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DEVELOPMENT OF CLIMATE FRIENDLY COOLING TECHNOLOGIES: TRENDS AND DRIVING FACTORS, 1990–2019

Sheng Zhong

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Sheng Zhong is a senior research fellow at the Energy Studies Institute, National University of Singapore, Singapore.

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Email: esizs@nus.edu.sg

Asian Development Bank Institute
Kasumigaseki Building, 8th Floor
3-2-5 Kasumigaseki, Chiyoda-ku
Tokyo 100-6008, Japan

Tel: +81-3-3593-5500
Fax: +81-3-3593-5571
URL: www.adbi.org
E-mail: info@adbi.org

Abstract

Cooling is an important area for which there is a rapidly increasing demand, but it accounts for a sizeable portion of electricity consumption and generates negative environmental externalities. Technological change directed towards environmental sustainability is essential for cooling to play a role in sustainable development pathways. This paper seeks to characterize important empirical patterns regarding climate friendly cooling technologies. This is mainly based on a patent search strategy following the Organisation for Economic Co-operation and Development (OECD) guidelines on environmental technologies. We identify 118,396 patent families in this field over the period 1990–2019, and the top five innovative economies, i.e., the People's Republic of China (PRC), Germany, Japan, the Republic of Korea, and the United States, accounting for 90.4% of total technologies. Global innovation in this field, dominated by Japan in the early years, has achieved a rapid growth since 2005, which was primarily driven by the PRC. The United States is the innovation leader in terms of scientific impact. Japan is found to be exclusively specialized in a single cooling field, whereas the other major economies have more diversified innovation portfolios. This suggests newcomers to this field should develop innovations that match their national needs and core competences. Using an index decomposition technique, this paper further quantifies the drivers of innovation in this field. Despite different GDP effects, the decomposition results highlight the crucial role of prioritizing cooling technologies and enhancing R&D intensity and productivity.

Keywords: patents, technological development, climate friendly cooling, LMDI decomposition

JEL Classification: C65, O30, O38, Q50

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1. INTRODUCTION

The Sustainable Development Goals (SDGs) adopted by the United Nations (2015) and the Paris Agreement (UNFCCC 2015) address the need for climate change mitigation, which has achieved general consensus across the economies of the world. However, the current trajectories for the economic growth of the global economy, given the increasing demand for resources and rapid demographic growth, would imply a development pathway that is unsustainable (Cumming and von Cramon-Taubadel 2018). Thus, searching for a pathway that is able to address both economic and climate targets is a major policy concern. This has been well addressed in SDG 13 "Climate Action." Cooling is an important area for such a sustainable pathway given the various types of cooling technologies in industrial production and buildings. Furthermore, the number of cooling units (e.g., air conditioners or fans) in the residential sector worldwide is projected to rise from about 3.4 billion in 2016 to more than 8 billion in 2050 (IEA 2018). However, cooling accounts for a sizeable portion of energy demand and generates negative environmental externalities. Residential cooling applications alone accounted for nearly 20% of total electricity use in buildings around the world in 2016, and is projected to be more than triple by 2050, equivalent to the People's Republic of China (PRC)'s total electricity demand today (IEA 2018). In addition, the refrigerants used for cooling (e.g., HFCs) are effective greenhouse gases and their usage is growing at a rate of 10% to 15% per year (Velders et al. 2012; Li et al. 2021).

For cooling to contribute positively to the sustainable pathway, the key is to develop cooling technologies that are climate friendly and energy efficient. This is in accordance with SDG 9 on Industry, Innovation, and Infrastructure and the crucial role of directed technological change towards environmental sustainability in sustainable development (Acemoglu 2002; Acemoglu et al. 2012). Climate friendly cooling technologies are not new. The first climate friendly cooling technology we have found is a patent titled "improvements in absorption cold producing machines," which was filed by a Swiss inventor in the UK in 1909.[1] However, as we will show later, the growth of climate friendly cooling technologies worldwide remained at a lower rate until the 2000s. In addition, cooling has long been considered as a "blind spot" of energy policy, as it receives relatively less policy attention (IEA 2018). This paper particularly focuses on the development of climate friendly cooling technologies in the world, and provides some empirical evidence that is meaningful for the ongoing policy debate regarding cooling.

Prior studies have already shed some light on the projections of market demand for cooling, and the associated energy demand for the whole world (IEA 2018), and for specific regions such as the Association of Southeast Asian Nations (ASEAN), in which rapid growth is taking place and the temperature is relatively higher (IEA 2019). For ASEAN in particular, the application of energy efficient air conditioning in ASEAN's residential sector can lead to a cumulative cost saving of at least 6.6 billion US dollars and reduce at least 267 $MtCO_2$ by 2040 (ACE 2020). Another strand of the literature has focused on the techno-economic assessment of different technological options for cooling, for example, the system- and pathway-level life cycle analysis of cooling options in ASEAN (Li et al. 2021) and refrigerant replacement in the PRC (Wang et al.

[1] The application number of this patent is GB190905299A. We only consider those patents with valid information of application year, inventor, location, and patent classifications. See Section 2.1 for the patent data source and Section 2.2 for detailed information on patent classifications of climate friendly cooling technologies.

2019), and the development of the life cycle model in complex buildings (Scheuer, Keoleian, and Reppe 2003; Chau, Leung, and Ng 2015). Regarding the technological development of cooling technologies, prior studies have utilized comprehensive patent data to provide an overview of energy efficient technologies used in data centers (Deshpande, Ahmed, and Khode 2016) and the global innovation landscape of not-in-kind active cooling technologies (Renaldi et al. 2021).

In this paper, we seek to characterize important empirical patterns regarding climate friendly cooling technologies around the world, following the prior studies that utilize patent data. Instead of focusing on a specific technological field, we look at a wider range of climate friendly cooling technologies that are explicitly defined in the Organisation for Economic Co-operation and Development (OECD) Patent Search Strategies for the Identification of Selected Environment-Related Technologies (known as the ENV-TECH list) (Haščič and Migotto 2015). In addition, we investigate the structure and evolution of climate friendly cooling technologies from the Science of Science (Sci-Sci) perspective (Fortunato et al. 2018; Wang and Barabási 2021), by providing quantitative information regarding the overall innovation trends and the influential factors that affect the technological development in this field. Based on the Sci-Sci perspective, the analysis in this paper utilizes comprehensive patent data (from an output perspective), as well as data from an input perspective, e.g., overall R&D expenditure and economic development (as measured by GDP). To do so, we develop a generic patent search strategy for identifying climate friendly cooling technologies, from which we further establish indicators to measure the number of innovations, scientific impact, and innovation portfolios. Using patent data, we have identified the top five innovative economies in this field, i.e., the PRC, Germany, Japan, the Republic of Korea, and the United States. By employing the index decomposition technique, we are able to decouple the effects of R&D expenditure and economic factors on the evolution of climate friendly cooling technologies.

This paper contributes to the literature by providing a patent search framework and a comprehensive international comparison for major innovative economies in climate friendly cooling. Understanding the innovation patterns can enable effective and tailored policymaking that can accelerate R&D investment and promote the best technologies in this field. This paper is structured as follows. Section 2 introduces the methods and data used in this paper. Section 3 presents the major empirical trends and innovation drivers. Section 4 discusses the important implications, followed by the conclusion in Section 5.

2. METHODS AND DATA

This section presents the methodological issues relevant to the analyses used in this paper. Section 2.1 introduces patent analysis and the data source used in this paper. Section 2.2 presents the patent search strategy for identifying climate friendly cooling technologies. Section 2.3 shows the indicator for characterizing the innovation portfolios of economies in this field, based on application areas of climate friendly cooling technologies. Section 2.4 provides a Logarithmic Mean Divisia Index (LMDI) decomposition of patent families, which allows us to quantify the factors driving innovation in this field.

2.1 Patent Analysis and Data

This paper investigates the technological development of climate friendly cooling technologies from the perspective of the Science of Science (Sci-Sci) approach (Fortunato et al. 2018; Wang and Barabási 2021). This approach seeks to provide a quantitative understanding of the interactions between various socio-economic agents (e.g., the academic community, governments, and business enterprises) in innovation, across diverse geographical locations and over time. It is helpful to understand the conditions behind creativity and important discovery, and support data-driven technological forecasting (Clauset, Larremore, and Sinatra 2017). The ultimate goal is to develop the institutional frameworks and policies that have the potential to promote the best research and accelerate science (Fortunato et al. 2018).

In a narrow sense, the Sci-Sci approach is analogous to the bibliometric analysis initially proposed by Pritchard (1969), which is largely based on publications. A strand of the bibliometric literature has focused on environmental issues and the development of a certain field by using information from academic journal publications, for example, the development of energy research (Chen et al. 2017), energy consumption and greenhouse gas emissions in the residential sector (Geng et al. 2017), and embodied flows in trade (Tian et al. 2018). However, the Sci-Sci approach goes beyond bibliometric analysis. The increasing availability of digital data on innovation inputs and outputs across different scales, for example, research funding / R&D expenditure, patents, and citations, allows researchers to comprehensively characterize the structure and evolution of innovation.

The primary data used in this paper are patents. In literature, the use of patent data has a long history for measuring technology (Griliches 1990). Patent-based statistics serve as output indicators of innovations (Keller 2004), and the ratio of patents to innovation input (e.g., R&D expenditure) can reflect the innovation productivity (Griliches 1994). As compared to publications, the main advantage of patents is that patents are available for a very long period, e.g., dating back to the 1820s in the UK, (Griliches 1990). This means patents can serve as a stable proxy indicator of the actual technological development, and are more likely to trigger the application/ commercialization of innovations. In particular, patents can provide detailed and highly standardized technological and bibliographical information across economies.

Based on patent data, the direct measure is simple patent counts, which reflect the quantity of innovations rather than the quality of innovations. A related indicator of the “importance” of innovation is citations (Hall, Jaffe, and Trajtenberg 2005). However, an issue regarding citation data is the uneven distribution of citations: some are distributed following the rich get richer rule, whereas some others are distributed at random, and thus simple citation counts may not fully capture the complex reality (Siudem et al. 2020). Hence, we also adopt the h-index developed by Hirsch (2005) as a proxy measure of overall scientific impact.

Using patent data, first, we examine the development of climate friendly cooling technologies by applying indicators such as patent counts, distribution of citations and h-index in those economies involved in this field. In particular, the focus of the analysis is on the five largest innovative economies in this field (in terms of number of patents), namely, the PRC, Germany, Japan, the Republic of Korea, and the United States, over the period 1990–2019. The patent database used in this paper is the IP Intelligence database developed by PatSnap (PatSnap 2021), which collects patent records from all major patent authorities in the world. Our access to the IP Intelligence database comes through a subscription contract with PatSnap.

2.2 Identifying Climate Friendly Cooling Technologies

The first step of the analysis is to identify the patents relevant to climate friendly cooling. In the patent system, a patent, or broadly speaking, a technology, can be classified in terms of the International Patent Classification (IPC) codes established by the World Intellectual Property Organization (WIPO) (WIPO 2021), or the Cooperative Patent Classification (CPC) codes developed by the European Patent Office (EPO) and the US Patent and Trademark Office (USPTO) (EPO and USPTO 2021). These two patent classification systems overlap. But the CPC system is more detailed, and in particular, covers additional codes for identifying the technologies relevant to climate change adaption and mitigation. This is what we will follow in this paper.

In the literature, there are three patent search strategies overall, i.e., searching using explicit patent classification codes (either IPC or CPC codes), searching based on keywords, and searching combined classification codes and keywords (Renaldi et al. 2021). In this paper, we exclusively search the patents of interest using classification codes. As Wu and Mathews (2012) and Haščič and Migotto (2015) have argued, the advantage of IPC or CPC codes is that the patent search can benefit from the expert knowledge of patent examiners. A search based on keywords or selected cases, however, can be biased, because a finite list of expected keywords from all languages may not be possible, or the patent documents do not always contain the expected keywords. As a guideline, the patent search is exclusively based on IPC or CPC codes in the OECD patent database (OECD 2009; Haščič and Migotto 2015). Thus, in this paper we follow the OECD approach.

This paper develops a list of patent classification codes related to climate friendly cooling using the CPC system, in which all climate change adaption and mitigation technologies are classified under Section “Y02” (UNIDO 2019). In the IPC system, WIPO develops its list of environmental patent codes (known as “IPC Green Inventory”) (WIPO 2019). However, the Green Inventory list does not include cooling technologies.

Table 1 below summarizes the CPC codes related to climate friendly cooling technologies. It is obtained through two sources. One source is the OECD list of Patent Search Strategies for the Identification of Selected Environment-related Technologies (ENV-TECH) (Haščič and Migotto 2015). Table 1 covers all CPC codes related to cooling, heating, ventilation, or air conditioning in the ENV-TECH list. We also include the additional CPC codes in the current CPC system (EPO and USPTO 2021), as the classification system was updated in 2021.

We searched the climate friendly cooling patents based on the CPC codes in Table 1.[2] As an inventor may patent the technology in multiple economies (known as “patent authorities”) to seek a wider coverage of legal protection, in this paper, the unit of research is patent family, i.e., a set of patent documents filed in different authorities that represent the same technology, in order to avoid double counting.[3] Specifically, we use the patent families identified through the EPO’s International Patent Documentation (INPADOC) system. The inventor economy of the patent family is identified based on the primary address disclosed in the original document, following the criterion applied in the WIPO patent database (WIPO 2021). As a patent family may contain several patent documents with different application years, the earliest year

[2] This means if the patent document contains any of the CPC codes in Table 1, it is considered as a climate friendly cooling technology.

[3] For example, a company can patent a technology in three patent authorities in the world, generating three different patent documents. In our analysis, these three patent documents are viewed as one technology (patent family).

among such patent documents, or the priority year, is defined as the year of a patent family. In this paper, the search of patent documents and citation information was conducted in August 2021. The complete dataset contains 118,396 patent families with valid information from 54 economies over the period 1990–2019.

Table 1: Patent Search Strategy of Climate Friendly Cooling Technologies

Category	Description	CPC Codes
Technologies for adaption to climate change	Adapting or protecting infrastructure or their operation • Relating to heating, ventilation, or air conditioning [HVAC] technologies • Solar heating or cooling	Y02A 30/27; Y02A 30/272
	Adaptation technologies in agriculture, forestry, livestock, or agroalimentary production • Greenhouse technology, e.g. cooling systems	Y02A 40/25
Climate change mitigation technologies related to buildings	Energy efficient heating, ventilation, or air conditioning [HVAC]: • Relating to domestic heating, space heating or domestic hot water heating, or supply systems [DHW] • Systems profiting from external/internal conditions • Other technologies for heating or cooling • Efficient control or regulation technologies Ultrasonic humidifiers Passive houses; Double facade technology	Y02B 30
Climate change mitigation technologies in the production or processing of goods	Technologies relating to agriculture, livestock, or agroalimentary industries • Food storage or conservation, e.g. cooling or drying	Y02P 60/85
	Climate change mitigation technologies for sector-wide applications • Efficient use of energy, e.g. using compressed air or pressurized fluid as energy carrier • On-site combined power, heat or cool generation, or distribution, e.g. combined heat and power [CHP] supply	Y02P 80/10 Y02P 80/15

Note that some CPC codes in this table may contain multiple sub-sections (e.g., Y02B 30). The CPC codes corresponding to such sub-sections are also included in the patent search and analysis. See EPO and USPTO (2021) for detailed description of CPC codes.

Source: Own elaboration based on Haščič and Migotto (2015); Haščič, Silva, and Johnstone (2015), and the updated CPC Schemes (EPO and USPTO 2021).

2.3 Characterizing Innovation Portfolios of Economies

The focus of analysis in this section is on economies' innovation portfolios in the field of climate friendly cooling technologies. As shown in Table 1, climate friendly cooling technologies can be applied to a wide range of areas, from the production of goods and infrastructure to sector-wide production. This means the innovation activities in this field require sector-specific technological knowledge and capabilities.

Hence, the analysis in this section seeks to characterize the innovation portfolios of economies: the extent to which an economy has specialized in each innovation field. This is useful to distinguish between specialization and diversification of an economy in this field. It is a major concern for various stakeholders, such as policymakers, funding agencies, entrepreneurs, and the academic community. To do so, we adopt the approach in Huang (2010) to calculate the relative technological advantage (RTA) index. This index is defined here as an economy's share of climate friendly cooling patent families in a certain innovation field, divided by that economy's share in total patent families in the world.

$$RTA_{i\,j} = (\frac{P_{i\,j}}{\sum_i P_{i\,j}}) / (\frac{\sum_j P_{i\,j}}{\sum_{i\,j} P_{i\,j}}) \quad (1)$$

Where $RTA_{i\,j}$ and $P_{i\,j}$ are the relative technological advantage and number of patent families of economy i in the $j-th$ innovation field, respectively.

In this paper, we specifically focus on the top five innovative economies in this field, namely, the PRC, Germany, Japan, the Republic of Korea, and the United States. In addition, Table 1 provides 5 major innovation fields, i.e., adaption related to infrastructure, adaption related to production of goods, mitigation related to buildings, mitigation related to production of goods, and mitigation related to sector-wide production. As a patent family can fall under multiple innovation fields (i.e., containing multiple CPC codes), we calculate the fraction of each innovation field to which this patent family was classified (Huang 2010; Nomaler and Verspagen 2016). By doing so, the sum of patent families over all innovation fields would be equal to the number of total patent families. For an economy, a larger-than-one RTA in a certain innovation field means the economy has a relative strength in that field, otherwise it means a relative weakness.

2.4 Quantifying the Factors Driving Innovation in This Field

The analysis in this section focuses on the influential factors that drive the development of climate friendly cooling technologies. In innovation literature, the important roles of innovation input (e.g., R&D expenditure), economic development, and innovation productivity have been extensively documented (Griliches 1989; Griliches 1994; Adams and Griliches 1996). In this paper, we seek to quantify the effects of such factors on the development of climate friendly cooling technologies, using the Logarithmic Mean Divisia Index (LMDI) Decomposition techniques.

The LMDI decomposition is widely used in energy and environmental studies to decouple the effects of various factors on the changes in energy use or emissions (Ang and Liu 2001; Ang 2015). This approach has been applied to assessing the evolution of academic research in the field of energy (Inglesi-Lotz 2019) and renewable energy patents in the PRC (Chen and Lin 2020). Following the factors identified in the literature, we obtain the decomposition equation that relates P_i, the number of climate friendly cooling patent families of economy i, to its influencing factors as shown below:

$$P_i = \frac{P_i}{PT_i} \times \frac{PT_i}{RD_i} \times \frac{RD_i}{GDP_i} \times GDP_i \quad (2)$$

Where for economy i, PT_i is total patents across all fields, RD_i denotes the total R&D expenditure, and GDP_i stands for the Gross Domestic Product.

The right hand side of Equation (2) shows four factors which represent the share of climate friendly cooling technologies in total patents ($PR_i = \frac{P_i}{PT_i}$), the number of patents per unit of R&D expenditure ($PTY_i = \frac{PT_i}{RD_i}$), the amount of R&D expenditure per unit of GDP ($RI_i = \frac{RD_i}{GDP_i}$), and GDP.

Following the terminology similar to that of Inglesi-Lotz (2019) and Chen and Lin (2020), the changes in economy i's climate friendly cooling technologies between year t and year $t+1$, ΔP_i, can be decomposed into changes arising from four factors, namely, the priority of climate friendly cooling technologies in an economy's total innovation activities ($\Delta F_{priority,i}$), the overall R&D productivity of an economy

($\Delta F_{RDPTY,i}$), the effect of R&D intensity ($\Delta F_{RDInt,i}$), and the effect of GDP (ΔGDP_i). According to the additive LMDI-I, the decomposition is perfect as it does not include any residual term (Ang and Liu 2001; Ang 2004; Ang 2005; Ang 2015). The decomposition equation is shown as follows:

$$\Delta P_i = \Delta F_{priority,i} + \Delta F_{RDPTY,i} + \Delta F_{RDInt,i} + \Delta GDP_i \quad (3)$$

Where,

$$\Delta F_{priority,i} = L(P_{i,t}, P_{i,t+1}) \ln(\frac{PR_{i,t+1}}{PR_{i,t}})$$

$$\Delta F_{RDPTY,i} = L(P_{i,t}, P_{i,t+1}) \ln(\frac{PTY_{i,t+1}}{PTY_{i,t}})$$

$$\Delta F_{RDInt,i} = L(P_{i,t}, P_{i,t+1}) \ln(\frac{RI_{i,t+1}}{RI_{i,t}})$$

$$\Delta GDP_i = L(P_{i,t}, P_{i,t+1}) \ln(\frac{GDP_{i,t+1}}{GDP_{i,t}})$$

Here, $L(P_{i,t}, P_{i,t+1})$ is the logarithmic mean, defined as $\frac{P_{i,t+1}-P_{i,t}}{\ln P_{i,t+1}-\ln P_{i,t}}$. It serves as the weight in calculation.

The decomposition is performed for all pairs of consecutive years, and the final results are chained to calculate the aggregate results for the period 1990–2019. We apply the decomposition for each of the top five innovative economies in this field. In addition to the climate friendly cooling patent data, we further utilize the resident patent data and GDP (in PPP, 2017 constant USD) from the World Development Indicators developed by the World Bank (2022). The R&D expenditure of the economies under research over 1990–2018 are obtained from the World Bank (2022) as well, whereas the 2019 data for those economies are collected from various sources (Eurostat 2021; Eurostat 2021; Federal Statistical Office of Germany 2021; National Bureau of Statistics of China 2021).

3. RESULTS

The results section consists of four sub-sections. Section 3.1 presents the development trends of climate friendly cooling technologies, followed by the quantification of economies' innovation impacts in Section 3.2. Section 3.3 characterizes major economies' innovation portfolios in this field. Section 3.4 presents the LMDI decomposition results for the selected economies and discusses the drivers of innovation in this field.

3.1 Trends in the Development of Climate Friendly Cooling Technologies

This section focuses on the overall trends in the innovations of climate friendly cooling technologies from different aspects (see Figure 1). The complete patent dataset covers 118,396 patent families from 54 economies in the world, in which the top five economies, i.e., the PRC (64,285), Japan (18,338), the Republic of Korea (12,574), Germany (6,192), and the United Sates (5,657), jointly account for about 90.4% of total patent families in this field.

Panel A of Figure 1 plots the number of patent families related to climate friendly cooling technologies in the world, over the period 1990–2019, together with the average number of inventors per patent family. In the years prior to 2005, the number of patent families in this field grew at a lower level (with an average annual growth of about 7.5%). From 2005 onwards, the global innovation in this field started to accelerate and experienced a greater growth than before (with an average annual growth of about 13.9%). But the global trend has remained relatively stable since 2017, probably due to the long process of patent application.[4] In addition, the average number of inventors per patent family also shows an increasing trend, despite some fluctuation prior to 2005, increasing from around 2 to more than 3 R&D researchers per patent family. This indicates innovation in climate friendly cooling technologies is shifting towards larger teams, probably due to the increasing innovation complexity and the benefits of collaboration. This finding is consistent with the literature on team size in research (Wuchty, Jones, and Uzzi 2007; Fortunato et al. 2018).

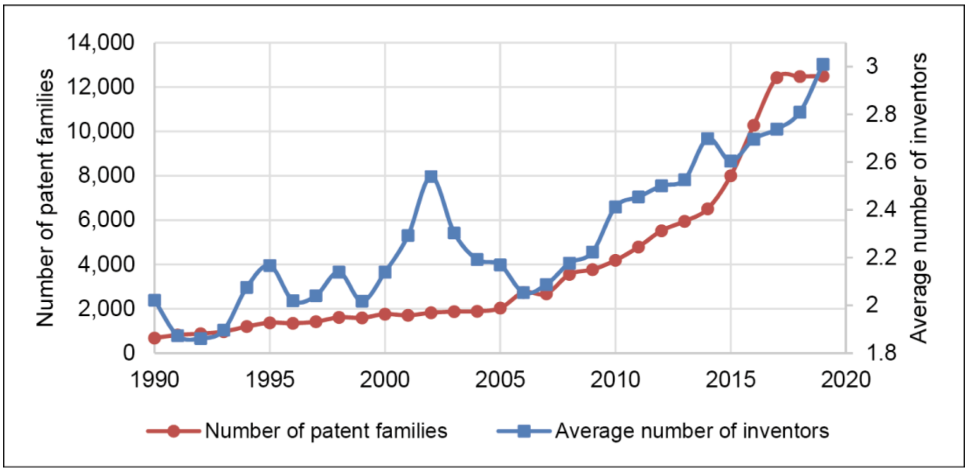
Panel B of Figure 1 presents the trends of three broad innovation fields which are summarized in Table 1. Cooling technologies for climate change mitigation related to buildings account for most in this field (52,395), followed by the adaption related to infrastructure and production (49,241), and climate change mitigation related to production (16,760). In particular, the curve of adaption technologies overtook the curve of climate change mitigation technologies related to buildings in 2015, whereas the growth of climate change mitigation technologies related to production is relatively smaller.

As shown in Panel C of Figure 1, there has been a major transition of the innovation hub from Japan to the PRC for climate friendly cooling technologies. Across all years, the innovation in this field is primarily driven by the top five economies, namely, the PRC, Japan, the Republic of Korea, Germany, and the United States (from about 80.3% in 1990 to about 95.9% in total patent families). Among the top five economies, the innovation in this field was dominated by Japan in the early years prior to 2005, but Japan's share in innovation outputs started to decline in 1998, and was overtaken by the PRC in 2006. Since 2005, the PRC's share in this field has grown faster than any other economy and reached about 81.8% in 2019, rising from about 1.6% in 1990. Since 2015, each of the other economies has accounted for a share smaller than 10% in the world. This means that the recent innovation trend in this field is mainly driven by the PRC, which is consistent with the finding in Renaldi et al. (2021). This is probably due to the implementation of the PRC's 11th Five Year Plan (FYP) during the period 2006–2010, in which several major policy changes took place, such as the implementation of Renewable Energy Law, feed-in tariff policy for renewables, and energy intensity as binding target for the FYP (Chen and Lin 2020; Zheng et al. 2020). In the follow-up FYPs since 2010, energy conservation and national plans for climate change mitigation have been policy priorities (Zheng et al. 2020), which leads to the innovation growth of low-carbon technologies in the PRC at a massive scale (Helveston and Nahm 2019; Zhu et al. 2019).

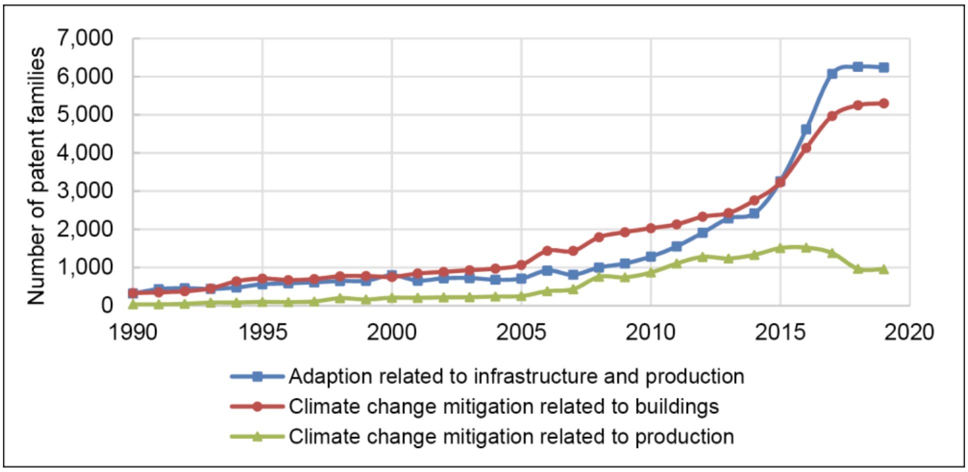
[4] According to OECD (2009). OECD Patent Statistics Manual. Paris, OECD, WIPO. (2021). "WIPO Statistics Database." Retrieved 4 August 2021, from https://www3.wipo.int/ipstats/index.htm., it takes 18 months or even more time to file a patent under current patenting institutions across the world. A portion of patent documents in the most recent years (e.g., 2018 and 2019) might be still in the stage of data processing.

Figure 1: Development of Climate Friendly Cooling Technologies, 1990–2019

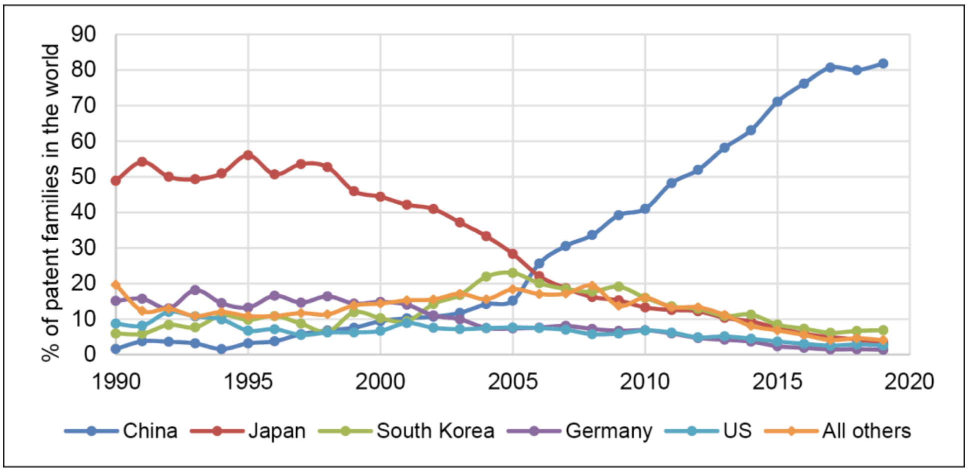
(A). Number of patent families and average number of inventors, 1990–2019



(B). Number of patent families by field, 1990–2019



(C). Innovation activities of selected economies, 1990–2019



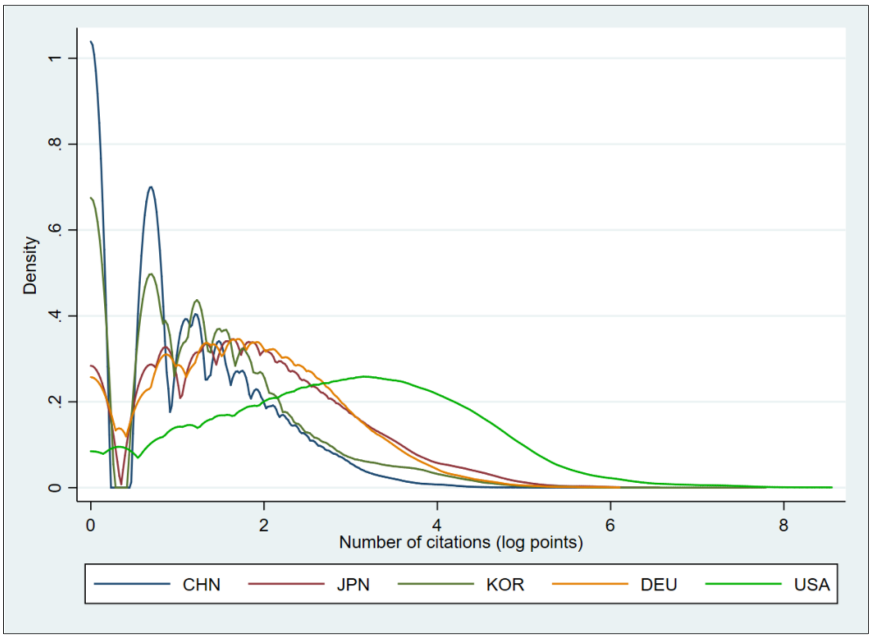
Note that (1) the field classifications in Panel B of this figure refer to the classifications in Table 1. (2) In Panel B, a patent family may be classified in multiple fields. For such cases, the fraction of each field in which that patent family is assigned is calculated, following the approach used in Huang (2010).

Source: Own elaboration.

3.2 Innovation Impacts of Economies

In this section, we investigate economies' scientific impacts by looking at their citations and h index. Figure 2 plots the distribution of citations from the top five economies. It shows that the PRC and the Republic of Korea have a large number of patent families that receive very few citations, but the patent families from the Republic of Korea are more cited, as the curve of the Republic of Korea shifts to the right. The curves of Germany and Japan shift further to the right, but the curve of Japan has a longer tail to the right, meaning Japan has more patent families that receive lots of citations. The patent families from the United States have the most citations, as the curve of the United States is distributed above the others for patent families with lots of citations, and has a longer tail on the right side. This suggests the United States has the largest scientific impact in this field.

Figure 2: Distribution of Patent Citations in Selected Economies, 1990–2019

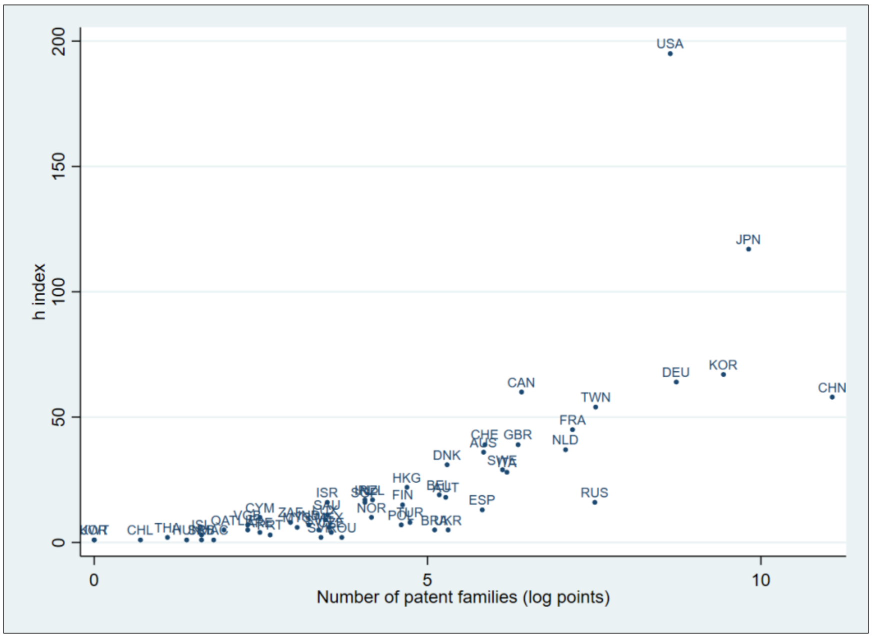


Note that (1) citations are based on patent families. (2) Each curve in this figure is plotted by covering all the patent families with valid citation information belonging to the economy over the entire period under research. (3) The density estimation is based on the Epanechnikov kernel. (4) CHN: People's Republic of China; JPN: Japan; KOR: Republic of Korea; DEU: Germany; USA: United States.

Source: Own elaboration.

We then calculate the h index of patent families for all economies in the dataset. Following the approach proposed by Hirsch (2005), this is a widely-used index for measuring overall scientific impact. A larger (smaller) h index indicates a larger (smaller) overall scientific impact in the field of climate friendly cooling innovation. Figure 3 below shows the h index and the number of patent families. The results show a large disparity in scientific impact across economies. The US capabilities in high-impact innovation in this field are unmatched among all economies, with an h index of 195, followed by Japan (117); the Republic of Korea (67); Germany (64); Canada (60); the PRC (58); and Taipei,China (54). All other economies have an h index smaller than 50.

Figure 3: h Index of All Economies in the Field of Climate Friendly Cooling Technologies



Note that (1) citations are based on patent families. (2) Each dot in this figure covers all patent families of the economy over the entire period under research. (3) The calculation of h index is based on Hirsch (2005).

Source: Own elaboration.

3.3 Economies' Innovation Portfolios in Climate Friendly Cooling Technologies

This section focuses on the innovation fields of all climate friendly cooling patent families in our sample (see Table 1), and quantifies the extent to which an economy has focused on each field, on the basis of Equation 1. As shown in Table 2, current global innovation activities in this field are concentrated in climate mitigation related to buildings (44.25%), followed by adaption related to production of goods (35.57%). These two fields combined account for about 79.82% of total patent families in this field, and can be considered as the major fields. The others are minor fields, with a share of about 10% or below.

Table 2 reports the RTA of the top five economies in each field. If the RTA is larger (smaller) than one, it indicates relatively strength (weakness) of specializing in that field. As shown in Table 2, there are important patterns across economies. The innovation activities of Japan are highly specialized in a single innovation field, i.e., adaption related to production of goods. In contrast, the other economies have a higher level of diversification in this field, as they have a larger-than-one RTA (relative strength) in multiple innovation fields. All other economies have relative strength in one major field as well as in a (or multiple) minor field. The PRC and the Republic of Korea have the most diversified innovation portfolios, as they have relative strength in more innovation fields than the other economies. In particular, the Republic of Korea has a high strength in the field of adaption related to infrastructure (2.24).

Table 2: Economies' Innovation Portfolios in Climate Friendly Cooling Technologies

			RTA				
Innovation Field	**World**	**Share** (%)	**CHN**	**KOR**	**JPN**	**DEU**	**USA**
Adaption related to infrastructure	7,130	6.02	0.77	2.24	0.72	1.00	0.96
Adaption related to production of goods	42,110	35.57	1.19	0.78	1.23	0.19	0.28
Mitigation related to buildings	52,394.50	44.25	0.84	1.02	0.98	1.84	1.53
Mitigation related to production of goods	4,452.33	3.76	1.26	0.46	0.68	0.17	0.31
Mitigation related to sector-wide production	12,309.17	10.40	1.05	1.18	0.57	0.50	1.48
Total	**118,396**	**100.00**					

Notes: (1) innovation fields in this table are based on Table 1. (2) For the patent family falling under multiple innovation fields, the fraction of each field in which that patent family is classified is calculated, based on the approach used in Huang (2010). By doing so, the sum of patent families over all innovation fields would be equal to the number of total patent families. (3) Blue color indicates a low RTA, whereas red color indicates a high RTA. (4) CHN: People's Republic of China; JPN: Japan; KOR: Republic of Korea; DEU: Germany; USA: United States.

3.4 Driving Factors of Development of Climate Friendly Cooling Technologies

Using Equation (3), the change in patent families between 1990 and 2019 is decomposed into four factors, i.e., priority effect, R&D productivity effect, R&D intensity effect, and GDP effect. Table 3 reports the decomposition results for the top five innovative economies in this field. In addition, the effect of each factor is compared to the change in patent families (see Figure 4), in order to measure the extent of each effect within the economy and account for the heterogeneity across economies.

As shown in Table 3, the PRC has the largest increase in innovation output in this field (10,062 patent families between 1990 and 2019), followed by the Republic of Korea (679 patent families), and the United States (200 patent families). The innovation output from Japan and Germany declined during this period.

According to Figure 4, R&D intensity effect and GDP effect are the most common factors driving the increase in innovation output, as these two factors are positive across all economies. In the PRC, the GDP effect, which reflects the effect due to economic growth, is the most important positive factor, contributing to an increase of 4,128 patent families (i.e., about 41% of total change) if holding other factors unchanged. The effect due to changes in GDP is also the most important driver in Japan. The R&D intensity effect, which measures the extent of R&D investment, plays a major role in Germany and the Republic of Korea. The positive R&D intensity effect in cooling innovation also provides complementary evidence to the study by Helveston and Nahm (2019) which focuses on low-carbon innovation in the PRC.

The R&D productivity effect is the most influential factor that causes the decline in innovation output in all economies except for the PRC in which R&D productivity contributes to about 9.9% of the total change. This may reflect the increasing complexity in R&D activities and calls for better R&D planning and management. The priority effect, which reflects the role of climate friendly cooling technologies in an economy's total innovation activities, is negative in Germany and Japan, whereas it drives the increase in innovation output in all other economies. In particular, the priority effect in the United States is the strongest driver and exceeds the contribution of GDP effect, suggesting the importance of climate friendly cooling technologies in the United States. In addition, the priority effect is the second strongest driver in the PRC, reflecting the key role of energy conservation and climate change in the PRC's national development strategies (Chen and Lin 2020; Zheng et al. 2020).

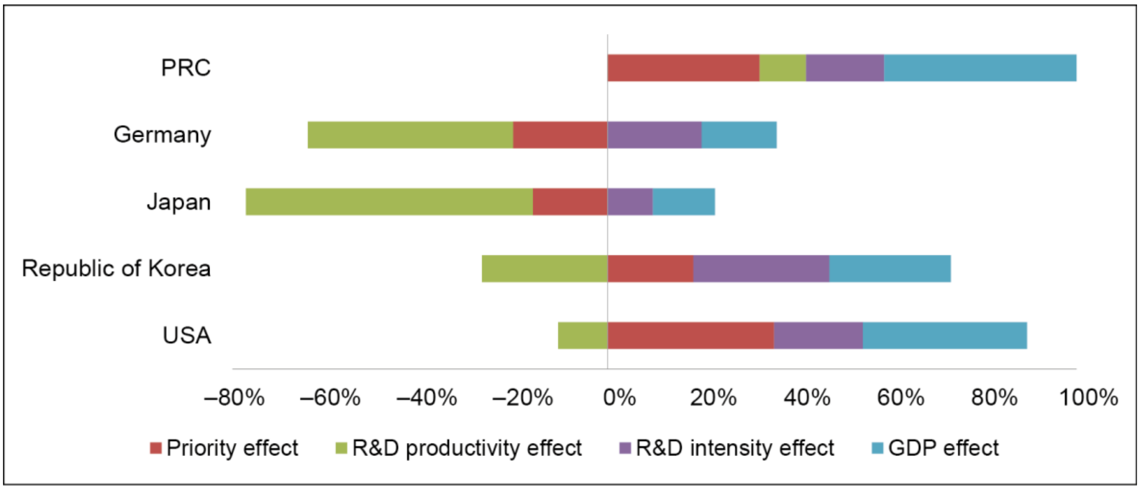
Table 3: LMDI Decomposition Results of Climate Friendly Cooling Technologies, 1990–2019

	Change in Patent Families	Priority Effect	R&D Productivity Effect	R&D Intensity Effect	GDP Effect
PRC	10,062	3,266.08	993.97	1,673.95	4,128.00
Germany	–89	–64.44	–139.73	64.07	51.10
Japan	–379	–111.41	–427.45	67.50	92.37
Republic of Korea	679	267.39	–392.31	424.45	379.47
US	202	90.92	–26.98	48.46	89.60

Note that for each economy, the sum of all four effects is equal to the changes in patent families.

Source: Own calculation.

Figure 4: Factors Driving Development of Climate Friendly Cooling Technologies, 1990–2019



Note that for each economy, the effect of each factor is compared to the changes in patent families and expressed in terms of percentage (see Table 3 for the decomposition results). A negative percentage indicates that the factor lowers the growth of patent families, whereas a positive percentage represents a positive contribution to the growth of patent families.

Source: Own elaboration.

4. DISCUSSIONS

Since 2005, the world has seen rapid growth of innovations in climate friendly cooling technologies, with the rise of the PRC in this field. In this paper, we investigate the major trends regarding the technological development in this field, with a focus on the top five innovative economies, i.e., the PRC, Germany, Japan, the Republic of Korea, and the United States. The empirical findings offer several important implications.

First, it is necessary for the PRC and the Republic of Korea, which are widely considered as latecomer economies, to further improve their innovation quality. In particular, the PRC has an h index of 58, which is higher than most economies in this field. However, this is achieved by generating more patent families, most of which receive very few or zero citations. This requires policymakers and funding agencies to monitor the scientific impacts of the PRC's innovation in this field, optimize the innovation portfolios, and share experience learnt from those high-impact innovations.

Second, the top five innovative economies in this field have developed their innovation portfolios differently. The choice of specializing in a certain field can reflect economy-specific needs and technological competencies. The design of effective policies that target at promoting the best climate friendly cooling technologies should consider such local circumstances and the diversified applications of the cooling technologies. For innovators, e.g., individuals, firms, and academia, matching their core knowledge to appropriate locations and innovation fields is crucial for the success of innovation.

Third, the LMDI decomposition results show that innovation in climate friendly cooling technologies is driven by different factors across economies. This should be taken into account in policymaking. In particular, the decline of overall R&D productivity is the most influential factor that limits innovation in this field. It is necessary for policymakers, business experts, and academic researchers to further investigate the mechanism behind the observed empirical pattern. In addition, policy support would be needed to help innovators overcome technological complexity (e.g., through capacity building, knowledge sharing, and collaboration) and institutional barriers, and promote better R&D funding management.

Fourth, the priority effect contributes negatively to the development of climate friendly cooling technologies in Germany and Japan. Given the increasing cooling demand and the associated energy demand and environmental impacts, the important role of climate friendly cooling technologies should be recognized, and incorporated in national climate planning. This paper has developed the patent search strategy from an innovation output perspective. The information regarding the innovation inputs which are specific to cooling (e.g., R&D budget, expenditure, and researchers), however, has not been available. A better established institution for information disclosure is needed. This would require the harmonization of standards for data measurement, reporting, and accounting, and well-established international cooperation.

5. CONCLUSION AND POLICY RECOMMENDATIONS

This paper has investigated the technological development of climate friendly cooling technologies from the Sci-Sci perspective. This is mainly based on worldwide patent data over the period 1990–2019. The complete patent dataset used in this paper identifies 118,396 patent families from 54 economies at different levels of development. But five economies, namely, the PRC, Germany, Japan, the Republic of Korea, and the United States, are identified to be the top five innovative economies in this field, accounting for about 90.4% of total patent families in this field. The patent search strategy based on the CPC codes developed in this paper can be used for further technological assessment of climate friendly cooling technologies. The analytical framework used in this paper can also be applied to other environmental technologies.

For those emerging Asian economies that plan to enter the field of climate friendly cooling technologies, there are several lessons learnt from the results. First, the overall trend in development of technologies in this field shows a transition in the innovation hub characterized by the fast growth of innovation from the PRC since 2005 when the PRC implemented its 11th FYP with policy targets for renewables and energy conservation. In addition to the economic size and GDP effects, the priority effect contributes the most to the innovation growth in this field. For those emerging Asian economies, climate targets should be included in the national development strategies, and targeted fields such as cooling can be explicitly addressed in nation-wide planning for science and technology. Such policy efforts can promote the prioritization of climate friendly cooling in innovation activities.

Second, the results show that overall R&D intensity is the most common innovation driver in this field (except for GDP). Emerging Asian economies can further enhance their economy-wide R&D intensity. This requires a better coordination between public finance and science and technology policy. As R&D productivity is the most common negative factor that lowers innovation growth in this field, it also requires a better monitoring and management of R&D.

Third, climate friendly cooling is a field covering diversified applications, which requires different science and engineering knowledge. The top five economies in this field have very different innovation portfolios. For newcomers in this field (e.g., emerging Asian economies), it is important to learn that innovation capabilities develop “locally,” i.e., national needs and technological competencies. Those emerging Asian economies should identify their own needs and competencies and search for suitable innovation portfolios. In this process, international collaboration (e.g., learning and knowledge transfer) can play a key role. Identifying appropriate locations is also crucial in order to optimize the exchange and application of knowledge.

The analysis in this paper also shows that patent data and a search strategy based on patent classifications can be useful for evidence-based policymaking and policy evaluation. More importantly, it can build the linkages between energy policy, public finance policy, and science and technology policy. In response to this, we will need more research, at least in two forms. First, we need more empirical evidence, for example, on how climate friendly cooling technologies are applied in different industrial projects and the evaluation of the impacts of policies supporting innovation in this field, e.g., public R&D subsidy (Lin, Wu, and Wu 2021). Second, we also need more theoretical research, on the causal mechanism behind the factors driving innovation, the choices of certain innovation portfolios, and how major innovators in different economies relate to those portfolios. In order to make climate friendly cooling technology a key technology contributing to sustainable development, these are the key areas that we need to analyze.

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