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What is behind the globalization of technology? Exploring the interplay of multi-level drivers of international patent extension in the solar photovoltaic industry

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ABSTRACT

The increasing internationalization of economic activities highlights the necessity of expanding protections for technologies outside their home countries. Given the large scale and fast growth in international patent filings, understanding the motivations of international patenting behaviors has attracted much attention. This study extends prior literature by exploring additional important determinants of international patenting behaviors and the heterogeneity in international patenting across technology and assignee categories. This study focuses on the solar photovoltaic (PV) industry, which is a major sector in the renewable energy industry and plays a key role in achieving energy transition. As a critical application for semiconductors, PV technologies have grown into a substantial field of research and development through strong patents. In this study, we found that the quality and applicability scope of a patent, as well as the market size, manufacturing capacity, and imitation threats in a destination country, can impact international patent extensions in the solar PV industry. We also found that the strength of these motivators varies based on different types of technologies and assignees.

1. Introduction

The increasingly integrated global economy is boosting the globalization of firms' technological activities, which also asks innovators to make new decisions about what, where, and how to expand their technologies on a global scale. Most new technological innovations are grown in a specific home country, and the patents filled in the home country only provide protection in that country. The increasing internationalization of economic activities, such as international trade and foreign direct investment, suggests the necessity of expanding the protections for technologies embodied in exported products and overseas operations. Therefore, to exclude others from making, using, selling, and offering for sale the claimed invention in foreign countries, inventors have to file patents in foreign countries to appropriate value internationally. The above observations accord with the significant increase in the number of international patents in the past decade. The international patents through WIPO's Patent Cooperation Treaty (PCT) System have increased from 155,408 in 2009 to 265,800 in 2019, with a 10-year growth rate of 71% [63]. The total number of international patents is more than 3 million since 1978 [37].

While the intensifying globalization of technologies, innovators are very unlikely to file international patents in every country because of the substantial costs and efforts associated with the international patenting process. Therefore, understanding the motivations of international patenting extension has become a particular topic of continuing and lively interest. International patenting extension refers to inventions that initially applied for patent protection in a single country and then expanded to other countries. The literature has shown that patent quality, industry sectors, and destination country factors are important determinants of international patenting extension decisions, but additional important determinants at multiple dimensions and how these determinants interact to shape the globalization of technologies have not been fully explored [5,8,16,17,21,39]. Therefore, to complement prior literature and to provide a better understanding of the motivations for the internationalization of technologies, this study conducts a multi-level analysis that covers a comprehensive set of determinants for international patenting at multiple levels including the patent, technology, assignee, and destination country levels and focuses on the interplay of the drivers at different levels.

To investigate the determinants of international patenting extensions

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at multiple levels, this study examines the globalization of technologies in the solar photovoltaic (PV) industry by collecting a unique and rich solar PV patent dataset across 43 countries with international patents from 1968 to 2018. As a major sector in the renewable energy industry, the solar PV industry plays a key role in achieving energy transition [7,31]. But to achieve the objectives of limiting the average global surface temperature increase below 2° Celsius, the deployment of solar PV technology needs to be accelerated at least six times [30,34]. As a critical application for semiconductors, PV technologies have grown into a substantial field of research and development through strong patents and scientific publications [57]. The rapid growth of the solar PV market and its huge market potential in the future have also intensified the competition in this industry. Building large patent stocks is widely used in such highly competitive industries to reduce a company's vulnerability to infringement lawsuits by rivals or to legally produce or sell its products [28,67]. Our patent dataset also demonstrates the wide-ranging extension of international patents in the solar PV industry: while the patents for solar PV technologies mainly originate from five countries, the patent protection of these inventions substantially extends across 43 countries. Therefore, the importance and wide global extension of patent protections in the solar PV industry provide a good empirical opportunity to study the determinants for seeking patents internationally.

There is a growing interest in using patents data to study technological innovation in the solar PV industry. Previous literature has examined assignees' cooperation network, technology trajectories, technological catch-up by latecomers, and the impact of energy policy on innovations using solar PV patent data [15,20,29,41,62]. Beyond the scope of the existing literature, this study uses solar PV patent data to study the determinants of international patenting extensions. To be specific, this study contributes to the literature in two ways. First, we extend previous studies of the determinants of international patenting behaviors by identifying additional important determinants at the patent and destination country levels. At the patent level, we adopted an innovative way of using the geographic diversity of backward citations to measure the geographic scope of patent applicability. At the destination country level, this study contributes to the literature by quantitatively distinguishing the roles of manufacturing capacity and market size in international patent extensions. A clear distinction between the countries of manufacturing and markets in the solar PV industry provides a good empirical setting to explore the roles of these two determinants in international patent extensions. In addition, this study also distinguishes imitation threats that are specific to the solar PV industry and general within a destination country and discusses whether and how these two types of imitation threats may influence the international patent extensions differently.

Second, we contribute to the literature by exploring the interplay of the determinants of patent extensions at multiple levels with a focus on how the destination country-level determinants vary based on different types of technologies and assignees. Solar PV technologies can be clearly classified into three generations based on different types of materials, including crystalline silicon, thin-film, and emerging solar cell technologies [36,46]. More than 90% of the current solar PV market is held by first-generation technologies, while the new generations are still in the R&D stage and on their way to markets. However, these advanced technologies have great potential for being significantly more efficient and much cheaper in the future. Therefore, a clear distinction between technology generations and the unique features associated with each technology generation enables us to provide a better understanding of how different technology generations may impact international patenting decisions differently. Furthermore, this study also found that the patenting strategy of firm assignees is more market-oriented compared to non-firm assignees, and firm assignees have a stronger incentive for using international patents to address the imitative threats posed by rivals compared to non-firm assignees. Therefore, this study improves our understanding of the differences in international patenting behaviors and the strategic uses of patenting based on different types of technologies and assignees.

The paper is structured as follows: Section 2 reviews the motivations and determinants of international patent extensions in the literature and discusses the research hypotheses in this study. Section 3 describes our data construction, the pattern and the trend of international patents in five leading countries, and econometric models. Section 4 presents the regression results on the determinants of the international patenting extensions. Section 5 discusses the main findings and the future directions.

2. Literature and hypotheses

This section discusses the theoretical perspective of the paper by providing a systematic review of the literature on the determinants of international patenting extension, which offers a basis for developing hypotheses for the solar PV industry. This section also provides the rationale for developing hypotheses to understand the impacts of additional determinants at the patent and destination country levels and the heterogeneity in international patent extension.

2.1. Patent quality and the scope of applicability

Previous literature has found that inventors are inclined to expand the protection of inventions of high quality, and a major reason is that high-quality inventions are more likely to justify the costs of patenting in foreign markets. Ref. [18] pointed out that quality is a key dimension of an invention. The higher the quality of an invention, the higher the return from patenting, and thus inventions of higher quality are more likely to be patented. Ref. [11] also suggested that invention quality plays an important role in firms' decisions to patent abroad. Ref. [43] used the number of forward citations to measure a patent's quality and found that the quality of an invention increases the propensity to apply for international patent protection. The fact that patenting abroad is costly is consistent across different types of assignees, technologies, and destination countries, and thus this study argues that the positive relationship between patent quality and international patenting decisions should be robust across these different categories.

In addition to patent quality, some studies also indicated that inventors are more prone to patent inventions with a higher geographic scope of applicability in foreign markets, as those inventions are more likely to be made, used, sold, and offered for sale in foreign markets [5,39]. But in terms of measurement, previous literature makes no clear distinction between patent quality and the geographic scope of applicability. Ref. [39] used the patent quality indicators to measure both patent quality and how broadly patents are applicable to other countries. Ref. [5] used the R&D intensity of firms to measure both the scope and quality of patents. They found that the higher the scope and quality of the innovations, the more likely the inventors would seek patent protection abroad. However, only including the indictor of patent quality without a direct measurement of applicable scope cannot separate the variations between quality and scope. To address this challenge, this study uses a patent's geographic diversity of its backward citations to measure its geographic scope of applicability. Inventors often acquire knowledge at different geographic levels as sources in their innovation process. Citing studies from the same local area is mainly driven by 1) the sticky and hard-to-codify nature of local knowledge and 2) the usefulness of local knowledge in an invention [4,10,35,49,53,60]. Regarding the characteristics of local and non-local knowledge, previous literature shows that the pool of local knowledge tends to differ from the knowledge in any other location and the content of local knowledge is more likely to be related to local contexts [9,20,45,52,54,55]. As backward citations are codified knowledge that is much less sticky and geographically bounded, the relevance of such context-relevant knowledge in an invention should be a more salient factor for citing local knowledge in a patent. The literature discussed above indicates that patents citing backward citations from a more diverse set of countries are more likely to be general inventions with a more extensive international focus and wider geographic applicability. Therefore, patents with a larger geographic scope of applicability are expected to have a greater propensity to be patented in foreign markets. Based on the discussion about the impacts of patent quality and geographic scope of applicability on international patenting decisions, we propose the following two hypotheses of the determinants at the patent level:

Hypothesis 1. The higher the quality of an invention, the more likely the invention will be patented abroad.

Hypothesis 2. The wider the geographic applicability of an invention, the more likely the invention will be patented abroad.

2.2. Manufacturing and market

A large amount of the literature relates the decision for international patents extensions with the market size and purchasing power in the destination countries, as the commercial exploitation of patented technologies in the destination countries is a major motivation of foreign inventors [3,17]. Ref. [23] provided case studies to show that a firm tends to patent in a foreign country when that country is perceived as a preferred market. Ref. [59] used international patenting data to build the gravity model and found that market size positively influences bilateral international patent patterns. Ref. [8] focused on foreign patent flows to and from the United Kingdom and found that the number of U. K. patent applications abroad is impacted by the effective purchasing power in recipient countries. Ref. [17] used the aggregate data from OECD countries and found that the destination country's market size is a significant factor that explains international patenting behaviors. Ref. [5] used a panel dataset of Spanish innovative firms between 2005 and 2013 and found that the international patenting in EPO and USPTO seems to be more oriented towards market enlargement.

In addition to cover major markets for sales, previous literature indicates that the patent holders may choose to file patents in the countries where the products are manufactured, as Ref. [23] have stated, patenting in multiple foreign countries shows two motivations: that the assignees intend to cover both the countries of manufacturing and the markets for sales. Filing patents in major markets and manufacturing countries would put firms in favorable positions with respect to cross-licensing negotiations and patent infringement suits [12,28]. Ref. [12] found that firms in a complex product industry such as semiconductors (the solar PV industry is one of the critical applications for semiconductors) are much more likely to use patents to force competition into negotiations. In particular, Ref. [26] pointed out that the advantage of covering the major manufacturing countries is to better prevent other manufacturers from entering into markets regardless of where the markets may develop. However, Ref. [26] also discussed the possibility of shifting manufacturing to a different country to avoid a patent, and in this case, greater focus should be given to covering the major market countries. Therefore, it is still unclear about the role of manufacturing size in international patenting decisions.

The solar PV industry is characterized by a large concentration of manufacturing countries and a wide range of deployment markets. By the end of 2019, PV module productions in China (72%), South Korea (8%), the U.S. (6%), Canada (6%), and India (2%) accounted for about 94% of global production, but solar PV technologies are widely deployed in at least 39 countries [6]. Therefore, patenting in major manufacturing markets would prevent other manufacturers from making and using the claimed invention even though markets are widely deployed to many other countries. Furthermore, the shifting of manufacturing is highly relevant in the solar PV industry, as many countries plan to substitute solar PV imports with domestic production [33]. Most of the solar PV markets set aggressive goals for solar installations for 2030 or 2050. In face of the potential future demand, these countries have tended to localize the manufacturing of solar PV components. For example, according to Saudi Arabia's 2030 vision, the localization of PV module manufacturing is considered a top priority by the government [2]. Therefore, covering foreign markets is also expected to be an important patenting strategy in the solar PV industry.

To the best of our knowledge, there is no empirical evidence on the relationship between manufacturing markets and international patent extensions. This study provides a quantitative estimate for the above relationship in the context of the solar PV industry. The solar PV industry is a marketable example that heavily depends on both the manufacturing and the market. The former mainly refers to the production of solar cells and panels, and solar PV technologies are directly applied in the manufacturing sector. The latter is the deployment market of solar PV technologies, which mainly involves system installation and maintenance. Therefore, this industry-specific feature provides a good empirical setting to distinguish the strategic uses of patenting between covering the countries of manufacturing and covering the markets for sales. Inventors in the solar PV industry are expected to file international patents in both foreign markets and the countries of manufacturing to seek legal protection across the value chains, to win favorable terms in negotiations, and to avoid lawsuits. Therefore, based on the previous discussion about the importance of covering both, we propose the following two hypotheses of the determinants at the destination country level:

Hypothesis 3. The larger the manufacturing capacity in a destination country, the more likely an invention will be patented in that destination.

Hypothesis 4. The larger the market size in a destination country, the more likely an invention will be patented in that destination.

2.3. Imitation risks

Previous studies have also explored how imitation threats in a foreign country can impact the decision for international patenting. To reduce the risks of being imitated is another strong motivation for assignees to extend intellectual property protections in foreign countries. Ref. [17] conducted a pioneering study and argued that imitation risk plays a significant role in the decision to patent in a foreign country. A key aim of patenting is to impede other agents in a destination country from imitating the new technology, particularly local competitors [12,28,44,64,68]. Meanwhile, Ref. [68] found that patenting is helpful to reduce the level of competition and increase profitability by increasing competitors' overhead costs.

Some studies measure the imitative threats at the industry level and argue that strong imitative risks to the focal industry in a country provide incentives for assignees to patent in that country [27,28]. focused on industry-level foreign patenting behaviour in China and found that the imitative threat of domestic industries, which is measured by the number of triadic patents[1] in China, is positively related to foreign patents in China. Other studies have focused on the country-level imitation threats. Ref. [43,44] conducted country-level studies and found that the countries which exhibit high innovative activity attract patents from abroad, as higher innovative capacity in a country indicates higher risks of being imitated.

This study contributes to the literature by distinguishing the imitative threats in an industry and the national imitative threats in a destination country in the context of the solar PV industry. Both industry-level and country-level imitative threats are highly relevant in the solar PV industry. On one hand, solar PV technologies are concentratively held by a handful of countries, and the imitative threats posed by local rivals in these countries would motivate the international extensions of patent protection. On the other hand, many other solar PV

[1] Triadic patents refer to patent families consisting of patents applied for in Europe, Japan, and the US.

markets that have strong national innovative capacity but do not specialize in solar PV technologies may also motivate international patent extensions to these countries. One reason is that many of these countries are considering manufacturing the key solar PV components domestically [33], as it is clear that solar power will continue to have huge market potential in the coming decades. Ref. [31] predicted that Solar PV would generate a quarter (25%) of total electricity needs globally. The total solar PV capacity would increase from a global total of 480 GW in 2018 to 2,840 GW by 2030, and to 8,519 GW by 2050. Therefore, in the face of the continuing expansion of future markets and the progress in R&D being made in various countries, inventors would also be motivated to file patent protection in those destination countries with a high national innovative capacity to reduce the imitative threats posed by these future rivals. Based on the previous discussion on the importance of preventing imitation threats in a destination country, we propose the following hypothesis of the determinant at the destination country level:

Hypothesis 5. The higher the imitation risks in a destination country, the higher the propensity to patent in that destination country.

2.4. The heterogeneity in international patent extension

This study argues that the strategic uses of patents are expected to vary considerably based on different types of technologies and assignees. As for different generations of technologies, Ref. [38,47] have pointed out that the patenting strategy may depend on the complexity and advancement of the technology. In the solar PV industry, more than 90% of the current solar PV products are held by first-generation technologies due to their high performance and low costs, while the second and third generations are mainly in the R&D stage and still on their way to market. Therefore, the current solar PV market size in destination countries is expected to be an important motivation for the international patenting of first-generation technology. As for advanced-generation technologies, while these technologies are absent from existing markets, there is currently a lot of solar research going on, and these advanced technologies have great potential for being significantly more efficient, having more diverse uses, using less material, and lowering manufacturing costs in the future. Therefore, the patenting for these advanced technologies would emphasize the market potential in the future. The countries with huge market potentials in the future are very likely to be different from the existing markets, and thus the current solar PV market size and the manufacturing capacity in a destination country tend to play a less pronounced role in influencing international patenting decision-making for advanced-generation technologies compared to first-generation technologies.

In addition, we also argue that patenting for advanced-generation technologies is more likely to emphasize the mitigation of imitation risks and the enhancement of future competitive advantages. Ref. [50] found that the impact of imitation risks on the internationalization of technology depends on technology characteristics. High imitation risks are a hindrance to the internationalization of cutting-edge technologies, but not a barrier to the relatively mature and low-to-medium cost low carbon technologies. This indicates that patent protection against imitation risks would be more important for advanced-generation technologies than for first-generation technologies. Moreover, as there is no existing market for advanced-generation technologies but huge market potential in the future, reducing the imitative threats posed by rivals and gaining competitive advantages to strengthen future market positions in destination countries are expected to be more critical for advanced-generation technologies. Therefore, we argue that preventing the imitation threats posed by rivals in the destination countries would be a more pronounced factor in international patenting decisions for advanced-generation technologies compared to first-generation.

As for different types of assignees, Ref. [38,47] also underlined that the strategies of assignees' international patenting decisions vary considerably. The research directions and patenting strategy of firms are fully market-oriented, but for non-firm assignees (i.e., individuals and research institutes), their research and patenting plans are not fully driven by the markets because they are impacted by the funding availability, research interests, patenting resources, and policies in their research institutions. Furthermore, firms are more likely to have a higher intention of exploiting technology in a destination country to pursue profits compared to non-firm assignees, while non-firm assignees' patenting strategy may also consider scientific research reputation in the destination countries. Therefore, we expect that covering the market and the countries of manufacturing plays a more pronounced role in firm assignees' patenting decisions.

Furthermore, compared to non-firm assignees, firm assignees are expected to have stronger incentives to use international patents to enhance their strategic resources and reduce the imitative threats posed by rivals. Firms typically conduct in-depth analyses of their technology on a global scale and obtain a listing of competitors and their markets before filing international patents [26]. Firms typically also have sufficient financial resources to fully support their patenting strategy of enhancing competitive advantages and reducing imitation risks. However, the international patenting plan for non-assignees may be restricted by their financial resources and limited market information about the focal industry. As for research institutions, their Office of Technology Transfer may also place additional limitations on their patenting plans. As a result, we expect that reducing the imitative threats posed by rivals would be a more pronounced determinant in international patenting decisions for firm assignees compared to non-firm assignees. Based on the discussions in this section, we propose the following two hypotheses:

Hypothesis 6. The positive impacts of manufacturing capacity and market size on the propensity to patent in a destination country are stronger for first-generation technologies, while the positive impact of imitation threats on the propensity to patent in a destination country is stronger for advanced-generation technologies.

Hypothesis 7. The positive impacts of manufacturing capacity, market size, and imitation threats on the propensity to patent internationally are stronger for firm assignees than non-firm assignees.

3. Data and methodology

3.1. Data

Our data were derived from the Derwent World Patents Index (DWPI), International Renewable Energy Agency (IRENA), United Nations Commodity Trade Statistics Database (UN Comtrade), and World Bank. As one of the most representative bibliometric databases for patents, DWPI[2] was selected for this study for two major reasons. First, DWPI is known as the most comprehensive database of enhanced patent information, manually indexed by subject experts from Derwent's editorial team, covering around 41.7 million patents from more than 62 authorities, and unifying these global records in English. Second, a large number of bibliometric studies have been based on the DWPI database, so the analytical methods, approaches, and software tools associated with this corpus are relatively mature and trustworthy. Based on the literature review and expert knowledge, we have identified keywords for each of three generations of solar PV technologies based on different types of materials used in the technologies. These three generations include 1) single and multi-crystalline silicon, 2) thin-film solar cells, and 3) emerging solar cell technologies, such as Dye-Sensitized Solar Cells (DSSC), Colloidal Quantum Dot (CQD), Perovskite, and many kinds of organic materials. The keywords used in our search strategy are

[2] More information can be found on the website: https://clarivate.com/derwent/solutions/derwent-world-patent-index-dwpi/.

presented in Table B.1 in Supplementary Information. Based on our search strategy, 55,847 patents were collected from the DWPI.

We constructed a patent dataset that covered all the patents that were initially filed in the U.S, Japan, Germany, South Korea, and China. Ultimately, the patent dataset contained 50,316 patents from 1968 to 2018. This study focuses on inventions that initially applied for patent protection in a single country and then expanded to other countries, and thus patents initially filed through the World Intellectual Property Organization (WIPO) and European Patent Office (EPO) were removed from the dataset. In the regression analysis, one of the most important independent variables, solar PV installed capacity, is only available beginning in 2000 because solar deployment mainly started around 2000. In 2000, South Korea had 0 MW, China had 3 MW, the US had 21 MW, Japan had 121 MW, and Germany had 44 MW. The number of patents before 2000 only accounts for about 7% of the total number of patents, and thus using the patent data prior to 2000 was not a concern for this study. Furthermore, the patent data in 2017 and 2018 is not complete, as it takes 1–2 years on average to approve and publicize patent applications. Therefore, the regression analysis covers patents that were filed between 2000 and 2016.

The solar cell patent database we collected contains detailed data on each patented invention, including patent number, patent application date, patent assignees, the origin of application country, family member countries/regions, cited patents, and cited patent assignees. The detailed patent data allows us to understand the international mobility of technology. Many technological inventions that initially applied for patent protection in one country (the origin of application country) will also apply for patents in other countries (family member countries and regions). Therefore, examining the sequences of patent applications in different countries/regions for the same technology invention allows us to track the internationalization of each invention, which allows us to construct the dependent variable (see Section 3.2).

The UN Comtrade dataset includes the statistical data of international imports and exports detailed by commodities/service categories and more than 170 reporter countries/areas. We obtained the solar PV imports and exports value for all 43 destination countries from this dataset (Commodity Code: 854,140). The annual solar PV installed capacity for these 43 countries was obtained from the IRENA Data & Statistics. All other country-level variables, including CO2 emission per capita, GDP, RD percent of GDP, and the number of patent applications from nonresidents were derived from the World Bank dataset (see Fig. 1).

3.1.1. The trend and strength of international solar PV patents

In this section, we will review the trend and strength of international patents in the five major countries: the U.S, Japan, Germany, South Korea, and China. While these five countries account for 93% of the global solar PV patents, about 44% of the patents initially filed in these countries sought patent protection for the same invention in foreign countries. Fig. 2 demonstrates that the strength of seeking international patent protections varies significantly across countries. By the end of 2016, 51% of the patents that were initially granted in Germany sought

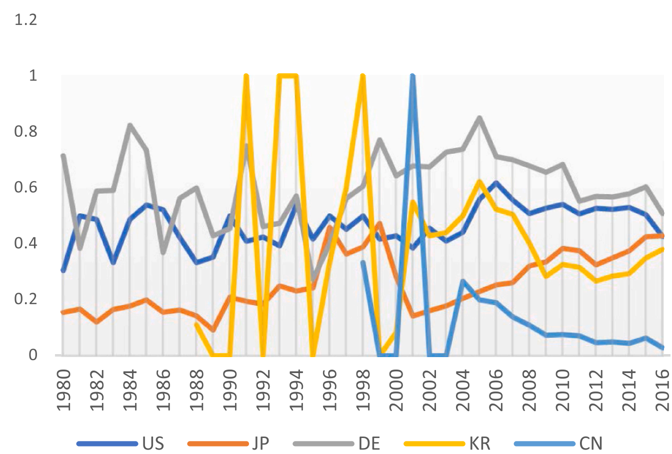

Fig. 2. The share of international patents.

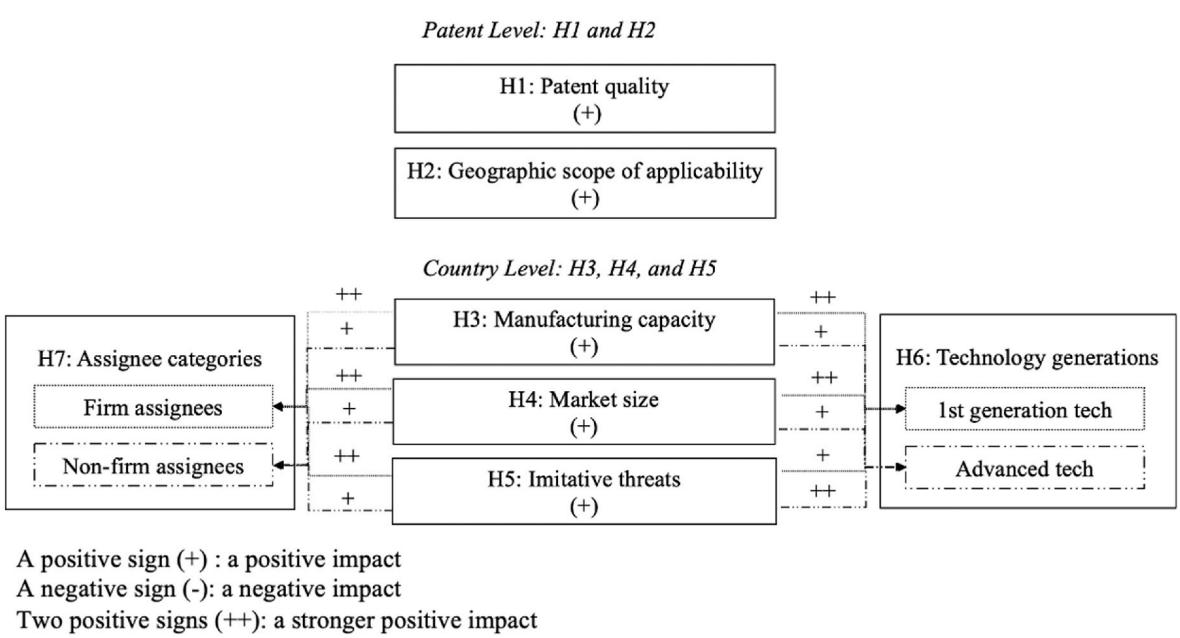

Fig. 1. The summary of research hypotheses. H1 and H2 are hypotheses at the patent level. H3, H4, and H5 are hypotheses at the destination country level. H6 distinguishes different technology generations, and H7 distinguishes firm assignees and non-firm assignees. A positive sign (+) indicates a positive impact on international patent extensions, while a negative sign (−) indicates a negative impact on international patent extension. As for H6 (or H7), two positive signs (++) above an arrow means that the positive effect of a determinant on the propensity to patent internationally is stronger for this type of technology (or assignee) compared to the other type of technology (or assignee) with only one positive sign (+). For example, H7 is that the positive impact of manufacturing capacity, market size, and imitative threats are stronger for firm assignees than non-firm assignees.

to patent in foreign countries, followed by those in the U.S. (45%), Japan (43%), South Korea (35%), and China (3%). Fig. 3 shows the historic trend of international patents in these five countries. The U.S, Japan, and Germany all had international solar cell patents before 1980, while South Korea and China were two “latecomer countries.“. South Korea and China started to have solar cell patents in 1985 and 1992, respectively, and started to file their patents in foreign countries in 1988 and 1998, respectively. Except for China, all four countries experienced a significant downturn in patents beginning in 2010, although the increase in the number of international patents in China is slow-paced.

The downturn trend of international patents could result from the decline in the number of assignees and/or the fall in the number of international patents held by each assignee. To separate these two potential reasons, we further plotted the number of assignees associated with international patents and the number of international patents belonging to each assignee in each country (Figs. 4 and 5). We found that the trend of the number of assignees closely resembles that of the number of international patents, which suggests that many firms exiting the market might be a key reason for the downturn in patents since 2011. However, the number of international patents belonging to each assignee is surprisingly increasing (Fig. 5). This phenomenon—that while many firms exited the solar PV market, the surviving companies increased their research investment and patent filings—indicates that seeking overseas patent protection is increasingly important for the surviving assignees. China is an exception to the above phenomenon: there is an increasing number of assignees seeking to patent abroad, but the number of international patents per assignee has not increased in the last decade.

3.2. Dependent variables

The dependent variable in this study measured the international patenting decisions. We measured the decision of patenting abroad as a binary variable, which means the value of the dependent variable is 1 if a patent i filed an international patent for the same invention in country j in year t, and the value of the dependent variable is 0 if a patent i didn't file an international patent for the same invention in country j in year t. In other words, the dependent variable is to measure whether a patent i filed an equivalent patent in country j. Each patent appears multiple times in the final dataset, and the dependent variable measures whether this patent filed an international patent in all the other countries besides the home country where it initially registered the patent. For example, if a patent was initially filed in the U.S, this patent would appear multiple times in the final dataset to indicate whether this invention filed an international patent in all the other countries except the U.S.

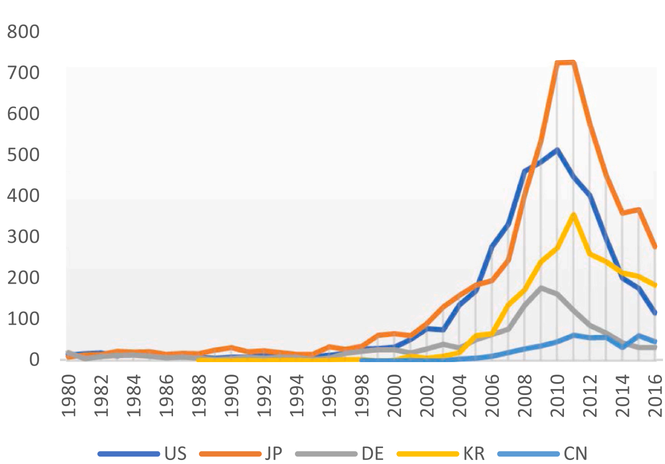

Fig. 3. The number of international patents by country.

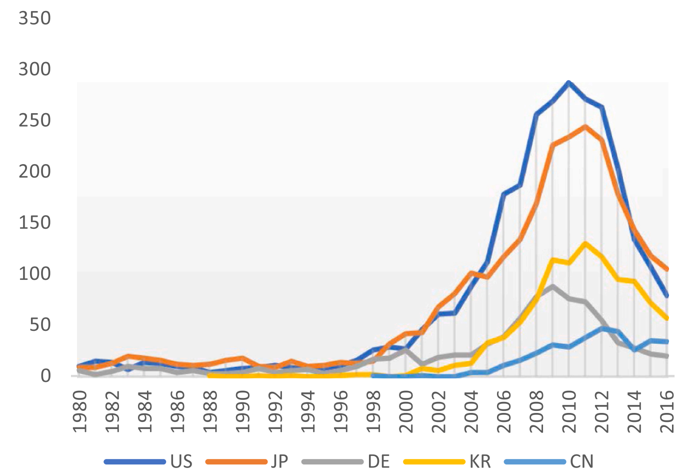

Fig. 4. The number of assignees by country.

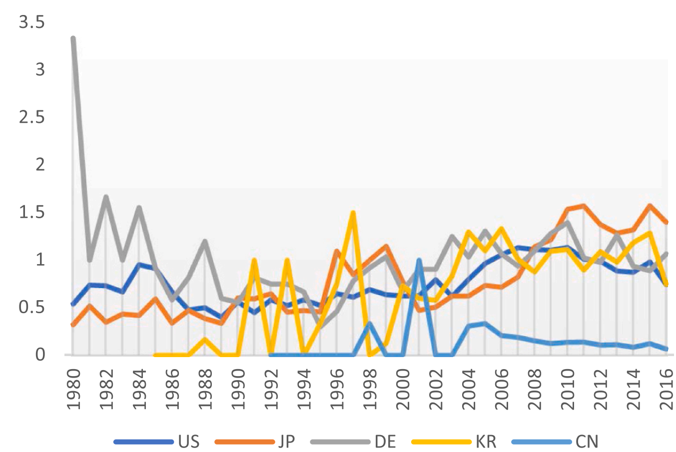

Fig. 5. The number of international patents per assignee.

3.3. Independent variables

3.3.1. Patent-level variables

The first patent-level variable is the geographic scope of applicability, which is measured by the geographic diversity of backward citations in a patent. The more diverse the backward citations that are cited by a patent, the more likely this patent has a wider geographic scope of applicability. We used the normalized entropy to measure the geographic diversity of backward citations. Introduced by Ref. [56]; entropy has been widely used as an indicator for measuring divergence [66]. We calculated the entropy of each patent through the following formula:

$$H_i = -\sum_{j=1}^{n} p_{ij} \ln p_{ij}$$

Where H_i is the entropy of a focal patent i, p_{ij} represents the percentage of the focal patent i's cited patents from country j and n is the total number of cited countries associated with the focal patent i. When considering H_i varies from 0 to $ln(max(n))$, we normalized H_i using min-max normalization. The higher value of normalized entropy, the greater the diversification of backward citations across various countries. A greater diversification of backward citations indicates a higher probability of being a general invention with wider geographic applicability and more extensive international focus, and thus we expect that this invention is more likely to be patented in foreign countries.

The previous literature showed that integrating knowledge sources across a more diverse region is associated with a higher level of quality [19,58], and thus this study controlled the patent quality to separate the variations between patent quality and the applicability scope. In other words, after controlling for a patent's quality, the remaining variations of the diversity of backward citations should reflect the applicability scope of a patent. Including the indicators of patent quality and geographic scope of applicability in the model let us test Hypothesis 1 and Hypothesis 2.

The most commonly used indicators of patent quality are the number of forward citations and family size [22,25,40,48], but the former one is not available for our dataset and using the latter might cause the endogeneity issue as our dependent variable is built upon the patent extension. Therefore, following Ref. [61]; we constructed three indicators of patent quality based on backward citations, grant lags, and an incomplete set of forward citations in this study, and we compared the regression results of using these three indicators to check the robustness of our results.

First, backward citations are the knowledge sources of an invention, showing all the related prior knowledge that an invention relied on. Making sure to include all the relevant prior knowledge as backward citations is a task for examiners during the patent application process [1, 13]. The indicator based on backward citations is helpful to assess the novelty of patents and has been found to be positively related to patent quality [14,25]. Following Ref. [61]; we normalized the number of backward citations based on the maximum value of the backward citations in the same year-and-technology cohort. Second, the length of grand lag is defined as the number of days between application date and granting date. To make the variable more comparable between patents across years, we also normalized this indicator based on the maximum length of grant lag in the same year-and-technology cohort. The length of grant lag depends on the efforts made by applicants; to accelerate the application process, applicants are more likely to fully prepare and document the applications to a high standard and closely work with patent offices for these applications [24,51,61]. Third, as for the forward citations, we do not have available data on the forward citations for all the patents in our dataset. We constructed an incomplete set of forward citations based on the backward citations. 13,100 patents were found to appear in the backward citations of all the patents (50,316 patents) in the dataset. Based on this, we were able to count the number of forward citations for these 13,100 patents, but it is an incomplete set of forward citations, as it only shows the number of times these 13,100 patents are cited by the 50,316 patents in the dataset. As patents issued in different years vary in the number of years in which forward citations can occur, we only counted the number of forward citations that were received by the patent within 5 years.

3.3.2. Technology generations

The solar cell technologies experienced three generations based on different types of materials used in the technologies, including single and multi-crystalline silicon, thin-film solar cells, and emerging solar cell technologies. The second and third generations are more advanced and complicated than the first generation. Considering the large size of the dataset, as well as the limited aid of expert knowledge, a semi-automatic classification method was proposed. We used an approach incorporating topic extraction with word embedding techniques to classify these patents into three technology categories [42,65]. A stepwise description of the algorithm can be found in Supplementary Information. After this classification method, 30,243 patents were assigned to the category of silicon, while the categories of semiconductor and emerging materials got 4,660 and 15,413 patents, respectively. We merged the categories of semiconductor and emerging materials into a new category called advanced-generation technology.

3.3.3. Assignee categories

The variable we included as an assignee-level variable was to indicate whether a patent was filed by firms, individuals, or public research institutes (including universities). We manually reviewed the names of all the patents' assignees and classified the assignees into one of these three categories. Ultimately, 36,147 patents were filed by firms, 4,130 patents were filed by individuals, and 8,149 patents were filed by public research institutes including universities. 1,890 patents had no information about their assignees.

3.3.4. Destination country-level variables

The first set of destination country-level variables was to measure *the market size* and *the manufacturing capacity* in a destination country, as one major motivation of patenting abroad is to cover the markets and the countries of manufacturing (*Hypotheses 3 and 4*). In this study, we used solar PV installed capacity to measure the market size of solar PV technology, and solar PV export value to measure the manufacturing capacity. The higher the PV export value in a destination country, the higher the manufacturing capacity in that destination country.

Another set of variables measured *imitation threats* (Hypothesis 5). We used the total number of assignees in the solar PV industry in a destination country to measure the potential threats from local imitators in the destination countries. This measurement refers exclusively to assignees of solar PV patents that originate in a destination country. In addition to imitation threats in the solar PV industry, we also included general imitation (non-industry specific) threats in a destination country, which were measured by Research & Development (RD) as a percent of GDP. The countries with a higher RD percentage of GDP would have a higher potential and capacity to imitate new inventions.

3.3.5. Control variables

As patenting abroad is costly and risky, international patenting behaviors also depend on *the general patent conditions for nonresidents* (e.g., the strength of the intellectual property rights, the complexity degree of the application process, and patent application costs) in a foreign country. In this study, we used the total number of patent applications from nonresidents in a destination country as a proxy for the general patent conditions in that country. We also controlled GDP, CO2 emissions per capita, geographic distance, and solar PV import in the models. We measured the geographical distance between two countries with the following steps: (1) We retrieved World Cities Database[3] and used the geographic latitude and longitude of a country's capital to proxy its location. In very few cases, if a country has multiple capitals, we used the average latitude and longitude of the capitals. (2) We employed the Haversine library,[4] a Python-based distance calculation library, to calculate the pairwise distances between each priority country and its family countries. Country dummy variables and year dummy variables were also included in this study to control for unobserved year-specific and country-specific variables affecting assignees' international patenting decisions.

3.4. Econometric models

The empirical model studies the determinants of international patenting. Our dependent variable Y_{ijt} measured whether a patent i filed an equivalent international patent in country j in year t. As the dependent variable is a dichotomous variable, logistic regression models are the most appropriate modelling technique. Logistic regression estimates the probability of a binary outcome given a vector of independent variables $\mathbf{X}$ (i.e., $P(Y_{ijt} = 1|\mathbf{X})$). Our independent variables included the determinants of international patenting at the patent, assignee, technology, and destination country levels. We also included country dummy variables (μ_j) and year dummy variables (γ_t) to control for unobserved year-specific and country-specific variables affecting assignees'

[3] https://simplemaps.com/data/world-cities.

[4] https://pypi.org/project/haversine/.

international patenting decisions. e_{ijt} is the error term. Including country and year fixed effects is helpful to reduce the problem of omitted-variable bias. More importantly, adding country fixed effect enabled us to exploit only within-country variations over time. The patents granted in different national patent offices are not comparable. For example, USPTO uses full disclosure to show prior art, while other patent authorities may not include all the relevant prior art, which indicates that the citation-based variables are not particularly comparable across patent authorities. Therefore, our solution was to exploit only within-country variations over time by adding country fixed effects. Put differently, cross-country variations and comparisons were not involved in the econometric models. In addition, as we had a comprehensive set of independent variables in the model, the collinearity issue might have been a concern. We have included correlation matrix and variance inflation factor (VIF) tests in Supplementary Information, which show that the collinearity issue was not a concern for this study.

Table 1 lists the three model specifications and Table 2 lists the variables and the corresponding hypotheses. Equation 1 is the basic model, which includes all the variables at the patent, technology, assignee, and destination country levels. We introduced interaction terms in Equations 2 and 3 to examine the differences in international patenting behaviors based on different types of assignees, technologies, and technology development status of destination countries. To be specific, Equation 2 includes the interaction terms between technology categories (advanced generations vs. first generation) and variables at the destination country level, and Equation 3 includes interactions terms between assignee categories (firms vs. individuals vs. research institutes). We included regression results for 9 models in section 5. Model 1 is the model that includes all the variables at the patent, technology, and destination country level. Models 2 and 3 used a subsample of the first generation of solar cell technology and the advanced generations, separately. Model 4 introduced the interaction terms between destination country variables and technology categories (first-generation vs. advanced generations). Models 5–7 used a subsample of firm assignees, individual assignees, and public research institute assignees, respectively. Models 8 and 9 included the interaction terms between destination country variables and assignee categories (firms vs. individuals vs. public research institutes).

Table 1
List of model specifications.

Equation 1	$P(Y_{ijt}=1\|\mathbf{X}) = \boldsymbol{F}\,(\alpha + \beta * Technology_i + \chi * Assignee_i + \boldsymbol{\delta} * \boldsymbol{Patent}_i + \boldsymbol{\eta} * \boldsymbol{Country}_{jt} + \mu_j + \gamma_t + e_{ijt})$
Equation 2	$P(Y_{ijt}=1\|\mathbf{X}) = \boldsymbol{F}\,(\boldsymbol{\alpha} + \beta * Technology_i + \chi * Assignee_i + \boldsymbol{\delta} * \boldsymbol{Patent}_i + \boldsymbol{\eta} * \boldsymbol{Country}_{jt} + \boldsymbol{\lambda} * \boldsymbol{Country}_{jt} * Technology_i + \mu_j + \gamma_t + e_{ijt})$
Equation 3	$P(Y_{ijt}=1\|\mathbf{X}) = \boldsymbol{F}\,(\alpha + \beta * Technology_i + \chi * Assignee_i + \boldsymbol{\delta} * \boldsymbol{Patent}_i + \boldsymbol{\eta} * \boldsymbol{Country}_{jt} + \boldsymbol{\lambda} * \boldsymbol{Country}_{jt} * \ Firm_i + \mu_j + \gamma_t + e_{ijt})$

Note: $P(Y_{ijt}=1|\mathbf{X})$ is the probability of a patent i filed an equivalent international patent in country j in year t ($Y_{ijt}=1$) given a vector of independent variable $\mathbf{X}$. $Technology_i$ is a binary variable indicating whether the focal patent i belongs to advanced solar cell generations. $Assignee_i$ is a binary variable indicating the categories of assignees, including firm, individual, and public research institute. $\boldsymbol{Patent}_i$ is a vector of determinants at the patent level, including patent quality and applicability scope. $\boldsymbol{Country}_{jt}$ is a vector of determinants at the destination country level, including manufacturing capacity, market size, imitation threats in the industry, and national imitation threats. $\alpha, \beta, \chi, \delta,$ and η are constant and the coefficients of the variables at each level, respectively. $\boldsymbol{\lambda}$ is a vector of the coefficients of the interaction terms. μ_j is the country dummy variable and γ_t is the year dummy variables. e_{ijt} is the error term. The measurements of the variables at each level are shown in Table 2. The description of these measurements is presented in Section 3.3.

Table 2
List of variables and the corresponding hypotheses.

Level	Variables	Measurement	Hypotheses
Patent	Patent quality	Number of backward citations	H1
	Applicability scope	Diversity of backward citations	H2
Country	Manufacturing capacity	Solar PV export	H3
	Market size	Installed capacity of solar PV systems	H4
	Imitation threats in the industry	Number of assignees of Solar PV patents	H5
	National imitation threats	RD as a percent of GDP	
	Control variable	GDP	
	Control variable	CO2 emissions per capita	
	Control variable	Solar PV import	
	Control variable	Patent applications from nonresidents	
	Control variable	Distance	
Technology	Technology generations	First generation (vs. advanced generations)	H6
Assignee	Assignee categories	Firms (vs. individuals vs. research institutes)	H7

4. Results and discussion

4.1. Patent, technology, and assignee level determinants

Our regression results provide answers to the following two research questions: 1) how international patenting behaviors are impacted by factors at the patent, technology, assignee, and destination country levels; and 2) what the differences are in international patenting behaviors based on different types of assignees and technologies.

Model 1 provides answers to the first research question. The coefficients of patent quality and diversity of backward citations support our hypotheses 1 and 2. High-quality patents are more likely to be patented in foreign countries, and the potential reason might be high-quality patents are more likely to be worth the costs and efforts associated with the international patenting process. Patents that cite backward citations from a more diverse set of countries are also more likely to be patented abroad, as patents that cite prior knowledge from more diverse countries would have a wider geographic scope of applicability and a larger potential for applying to foreign markets. In terms of assignee and technology categories, we found that compared to firms, individual assignees are more likely to apply for patents abroad, while public research institutes (including universities) are less likely to register international patents. We also found that first-generation technologies are more likely to apply for equivalent international patents in foreign countries compared to advanced-generation technologies.

4.2. Destination country level determinants

All the factors at the destination country level are important determinants that impact the international patenting decision-making process. First, we found that an invention is more likely to be patented in a foreign country with larger market size and higher manufacturing capacity in the solar PV industry, which supports our hypotheses 3 and 4. It indicates that covering both the countries of manufacturing and the markets are two motivations for patenting abroad in the solar PV industry. To seek patents in both the countries of manufacturing and the solar PV markets would protect the assignees' legal rights to exclude others from making, using, selling, and offering for sale the claimed invention in those countries. However, we surprisingly found that GDP is negatively related to international patenting in all models. It might be because 1) market size for the solar PV technology has been included in the model and/or 2) GDP is highly related to other variables in the model including PV export, PV import, total PV assignee, and the number of non-residents patents, and thus it is likely that the remaining variation of GDP is unrelated to market size.

Second, the regression results show that the imitation threats of the solar PV firms in the destination countries, measured by the total number of PV assignees, are positively related to the propensity for foreign patenting in the destination countries. The higher the imitation threats in a destination country, the more likely an invention will be patented in that destination country. Moreover, the national imitation risks, which are measured by the RD percentage of GDP, are also positively associated with the propensity for patenting abroad. The higher the national imitation risks in the destination country, the more likely an invention will be patented in that destination country. As indicated by the coefficient of patent applications from nonresidents, we also found that an invention is more likely to be filed in a foreign country with more favorable patent conditions for nonresidents such as high strength of intellectual property rights, simplified patenting process, and low patent application costs.

Third, we distinguished the first generation of solar cell technology from advanced generations in Models 2 and 3. In Table 3, Model 2 ran the regression on a sample of first-generation technologies, and Model 3 on a sample of advanced-generation technologies. The signs and significance levels of all the variables in Models 2 and 3 are the same as those in Model 1, except that the coefficient of CO2 emissions is not significant for advanced-generation technologies. We also distinguished different types of assignees including firms, individuals, and research institutes. In Table 4, Models 5–7 are regression results based on samples of firm assignees, individual assignees, and public research institute assignees, respectively. Most of the coefficients in Models 5–7 have the same signs as Model 1, while the coefficients of total PV assignees for individuals and research institutes are negative and the coefficient of CO2 emissions for research institutes is not significant. We will have more discussions on the differentiated impacts of country-level determinants on international patenting behaviors based on different categories of technology and assignees in Sections 5.3.

4.3. *The heterogeneity in international patenting across technology and assignee categories*

To test the heterogeneity in international patenting behaviors, we introduced the interaction terms between destination country variables and technology categories (first-generation vs. advanced generations), and between destination country variables and assignee categories (firms vs. individuals vs. public research institutes) in Models 4, 8, and 9.

The regression results in Model 4 show that both the manufacturing capacity and the market size in a destination country are more important factors that impact patenting abroad decisions for first-generation technology. This could be explained by the dominant position of first-generation technologies in the current markets, while advanced-generation technologies are still in the R&D stage and far away from the market. However, Models 8 and 9 show that there are no significant differences in the magnitudes of the impacts of market size on the propensity to patent between firm and non-firm assignees. This indicates that covering foreign markets is an important patenting motivation for all types of assignees. However, the impact of manufacturing capacity is higher for firm assignees than non-firm assignees.

As for imitation threats, the regression results in Model 4 show that both the national and industry-specific imitation threats in a destination country are more pronounced factors in international patenting decisions for advanced technologies compared to first-generation technologies. While advanced generations are absent in the existing market, they are very likely to have huge market potential in the future, as they have great potential for being significantly more efficient and much cheaper in the future. Therefore, the patenting for advanced technologies is more likely to emphasize the mitigation of imitation risks and the enhancement of future competitive advantages. As for different types of

Table 3
The regression results based on technology categories and their interactions.

	Model 1	Model 2	Model 3	Model 4
	All patents	First-generation technology	Advanced-generation technologies	Interaction
log (Normalized entropy)	0.073***	0.074***	0.074***	0.072***
	(0.001)	(0.001)	(0.002)	(0.001)
log (Normalized backward citations)	0.678***	0.607***	0.659***	0.683***
	(0.007)	(0.009)	(0.011)	(0.008)
log (solar PV installed capacity)	0.008***	0.006**	0.013***	0.019***
	(0.002)	(0.002)	(0.003)	(0.003)
log (PV export value)	0.161***	0.154***	0.170***	0.192***
	(0.011)	(0.014)	(0.017)	(0.015)
log (PV import value)	0.030***	0.040***	0.009	0.083***
	(0.012)	(0.015)	(0.019)	(0.015)
log (Total PV assignee)	0.375***	0.388***	0.359***	0.326***
	(0.021)	(0.028)	(0.032)	(0.026)
log (Patent applications from nonresidents)	1.433***	1.418***	1.441***	1.394***
	(0.019)	(0.024)	(0.031)	(0.023)
log (RD of GDP)	0.532***	0.537***	0.507***	0.473***
	(0.055)	(0.071)	(0.085)	(0.063)
log (GDP)	−0.431***	−0.431***	−0.424***	−0.434***
	(0.016)	(0.021)	(0.025)	(0.016)
log (CO2 emission per capita)	−0.267***	−0.271***	−0.244***	−0.272***
	(0.027)	(0.035)	(0.043)	(0.027)
log (Distance)	−0.106***	−0.115***	−0.100***	−0.108***
	(0.013)	(0.017)	(0.020)	(0.013)
Individual	0.202***	0.175***	0.223***	0.199***
	(0.019)	(0.025)	(0.031)	(0.019)
Public research institute	−0.867***	−0.886***	−0.972***	−0.868***
	(0.025)	(0.033)	(0.040)	(0.026)
Advanced generations	−0.293***			2.052***
	(0.014)			(0.535)
log (solar PV installed capacity) * Advanced generations				−0.021***
				(0.003)
log (PV export value) * Advanced generations				−0.069***
				(0.021)
log (PV import value) * Advanced generations				−0.125***
				(0.021)
log (RD of GDP) * Advanced generations				0.182***
				(0.062)
log (Total PV assignee) * Advanced generations				0.103***
				(0.031)
log (Patent applications from nonresidents) * Advanced generations				0.119***
				(0.026)
Constant	−5.856***	−6.187***	−5.910***	−6.835***
	(0.472)	(0.617)	(0.733)	(0.537)
Year fixed effect	Yes	Yes	Yes	Yes
Country fixed effect	Yes	Yes	Yes	Yes
Pseudo R-squared	0.67	0.66	0.68	0.67
Observations	468,983	283,779	185,204	468,983
Log Likelihood	−75,953	−45,589	−30,549	−75,788
Akaike Inf. Crit.	151,972	91,243	61,161	151,654

Robust standard errors in parentheses.
Significance levels: ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

Table 4
The regression results based on assignee categories and their interactions.

	Model 5	Model 6	Model 7	Model 8	Model 9
	Firm	Individual	Public research institute	Firm vs. Individual	Firm vs. Public research institute
Advanced generations	−0.278***	−0.291***	−0.571***	−0.274***	−0.302***
	(0.016)	(0.034)	(0.057)	(0.014)	(0.015)
log (Normalized entropy)	0.075***	0.068***	0.061***	0.074***	0.074***
	(0.001)	(0.002)	(0.003)	(0.001)	(0.001)
log (Normalized backward citations)	0.696***	0.492***	0.906***	0.660***	0.716***
	(0.009)	(0.017)	(0.031)	(0.008)	(0.008)
log (solar PV installed capacity)	0.008***	0.004	0.026*	0.012***	0.007
	(0.002)	(0.003)	(0.014)	(0.003)	(0.008)
log (PV export value)	0.165***	0.142***	0.095**	0.071***	0.029
	(0.013)	(0.023)	(0.044)	(0.024)	(0.040)
log (PV import value)	0.018	0.079***	0.111*	0.134***	−0.075
	(0.014)	(0.026)	(0.057)	(0.027)	(0.047)
log (Total PV assignee)	0.442***	0.084*	0.018	0.151***	0.398***
	(0.025)	(0.044)	(0.096)	(0.041)	(0.069)
log (Patent applications from nonresidents)	1.383***	1.627***	1.776***	1.882***	1.545***
	(0.022)	(0.045)	(0.091)	(0.042)	(0.053)
log (RD of GDP)	0.412***	0.799***	1.927***	1.011***	0.914***
	(0.064)	(0.126)	(0.278)	(0.097)	(0.129)
log (GDP)	−0.435***	−0.195***	−0.373***	−0.412***	−0.439***
	(0.019)	(0.036)	(0.072)	(0.016)	(0.018)
log (CO2 emission per capita)	−0.303***	0.011	−0.424***	−0.236***	−0.311***
	(0.032)	(0.061)	(0.144)	(0.028)	(0.031)
log (Distance)	−0.168***	0.128***	0.008	−0.133***	−0.145***
	(0.015)	(0.030)	(0.056)	(0.013)	(0.015)
Firm				5.691***	−2.701**
				(0.76)	(1.062)
log (solar PV installed capacity) * Firm				−0.004	0.002
				(0.004)	(0.008)
log (PV export value) * Firm				0.107***	0.143***
				(0.027)	(0.041)
log (PV import value) * Firm				−0.136***	0.103**
				(0.029)	(0.048)
log (RD of GDP) * Firm				−0.677***	−0.424***
				(0.091)	(0.123)
log (Total PV assignee) * Firm				0.290***	0.018
				(0.043)	(0.068)
log (Patent applications from nonresidents) * Firm				−0.557***	−0.139***
				(0.042)	(0.052)
Constant	−4.468***	−16.770***	−13.642***	−10.449***	−2.547**
	(0.547)	(1.138)	(2.404)	(0.814)	(1.138)
Year fixed effect	Yes	Yes	Yes	Yes	Yes
Country fixed effect	Yes	Yes	Yes	Yes	Yes
Pseudo R-squared	0.67	0.68	0.63	0.67	0.67
Observations	338,990	57,485	72,508	396,475	411,498
Log Likelihood	−58,159	−11,679	−5,132	−70,233	−63,614
Akaike Inf. Crit.	116,379	23,421	10,327	140,542	127,303

Robust standard errors in parentheses.
Significance levels: ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

assignees, the results in models 8 and 9 show that the general level of imitation threats in a destination country plays a more pronounced role for non-firm assignees, but the imitation risks in the solar PV industry is a more pronounced factor for firm assignees compared to individuals. However, the interaction terms between the imitation threats in the solar PV industry and firms (vs. public research institutes) are not statistically significant. In addition, the general patenting condition is a stronger factor that impacts non-firm assignees' international patenting decisions, which may be because individuals and research institutes have more concerns about patenting costs and the difficulties of the process.

In summary, we found that market coverage is a more pronounced motivation in international patenting decisions for first-generation technologies compared to advanced technologies, while preventing imitation threats in a destination country plays a more powerful role for advanced technologies. In terms of different types of assignees, market coverage and imitation reduction are more pronounced factors for firms in their international patenting decision-making, while general patenting conditions and general imitation threats in foreign countries play a more pronounced role in non-firm assignees' patent extensions overseas.

5. Conclusion

In this study, we analyzed the pattern of internationalization of technology in the solar PV industry using a unique and rich patent dataset across 43 countries from 1980 to 2016. While 93% of solar PV patents are concentrated in five countries, the U.S, Japan, Germany, South Korea, and China, the internationalization of these patents is much less concentrated, widely extending across all 43 countries. We found that the strength and the direction of patenting abroad vary across different home countries. The share of the international patents in Germany, the U.S, Japan, South Korea, and China were around 51%, 45%, 43%, 35%, and 3% in 2016, respectively. We also found a significant downturn in international patenting around 2010, which was probably caused by many firms exiting the market. But another interesting phenomenon is that the number of international patents per assignee has been increasing since 2010, which indicates that the surviving companies increased their research investment and patent filings to gain competitive advantages in the global market.

More importantly, this study contributes to the literature by identifying additional important determinants of international patenting extension and exploring the differences in international patenting behaviors based on different types of technologies and assignees. The regression results show that the factors at the patent, assignee, technology, and destination country levels all significantly contribute to decisions about patenting abroad. We found that patents with higher quality and a wider scope of applicability are more likely to be patented in foreign countries, and it may be because these patents are more likely to be profitable in foreign countries. The destination countries with larger manufacturing capacity and market size, as well as higher imitation risks, are more attractive to international patents. That suggests that international patenting extensions in the solar PV industry are motivated by market coverage in both the countries of manufacturing and the markets and by imitation threats reduction in the destination countries.

We also found heterogeneity in international patenting decisions based on different types of technology and assignees. While the signs of all the determinants are the same for each type of technology and assignee, the strength of these determinants is different. The positive impacts of manufacturing capacity and market size on the propensity to patent in a destination country were found to be stronger for first-generation technologies, while the positive impact of imitation threats on the propensity to patent in a destination country was found to be stronger for advanced technologies. It suggests that the propensity for patenting in foreign countries depends on the characteristics of technologies. In the solar PV industry, more than 90% of the solar PV market is held by first-generation technologies while advanced technologies are still far away from the markets, which would explain why current market size and manufacturing capacity are more important for first-generation technologies. However, while the advanced-generation technologies are mainly in the R&D stage, these advanced technologies have great potential for being significantly more efficient and much cheaper in the future. Therefore, reducing the imitation risks and gaining competitive advantages in the future would be more powerful factors for these advanced technologies. We also found that firm assignees' international patenting decisions are more closely related to market-related factors, including the manufacturing capacity and imitation threats in the solar PV market. However, compared to firm assignees, individual and public research institute assignees put more emphasis on the general patenting conditions and general imitation threats in foreign countries.

This paper also has some limitations that future work could address. First, this study investigated the motivations of international patent extensions at the patent and destination levels and explored the different patenting behaviors based on different types of assignees and technologies. However, it would be interesting to examine the strategical use of international patent protections at the firm level. Future research could create a firm-level dataset to explore the heterogeneity in international patenting behaviors based on firm-level features. Conducting in-depth case studies based on a handful of firms would also be helpful to understand the firms' strategic use of patenting abroad. Second, this paper focuses on *the motivations* of international patent extensions. Given the large scale and fast growth in international patent filings, it is critical to study the *impacts* of international patent extensions on both assignees and destination countries. Third, our patent dataset presents the huge technology gap between leading countries and lagging countries in the solar PV industry, as five leading countries account for 93% of all the solar PV patents globally. Exploring how the technology gap could be narrowed and how the lagging countries could catch up with leading countries would be intriguing and impactful avenues for further research.

Author statement

Xue Gao: Conceptualization, Methodology, Software, Data collection, Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, and Writing – review & editing.; **Yi Zhang**: Data collection, Measurement calculation, and Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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