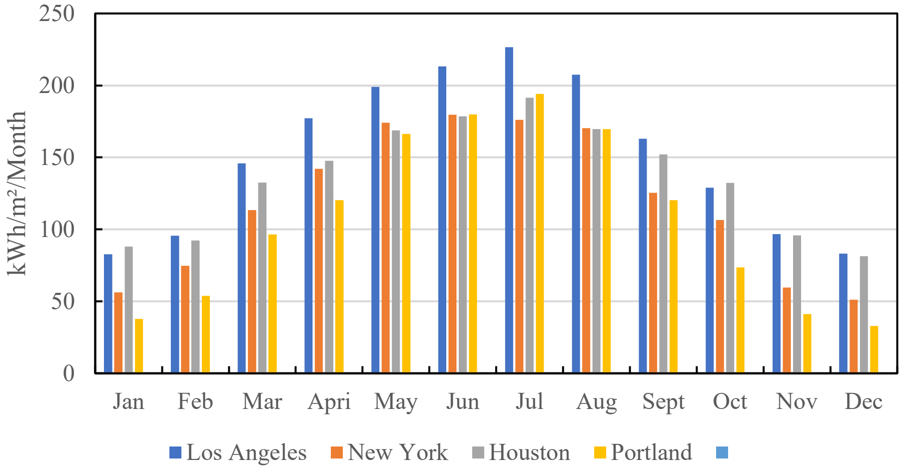

Figure 5-27 Monthly average global solar radiation in study cities

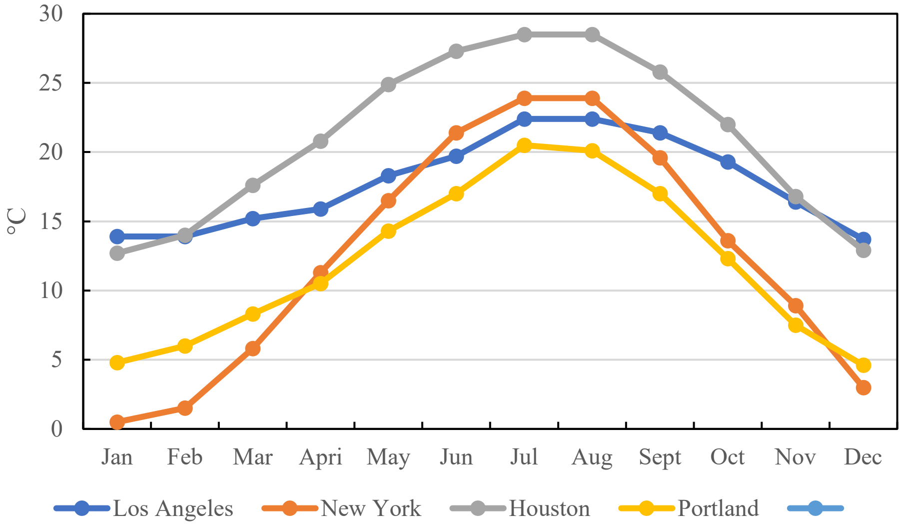

Figure 5-28 Monthly average temperature in study cities

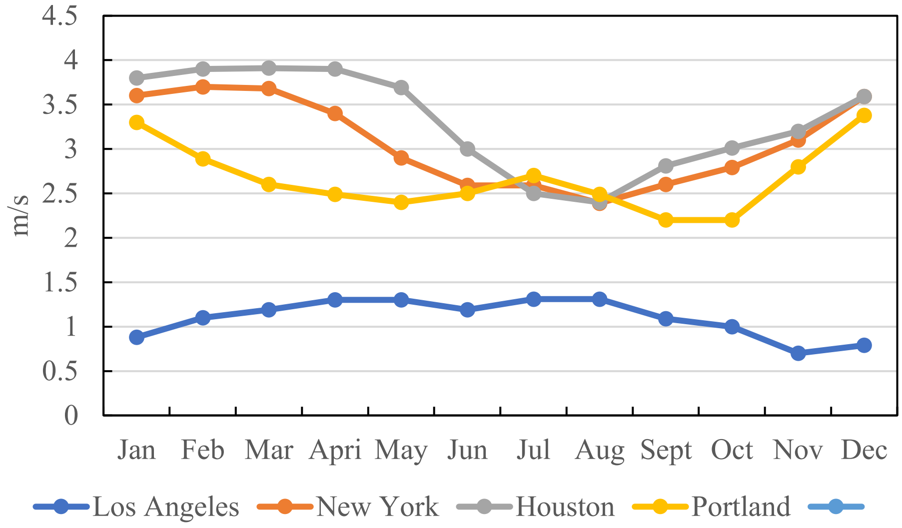

Figure 5-29 Monthly average wind speed in study cities

5.3.2.3 Annual residential load profile

Figure 5-30 shows the year-round electricity load for U.S. residential customers as provided by SAM software. Low demand occurs between 07:00 and 16:00, when most people have gone to work or school, resulting in low electricity consumption. On the other hand, peak load demand occurs at night between 18:00 and 22:00 hours. This is mainly because all the family members go home in the evening and start their own recreational activities, resulting in high power consumption. Summer load occurs mainly from 12:00 to 22:00, which is due to summer vacation and summer cooling load.

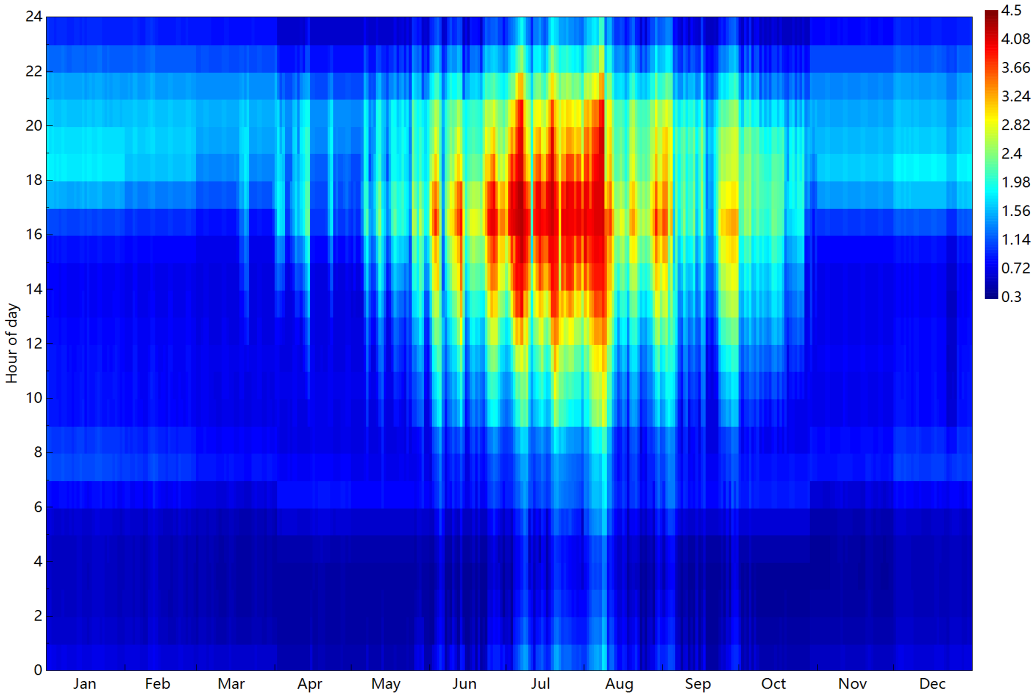

Figure 5-30. Heat map of annual household electricity load in USA

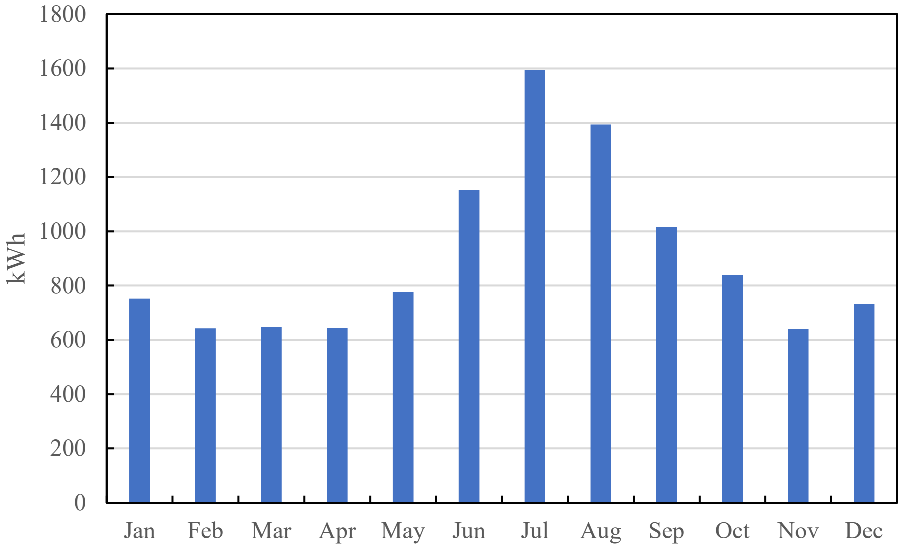

Figure 5-31. Monthly load characteristics of household in USA

5.3.4.4 Electricity tariffs in study regions

Table 5-13 describes the electricity price of regional residents, which we used to calculate the income from self-consumed electricity. These electricity prices vary according to the geographic location where the PV energy storage system is installed. The current electricity price in the country highly depends on the consumption level, time of use, region and time of year (summer and winter times). The average prices are between 0.23 USD/kWh to 0.11 USD/kWh for residential consumers.

Table 5-13 The electricity tariff in selected cities.

Region	**Major electricity grid interconnect companies**	**City**	**Average Tariff (cent/kWh)**
North	Western Interconnect	New York	23.2
East	Eastern Interconnect	Houston	13.5
Southern	Texas Interconnect	Los Angeles	17.1
Northeast	Western Interconnect	Portland	10.7

5.4.Results

5.4.1.Techno-economic analysis results of residential PV systems

5.4.1.1 China

(1) Technical analysis

Figure 5-32 shows the average monthly energy production of 5 kW residential PV systems in the cities studied. The lowest energy production in Beijing was 521 kWh in December, while the highest was 683 kWh in May. The lowest energy yield for 5 kW PV systems in Shanghai was 381.7 kWh in

January, while the highest was 598 kWh in August. In Guangzhou, the lowest energy production was 238 kWh in March and the highest was 491 kWh in October. In Lanzhou, the lowest generation was 561 kWh in December and the highest was 705 kWh in August.

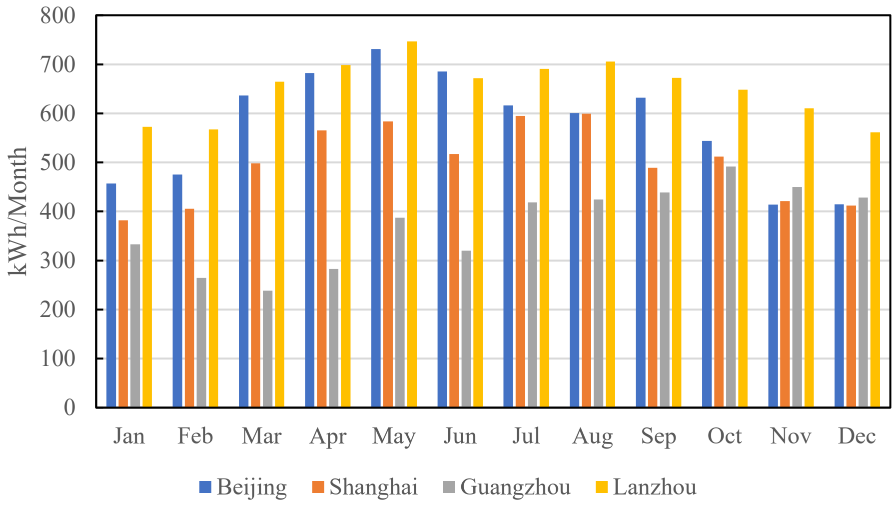

Figure 5-32 Energy production per month in study cities

Figure 5-33 shows the annual energy production of the selected cities, with Guangzhou having the lowest energy production of 4479 kWh and Lanzhou the highest at 7810. solar power plants perform best in Lanzhou because it is located in the solar-rich northwest region with an annual energy production of 1593 kWh per kWh. the average solar radiation of 5.07 kWh/m^2/day is most suitable for photovoltaic power plants . Guangzhou has the lowest power plant production with its annual energy production of 914kWh/kW and its hot weather and less supportive power generation conditions. The main simulation results for all locations are compared in Table 5-14.

The most important parameters for comparing the performance of different systems are the performance ratio and CF. The simulation results for the five selected locations show that Lanzhou City has the highest energy yield with a performance ratio of 86% and a CF of 18.2%. Guangzhou has the lowest energy yield with a PR of 0.79 and a CF of only 10.4%

Table 5-14 Performance parameters in study cities

Performance Parameters				
	Beijing	Shanghai	Guangzhou	Lanzhou
Solar Radiation (kWh/m²/day)	4.86	4.1	3.26	5.07
Energy Production (kWh/year 1)	7166	5979	4478	7810
Energy Yield (kWh/kW/year 1)	1462	1220	914	1593
Performance ratio	0.82	0.81	0.79	0.86

Capacity factor	16.70%	13.90%	10.40%	18.20%

(2) Economic analysis

Scenario 1: PV system with support policies

The economic aspects should be considered to assess the investment benefits of PV power systems. Proper economic analysis, such as NPV, LCOE and payback period, can ensure the profitability of the PV system investment.

In the case of China, the feed-in tariff (FiT) is 1.1594 cent/kWh set by the government in 2020, which is used to calculate the price of PV energy to be fed into the grid. Table 5-15 shows the residential electricity prices and local government generation subsidies for four cities, there are no subsidy for battery system in four cities. Both Shanghai Beijing and Guangzhou have generation subsidies for a period of 5 to 6 years. Figure 5-33 shows the cash flows for the proposed projects in the four cities. The results show that Beijing has the highest return on investment due to its higher annual energy production from PV and local generation subsidies. The study shows that Guangzhou has the lowest NPV because it has the lowest annual energy production and lower local generation subsidy prices.

Table 5-15 Support policy and electricity tariff

City	**Subsidy (cent/kWh)**	**Duration(year)**	**Tariff (cent/kWh)**	**Feed-in Tariff (cent/kWh)**
Shanghai	4.34	5	8.8407	1.1594
Beijing	4.34	5	11.3045	1.1594
Guangzhou	2.17	6	13.6234	1.1594
Lanzhou	-	-	11.7393	1.1594

Table 5-16 shows that Beijing has the lowest LCOE and the shortest payback period due to energy production capacity and policy. In terms of electricity bill savings, Lanzhou has the highest electricity bill savings due to its highest annual generation capacity. Shanghai has the lowest NPV and the highest payback period because of the lower electricity tariff.

Table 5-16 Economic indicators in scenario 1

	Beijing	**Guangzhou**	**Lanzhou**	**Harbin**
LCOE(nominal)	3.73	7.69	4.9	5.43
LCOE(real)	3.04	6.28	3.99	4.43
Energy bill without system (USD/year1)	367	443	381	381
Energy bill with system (USD/year1)	126	215	111	144
Net savings (year 1)	241	227	270	237
NPV(USD)	369	-417	-175	-733
PBP(years)	10.7	15	14.4	16.4

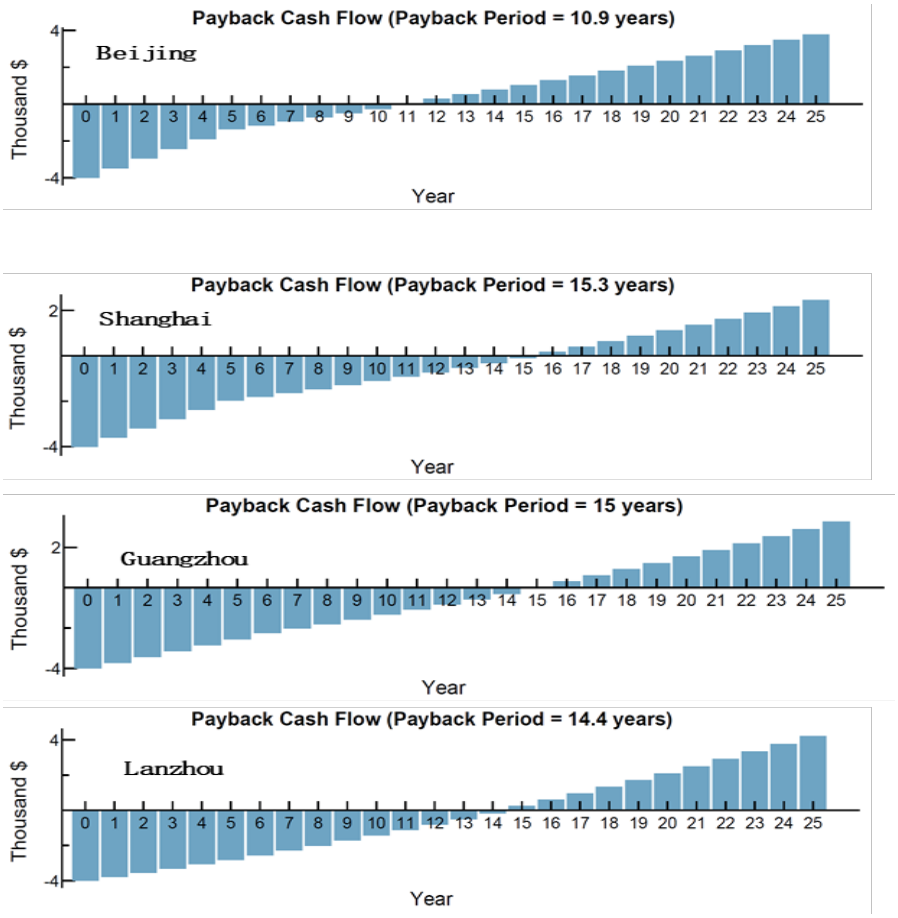

Figure 5-33 Payback Cash Flow in four cities

2) Scenario 2: PV system without support policies

In the second scenario setting, PV systems in four cities will lose all PV subsidies. The LCOE is still the highest in Guangzhou and the lowest in Lanzhou due to generation capacity. Shanghai has the lowest NPV and investment that cannot be recovered over the life of the project, and the best economics is Lanzhou, but the NPV is still negative. It can be seen that after leaving the PV subsidy policy, residential PV is not investment feasibility in China.

Table 5-17 Economic indicators in scenario 2

	Beijing	**Shanghai**	**Guangzhou**	**Lanzhou**
LCOE(nominal) (cent/kWh)	5.29	6.41	8.56	4.9
LCOE(real) (cent/kWh)	4.32	5.23	6.99	3.99
NPV(USD)	-2002	-2657	-1770	-1656
PBP(years)	24.3	NaN	22.3	21.3

3) Scenario 3: PV and battery system with support policies

In the third scenario, the PV system will be combined with a battery system. In this scenario, the self-consumption rate of PV electricity will be increased, thus the amount of electricity purchased from the grid are decreased. The LCOE is increasing and the NPV is negative in all four cities and no profit on investment can be obtained. The highest return on investment among the four cities is in Beijing with a payback period of 13.1 years.

Table 5-18 Economic indicators in scenario 3

	Beijing	**Shanghai**	**Guangzhou**	**Lanzhou**
LCOE(nominal) (cent/kWh)	5.6	7.1	11	6.5
LCOE(real) (cent/kWh)	4.5	5.8	8.7	5.3
NPV(USD)	-195	-1444	-1629	-1202
PBP(years)	13.1	18.3	18.5	16.9

5.4.1.2 Germany

(1) Technical analysis

Figure 5-34 shows the average monthly energy production of 5 kW residential PV systems in the studied cities. The lowest energy yield for 5kW PV systems in Berlin was 73 kWh in December, while the highest was 631 kWh in July. The lowest energy yield for a 5kW PV system in Munich was 134 kWh in December, while the highest was 684 kWh in July. In Dortmund, the lowest energy production was 96 kWh in December, while the highest was 593 kWh in May. In Stuttgart, the lowest generation was 148 kWh in December and the highest was 679 kWh in July.

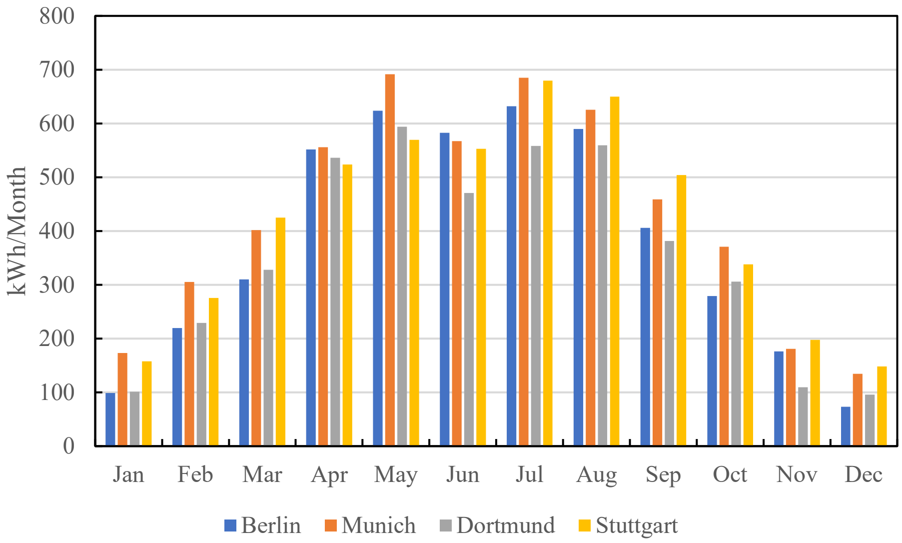

Figure 5-34. Energy production per month in study cities

Table 5-19 shows the annual energy production of the selected cities, with Berlin having the lowest energy production of 73 kWh and Munich the highest at 684 kWh. Solar power plants perform is best in Munich because it is located in the solar-rich northwest region with an annual energy production of

5150 kWh/year. The average solar radiation of 3.46 kWh/m2/day is most suitable for PV system in those four cities. Dortmund has the lowest energy production with its annual energy production of 871kWh/kW, because its less supportive energy generation environment with 2.88 kWh/m2/day. The main simulation results for all cities are compared in Table 5-18.

The most important parameters for comparing the performance of different systems are the PR and CF. The simulation results for the four selected cities in Figure 13 show that Munich City has the highest energy yield with a PR of 83% and a CF of 12%. Dortmund has the lowest energy yield with a PR of 82% and a CF of only 9.9.

Table 5-19 Performance parameters in study cities

Performance Parameters				
	Berlin	**Munich**	**Dortmund**	**Stuttgart**
Solar Radiation (kWh/m²/day)	3.06	3.46	2.88	3.39
Energy Production (kWh/year 1)	4542	5150	4269	5021
Energy Yield (kWh/kW/year 1)	927	1051	871	1024
Performance ratio	0.82	0.83	0.82	0.83
Capacity factor	10.60%	12.00%	9.90%	11.70%

(2) Economic analysis

In the case of Germany, the average feed-in tariff (FiT) is 11.844 cent/kWh in 2020, which is used to calculate the price of PV energy to be inject into the grid. Table 5-20 shows the residential electricity tariff and local government PV generation subsidies for four cities. Munich, Dortmund and Stuttgart have investment subsidies for residential PV system. Figure 5-35 shows the cash flows for the proposed projects in the selected cities. The results show that Stuttgart has the highest NPV due to its higher residential tariff and local subsidies. The study shows that Berlin has the lowest NPV because there is no local investment subsidy in Berlin.

Table 5-20 Support policy and electricity tariff

City	**Subsidy (USD)**	**Tariff (cent/kWh)**	**Feed-in Tariff (cent/kWh)**
Berlin	-	32.1	11.844
Munich	240/kW	31.104	11.844
Dortmund	360 /set	32.28	11.844
Stuttgart	420-540/kW	34.452	11.844

Table 5-21 shows that Stuttgart has the lowest LCOE and the shortest payback period due to energy production capacity and policy. While Berlin has the lowest NPV and the highest payback period because of the lower electricity tariff and lower energy yielded. In terms of electricity bill savings, Stuttgart has the highest electricity bill savings due to its highest annual generation capacity. Berlin has the lowest NPV and the highest payback period because of the lowest electricity tariff.

Table 5-21 Economic indicators in scenario 1

	Berlin	**Munich**	**Dortmund**	**Stuttgart**
LCOE(nominal) (cent/kWh)	26.12	22.1	26.08	21.78
LCOE(real) (cent/kWh)	21.31	18.03	21.29	17.77
Energy bill without system (USD/year 1)	1439	1394	1447	1544
Energy bill with system (USD/year 1)	578	464	613	568
Net savings (USD/year 1)	860	930	834	976
NPV(USD)	-1673	-71	-1179	1176
PBP(years)	14.8	13.4	14.5	12.3

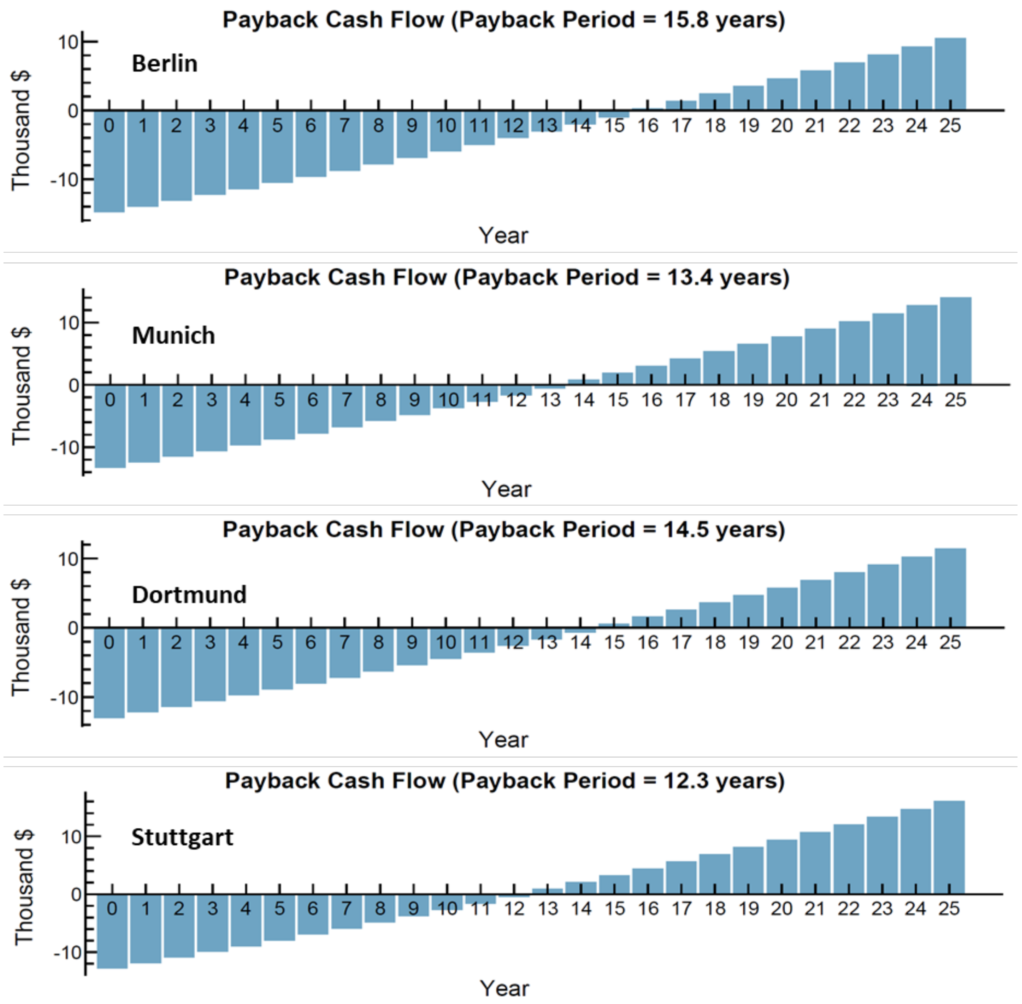

Figure 5-35 Payback Cash Flow in four cities

2) Scenario 2: PV system without support policies

In the second scenario, the PV systems in four cities are all without PV support policies, including national and local investment. The LCOE is the highest in Dortmumd and the lowest in Munich due to energy production capacity. Berlin has the lowest NPV and investment that cannot be recovered over the lifetime of the project, and the best economics is in Stuttgart, but the NPV is still negative. Compared to the NPV and PBP values in the situation of implementing the PV support policies in Germany, it can be seen that the 5kW residential PV system is not investment feasible in Germany after the cancled policies of PV support policies.

Table 5-22 Economic indicators in scenario 2

	Berlin	**Munich**	**Dortmund**	**Stuttgart**
LCOE(nominal) (cent/kWh)	26.12	24.45	29.51	25.08
LCOE(real)	21.31	19.95	24.08	20.47
NPV(USD)	-7549	-7450	-7440	-6474
PBP(years)	24.8	24.5	24.5	22.1

3) Scenario 3: PV and battery system with support policies

In the third scenario, the PV system will be combined with a battery system. In this scenario, the self-consumption rate of PV electricity will be increased, thus the amount of electricity purchased from the grid are decreased. The LCOE is increasing and the NPV is negative in three cities ,except Stuttgart, and no profit on investment can be obtained. The only profitable investment in a PV battery system was in Stuttgart with an NPV of 1587 USD and a payback period of 12 years.

Table 5-23 Economic indicators in scenario 3

	Berlin	**Munich**	**Dortmund**	**Stuttgart**
LCOE(nominal) (cent/kWh)	30	26	30	25
LCOE(real) (cent/kWh)	25	21	25	21
NPV(USD)	-1777	-113	-1223	1587
PBP(years)	14.6	13.3	14.3	12

5.4.1.3 Japan

(1)Technical analysis

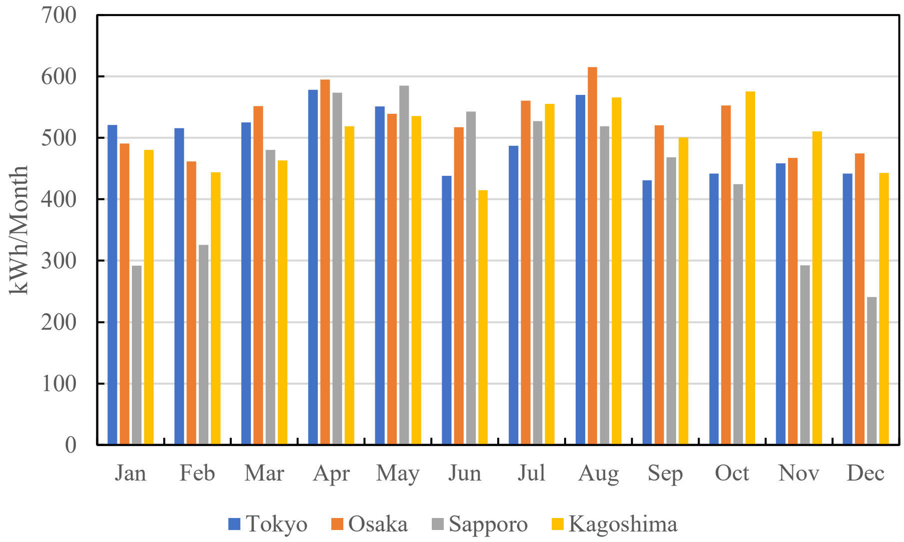

Figure 5-36. Energy production per month in study cities

Figure 5-36 shows the average monthly energy production of 5 kW residential PV systems in the cities studied which is distributed in Tokyo, Osaka, Sapporo, and Kagoshima of Japan. The lowest energy production for 5kW PV systems in Tokyo was 430 kWh in September, while the highest was 570 kWh in August. The lowest energy yield for a 5kW PV system in Osaka was 461 kWh in February, while the highest was 615 kWh in August. In Sapporo, the lowest energy production was 240 kWh in December, while the highest was 585 kWh in May. In Kagoshima, the lowest generation was 410 kWh in June and the highest was 566 kWh in August.

Table 5-24 shows annual energy production in selected zones, the lowest energy production is observed in Sapporo (240 kWh) and highest in Osaka (615 kWh). The solar plant gives the best performance in Osaka because it is located in the highest solar resource region with 4.34 (kWh/m²/day) normalized production. The plant energy production is lowest in Sapporo due to normalized production of 3.53 (kWh/m²/day) and less supportive weather conditions.

The most important parameters to compare the performance of different systems are normalized to PR and CF. Simulation results for five selected locations in Fig. 13 have shown the highest normalized production in Osaka city with 82% PR and 14.80% CF. While the lowest normalized production for per kW is located in Sapporo with 84% PR and 12.30% CF.

Table 5-24 Performance parameters in study cities

Performance Parameters				
	Tokyo	**Osaka**	**Sapporo**	**Kagoshima**
Solar Radiation (kWh/m²/day)	4.04	4.34	3.53	4.12
Energy Production (kWh/year 1)	5959	6347	5273	6009
Energy Yield (kWh/kW/year 1)	1216	1295	1076	1226
Performance ratio	0.83	0.82	0.84	0.81
Capacity factor	13.90%	14.80%	12.30%	14.00%

(2) Economic analysis

In the case of Japan, the feed-in tariff (FIT) is selected 0.2 USD / kWh to calculate annual saving from the solar plant. Table 5-25 shows the residential electricity tariff and local government PV generation subsidies for four cities, including Tokyo, Osaka, Sapporo, and Kagoshima. Both four regions show that the residential electricity tariff and local government PV generation subsidies are 10 years. The cash flow of the proposed project on selected locations is shown in Fig. 5-37. The results show that the highest NPV is obtained from Kagoshima location due to the higher annual energy production and support policies. The study reveals the lowest NPV at the Osaka site because of the lowest support policies obtained.

Table 5-25 Support policy and electricity tariff

City	**PV Subsidy (USD)**	**Battery subsidy (USD)**	**Tariff (cent/kWh)**	**Feed-in Tariff (cent/kWh)**	
Tokyo	922/set		25	20	10 years
Osaka	-		23	20	10 years
Sapporo	337 /kW		28	20	10 years
Kagoshima	190/kW		23	20	10 years

Table 5-26 shows that Kagoshima has the lowest LCOE and the shortest payback period due to energy production capacity and policy. In terms of electricity bill savings, Sapporo has the highest electricity bill savings due to its highest electricity tariff. Osaka has the lowest NPV and the highest payback period because of the lowest electricity tariff.

Table 5-26 Economic indicators in scenario 1

	Tokyo	**Osaka**	**Sapporo**	**Kagoshima**
LCOE(nominal) (cent/kWh)	18.36	18.44	19.56	18.17
LCOE(real)	14.98	15.04	15.96	14.83

(cent/kWh)				
Energy bill without system (USD/year 1)	1409	1297	1578	1297
Energy bill with system (USD/year 1)	143	-18	861	49
Net savings (USD/year 1)	1267	1315	718	1247
NPV(USD)	613	-23	11892	1713
PBP(years)	12.8	13.3	12.6	12.3

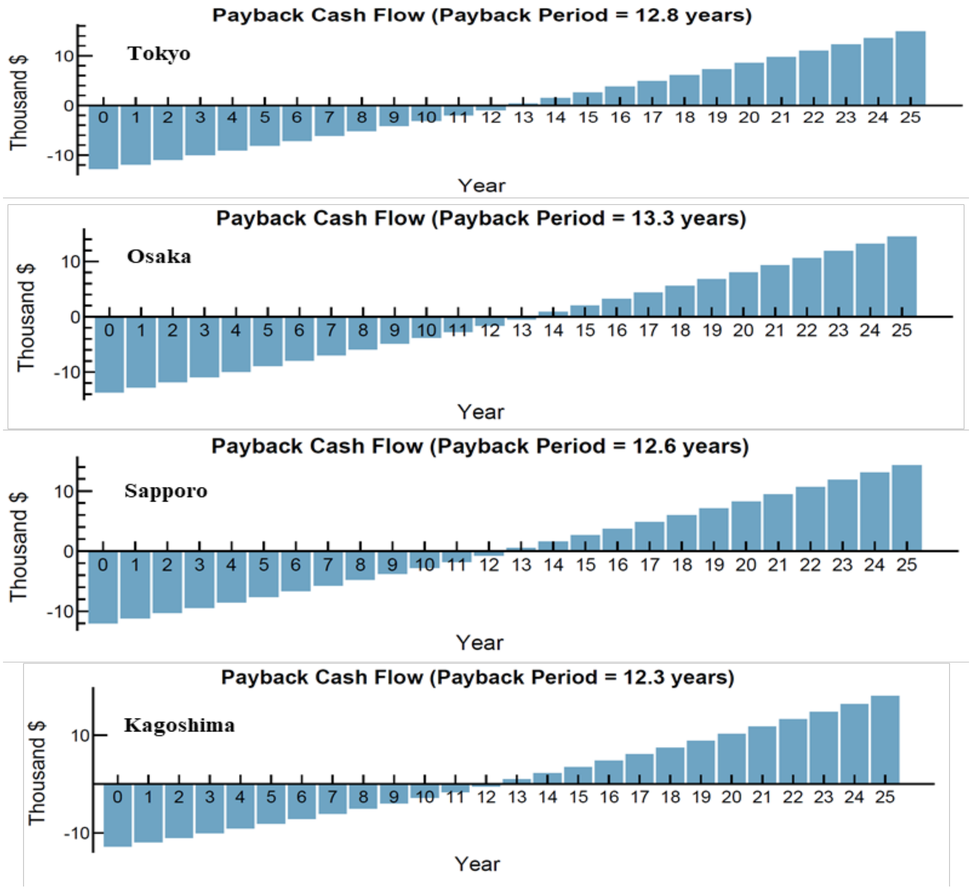

Figure 5-37 Payback Cash Flow in four cities

2) Scenario 2: PV system without support policies

In the second scenario, PV systems in four cities will without all PV support policies, including national and local investment. The LCOE is the highest in Sapporo and the lowest in Kagoshima due to energy production capacity. Berlin has the lowest NPV and investment that cannot be recovered over the lifetime of the project, and the best economics is in Kagoshima, but the NPV is still negative. It can be seen that after without the PV support policies, 5kW residential PV system is not investment feasible in Japan.

Table 5-27 Economic indicators in scenario 2

	Tokyo	**Osaka**	**Sapporo**	**Kagoshima**
LCOE(nominal) (cent/kWh)	18.36	18.44	19.56	18.17
LCOE(real) (cent/kWh)	14.98	15.04	15.96	14.83
Energy bill without system (USD/year 1)	1409	1297	1578	1297
Energy bill with system (USD/year 1)	143	-18	861	49
Net savings (USD/year 1)	1267	1315	718	1247
NPV(USD)	-2465	-3365	-1878	-1695
PBP(years)	16.2	17.2	15.6	15.5

3) Scenario 3: PV and battery system with support policies

In the third scenario, the PV system will be combined with a battery system. In this scenario, the self-consumption rate of PV electricity will be increased, thus the amount of electricity purchased from the grid are decreased. The LCOE is increasing and the NPV is negative in all four cities and no profit on investment can be obtained. The highest return on investment among the four cities is in Beijing with a payback period of 13.1 years.

Table 5-28 Economic indicators in scenario 3

	Tokyo	**Osaka**	**Sapporo**	**Kagoshima**
LCOE(nominal) (cent/kWh)	18.36	18.44	19.56	18.17
LCOE(real) (cent/kWh)	14.98	15.04	15.96	14.83
Energy bill without system (USD/year 1)	1409	1297	1578	1297
Energy bill with system (USD/year 1)	143	-18	861	49
Net savings (USD/year 1)	1267	1315	718	1247
NPV(USD)	-2465	-3365	-1878	-1695
PBP(years)	16.2	17.2	15.6	15.5

5.4.1.4 USA

(1) Technical analysis

Figure 5-38 shows the average monthly energy production of 5 kW residential PV systems in the studied cities. The lowest energy production in New York was 417 kWh in December, while the highest was 660.8 kWh in July. the lowest energy production of 480.0 kWh from PV systems in Houston occurred in December, and the highest was 671 kWh in May. In Los Angeles, the lowest generation was 603.1kWh in December, and the best was 870.1kWh in August. in Portland, the lowest generation was 227.4kWh in January, and the highest was 732.1kWh in July.

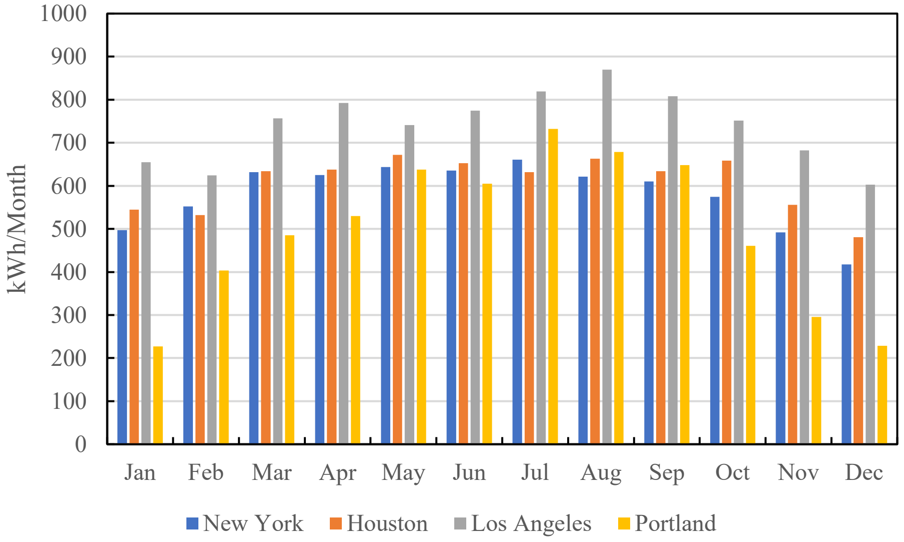

Figure 5-38 Energy production per month in study cities

Table 5-29 shows annual energy production in selected cities, the lowest energy production is observed in Portland 227.4 kWh and highest in Los Angeles 870.1 kWh. The solar plant gives the best performance in Los Angeles because it is located in the highest solar resource region with 6.25 kWh/m²/day normalized production. The plant energy production is lowest in Portland due to normalized production of 4.16 kWh/m²/day and less supportive weather conditions. The main simulation results are compared for all locations in Table 5-29.

The most important parameters for comparing the performance of different systems are the performance ratio (PR) and capacity factor (CF). The simulation results for the four selected cities in Table 5-29 show that Los Angeles City has the highest energy yield with a PR of 80% and a CF of 20.70%. Portland has the lowest energy yield with a PR of 80% and a CF of only 13.8%.

Table 5-29 Performance parameters in study cities

Performance Parameters				
	New York	Houston	Los Angeles	Portland
Solar Radiation (kWh/m²/day)	4.72	5.36	6.25	4.16
Energy Production (kWh/year 1)	6961	7298	8878	5932
Energy Yield (kWh/kW/year 1)	1420	1489	1811	1210
Performance ratio	0.82	0.78	0.8	0.8
Capacity factor	16.20%	17.00%	20.70%	13.80%

(2) Economic analysis

The economic aspects should be considered to assess the investment benefits of PV systems. Proper economic analysis, such as NPV, LCOE and payback period, those parameters could ensure the profitability of the PV system investment.

In the case of USA, the ITC rate was set by the government in 2020, which is used to offset the taxes paid by PV generation. Table 5-30 shows the residential electricity tariff and local government PV generation subsidies for four cities. Figure 5-39 shows the cash flows for the proposed projects in the selected cities. The results show that Los Angeles has the highest NPV due to its higher annual energy production from PV and local generation subsidies. The study shows that Portland has the lowest NPV because it has the lowest annual energy production.

Table 5-30 Support policy and electricity tariff

City	**Support policies**		**Tariff (cent/kWh)**	**Net-metering**
New York	ITC 26%	State ITC 25%	23.2	Y
Houston	ITC 26%	-	13.5	Y
Los Angeles	ITC 26%	-	17.1	Y
Portland	ITC 26%	State 1500USD/set	10.7	Y

Table 5-31 shows that Los Angeles has the lowest LCOE and the shortest payback period due to energy production capacity. In terms of electricity bill savings, Los Angeles also has the highest electricity bill savings due to its highest annual energy generation capacity. Portland has the lowest NPV and the highest payback period because of the lower electricity tariff and energy production.

Table 5-31 Economic indicators in scenario 1

	New York	**Houston**	**Los Angeles**	**Portland**
LCOE(nominal) (cent/kWh)	11.63	14.25	8.94	15.39
LCOE(real) (cent/kWh)	9.45	11.58	7.29	12.55
Energy bill without system (USD/year 1)	1806	1505	2320	1353
Energy bill with system (USD/year 1)	692	491	573	685
Net savings (USD/year 1)	1114	1014	1757	668
NPV(USD)	6796	2338	16086	-1325
PBP (years)	7.4	8.2	5.9	15

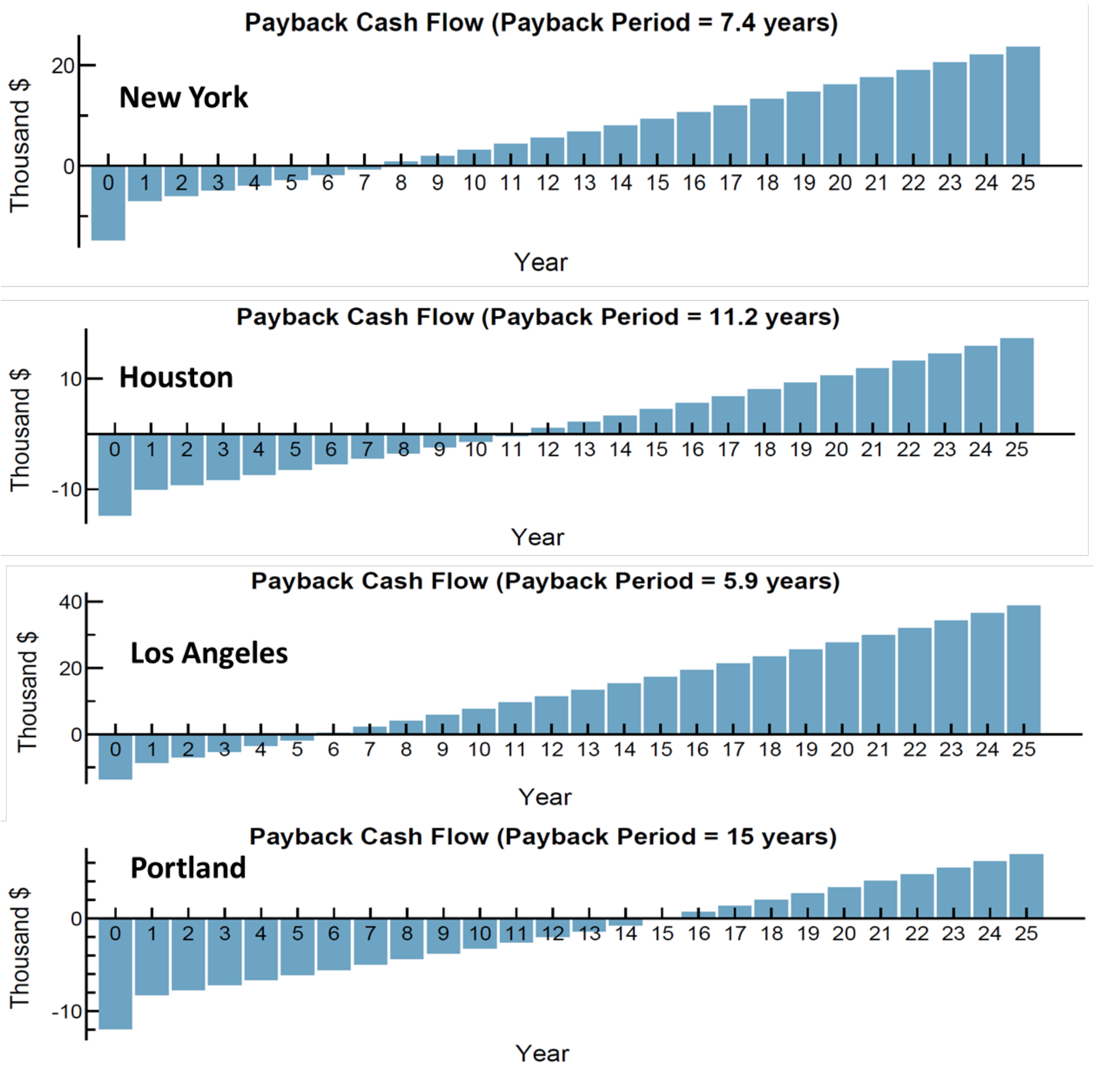

Figure 5-39 Payback Cash Flow in four cities

2) Scenario 2: PV system without support policies

In the second scenario, PV systems in four cities will without all PV support policies, including national and local investment (Table 5-32). The LCOE is still the highest in Portland and the lowest in Los Angeles due to energy production capacity. Portland has the lowest NPV and investment that cannot be recovered over the lifetime of the project, and the best economics is in Los Angeles. It can be seen that after without the PV support policies, 5kW residential PV system is not investment feasible in Portland, but there can be feasible in the other three area.

Table 5-32 Economic indicators in scenario 2

	New York	**Houston**	**Los Angeles**	**Portland**
LCOE(nominal) (cent/kWh)	19	18.12	12.95	19.93
LCOE(real) (cent/kWh)	15.43	14.17	10.57	16.26

NPV(USD)	-7818	-8432	-148	-1325
PBP(years)	NaN	14.6	NaN	NaN

3) Scenario 3: PV and battery system with support policies

In the third scenario, the PV system will be combined with a battery system (Table 5-33). In this scenario, the self-consumption rate of PV electricity will be increased, thus the amount of electricity purchased from the grid are decreased. The LCOE is increasing, but the NPV is only negative in all Portland. The highest return on investment among the four cities is in New York with a payback period of 8.7 years.

Table 5-33 Economic indicators in scenario 3

	New York	**Houston**	**Los Angeles**	**Portland**
LCOE(nominal) (cent/kWh)	13	16	15	18
LCOE(real) (cent/kWh)	11	13	12	15
NPV(USD)	5230	281	9530	-3326
PBP(years)	8.7	13	10	18.1

5.4.2.Techno-economic analysis results of large-scale PV plant

Considering the land region and solar radiation conditions required for large PV plants, we selected one city for each four countries as the site for large PV plants simulation. Lanzhou was selected for China, Munich for Germany, Osaka for Japan, and Los Angeles for the United States. The solar radiation conditions, temperature conditions, and wind speed conditions in each of the four cities are suitable for the construction of large PV plants. In the scale of the power plant, we selected a 2.5MW scale PV plant for technical and economic analysis and the economics of the PV plant will be influenced by the PV policies of each country in 2020. The technical parameters and detail cost of PV power plants are shown in Tables 5-34 to 37.

Table 5-34 System parameters in simulation

System parameters	
PV modules	248 strings of 24 modules in series, 5952 totals
Pnom	420 Wp
Pnom array	2500kW
Area	13243 m^2
Inverters	5 MPPT inputs

Table 5-35 Detail cost of PV power plant (Data source: IRENA, Cost report 2020)

Category	**Cost Component**	**China**	**Germany**	**Japan**	**USA**
Module and inverter hardware	Modules	266.553	374.891	450.813	358.097
(USD/kW)	Inverters	42.204	53.572	223.707	68.439
BoS hardware	Racking and mounting	8.673	85.37	116.45	113.671
(USD/kW)	Grid connection	61.674	81.961	112.121	61.781
	Cabling/ wiring	33.354	29.755	69.936	42.456
	Safety and security	6.373	12.898	19.884	18.672
	Monitoring and control	2.215	2.573	18.051	16.552
Installation	Mechanical installation	74.46	76.508	456.221	180.165
(USD/kW)	Electrical installation	34.513	26.118	292.125	68.323
	Inspection	25.589	5.273	34.731	21.441
Soft costs	Margin	91.131	99.06	123.725	173.29
(USD/kW)	Financing costs	73.332	5.49	63.477	19.811
	System design	30.089	36.399	5.073	22.843
	Permitting	11.535	4.286	50.199	8.868
	Support application	18.682	0.859	27.182	38.634
	Costumer acquisition	14.089	3.706	6.198	7.53
Total (USD/kW)		794.466	898.719	2069.893	1220.573

Table 5-36 Specification of the PV module in simulation

Specification of the module	
Manufacturer	Longi Solar
Module No.	LR4-72 HPH 420 M
Type	Si-mono
Reference conditions	
Gref	1000W/m2
Tref	25℃
Isc	11.040A
Voc	48.8V
Nominal operating cell temperature	45℃
Temperature coefficient of power	－0.36 % / ℃
Max Power Point	
Impp	10.450A
Vmpp	40.20V
Efficiency	
Cells	21.17%
Module	18.88%

Sizes & Technology	
Length	2115mm
Width	1052mm
Area	2.225m2

Table 5-37 Specification of the inverter in simulation

Specification of the inverter	
Manufacturer	Sungrow
Model	SG2500HV
Nominal PV power	2500kW
Maximum PV power	2750kW
Maximum PV Current	2624A
Minimum MPP voltage	800V
Maximum MPP Voltage	1300V
Maximum efficiency	99.00%

5.4.2.1 China

Figure 5-40 shows the monthly power generation and PR of large 2.5 MW PV plants in China. the highest month of energy injected into the grid (E_Grid) occurred in May with 326.8 MWh and the lowest month was December with 186.8 MWh. The highest PR in spring was above 85% in January, February and March, and the highest PR month of the year was January with 87.9% and the lowest was August with 71.5%. The total annual upload power of PV plants is 3310.9MWh with an annual average PR of 85%.

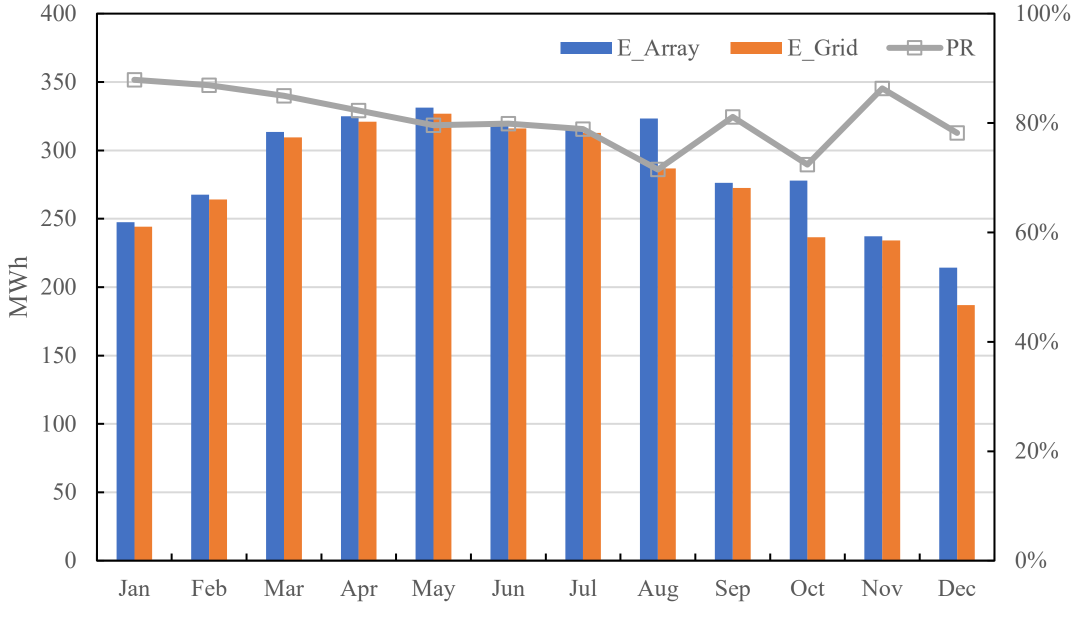

Figure 5-40 PV array energy production (E_Array), energy injected into the grid, and PR

Table 5-38 PV array energy production, energy injected into the grid, and PR

	E_Array	**E_Grid**	**PR**
	MWh	MWh	ratio
Jan	247.6	244.3	88%
Feb	267.5	264.1	87%
Mar	313.4	309.5	85%
Apr	325	320.9	82%
May	331.3	326.8	80%
Jun	320.1	316	80%
Jul	317	312.7	79%
Aug	323.4	286.7	72%
Sep	276.3	272.6	81%
Oct	278	236.5	72%
Nov	237.2	234.1	86%
Dec	214.2	186.8	78%
Year	3451	3310.9	81%

Table 5-39 shows the economic indicators of the PV plant. The LCOE of the PV plant is 3.7 cent/kWh, and the project can pay back the investment at 12.2 years with an IRR of 8.66%. It indicates that the power plant has a favorable return and is feasible for investment. Figure 5-41 shows the cashflow of the PV plant.

Table 5-39 Economic indicator of large-scale PV plant in China

Economic indicator	
LCOE(nominal) (cent/kWh)	3.7
NPV (USD)	489133.39
PBP (year)	12.2
IRR (%)	8.66

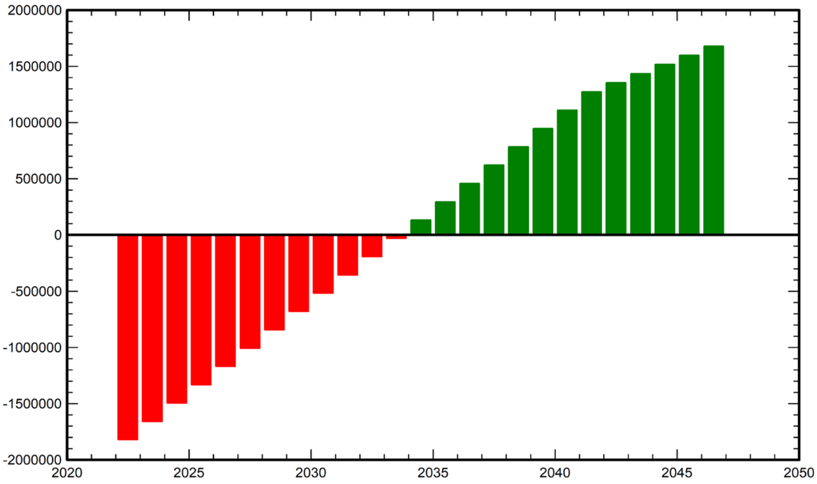

Figure 5-41 Cumulative cashflow of large-scale PV plant (USD/year)

5.4.2.2 Germany

Figure 5-42 shows the month-by-month power generation and PR for a large 2.5 MW PV plant in Germany. the highest month of uploading power to the grid occurred in July with 334.8 MWh and the lowest month was December with 128.8 MWh. the highest PR was above 89% in December and January/February in winter and the highest PR month of the year was 92% in December and the lowest was 72% in August. The total annual feed-in power of PV plants is 2873.8MWh, with an annual average PR of 84.4%.

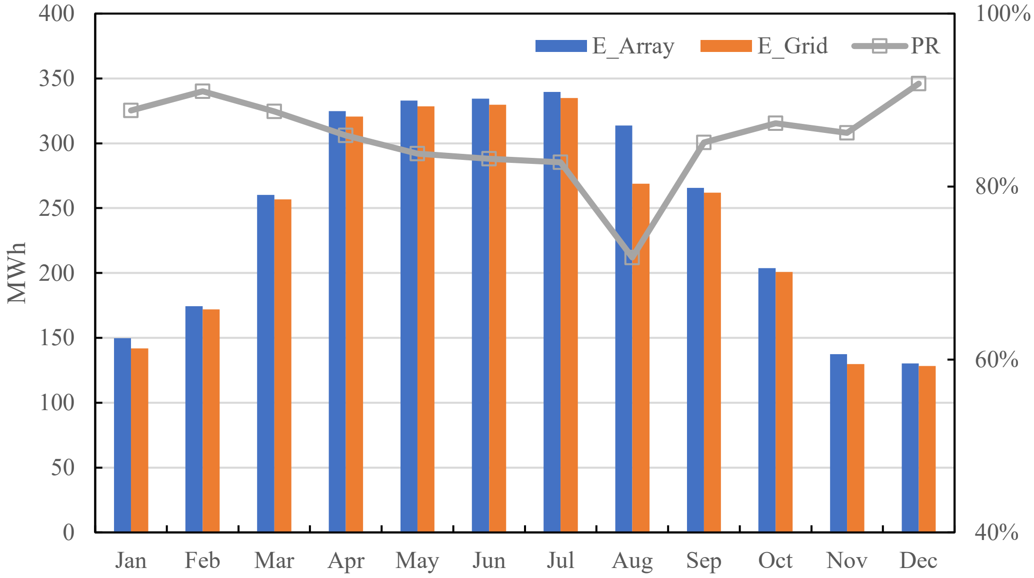

Figure 5-42 PV array energy production, energy injected into the grid, and PR

Table 5-40 PV array energy production, energy injected into the grid, and PR

	E_Array	**E_Grid**	**PR**
	MWh	MWh	ratio
Jan	149.8	141.8	89%
Feb	174.3	171.9	91%
Mar	260.2	256.7	89%
Apr	324.9	320.6	86%
May	332.9	328.4	84%
Jun	334.3	329.8	83%
Jul	339.6	334.9	83%
Aug	313.7	268.9	72%
Sep	265.6	262	85%
Oct	203.7	200.8	87%
Nov	137.5	129.8	86%
Dec	130.2	128.2	92%
Year	2966.7	2873.8	84%

Table 5-41 shows the economic indicators of the PV plant. The LCOE of the PV plant is 4.0 cent/kWh, and the project can pay back the investment at 9.9 years with an IRR of 10.62%. It indicates that the power plant has a favorable return and is feasible for investment. Figure 5-43 shows the cashflow of the PV plant.

Table 5-41 Economic indicator of large-scale PV plant in Germany

Economic indicator	
LCOE(nominal) (cent/kWh)	4.0
NPV (USD)	2427786
PBP (years)	9.9
IRR (%)	10.62

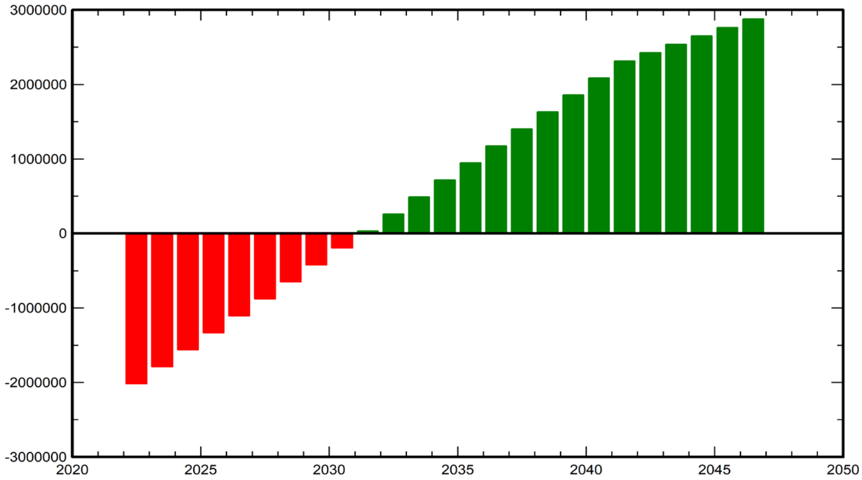

Figure 5-43 Cumulative cashflow of large-scale PV plant (USD/year)

5.4.2.3 Japan

Figure 5-44 shows the monthly energy production and PR of large 2.5 MW PV plants in Japan. The highest month of electricity into the grid occurred in August with 294.2 MWh, and the lowest month was December with 204.2 MWh. April and May in spring had the highest PR of PV plants at over 83%, and the highest PR month was December with 87.6%, and the lowest was August with 72%. The total annual on-grid power of PV plants was 2926.1MWh, with an annual average PR of 82.1%.

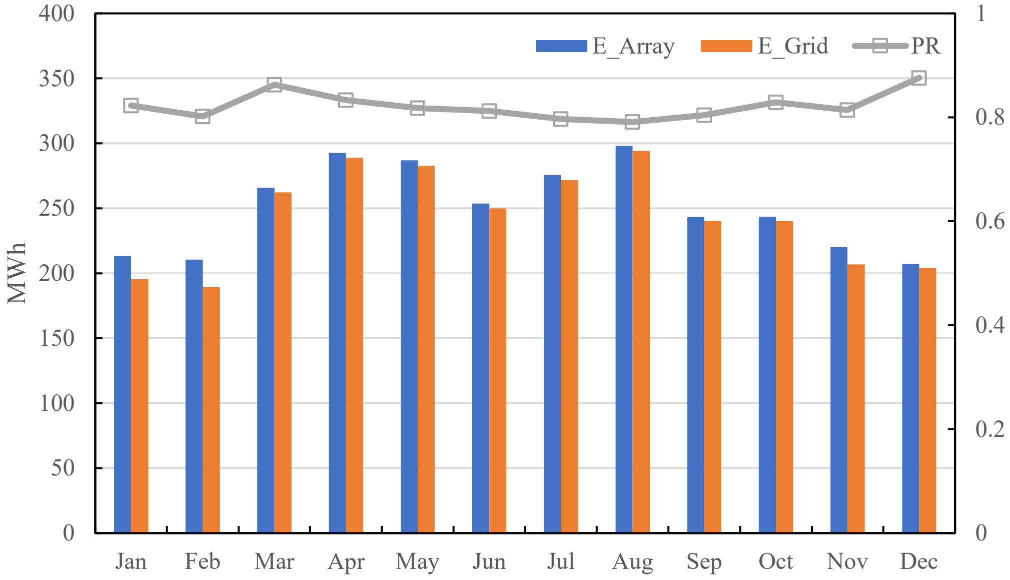

Figure 5-44 PV array energy production, energy injected into the grid, and PR

Table 5-42 PV array energy production, energy injected into the grid, and PR

	E_Array	**E_Grid**	**PR**
	MWh	MWh	ratio
Jan	213.2	195.8	82%
Feb	210.5	189.3	80%
Mar	265.8	262.2	86%
Apr	292.7	288.9	83%
May	286.9	282.8	82%
Jun	253.6	249.9	81%
Jul	275.6	271.7	80%
Aug	298.1	294.2	79%
Sep	243.4	240	80%
Oct	243.5	240.2	83%
Nov	220.2	206.7	81%
Dec	207	204.2	88%
Year	3010.4	2926.1	82%

Table 5-43 shows the economic indicators of the PV plant. The LCOE of the PV plant is 12.1 cent/kWh, and the project can pay back the investment at 20.7 years with an IRR of 2.17%. It indicates that the power plant has not a favorable return and is not feasible for investment. Figure 5-44 shows the cashflow of the PV plant.

Table 5-43 Economic indicator of large-scale PV plant in Japan

Economic indicator	
LCOE(nominal) (cent/kWh)	12.1

NPV (USD)	-862569
PBP (years)	20.7
IRR (%)	2.17

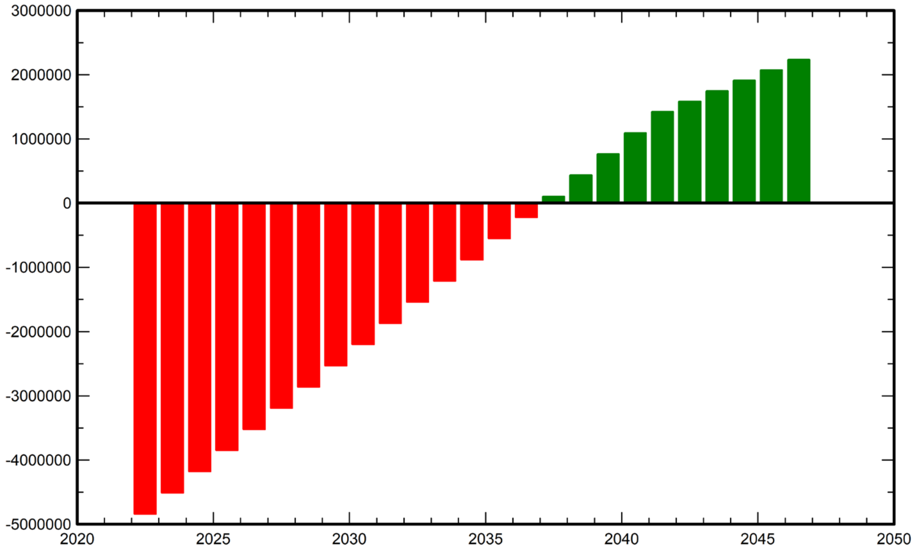

Figure 5-45 Cumulative cashflow of large-scale PV plant (USD/year)

5.4.2.4 USA

Figure 5-46 shows the monthly power generation and PR of large 2.5 MW PV plants in the U.S. The highest month of uploading power to the grid occurred in July with 402.6 MWh and the lowest month was January with 263.1 MWh. January, February, and March had the highest PR of PV plants at over 80%, and the highest PR month of the year was January with 82.7% and the lowest was August with 71.1%. The total annual feed-in power of PV plants was 4018.1MWh, with an annual average PR of 78.7%.

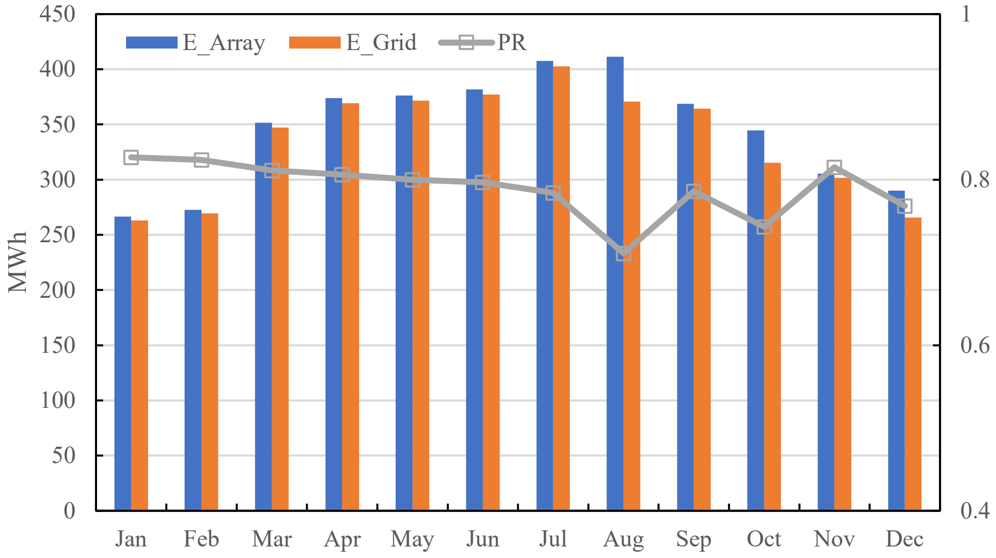

Figure 5-46 PV array energy production, energy injected into the grid, and PR

Table 5-44 PV array energy production, energy injected into the grid, and PR

	E_Array	**E_Grid**	**PR**
	MWh	MWh	ratio
Jan	266.5	263.1	83%
Feb	272.7	269.4	82%
Mar	351.6	347.3	81%
Apr	373.9	369.4	81%
May	376.4	371.6	80%
Jun	381.7	377	80%
Jul	407.7	402.6	78%
Aug	411.3	370.8	71%
Sep	368.8	364.4	79%
Oct	344.5	315.3	74%
Nov	305.3	301.7	82%
Dec	290.1	265.6	77%
Year	4150.5	4018.1	79%

Table 5-45 shows the economic indicators of the PV plant. The LCOE of the PV plant is 5.3 cent/kWh, and the project can pay back the investment at 6.7 years with an IRR of 15.7%. It indicates that the power plant has a favorable return and is feasible for investment. Figure 5-47 shows the cashflow of the PV plant.

Table 5-45 Economic indicator of large-scale PV plant in the USA

Economic indicator	
LCOE(nominal) (cent/kWh)	5.3
NPV (USD)	4254496
PBP (years)	6.5
IRR (%)	15.7

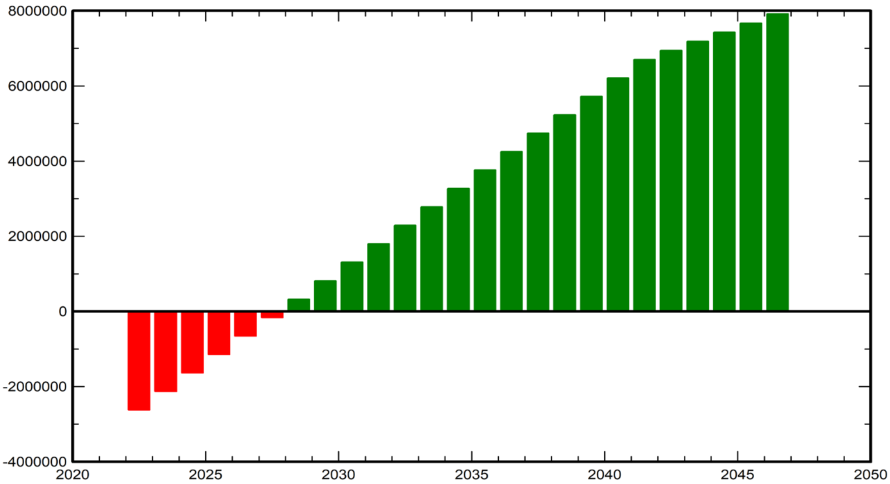

Figure 5-47 Cumulative cashflow of large-scale PV plant (USD/year)

5.5. Conclusion

Under different climatic and geographic conditions and based on different policy conditions, residential PV systems and large grid-connected PV plant were simulated using SAM and PVsyst software for four selected cities in China, Germany, Japan and the USA. Detailed technical and economic analyses were determined based on the energy production injected into the grid by the PV systems. It is concluded that in the context of combining all PV support policies, for residential PV systems in the four countries. In the case of China, Beijing is the most economically viable city with the lowest energy costs and the lowest payback period. In the case of Germany, Stuttgart is the most economically viable location. In the case of Japan, Kagoshima is the most economically viable location. The most economically viable city for residential PV system in the United States is Los Angeles. And after the without policy support, all cities lost the economic viability of their residential PV systems. Residential PV battery systems in the U.S. have been able to earn a return on investment in all cases except Portland. Only Stuttgart, Germany, is the only city in the rest of the world to receive a return on investment. This indicates that the current addition of battery systems to residential PV systems does not improve the return to investors, except for increasing the stability of the grid. Finally, we selected the city with the highest energy production among all the case cities in the four countries as the location for large-scale PV plants. The results of the analysis show that large-scale PV plants in three of the four countries, except for Japan, are economically viable with substantial revenues.

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Chapter 6. Comparative study and policy implication

6.1. Introduction

Despite the surprising price reductions for utility-scale solar PV projects, small-scale rooftop solar PV systems remain an important part of the market and bring the benefits of modern electricity services to households that previously had no access to electricity, reduce the cost of electricity on islands and other remote areas that rely on oil for electricity generation, and enable residents and small businesses to generate their own electricity.

Conventional PV technical and economic indicators will highlight the growing competitiveness of rooftop solar PV in the four countries and its potential to economically meet the electricity needs of households in different national markets.

This chapter first compares the results of solar PV technology learning in the four countries. Then, technical and economic indicators compare solar PV costs to electricity prices. With the rapid decline in PV costs, there is a clear need for up-to-date analyses of solar PV competitiveness in different markets. The purpose of these analyses is to help policy makers track the rapid improvement in PV energy competitiveness and to help decision makers design, adopt or maintain renewable energy policies to support solar PV deployment.

The indicators are based on a simple and transparent analysis of reliable cost and performance data from the previous chapters.

The technical indicators include three key components:

1. Annual PV generation.
2. Capacity factor
3. Performance ratio

The economic indicators include three key components:

1. PV installation costs in different countries (and within cities).
2. The "effective price" of the solar PV system when generating electricity at the local retail tariff (including the time-of-use tariff).
3. The location-specific LCOE of the solar PV system based on local radiation and installation costs.
4. Net present value based on depreciation rate and payback period

To help the reader understand the relevance of the indicators, this section gives a short overview of the support policies developed in the different markets. This gives an idea of the range of support policies in the markets examined. Rather than showing the impact of support policies on the attractiveness of solar PV for individual investors, the indicator is intended to show policy makers the evolution of cost trends for solar PV systems in different markets and to compare them with effective electricity.

In addition, considering the trend of PV policy changes, we also compare the comparison of the economic changes of PV systems in each country in the absence of policy support. This comparison allows us to see which countries are more dependent on the support policies. Afterwards, we provide policy recommendations and discussions on the development of PV in each country.

6.2.Comparative analysis of the effects of PV policies in four countries based on technological learning

6.2.1.Comparative analysis of policy impact base on result of one-factor learning curve in four countries

Table 6-1 Results of OFLC analysis in one period in four countries

Country	Time Period	LI	Learning Rate (LR)	R2	P-value
China	2007-2019	-0.430	25.78%	0.932	0.000
Germany	2000-2019	-0.538	31.12%	0.791	0.000
Japan	2000-2019	-0.260	16.49%	0.937	0.000
USA	2000-2019	-0.389	23.79%	0.933	0.000

Table 6-2 Results of OFLC analysis in different periods in four countries

Country	Time Period	Learning Rate	R2	Policies
China	2007-2012	33.51%	0.995	Production incentives
	2013-2019	30.98%	0.686	Feed-in tariff
Germany	2000-2012	21.03%	0.693	EEG
	2013-2019	85.40%	0.939	EEG Tender
Japan	2000-2011	10.88%	0.799	Investment subsidy
	2012-2019	19.50%	0.774	Feed-in tariff
USA	2000-2006	-5.08%	0.516	No incentives
	2007-2019	23.79%	0.947	ITC

The overall performance of government PV incentives can be measured by the LR. The indicators in Chapter 4 may indicate how these policies have been functioning. A learning curve-based method is then constructed to analyze the performance of government PV policies over a given period of time. The estimated LBR rate can measure the general effect of these policies. Table 6-1 presents the learning rates due to PV energy deployment in the selected countries. In this context, the data for China are from 2007 to 2019, while the other three countries are from 2000 to 2019. This is because the Chinese government has only been promoting large-scale PV deployment since 2007. As shown in Figure 6-1, OFLC can track PV module price changes based on the cumulative installed capacity in all regions. It attributes all production cost reductions to learning by doing. After GDP deflations, R^2 values are greater than 0.73 in all country cases, and the p-values of the coefficients are less than 0.01. Germany has an R^2 of 0.791, indicating that the change in cumulative installations reflects 79.1% of the change in unit price. The other three countries all have R^2 of 0.6 or more. This indicates that Learning by doing may be the main driver of PV cost reduction.

Since the 21st century, four countries have adopted different policies to promote the deployment of PV energy. The main PV policies in China, Japan, and Germany are FIT systems, and the main policy in the US is ITC. All four policies have successfully promoted the rapid development of PV energy. According to the Learning curve model, we can find that among the four countries, Germany has the highest LR, reaching 32.54%, which means that Germany has the best PV policy implementation and has obtained the greatest degree of unit price reduction. The next highest LR is China with 25.77%. The LR of the United States is 23.79%%, and the lowest LR is Japan, with only 16.49%.

This result is due to the fact that Germany was the first country to implement a market-driven policy, while the EAR has been in implementation since 2000 and has lasted for 19 years now. The long-term and stable effect of the policy has contributed to the effective reduction of unit costs. In addition, in order to promote price reductions, Germany has introduced flexible derating rules in the FIT program, with the rate of derating depending on the newly installed capacity (Hoppmann, Huenteler, and Girod 2014). For example, under the German FIT program, if the total additional PV capacity exceeds or falls below a certain amount, the percentage reduction in the standard FIT price is increased or decreased by a statutory fixed percentage (Jan Frederik Braun 2019). However, this solution is not perfect. After this, Germany introduced a market-oriented procedure in the solar support system, a tendering procedure or auction, according to which the standard price of PV power will no longer be determined by the government, but by auction. The bidding process has contributed significantly to the reduction of PV unit costs and has driven the growth of learning rate in Germany.

The main driver of the change in China LR is the implementation of the FIT system. The implementation of projects such as the Golden Sun program from 2009 did not have a decisive impact on the domestic PV market. The Golden Sun Program and other projects implemented since 2009 have not had a decisive impact on the domestic PV market. Therefore, the reduction of PV module products mainly depends on the foreign market (Zou et al. 2017). Until 2012, the implementation of the FIT system quickly contributed to the explosion of the domestic market. Therefore, the growth of the installed volume caused a learning effect. Especially, the continuous growth of the installed capacity in the last two years has led to a rapid increase in LR.

The Energy Policy Act 2006, which established a 30 % investment tax credit（ITC）for the qualified PV system. The ITC has proven to be one of the most important federal policy mechanisms to incentivize PV development in the USA (SEIA 2018). The rapidly expanding PV market has increased the demand for components. This once led to an increase in PV module prices, especially in 2006, when the ITC was implemented. However, the ensuing low-cost PV modules from China caused a huge impact on the U.S. PV market, quickly driving down the price of PV modules in the U.S. market. The ITC was extended to 2008, and then again extended to 2016. PV development in U.S. supported by both national and state-level policies and financial incentives. The major Federal policy driver of growth in U.S. PV market development was the ITC (Seel, Barbose, and Wiser 2014). Especially compared to other countries implementing FIT, as the FIT price continues to decrease, the promotion of the PV market will become smaller and smaller, while the ITC for the percentage reduction in investment costs is the obvious result. The growth of the LR in U.S. can be attributed to the implementation of the ITC.

As shown in Figure 6-1, compared with the three countries that are implementing the PV incentives, Japan had the lowest LDR for PV cost reduction. Due to differences in the natural environment, such as the risk of typhoons and earthquakes in Japan, the technical requirements and standards for certified PV modules are relatively complex, preventing the use of low-cost foreign modules in Japan (Myojo and Ohashi 2018). Hence, a larger fraction of PV modules comes from domestic manufacturers, who have higher manufacturing costs. In addition, the FIT's high fixed price restricts further module price reductions. Furthermore, the high PV module manufacturing costs are largely attributable to the high labor costs in Japan. From 2013 to 2019, labor costs have remained virtually unabated (JPEA 2020). In sum, the implementation of the FIT has not led to a significant reduction in PV costs in Japan, this is also reflected in the LR.

In summary, at present, from the perspective of the learning rate of LBD, Germany has the most effective PV policy implementation, followed by China and the United States, and the least effective is Japan. However, in terms of market potential, China PV market will be much larger than Germany and Japan. China PV module cost has reached the lowest price in the four countries, according to the learning curve model, in the future this price advantage will continue to maintain. The United States also has a huge PV market potential, ITC to reduce the cost of investment, for the development of the PV market has a huge attraction, as long as the policy continues, the cost reduction will definitely exceed Germany. Japan because of its own development environment restrictions, market policies on cost reduction will promote the role of less and less, unless take other ways, or cost reduction will be bottlenecked.

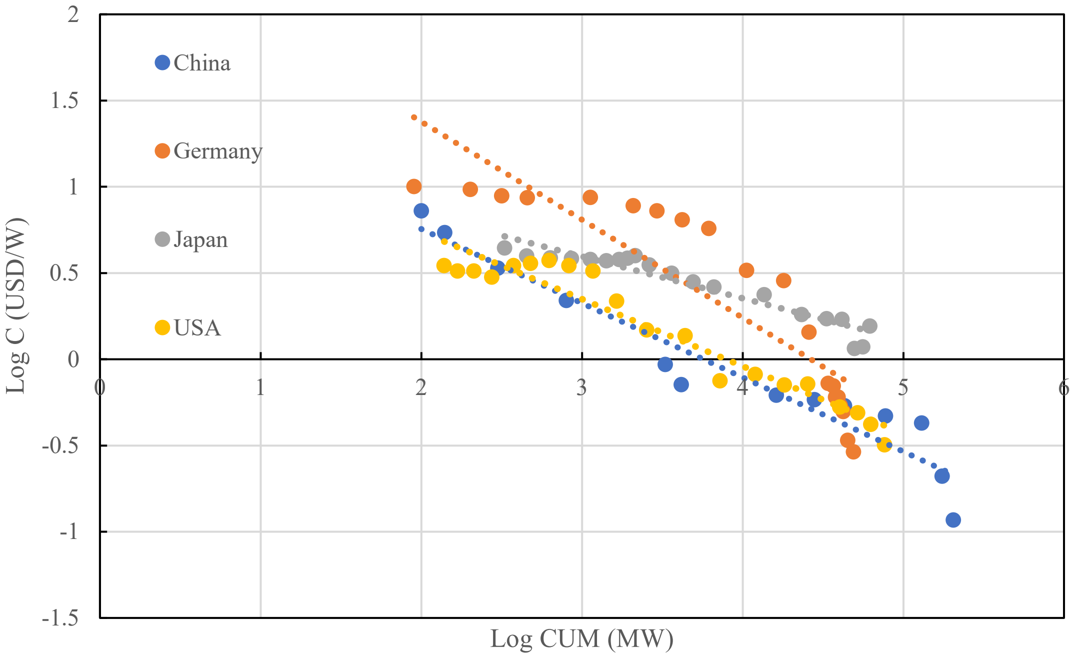


Figure 6-1 The PV learning curve of LBD in four countries

6.2.2.Comparative analysis of policy impact base on result of two-factor learning curve in four countries

In China, three most significant national research programs have included: “National Basic Research Program of China (973 Program)”, the “National High Technology Research and Development Program of China (863 Program)”, and the “Plan of National Key Science and Technology”. These three national R&D programs were regarded as guidelines for the development of national strategic key technologies (Sun et al. 2014). However, the use of funds for these public R&D projects is not publicly available, so we lack data on this. In addition, R&D and cost reduction efforts in Chinese PV are mainly carried out by private PV companies, so country-wide statistical values are difficult to obtain, and therefore we did not analyze the two-factor learning curve for China. In this section, we focus on three countries, Germany, Japan, and the United States, for the analysis of the two-factor learning curve.

According to the analysis results of the two-factor learning curve model, we can notice that Germany's LBS rate and LBD rate are much higher than the other two countries, with LBS rate reaching 20.83% and LBD rate reaching 19.72%. This indicates that the impact of PV R&D investment and installed capacity changes on PV prices in Germany is significant. The high LBS rate may have benefited from the higher PV module costs and stable R&D investments in Germany in the early years, and these have contributed to the rapid reduction of PV costs. The development of PV technology in

Germany was also triggered by the oil crisis in 1970s. Beginning of public funding for R&D is the "Energy Research and Energy Technology Plan" from 1977 by Federal Ministry for Research and Technology. PV R&D has been financed on a scale in Germany. So far, the 6th Energy Research and Energy Technology Plan ends in 2017 (BMWi 2018). The Federal PV R&D program were allocated to the exploration of the full range of solar PV technology chains. The distribution of the budget to the various sectors of R&D, including universities, research institutes, and firms. RD&D spending can more efficiently improve its technology in early development stage and thus reduce costs. The steadily growing PV market size due to subsequent market promotion policies EEG is also reflected in the higher LBD rate. Furthermore, the LBS rate in the USA is 8.1% and the LBD rate reaches 16.38%. This means that market policies have a more significant effect on cost reduction than R&D policies. Although the SunShot Initiative plan of 2011 clearly sets the goal of PV cost reduction by 2020, the U.S. PV R&D is more oriented to technology improvement and breakthrough innovation, and many types of PV cell efficiency records are currently created by U.S. laboratories. The average efficiencies of PV cells show no significant improvement, but the differences in technology efficiencies have been enlarged significantly (Clark 2018). Compared with LBS and LBD, the increase in PV conversion efficiency appears small. Therefore, the effect of the R&D policy is not completely reflected in the LBS. Germany and the US have higher LBR rates compared to Japan. This is partly attributed to their PV module imports from China, which can lead to knowledge spillover. In Chapter 2 we present the share of China's PV module exports to three other countries. Germany was China's main PV importer until 2013, but its imports have fallen sharply due to reduced demand. In contrast, Japan's PV imports from China were much lower until 2013, but have increased since then. The percentage of U.S. PV module imports from China has remained the same, which is similar to China's cost curve. The LBS rate in Japan is only 4%, and the LBD reaches 8% compared to the LBS, which indicates that market-driven policies have a greater impact on PV cost reduction, and a not so effective implementation of R&D policies. In 2001, “the new 5-year plan for PV Power Generation Technology R&D” was initiated in Japan, which aims mainly at four areas: advanced solar cell technologies; investigation common basic technologies toward full-scale PV introduction; innovative next-generation PV power technologies, and advanced manufacturing technology of PV systems (Chowdhury et al. 2014). This policy does not set specific cost reduction targets and is more oriented toward innovation of new PV technologies. It was not until 2008 that the "Project for Development of Technologies to Accelerate the Practical Application of Photovoltaic Power Generation Systems" in 2008, large production cost reductions have been achieved in this time (Suwa and Jupesta 2012). The results of the two-factor learning curve analysis show that Japan's R&D and market-driven policies are not as effective in reducing costs compared to the other two countries.

Table 6-3 Result of LBS in TFLC analysis

Country	Time Period	Learning Parameter	PR	LSR	R2
Germany	2000-2019	-0.337	0.7916	20.83%	0.753
Japan	2000-2019	-0.059	0.9599	4%	0.755
USA	2000-2019	-0.122	0.9189	8.10%	0.868

Table 6-4 Result of LBD in TFLC analysis

Country	Time Period	Learning Parameter	PR	LDR	R2
Germany	2000-2019	-0.317	0.8362	19.72%	0.753
Japan	2000-2019	-0.125	0.917	8.30%	0.755
USA	2000-2019	-0.258	0.8362	16.38%	0.868

6.3.Comparative analysis of the techno-economic assessment of PV plants in four countries

6.3.1.Comparative analysis of PV plants technical indicators in four countries

Fig. 6-2 shows annual PV energy production and solar radiation in selected city in four countries, the lowest average solar radiation is observed in Germany (3.21 kWh/m^2/day) and highest in USA (5.02 kWh/m^2/day). The solar plant gives the best performance in Los Angeles, USA, because it is located in the highest solar resource region. The weather conditions of Los Angeles with average ambient temperature 17.7 °C, average wind speed 1.1 m/s and the average solar radiation 6.22 kWh/m^2/day are best suitable for PV plant generation. The plant energy production is lowest in Dortmund, Germany, due to lower solar radiation and less supportive weather conditions.

Table 10 shows the first year of energy generation for PV systems in the study region. In the four Chinese cities, Guangzhou has the lowest annual electricity production of 4478 kWh due to low solar radiation and Lanzhou has the highest annual production of 7810 kWh. In the four German cities, Munich has the highest annual production of 5150 kWh and Dortmund has the lowest with 4269 kWh. The city with the lowest annual PV energy production in Japan cases is Sapporo and the highest is Osaka with 6347kWh. The city with the highest annual PV energy production is Los Angeles with 8,878kWh in the United States. In all the cases we have chosen, the United States has a higher average PV energy production than other countries, followed by China, and Germany has the lowest average PV energy production, which is related to the solar radiation and climate. The main simulation results are compared for all locations in Table 6.

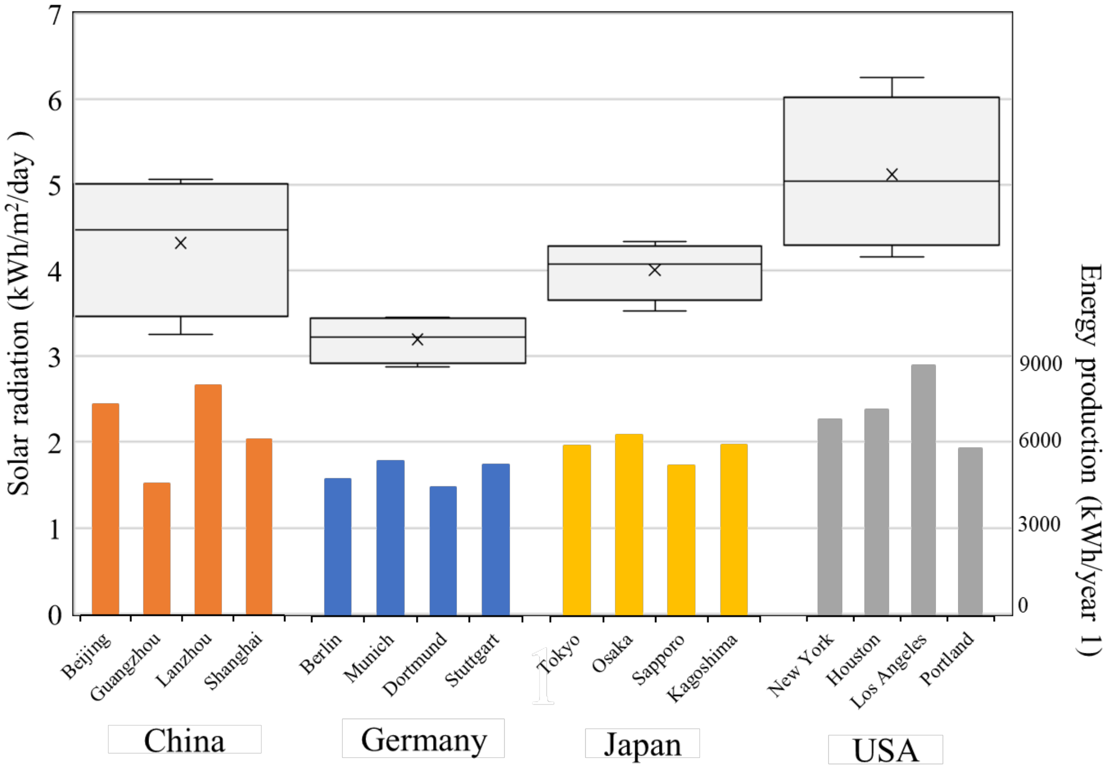


Figure 6-2 Energy generation and solar radiation for PV systems in the four countries

The most important parameters to compare the performance of different systems are performance ratio and capacity factor. The efficiency of a PV power plant is defined by the performance ratio (PR). The ratio of the reference yield (kWh/kW/m^2) to the final yield (kWh/kW/m^2) is called the performance ratio. The PR is used to compare the deployed PV systems at various locations and is generally calculated as a percentage. The performance ratio shows the energy efficiency and reliability of PV plant. The performance ratio allows to compare the energy output of a PV plant with the energy output of other PV plants or to monitor the state of a PV plant over time. Determining performance ratios at fixed regular intervals does not provide an absolute comparison. Instead, it provides the operator with the option to check performance and output: If it is assumed that the PV plant operates optimally after commissioning and therefore has an initial value of 100% for the performance ratio, other PR values can be obtained Deviations can be identified as time passes, which means that appropriate countermeasures can be taken quickly. Thus, deviations in PR values in the form of values below the normal range indicate that PV plant may have failed at an early stage. The capacity factor is the ratio between real production over one year and output if it has been running at nominal power over the year (Ahmed et al. 2021). The inherent limitation of its capacity factor comes from the requirement for daylight, preferably without shading from the sun by clouds, smoke or smog, trees and building structures. Since the amount of sunlight varies with the time of day and the season of the year, the capacity factor is usually calculated annually (Magazine 2019). The amount of available sunlight depends largely on the latitude of the installation and the number of local clouds. Actual production is also affected by local factors such as dust and ambient temperature, and ideally should be lower than this. For any power plant, the maximum possible generation is the nameplate capacity multiplied by the number of hours in a year, while the actual generation is the amount of electricity delivered to the grid each year. Simulation results of capacity factor for four selected countries in Fig 6-3 and results of performance ratio shows in Table 6-4.

Among the four countries, the highest PR is 86% in Lanzhou, China, and in second place is 84% in Sapporo, Japan. The lowest PR is in Houston, the USA at 78%. From a country perspective, the PR in the USA is low as compared to other countries, cities in Germany and Japan are more average at around 83%, and all cities in China, except Guangzhou, have a PR above 80%.

Among the four countries, Los Angeles has the highest CF for PV plants at 20.7%. This is followed by Lanzhou, China, with 18.2%. Among all countries, Dortmund, Germany, has the lowest CF for PV plants at 9.9%. All four cities in Japan have PV plants with a capacity factor of around 14%, while the other cities with high CF are Beijing and New York with 16.7% and 16.2% respectively. From a national point of view, the CF of PV plants in all German cities is low, in China the CF of PV plants is high in all cities except Guangzhou, and the US is similar, with the CF of PV plants remaining high in all cities except Portland.

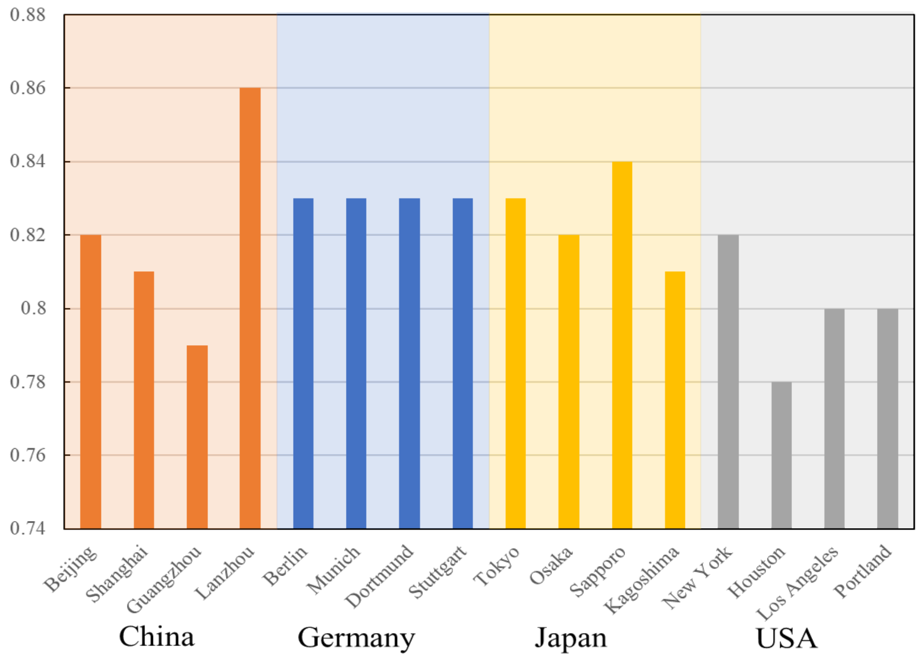


Figure 6-3 PR of residential PV system in four countries

Table 6-5 The PR and CF of PV systems in four countries

Country	**City**	**Performance ratio**	**Capacity factor**
China	Beijing	0.82	16.7%
	Shanghai	0.81	13.9%
	Guangzhou	0.79	10.4%
	Lanzhou	0.86	18.2%
Germany	Berlin	0.83	10.6%
	Munich	0.82	12.0%
	Dortmund	0.82	9.9%
	Stuttgart	0.83	11.7%
Japan	Tokyo	0.83	13.9%
	Osaka	0.82	14.8%
	Sapporo	0.84	12.3%
	Kagoshima	0.81	14.0%
USA	New York	0.82	16.2%
	Houston	0.78	17.0%
	Los Angeles	0.8	20.7%
	Portland	0.8	13.8%

6.3.2.Comparative analysis of PV plants economic indicators in four countries

Figure 6-4 shows the LCOE of residential PV systems for the four countries in all cases. The lowest LCOE of PV among the four countries is in China, which can be contributed to the fact that China has the lowest residential PV investment cost. At the same time, with national FIT and local-level PV subsidies, especially in Beijing, the Real LCOE for residential PV reaches 3.04 cent/kWh, the lowest of all cities and less than one-third of the residential electricity price. Even Guangzhou, which has the lowest annual PV generation among the four cities, has an LCOE of 6.28 cent/kWh, which is less than half of the residential electricity rate. The country with the highest residential PV LCOE is Germany, due to higher system installation costs and low solar radiation. the highest LCOE is Berlin, with a real LCOE of 21.31 cent/kWh, which is related to the rapid decline in German subsidy prices in recent years, as well as the reduction and elimination of subsidies at the local level. in the last two years, Berlin has eliminated its residential PV. This has led to the highest LCOE in Berlin. However, the LCOE of PV in Germany is still at a low level compared to the high residential electricity costs. Japan has the highest PV system cost among the four countries, however, because of local-level investment subsidies, the LCOE of residential PV in Japan is lower than in Germany, at around 14 cent/kWh in all four cities. The U.S. residential PV LCOE is only higher than China's among all countries, and relative to the highest system costs among the four countries, the LCOE is only half of Germany's, especially in Los Angeles and New York, where the LCOE has dropped below 10 cent/kWh, especially in Los Angeles, where it is only 7.85 cent/kWh, compared to the residential electricity rate of 17.1 cent/kWh. The LCOE is less than half of the residential rate. A special case is Portland, where the LCOE is higher than the residential rate among all countries, and the residential rate in Portland is less than half of the residential rate in New York. Overall, the LCOE of residential PV plants is lower than residential electricity rates, with the lowest being in China, followed by the United States, the third highest being in Japan, and the highest being in Germany.

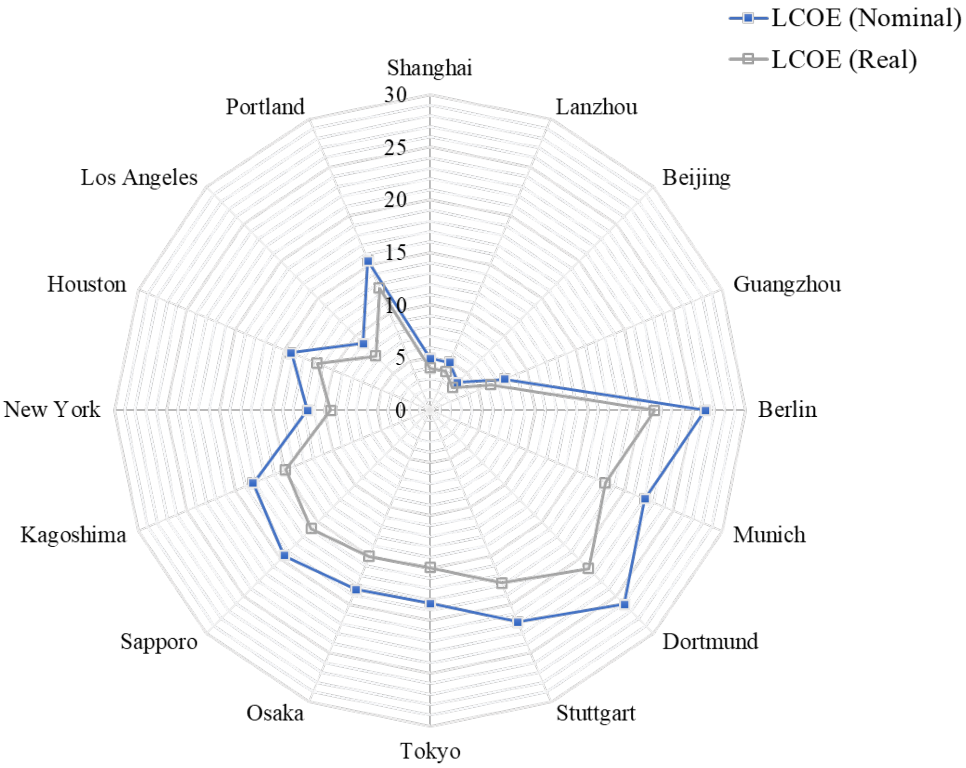


Figure 6-4 The LCOE of PV energy in four countries’ cases

Figure 6-1.

Table 6-6 Comparison of LCOE and average electricity costs

Country	City	Nominal LCOE (cent/kWh)	Real LCOE (cent/kWh)	Average tariff (cent/kWh)
China	**Beijing**	3.73	3.04	11.3
	Shanghai	4.92	4.01	8.8
	Guangzhou	7.69	6.28	13.6

	Lanzhou	4.9	3.99	11.7
Germany	**Berlin**	26.12	21.31	32.1
	Munich	22.1	18.03	31.1
	Dortmund	26.08	21.29	32.3
	Stuttgart	21.78	17.77	34.5
Japan	**Tokyo**	18.36	14.98	25.4
	Osaka	18.44	15.04	23.2
	Sapporo	19.56	15.96	28.1
	Kagoshima	18.17	14.83	23.3
USA	**New York**	11.63	9.45	23.2
	Houston	14.25	11.58	13.5
	Los Angeles	9.61	7.85	17.1
	Portland	15.39	12.55	10.7

In terms of savings on electricity bills for residential PV systems, the highest percentage of savings among the four countries is in Japan, partly due to higher electricity prices, however, the most important is the high FIT price setting, so that the benefits of PV power generation after on-grid are obvious over the ten years of the FIT contract period. Especially in Osaka, where the solar radiation conditions are favorable, the annual revenue from PV energy generation is already higher than the electricity bill. The revenue from electricity bills in Germany and China also benefit from FIT, with all cities except Guangzhou, where PV is less efficient, saving more than 60% on their electricity bills each year. The situation is similar in the U.S., with the exception of Portland, where all other cities save more than 60% on their electricity bills, especially Los Angeles, where the percentage of electricity savings is nearly 80%.

In terms of the amount of electricity bill savings, cities in the US were able to achieve more bill savings, which can be attributed to Net metering, which is also the only country out of the four that has implemented Net metering. China's PV systems save the least amount of electricity because the price of electricity and FIT prices are lower in China compared to other countries.

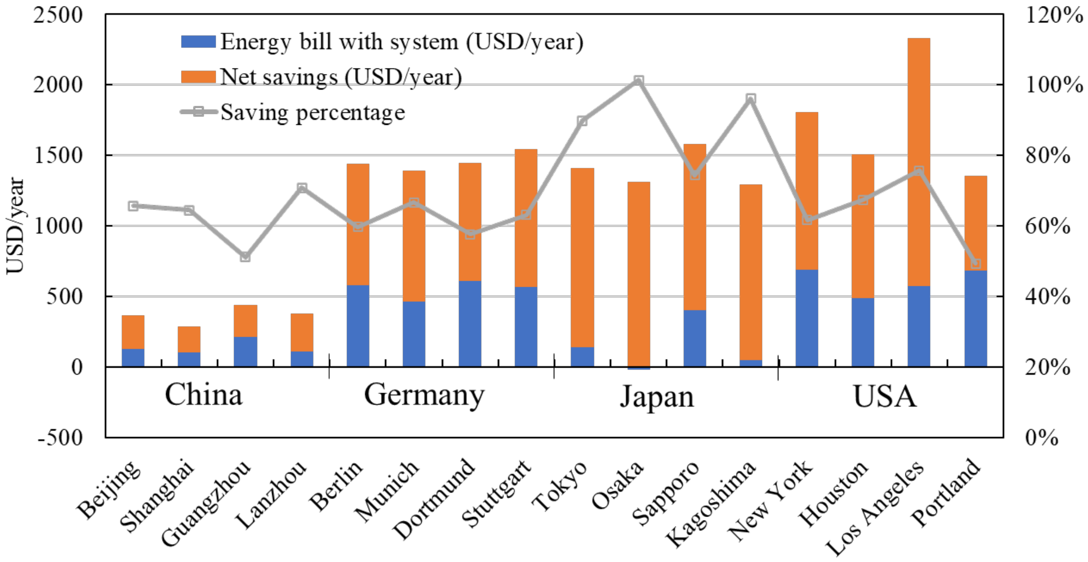
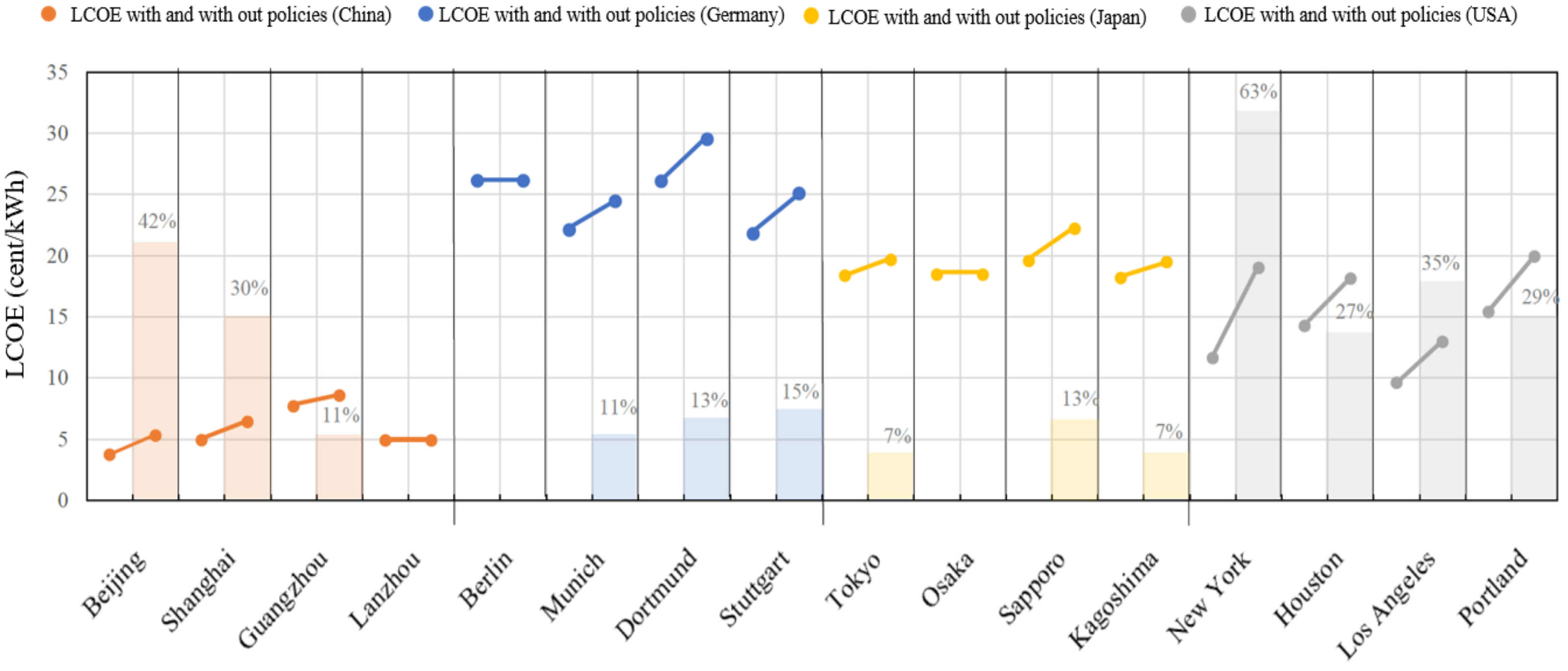


Figure 6-5 Energy bill and net saving in all cases

Figure 6-6 shows the change in LCOE for the case cities of the four countries with and without incentives. the LCOE is mainly influenced by the upfront investment cost. We could observe that after the removal of incentives, the LCOE of residential PV in the U.S. grew the most significantly, especially in New York, where the LCOE grew by 63%, from 11.63 cent/kWh to 19 cent/kWh, and in all other cities the growth rate was above 25%. This indicates that investment in residential PV in the US is more dependent on incentives, and changes in incentives have a huge impact on LCOE. The next highest LCOE change for residential PV is in Beijing, which ranks second among all cities, with a 42% increase, where LCOE rapidly increased from 3.73 cent/kWh to 4.32 cent/kWh in the absence of incentives. The second highest increase in China is in Shanghai, with a 30% increase, and Lanzhou, where LCOE did not change because there were no local-level incentives. change. The incentive policies had less impact on the LCOE of residential PV plants in Japan and Germany, with increases of 11% to 15% in the three German cities, 7% and 13% in the three Japanese cities, and no change in LCOE in Berlin and Osaka due to the lack of local incentives.



			Beijing	Shanghai	Guangzhou	Lanzhou	Berlin	Munich	Dortmund	Stuttgart	Tokyo	Osaka	Sapporo	Kagoshima	New York	Houston	Los Angeles	Portland
Scenario 1 and 2	Nominal LCOE (cent/kWh)	With policies	3.73	4.92	7.69	4.9	26.12	22.1	26.08	21.78	18.36	18.44	19.56	18.17	11.63	14.25	9.61	15.39
		No policies	5.29	6.41	8.56	4.9	26.12	24.45	29.51	25.08	19.65	18.44	22.2	19.47	19	18.12	12.95	19.93
	Increasing rate		42%	30%	11%	0%	0%	11%	13%	15%	7%	0%	13%	7%	63%	27%	35%	29%
Scenario 3	Nominal LCOE (cent/kWh)		5.57	7.11	10.61	6.54	30.21	25.64	30.41	25.42	24	23.72	25.18	23.08	13.35	16.48	14.97	18.22

Figure 6-6 Comparison of LCOE for different scenarios

Fig. 6-7 shows the change in NPV for the case cities of the four countries with and without incentives. The NPV allows us to know the revenue of PV plants in different locations. Under the condition of 4% discount rate we are setting, with incentives, the best revenue of residential PV power plant overall is the United States, except Portland, all other cities have positive NPV, Los Angeles reached more than 15000USD, the best revenue among all cities. In second rank is Japan, except for Osaka, which has no local incentives, all other cities have positive NPV, and the highest NPV is Kagoshima City. In Germany, the NPV is negative in all cities except Stuttgart, which has better insolation conditions, indicating that it is risky for residents of PV to invest in these three cities. The worst NPV performance is in China, except for Beijing, which has a positive value, the other three cities are all negative, residential PV plants in the inability to gain revenue.

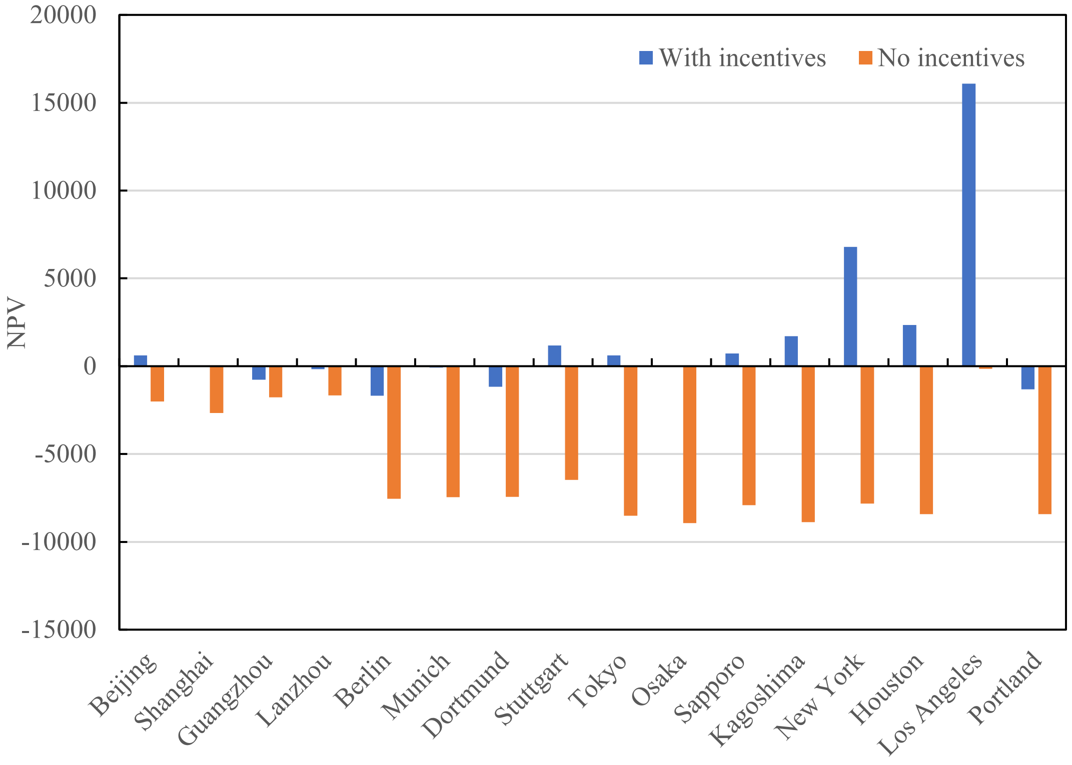


Figure 6-7 Comparison of NPV of Scenario 1 and Scenario 2

Table 6-6 shows the change in payback years of the residential PV system in all cities with and without incentives. We can find that in the absence of incentives, the payback period of residential PV systems in both Japan and the U.S. will exceed 25 years of life time. This indicates that Japan and the US are dependent on PV incentives during the 25-year life cycle of residential PV plants. Germany is able to recover its costs over a 25-year lifecycle mainly because the electricity tariff is the highest among all countries, and therefore PV self-generation maximizes returns. In China, the payback period for residential PV systems in Beijing and Lanzhou can be within 25 years, mainly because of the lower investment cost of Chinese PV systems, which shortens the payback period. Therefore, in the case of low cost PV systems or high electricity rates, PV plants are likely to recover their costs over their life time without stimulus policies.

Table 6-7 The PBP of the residential PV systems in four countries with or without incentives

Country	**City**	**PBP (With incentives)**	**PBP (No incentives)**
China	Beijing	12.8	24.3
	Shanghai	13.3	NaN
	Guangzhou	16.2	NaN
	Lanzhou	14.4	21.3
Germany	Berlin	14.8	24.8
	Munich	13.4	24.5
	Dortmund	14.5	24.5
	Stuttgart	12.3	22.1
Japan	Tokyo	12.8	NaN
	Osaka	13.3	NaN
	Sapporo	12.6	NaN
	Kagoshima	12.3	NaN
USA	New York	7.4	NaN
	Houston	8.2	NaN
	Los Angeles	5.9	16.4
	Portland	15	NaN

6.3.3.Comparative analysis of Largescale PV plants

6.3.3.1 The results of technical analysis

In the techno-economic analysis in the previous chapter, we selected the city with the best insolation conditions in each country as the location for our large power plant installation. We selected the city Lanzhou for China, Munich for Germany, Osaka for Japan and Los Angeles for the United States. The results of the comparison of large PV plants will be presented as follows.

Table 6-8 The average investment costs of large power plants in four countries (USD/kW)

Category	**China**	**Germany**	**Japan**	**USA**
Module and inverter hardware	308.757	428.463	674.52	426.536
BoS hardware	112.289	212.557	336.442	253.132
Installation	134.562	107.899	783.077	269.929

Soft costs	238.858	149.8	275.854	270.976
Total	794.466	898.719	2069.893	1220.573

Data source: RENA (International Renewable Energy Agency - IRENA 2019)

Tables 6-7 show the average investment costs of large power plants in four countries. The cost of large PV plants has a significant impact on the profitability of PV plants. Among the four countries, Japan has the highest investment cost of 2069.893 USD per kW, which is much higher than China's 794.466 USD per kW and Germany's 898.719 USD per kW. The main reason for this is because of the installation costs, which are 6-7 times higher than in the other countries. The second highest price is in the United States, with a cost per kW of 1220.573 USD. China has the lowest total investment cost for PV systems.

Fig. 6-8 shows the annual energy production of PV plants injected into grid and the annual performance ratio. In the case of large-scale PV plants in the four countries, the highest annual power generation is in the U.S. with 4018.1 MWh. The second is a large-scale PV plant in China with 3310.9 MWh, followed by Japan with 2926.1 MWh. Germany is close to Japan with 2873.8 MWh. In the PR of large PV plants, Germany has the highest plant PR at 84.4%. The U.S. has the lowest PR for power plants at 78.7%. Japan and Germany are close, at 82.1% and 84.4%, respectively.

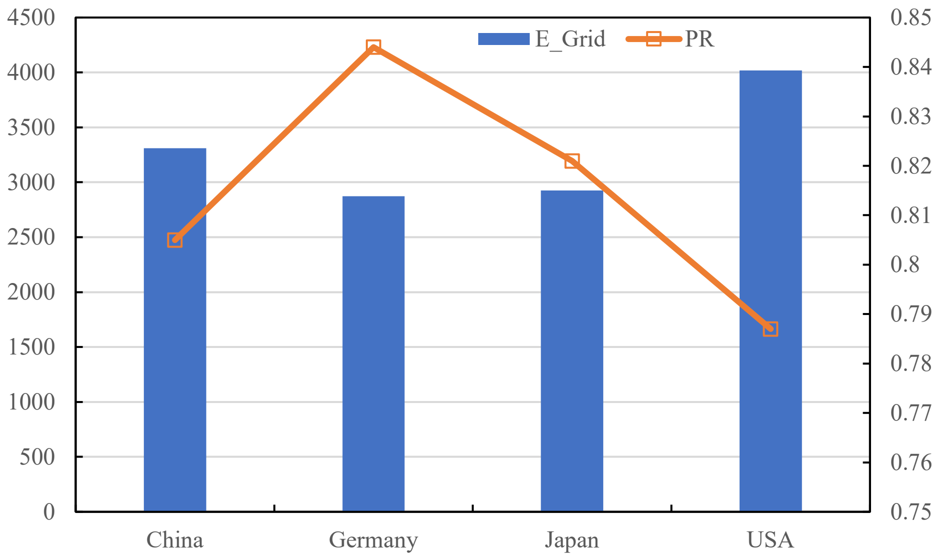


Figure 6-8 The annual energy production of PV plants injected into grid and the annual performance ratio

Table 6-8 shows the energy production of PV plants injected into grid per month and table 6-9. Shows the performance ratio per month in four countries cases. The highest PV energy production in China was 326.8MWh in May and the lowest was 186.8MWh in December. The highest energy generation in Germany was 334.9MWh in July and the lowest was 128.2MWh in December. In Japan, the highest PV energy production was 294MWh in August and the lowest was 189.3MWh in February. The highest energy production in the United States was 402.6MWh in July and the lowest was 263.1MWh in January. The highest PR for PV plants in China was 87.9% in January and the lowest was 71.5% in August. The highest PR in Germany was 92% in December and the lowest was 72% in August. The highest PR for Japanese PV plants was 87.6% in December and the lowest was 79.1% in August. The highest PR in the U.S. occurred at 82.7% in January and the lowest was 71.1% in August.

Table 6-9 The energy production of PV plants injected into grid per month in four countries

	China	**Germany**	**Japan**	**USA**
	MWh	**MWh**	**MWh**	**MWh**
Jan	244.3	141.8	195.8	263.1
Feb	264.1	171.9	189.3	269.4
Mar	309.5	256.7	262.2	347.3
Apr	320.9	320.6	288.9	369.4
May	326.8	328.4	282.8	371.6
Jun	316	329.8	249.9	377
Jul	312.7	334.9	271.7	402.6
Aug	286.7	268.9	294.2	370.8
Sep	272.6	262	240	364.4
Oct	236.5	200.8	240.2	315.3
Nov	234.1	129.8	206.7	301.7
Dec	186.8	128.2	204.2	265.6
Year	3310.9	2873.8	2926.1	4018.1

Table 6-10 The performance ratio per month in four countries

	China	**Germany**	**Japan**	**USA**
	ratio	**ratio**	**ratio**	**ratio**
Jan	87.9%	89.0%	82.3%	82.7%
Feb	86.9%	91.0%	80.2%	82.4%
Mar	85.0%	89.0%	86.3%	81.1%
Apr	82.3%	86.0%	83.3%	80.6%
May	79.6%	84.0%	81.8%	80.0%
Jun	79.9%	83.0%	81.2%	79.7%

Jul	78.9%	83.0%	79.7%	78.4%
Aug	71.5%	72.0%	79.1%	71.1%
Sep	81.1%	85.0%	80.4%	78.6%
Oct	72.4%	87.0%	82.9%	74.3%
Nov	86.3%	86.0%	81.4%	81.5%
Dec	78.2%	92.0%	87.6%	76.8%
Year	80.5%	84.4%	82.1%	78.7%

6.3.3.2 The results of economic analysis

Table 6-10 shows the results of the economic analysis for large PV plants in four countries. Of the four countries, China, Germany, and Japan, all implemented a country-wide FIT or FIP policy, and in the U.S. case the California FIT policy was applied. The FIT prices in all cases are for the year 2020. The Chinese government has set the lowest FIT price of 5.8 cent/kWh, which is related to the low investment cost of large PV plants in China. Germany's EEG Act has an average FIP price of 8.3 cent/kWh in 2020, and Japan's FIT price is 11.4 cent/kWh. The highest FIT price among the four countries is found in California, USA, at 14.5 cent/kWh.

In terms of large PV plants, the lowest LCOE is still observed in China at 3.7 cent/kWh, while the difference between Germany and China is not significant, at 4 cent/kWh. The country with the highest LCOE is Japan at 12.1 cent/kWh, where high investment costs limit the reduction of LCOE. The US LCOE is 5.3 cent/kWh.

Figure 6-9 shows the PBP and IRR of large PV plants in four countries. the IRR of Japanese PV plants is only 2.17%, and the investment will not pay for itself over the lifetime of the PV plant. This indicates that Japan's large-scale power plants are not able to achieve the expected profitability and are not viable for investment. The US has the shortest payback period of 6.5 years for large PV plants and an IRR of 15.7%. This indicates that the U.S. has the highest return on investment for large PV plants. China's PV power plants do not generate a high rate of return due to low investment costs, with an IRR at 9.84% and a payback period of 12.2 years. Germany's PV plants have a higher IRR than China's, at 10.62%, with a payback period of 9.9 years. In terms of NPV except for Japan is negative all other countries are positive, which means that in the case of 4% depreciation rate, only Japan's PV plants cannot gain revenue.

Table 6-11 The results of the economic analysis for large PV plants in four countries

	Feed-in Tariff	**LCOE**	**PBP**	**IRR**	**NPV**
	Cent/kWh	Cent/kWh	Year	%	USD
China	5.8	3.7	12.2	9.84%	489133

Germany	8.3	4	9.9	10.62%	2427786
Japan	11.4	12.1	20.4	2.17%	-862569
USA (CA)	14.5	5.3	6.5	15.70%	4254496

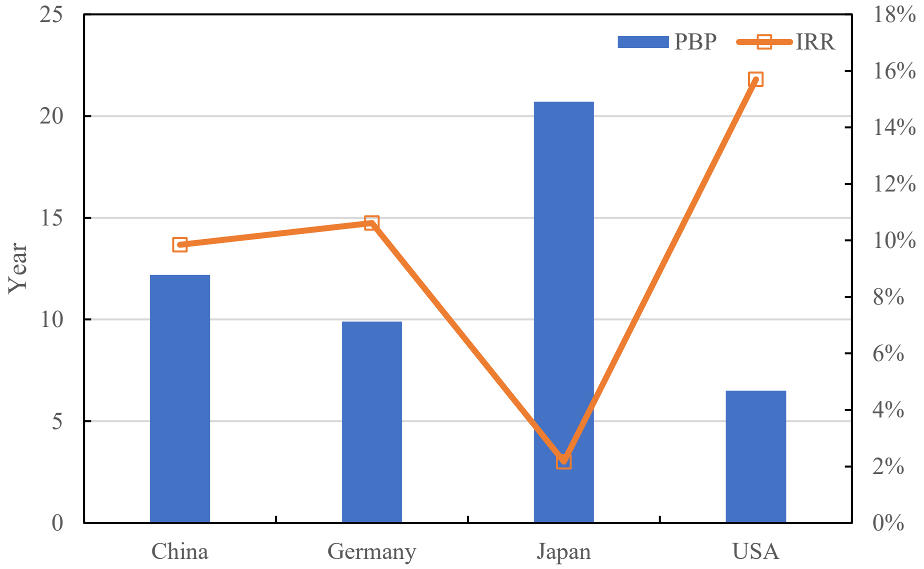


Figure 6-9 The PBP and IRR of largescale PV plant in four countries

6.4. Policy implication for PV energy development in four countries

6.4.1. Future challenge for solar PV energy development in four countries

6.4.1.1 China

In 2018, China's renewable energy share more than 26% of the total electricity generation, and the solar PV shared 2.5%. In the field of R&D, the PV R&D leads by the "Top Runner Program," which greatly enhanced the average PV cell and module efficiency. The 13th Solar Energy Development Five-year Plan (2016 -2020) was launched by NEA, establishing targets for solar energy deployment of at least 105 GW by 2020 (IEA, 2017). The solar PV cumulative installed capacity reached more than 175 GW in 2018 under the FiT, which has far surpassed the government's target. Therefore, the Chinese government has adopted a series of policies to reduce the FiT subsidy, aiming to rapidly realize grid parity and gradually remove the subsidy. These policies have a great influence on the PV market and industry. The annual PV installed capacity decreased by 32% in 2018. Another problem is the solar energy oversupply. The Chinese government has launched an action plan to reduce the PV curtailment rate by setting mandatory caps on curtailment and minimum consumption targets. The PV curtailment rate decreased from 10% in 2015 to 3.8% in 2018. In the report of China's renewable energy outlook 2019, the government expected a solar PV installed capacity of 532 GW in the 14th Five-Year (2021-2026) plan and 1109 GW in 15th Five-Year (2026-2030) plan (CNREC, 2019).

6.4.1.2 Germany

In 2018, renewable energy generation in Germany accounted for 43% of the total energy supply, including 8% for solar PV. In the same year, Germany introduced the Climate Protection Act 2030, with the goal of renewable energy reaching more than 65% of the total energy supply by 2030 (Sandra Enkhart, 2019). Therefore, there is a need to increase the contribution of renewable resources such as PVs. In R&D, in the 7th Energy Research Program launched in 2018, the federal government earmarked around EUR 6.4 billion for innovation activities, which targeted the PV system to have a 35% increase in efficiency and reduction of 50% in cost by 2030 (BMWi, 2018). In the PV industry, PV production has continuously declined in the recent years. However, the PV specialist group reported that PV production will increase again in 2020 (VDMA 2019). The German government has set a target of the PV installed capacity to 98 GW by 2030 (Xinhua 2018). In 2019, the cumulative PV installed capacity was 49.27 GW; when the 52 GW cap was reached, the government ceased the application of FiT to new solar PV projects. The abolition of FiT means that the profit of the solar PV will decrease significantly, which indicates that the PV deployment will be reduced. Although the government has set the 98 GW target for solar PV, there is no assurace that this target will be achieved, showing the uncertainty in the future of solar PV deployment in Germany.

6.4.1.3 Japan

In 2015, the Japanese government set a target to reach 22 -24% of the total energy from renewable energy by 2030, including 7% (67 GW) of solar PV by 2030 (METI, 2018b). In the "5th Strategic Energy Plan," the renewable energy was defined as a major power supply source. For PV R&D, the NEDO changed R&D strategies from the enhanced PV efficiency and reduced the cost to improve the reliability and safety of PV power generation. METI projected the generation cost to achieve 0.065 USD/kWh for residential PV and 0.047 USD/kWh for large-scale PV in 2030 (METI, 2018a). In the PV industry, local PV production is affected by the price advantage of foreign manufacturers. The major PV firms in Japan changed the strategies from "manufacturing of individual equipment" to the provision of "comprehensive solution services," and enhanced competitiveness through cooperation with Chinese companies in manufacturing (IEA, 2020). Mitsubishi has shut down the PV manufacturing business, and Panasonic transferred the PV manufacturing business to Chinese companies. In 2018, overseas PV production shared more than 74% of the domestic market. It is expected that the majority of PV manufacturing in Japan will be gradually replaced by foreign manufacturers in the future. In 2018, the cumulative installed capacity of solar PV was 56GW, which means that the 2030 target of 67 GW would be surpassed within 2019 or 2020. At present, the Japanese government has not set a new target for PV installation capacity. The JPEA forecasts that solar PV installed capacity in Japan will reach 100 GW in 2030 and 300 GW in 2050 (JPEA, 2020). Considering the national burdens, the FiT still needs continuous reform.

6.4.1.4 USA

In 2018, renewable energy shared more than 17% of the total power generation in the USA and the PV shared 1.5%. In the field of R&D, the SunShot Initiative in 2016 aimed to reduce the cost of solar power by 50% between 2020 and 2030. The DOE provided amounts of funding to further drive down the cost and accelerate PV deployment. SunShot 2030 was set up a new target for PV generation cost, and the cost has the great potential to further decrease. In 2020, the ITC Act will reduce the PV generation cost to 26%, and 22% in 2021, to 10% for utility and commercial-scale projects, to 0% for residential projects. This change will significantly impact the USA's PV deployments, which can be predicted to slow down over the next few years. However, the general trend is still increasing due to the rapid decline in PV generation costs. The IRENA projected that the PV market in the USA will reach 393 GW by 2030, making it the world's second-largest PV market (IRENA, 2019).

6.4.2. Policy implication for solar PV energy development

Except for Germany, governments in the other three countries lacked new long-term goals for PV deployment. Long-term goals can greatly impact the future of PV development. Long-term targets, update planning and stable measures are needed to meet the challenges and maintain healthy PV development. Governments in four countries should rapidly upgrade their long-term policies, including R&D, and supply-push and demand-pull policies, in line with the current state of PV development. Currently, China, Germany and Japan are scaling back or eliminating subsidies for PV power generation, which increases uncertainty in terms of policy form and market risk. According to the results of the techno-economic analysis in the previous chapters, although the LCOE of residential PV has been significantly reduced and is lower than residential electricity prices in all four countries. However, the results of the financial analysis show that none of the residential PV systems can achieve the expected returns, especially in Germany and China. This is mainly due to the adjustment of the FIT in recent years. Currently, residential PV systems in all cities and regions studied in the four countries must rely on national and local subsidies if they are to generate revenue. Current PV policies in China and Germany do not provide much support for investment in residential PV systems. Promoting policy reform is particularly important if we want to further promote residential PV in the future. With the LCOE of PV electricity lower than residential electricity prices and FIT prices continue to decrease, Net-mertering policy becomes more economic, in the United States, for example, residential PV has the highest return among the four countries.

China's FIT prices for residential PV have fallen rapidly in the last two years, however, unscheduled subsidy price reductions are not conducive to the development of residential PV. Japan's FIT fixed price is still higher other countries', and it is necessary to reduce the fixed price more frequently, and set an annual upper limit for the capacity PV plants of different sizes. In addition to the tender system, China and Japan could design a predetermined declining rate for fixed prices, taking a cue from the German FIT system. A predictable rate of price reduction could give PV product manufacturers a strong incentive to continually reduce costs in order to accommodate policy changes.

It is expected that PV deployment in the four countries will continue to grow at a high rate over the next decade. With the expansion of PV power generation, daily or seasonal demand-supply balance will be a problem (Li, Gao, and Ruan 2018). The resulting high PV penetration will be a major issue in the limited expansion of PV power generation. The continuous scaling-up of PV deployment would be a great challenge for the government to reduce PV curtailment and maintain grid balance. Policymakers should consider reorienting policies to overcome grid constraints and promote flexibility. The introduction of batteries in PV systems is a favorable solution. In Japan, Germany and the United States, a series of PV battery subsidy policies have been introduced from local to central government. The main focus is on investment subsidies, however, there is a lack of long-term planning for battery subsidy policies, which has led to insufficient revenue for residential PV BESS. The introduction of batteries in PV systems is a good solution. In addition, new demand-side management modes such as VPP virtual power plant can effectively achieve peak load reduction on the grid and optimize power resources.

China dominates the PV production market. However, overproduction is a serious problem. The promotion of a competitive environment and strengthening value creation from the development of the PV industry has become a huge challenge for the Chinese government. At the same time, as the growth rate of the domestic PV market gradually decreases, the heavy dependence on international markets will once again become a huge risk for China's PV industry. In addition, to maintain the competitiveness of PV products in the international market, the Chinese government should increase basic R&D investment to promote the progress of PV technology. The cost of both residential PV systems and large-scale PV plant in Japan is substantially higher than in other countries, which also results in the lowest return of PV systems in Japan among the four countries. The high system prices have also led to high FIT prices. The high FIT price is probably the main reason Japanese PV products have remained more expensive compared to other countries. The high FIT fixed price for PV power generation has made local manufacturers less willing to further reduce the cost of their products, while the high specification requirements for FIT-certified PV products have made it difficult to introduce lower-priced products from abroad into the Japanese PV market. These factors have curbed the reduction of PV system costs in Japan. In the future, the FIT fixed price is bound to continue to decrease, which will inevitably affect the domestic PV industry. Therefore, local PV manufacturers should be more proactive about reducing product costs through R&D and other means, or they should collaborate with foreign manufacturers to introduce lower-priced products through original equipment manufacturers (OEMs). When the PV systems investment cost is reduced, the relative FIT fixed price can also be reduced, thus forming a mutually beneficial virtuous circle.

Driven by policies and supportive measure changes in recent years, the residential PV installations will be increasing more rapidly. However, the high initial investment cost and long payback periods of distributed PV are barrier to private investors. The effective adoption of a systemic approach to support the deployment of distributed energy, including business model innovation and various renewable energy sources integration, would be a great challenge in these four leading countries.

6.5. Conclusion

In this chapter, first, the learning rates of LBD of OFLC in four countries are compared.

The purpose of PV support policy is to improve the competitiveness of PV power generation compared to conventional power generation, and cost reduction is an important manifestation of the policy effect. According to the comparison results of OFLC's analysis, the learning rate of German LBD is the highest among the four countries. The second highest learning rate of LBD is in the United States, where ITC has made a great contribution to the expansion of the PV market and the reduction of PV product prices, and the earlier implementation of ITC has also improved the policy effect. China and Japan are late in fully implementing the FIT, so the learning rate of LBD is lower than Germany and the US. In terms of policy effects, Germany's post-2012 FIT has the best effect on product price reduction, followed by the U.S. ITC, then China's FIT, and finally Japan's FIT. the results of the TFLC comparison continue to show that Germany's R&D policy has the best effect, followed by the U.S., and Japan's policy has the worst effect.

Second, the results of the technical and economic analysis of residential PV systems and large PV plants in the four countries were compared. China and Germany have minimal economic returns for residential PV systems under existing policies and lack the attractiveness of investment. The United States has the best economics for residential PV, and Japan has a reasonable return for residential PV systems. After the loss of PV support policies, residential PV plants in all countries lost revenue and most investments were not recovered. This shows that currently residential PV systems still rely on government policy support, and policies such as FIT will still persist.

In addition, according to the results of the comparison of technical and economic analysis of large-scale PV plants, in addition to Japan, the other three countries of large-scale PV power plants can still obtain more satisfactory profit, which indicates that the three countries for large-scale PV power plant policy still has a lot of room for revision, the future subsidies will continue to be adjusted downward.

Finally, the future PV development strategies of the four countries were overviewed, and then policy recommendations were made for PV industry development and demand-pull policies and supply-side promotion policies.

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Chapter 7. Conclusion and prospect

7.1. Conclusion

The expansion of world energy consumption caused by population growth and global economic expansion coupled with rapid industrialization has necessitated massive investments in renewables energy supplies. With rapid expansion of energy demand, concerns about climate change, high prices of fossil fuels, and depletion of fossil fuels, countries around the world are changing the focus of electricity production from traditional fossil energy power plants to renewable energy sources. solar PV energy, as an ideal renewable energy generation system and a clean renewable energy source, allows the energy to be consumed near the location of energy production, thereby reducing energy costs, carbon emissions and achieving energy self-sufficiency. With the reduction of the cost of PV energy systems, their economic performance is becoming more impressive, leading to an increasing interest of public in PV energy application. Thus, governments have introduced different types of policies to promote the development of PV energy. These support policies have been great effective in the expansion of PV energy, especially in the four largest PV markets in the world, China, Germany, Japan and the United States. This paper provides a quantitative assessment of the performance of PV energy policies on PV market development and technological innovation using four leading PV countries, China, Germany, Japan and the USA, as study cases. This study begins with a learning curve analysis of the cost reduction of PV policies in four countries using a technology learning approach. After that, residential PV systems and large-scale PV plants are modeled in the context of different policies in each country to examine the impact of PV policies on the economics of PV systems. Finally, the policy implications for PV development in the four countries are presented.

The main works and results can be summarized as follows:

In chapter one, Research background and Purpose of the study, presents the significance of the support policy for solar PV energy development. Through the overviews of the advantages of the PV energy, it shows that PV energy have the ability to reduce the energy crisis and environmental pollution as well as increase energy security. After that, the important role that PV support policies play in PV development is described. In addition, the current development status of PV energy was investigated and the policies that can be supported to PV energy development were introduced. Due to the advantages of energy conservation and environmental protection, PV has been vigorously developed by the governments in China, Germany, Japan and USA. However, the high investment cost and improper installed capacity are hindering the diffusion of the PV energy. Measuring the effect of the support policies and how to make the PV policies successfully promote the development of PV energy has become an important issue for every country at present day.

In chapter two, Support policies and PV energy development in China, Germany, Japan and USA, a detailed analysis of the rise of solar PV technology in China, Germany, Japan, and the USA are presented. The effects of different incentive policies implemented over the past decades on PV development in these four leading countries demonstrate. At different development periods, some special external factors may have guided the introduced policy, and the type of policy implemented may vary across different countries. Therefore, the trajectory of the PV incentive policy from three aspects: R&D, industry and market are traced systematically.

In chapter three, Research Methods, presented the methodological research and established the mathematical model. First, the research motivation of the study is described. Then, the model for technology learning and the single-factor learning curve and two-factor learning curve analysis of PV policy performance are presented. In addition, a simulation model of the PV system and the techno-economic analysis methods used in the subsequent chapters are provided.

In chapter four, Technology Learning Curves for Solar PV Energy Policy in China, Germany, Japan and USA, a one factor learning curve (OFLC) and two factor learning curve (TFLC) method was modeled, and the effect of different policy periods on the PV production cost reduction in the PV system was analyzed. A literature review of one-factor learning curves and two-factor learning curves for technology learning is presented, and the basic concepts of learning curve models are introduced. The reduction of PV product cost is correlated with PV installed capacity and R&D investment. After that, a technology learning model based on the one-factor learning curve was developed for four countries during different policy implementation periods. The effectiveness of different policies was found by analyzing the learning rates of LBDs in different periods. Long-term, stable support policies have higher learning rates. Germany's FIT policy has the best learning effect on PV product price reduction, followed by the US ITC policy. Both China and Japan have implemented FIT policies, with Japan's FIT fixed price being higher, however, the learning effect is not ideal. In addition, a two-factor learning curve analysis was conducted for the three countries, and the results showed that although the U.S. invested more public R&D funds, however, Germany had a higher learning rate for LBS, due to the planned and long-term nature of German R&D policy, while U.S. R&D policy was more oriented toward technological innovation.

In chapter five, Techno-economic evaluation of solar PV energy in China, Germany, Japan and USA, a techno-economic analysis of residential PV systems and large PV plants in typical cities in four countries was carried out. Under different climatic and geographic conditions and based on different policy conditions, residential PV systems and large grid-connected PV plant were simulated using SAM and PVsyst software for four selected cities. Detailed technical and economic analysis were determined based on the energy production injected into the grid by the PV systems. It is concluded that in the context of combining all PV support policies, for residential PV systems in the four countries, in the case of China, Beijing is the most economically viable city with the lowest energy costs and the lowest payback period. In the case of Germany, Stuttgart is the most economically viable location. In the case of Japan, Kagoshima is the most economically viable location. The most economically viable city for residential PV system in the United States is Los Angeles. And after the loss of policy support, all cities lost the economic viability of their residential PV systems. Finally, I selected the city with the highest energy production among all the case cities in the four countries as the location for large-scale PV plants. The results of the analysis show that large-scale PV plants in three of the four countries, except for Japan, are economically viable with substantial revenues.

In chapter six, Comparative study and policy implication, a comparative study of the results of the technical learning and the results of the techno-economic analysis of the PV plants in the four countries was carried out. First, according to the comparison results of OFLC's analysis, the learning rate of German LBD is the highest among the four countries. The second highest learning rate of LBD is in the United States, where ITC has made a great contribution to the expansion of the PV market and the reduction of PV product prices, and the earlier implementation of ITC has also improved the policy effect. China and Japan are late in fully implementing the FIT, so the learning rate of LBD is lower than Germany and the US. In terms of policy effects, Germany's post-2012 FIT has the best effect on product price reduction, followed by the U.S. ITC, then China's FIT, and finally Japan's FIT. The results of the TFLC comparison to show that Germany's R&D policy has the best effect, followed by the U.S., and Japan's policy has the worst effect. Second, the results of the technical and economic analysis of residential PV systems and large PV plants in the four countries were compared. China and Germany have minimal economic returns for residential PV systems under existing policies and lack the attractiveness of investment. The United States has the best economics for residential PV, and Japan has a reasonable return for residential PV systems. After the loss of PV support policies, residential PV plants in all countries lost revenue and most investments were not recovered. This shows that currently residential PV systems still rely on government policy support, and policies such as FIT will still persist. In addition, according to the results of the comparison of technical and economic analysis of large-scale PV plants, the three countries of large-scale PV power plants can still obtain more satisfactory profit, which indicates that the three countries for large-scale PV plant policy could gain a great revision, the future subsidies will continue to be decline. Finally, the future PV development strategies of the four countries were overviewed, and then policy implication were made for PV industry development and demand-pull policies and supply-side promotion policies.

In chapter seven, Conclusion and prospect have been presented.

7.2. Prospect

With the development of environmental protection policies, such as renewable energy certificates and carbon taxes, there might be further innovations in energy policies. Therefore, besides the study of current PV energy support policies, it is necessary to further investigate the potential for innovation in PV policies. In addition, the data in this study mostly used average data, and without considering the financial background such as loan ratio, and the environmental impact of PV systems, such as CO2 emission reduction. Therefore, the policy impact analysis will be further carried out combined with detailed data and environmental protection policies in future research.