Highlights

Patent landscape of not-in-kind active cooling technologies between 1998 and 2017

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- The study presents the global patent landscape of active cooling technologies.
- Top five countries: China, Japan, South Korea, United States, and Germany.
- Top assignees are dominated by East Asian manufacturers.
- Promising alternative cooling technologies include magnetic and absorption cooling.

Patent landscape of not-in-kind active cooling technologies between 1998 and 2017

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ABSTRACT

The rise in global cooling demand will have significant impacts on our efforts to limit climate change and foster sustainable development. Minimising these impacts requires further development of active cooling technologies, starting with an examination of existing technologies and their characteristics. This paper provides an overview of active cooling technologies using a patent landscape based on patent application data over the past 20 years. In developing the patent landscape, we searched the Derwent Innovation patent database, which contains more than 90 million patent documents, using technology-specific keywords and patent classification codes. A careful assessment of the resulting patent dataset shows a range of important trends about the evolution of cooling in the last two decades. Specifically, we discuss annual cooling technology patent application trends, countries of application, and patent assignees. The results show that patenting activity in the field of active cooling has increased significantly since 2010, mainly driven by the rapid patenting trend in China. Patents of the incumbent technology have been dominated by established manufacturers from Japan and the United States. Not-in-kind cooling technologies with a high number of patent applications include thermoelectric, magnetocaloric, evaporative, pulse-tube, absorption, and adsorption cooling. The results from examining this global patent help in understanding and shaping the global development of active cooling technology by providing new information on the major supplier countries, the key manufacturers, and maturity levels of alternative cooling technologies.

1. Introduction

This paper presents how the global patent landscape of active cooling technologies has evolved in the last two decades. Global space cooling demand is projected to triple from 2,020 TWh in 2016 to 6,200 TWh in 2050, with an equivalent of ten new air-conditioners to be sold every second for the next 30 years (IEA, 2018). This rise is largely driven by the rise of extreme heat from climate change and the rapid population and income growth in regions where air conditioning is vital for quality of life, such as China, India, and South-East Asia. Given that the current large cooling demand is fulfiled almost exclusively by the electric-driven vapour-compression cycle which is in common air conditioners, the growth of cooling demand is expected to place multiple environmental burdens – especially by exacerbating climate change as

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coal still dominates the electric power generation in the aforementioned regions (IEA, 2019). Moreover, the majority of refrigerants used in a vapour-compression cycle technology have relatively high global warming potentials (GWP), which is a major concern due to possible leakage during operation and disposal phase (Lickley et al., 2020).

Air conditioners and fans are arguably the most widely used active cooling technology for comfort space cooling. Active cooling corresponds to technological cooling solutions that require energy input during their operation, as opposed to passive cooling techniques that use minimal or no energy input. Despite the multiple benefits of passive cooling, it has climatic limitations which make active cooling a necessary solution to provide ideal indoor thermal comfort (Santamouris, 2016). Given the vital role of active cooling, it is essential to foster the development of high efficiency and low GWP active cooling technology to limit the impacts of rising global space cooling demand. To do so, however, the current technological landscape of active cooling has to be well assessed – a current gap in the research literature. Such assessment is important to understand the technological and scientific trends in the field, understand the future trajectory of cooling options, and assist in decision making by potential technology developers, researchers, and policymakers.

Although the technical development of active cooling technology is well documented in the literature, there is a gap of information on the overall technological landscape among various active cooling technologies. Two limitations exist in the available literature. First, the existing reviews in the space cooling field are typically quite narrow in scope, ranging from specific technology types (e.g. elastocaloric (Qian et al., 2016) and solar cooling (Al-Alili et al., 2014)) down to component-level reviews (e.g. expanders (Murthy et al., 2019) and control methods (Xu et al., 2018)). Second, in the handful of available comparative reviews between active cooling technologies (Fischer et al., 1994; Bansal et al., 2012; Goetzler et al., 2014; Brown and Domanski, 2014), the comparisons on technological maturity are mostly performed based on qualitative expert judgement in categorising the development status of a technology, e.g. R&D, emerging, and commercially available. Although this approach is useful, it is also prone to subjectivity. Furthermore, these reviews put less emphasis on key technology developers in the field, which is an important characteristic of the technology landscape. As a result, there is a growing need to understand the global technological development landscape of active cooling technologies with a more systematic approach. One of the tools that can assist in understanding technological landscape is a patent landscape review.

A patent landscape provides an overview of collated patent data of a particular technology and can be used to assess research and development activities in the field, inform policy discussions, or monitoring potential competitors (Trippe, 2015). Patent data has been acknowledged as a valuable source of information for tracking technological development and a good indicator of inventive activity in the market (Griliches, 1990). It has been argued that despite their shortcomings, patent counts are still the best available source of data on technological innovation due to their availability and comparability (Johnstone et al., 2010). Patent landscape review can be considered as a part of the larger patent analysis tools. Several potential outcomes of a patent analysis include trend analysis, technology forecasting, strategic technology planning, infringement analysis, competitor analysis, and technological roadmapping (Abbas et al., 2014).

Patent-based analysis has been employed in energy studies with various applications, such as providing technological landscape, policy assessment, measuring knowledge spillovers, and collaborations among developers. The energy technologies which have been a subject of patent landscape reviews include solar cooling (Kunz et al., 2012), batteries (Aaldering and Song, 2019), organic photovoltaics (Lizin et al., 2013), waste heat recovery (Karvonen et al., 2016), electric mobility (Golembiewski et al., 2015), carbon capture utilisation and storage (Norhasyima and Mahlia, 2018), and hydrogen technology (Martinez-Burgos et al., 2021).

In relation to climate change-related policy and technological change, studies based on patent data have identified that innovation responds quickly to incentives and the type of policy affects the nature of innovations (Popp, 2005; Johnstone et al., 2010). A patent-based study on policy-induced innovation of wind energy in Europe confirmed that innovation is endogenously determined and induced by targeted policy instruments (Lindman and Söderholm, 2016). The study also illustrated that using patent counts as a proxy for technological progress can be a useful way of evaluating public policies. Patent-based indicators have also been used to study the air pollution clean technology where a long innovation cycle and a large technological gap between countries were identified (Ahn and Yoon, 2020).

In addition to patent counts, the number of citations is typically employed in a patent analysis to measure the technological impact (Aristodemou and Tietze, 2018). For instance, patent citation data of wind, storage, and solar technolgies were analysed to investigate the knowldge spillovers from renewable energy technology (Noailly and Shestalova, 2017). The origin country and assignee of patents are also widely used data in a patent analysis. They have been used in measuring technological collaborations and competitions between assignees, for example in the case of alternative powertrain systems (Aaldering et al., 2019) and carbon capture and storage (Yin et al., 2020). In another example, the provincial origin of patent applications was employed to study the spatial correlation of low-carbon innovation in China (Yang and Liu, 2020).

Despite the wide use of patent-based analysis in examining the field of energy technology, active cooling technologies have not been specifically addressed in the literature. This is a significant knowledge gap given the growing problems surrounding space cooling (Khosla et al., 2020). We aim to help address this knowledge gap by undertaking a comprehensive patent landscape of active cooling technologies. The focus on a patent landscape review allows for a broader observation into various active cooling technologies, which can be used as a starting point for further in-depth studies using other patent analysis techniques.

The paper is structured as follows. Before describing the patent landscape itself, a brief overview of active cooling technology is given in Section 2. The patent landscape methods and data collection steps are described in Section 3. The assessment of the patent data are given in Section 4. Finally, major findings and their implications are elaborated in Section 5.

2. Overview on active cooling technologies

In this section, active cooling technologies considered in the patent landscape are briefly reviewed in terms of classification, working principles, and recent developments. Active cooling technologies can be categorised into two major groups: vapour-compression and not-in-kind technologies. The latter refers to all cooling technology that does not employ a vapour-compression cycle in producing the refrigeration effect. Given that the focus of this work is on air conditioning and refrigeration technology, electric fans are excluded from the patent landscape due to their high maturity level and limited innovation potentials.

2.1. Vapour-compression cycle

Vapour-compression cycle technology has been developed since the early 19th century and managed to hold on as the dominant technology in space cooling since the post-war growth of residential air conditioning in the United States (Biddle, 2008). This dominance can be attributed to its low cost, efficiency, operational safety, and scalability.

The cooling effect from a vapour-compression cycle is produced by modifying the phase of the working fluid (refrigerant) through compressing, condensing, expanding, and evaporating process. The performance of a vapour-compression cycle is measured by its coefficient of performance (COP), which is defined as the ratio between cooling load and work input (electricity).

Since it is a highly mature technology, recent advancements on vapour-compression cycle have been directed towards further performance improvement through cycle modification, for instance by implementing sub-cooling, expansion losses recovery, and multi-stage cycles (Chua et al., 2013; Park et al., 2015). In addition to increasing efficiency, significant efforts have been made to reduce the environmental impacts of refrigerants in the vapour-compression cycle. This follows the Montreal Protocol which started the phasing out of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) due to their contribution to ozone layer depletion. More recently, the Kigali Amendment initiated the phasing out of hydrofluorocarbons (HFCs) due to their high GWP (United Nations Environment Programme, 2020). Several replacement

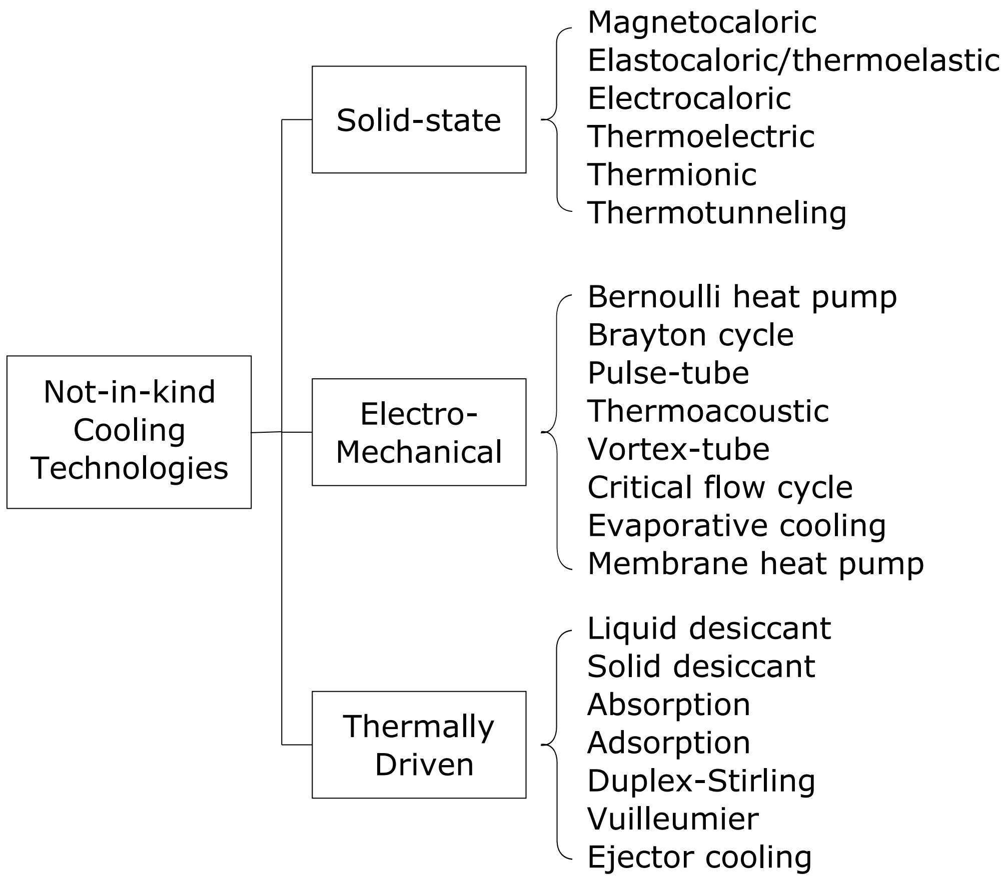

Figure 1: Classification of not-in-kind cooling technologies used in the study. Adapted from Goetzler et al. (2014).

refrigerants have been proposed, such as hydrofluoroolefins (HFOs) and natural refrigerants (e.g. ammonia and CO_2) (Mota-Babiloni et al., 2017; Ciconkov, 2018). However, the options of low-GWP refrigerants are limited when other important aspects like toxicity and flammability are considered (McLinden et al., 2017).

2.2. Not-in-kind technologies

Various alternative technologies to the vapour-compression cycle have been developed in the past decades to reduce the aforementioned environmental impacts of cooling equipment. These cooling technologies can be categorised based on different characteristics, such as primary energy input, main working fluid or material, and operating temperature range (Brown and Domanski, 2014). In this paper, a classification based on primary energy input and working material, as proposed by Goetzler et al. (2014), was selected to organise the cooling technologies, as illustrated in Fig. 1. Here, the technologies are divided into three major categories: solid-state, electro-mechanical, and thermally-driven cooling. This relatively compact categorisation was used to structure the wider technological scope of the patent landscape as will be seen in Section 4.

2.2.1. Solid-state cooling

Solid-state cooling technologies are based on the temperature change that occurs in caloric materials upon the application of a driving field (Moya et al., 2014). The technologies are grouped further according to the corresponding driving field, such as magnetocaloric (magnetic), electrocaloric (electric), and elastocaloric/thermoelastic (mechanical). Technologies based on the Peltier effect are also included in this category, i.e. thermoelectric, thermotunneling, and thermionic.

A generic cycle of solid-state cooling is illustrated in Fig. 2. Unlike in a vapour-compression cycle where the refrigerant is also acting as the circulating fluid, a separate heat exchange fluid is required to transport heat to and from the solid refrigerant/caloric materials. During the application of the driving field (right-hand side in Fig. 2), the caloric material undergoes a phase transition which is accompanied by an increase in temperature. The circulating fluid then transfers this thermal energy from the caloric material to the environment through the hot-side heat exchanger. By removing the driving field (left-hand side in Fig. 2), the caloric material is transitioning to its original phase with a decrease in temperature. The circulating fluid is then flowing towards the cold-side heat exchanger where thermal energy, $\dot{Q}_{in}$, is absorbed from the load.

2.2.2. Electro-mechanical cooling

In electro-mechanical cooling, the primary energy input to the cooling cycle is provided by electrical or mechanical work. This work assists the change of working fluid properties which produces the cooling effect.

An example of electro-mechanical cooling is evaporative cooling (Fig. 3). The cooling effect is achieved by spraying water into the air or forcing air through saturated cooling pad. Due to the relatively low humidity of inlet air ω_{in}, the water in the pad evaporates by using the thermal energy of the air stream. This process lowers the temperature of the outlet air, T_{out}. The electro-mechanical energy input in this system is provided to drive the fan required for forcing the airflow and to drive the pump required for replenishing the water.

2.2.3. Thermally-driven cooling

In a thermally-driven cooling system, thermal energy acts as the primary energy input to the cooling cycle. Typical sources of thermal energy include solar thermal, waste heat, and fossil-fuel combustion. For instance, liquid desiccant, solid desiccant, absorption, adsorption, and ejector cooling have been implemented as solar thermal cooling technologies (Al-Alili et al., 2014).

Well-known thermally-driven cooling cycles are absorption cycles. Fig. 4 shows the schematic of an absorption cycle. Unlike in vapour compression cycles, the compression process is achieved by additional steps involving an absorber, pump, and generator. First, the refrigerant exiting the evaporator at state 1 is

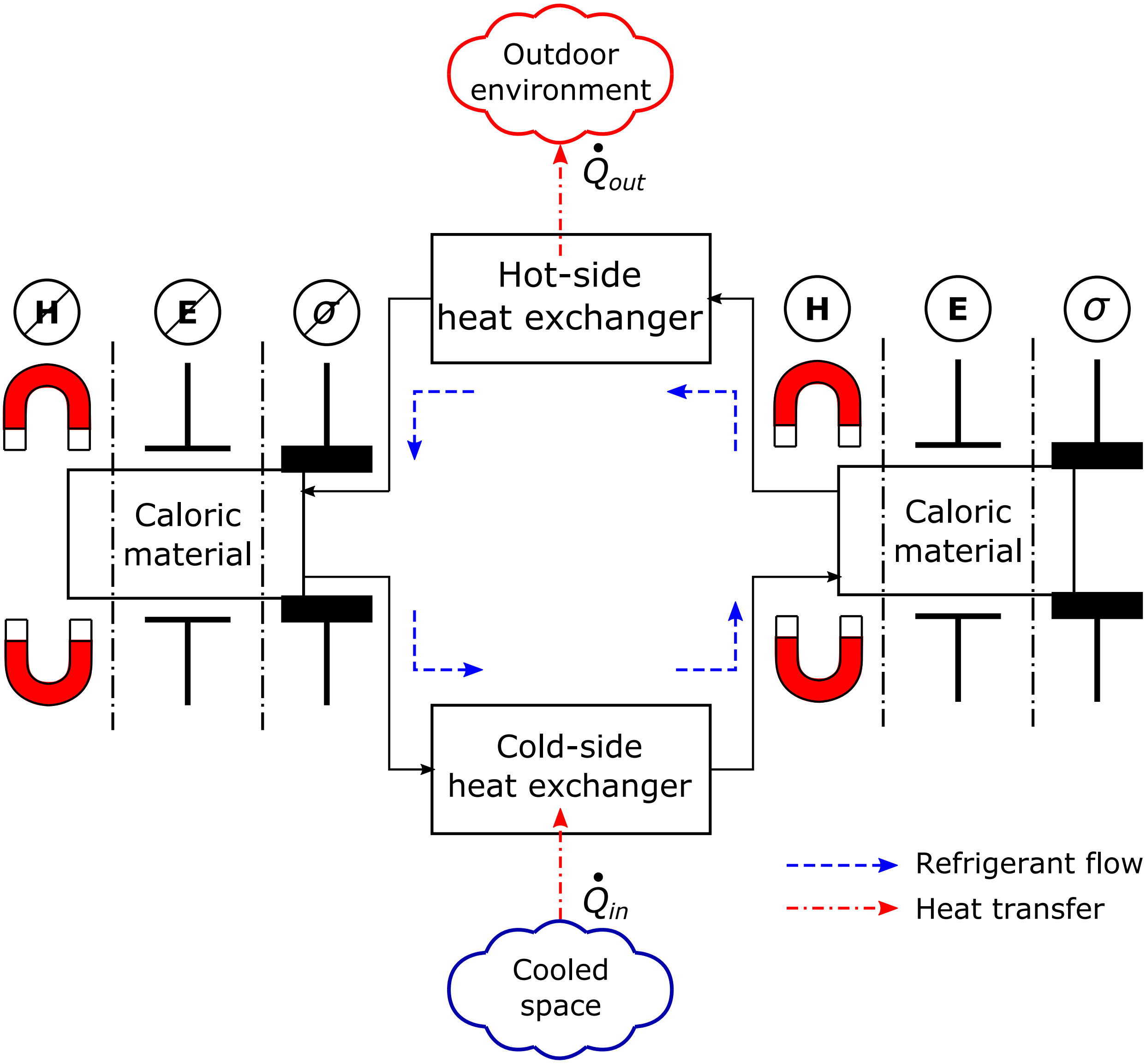

Figure 2: Simplified illustration of solid-state cooling cycles using magnetic (**H**), electric (**E**), or mechanical stress (σ) fields to modify the phases of the caloric material.

absorbed by the absorbent, forming a strong solution at state a. This process in the absorber is exothermic and cooling water is used to maintain a low absorber temperature by rejecting the thermal energy, $\dot{Q}_A$. Second, the strong solution is pumped to a higher pressure (Process a-b). This requires less work input than compressing the refrigerant vapour in a vapour-compression cycle due to the lower specific volume of the solution. Third, the refrigerant is extracted from the solution in the generator. Thermal energy, $\dot{Q}_G$, is used to drive this endothermic process. Finally, the extracted high-pressure refrigerant enters the condenser at state 2. Common refrigerant-absorbent pairs include ammonia-water and water-lithium bromide.

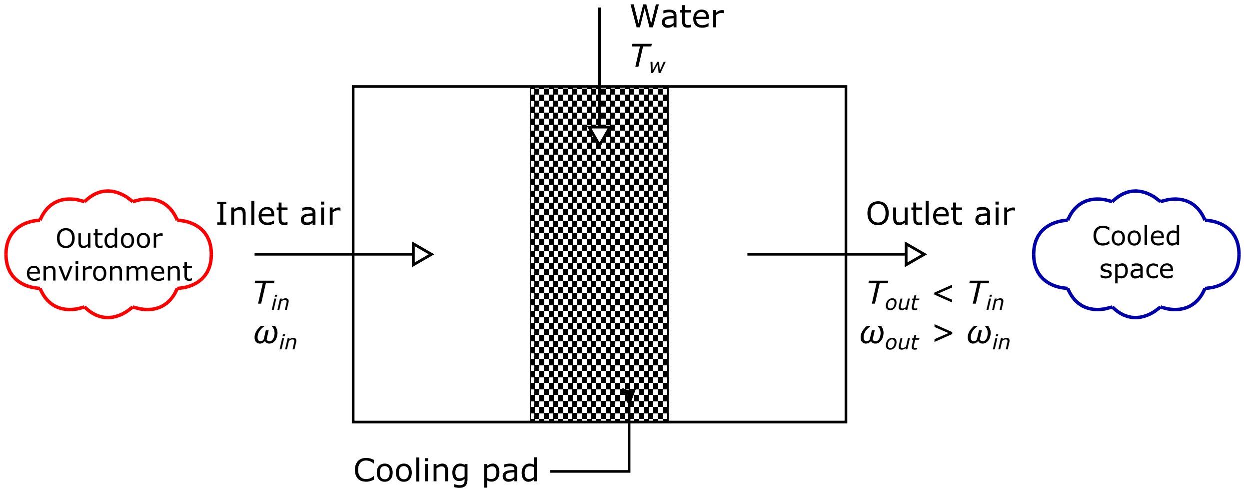

Figure 3: A simplified illustration of evaporative cooling mechanism. T : air temperature; ω : humidity ratio.

3. Methodology

This section presents the methodology used to identify relevant active cooling technologies patents. The patent landscape in this study was developed based on the guideline from World Intellectual Property Organization (WIPO) (Trippe, 2015) and a patent landscape reporting recommendations (Smith et al., 2018). Patents data were collected from the Derwent Innovation platform, which has access to over 50 patent authorities (Clarivate Analytics, 2020). The patent data acquisition workflow is given in Fig. 5.

Two types of patent search were performed in this study (Fig. 5). First, a generic search without technology-specific keywords was conducted to provide a general view of patent activity in active cooling technology. Second, specific searches with technology keywords were performed to identify patents related to every considered technology. In the identification phase, we performed the searches by querying the Derwent Innovation Platform patent database. The query for both types of search is structured as follows:

- Generic search

  Search= (generic cooling keyword 1 OR generic cooling keyword 2 OR ...) AND IPC=(Code 1 OR Code 2 OR ...) AND Year>=(1998) AND Year<=(2017)

- Specific search

  Search=(technology-specific keyword 1 OR technology-specific keyword 2 OR ...) AND (generic cooling keyword 1 OR generic cooling keyword 2 OR ...) AND IPC=(Code 1 OR Code 2 OR ...) AND Year>=(1998) AND Year<=(2017)

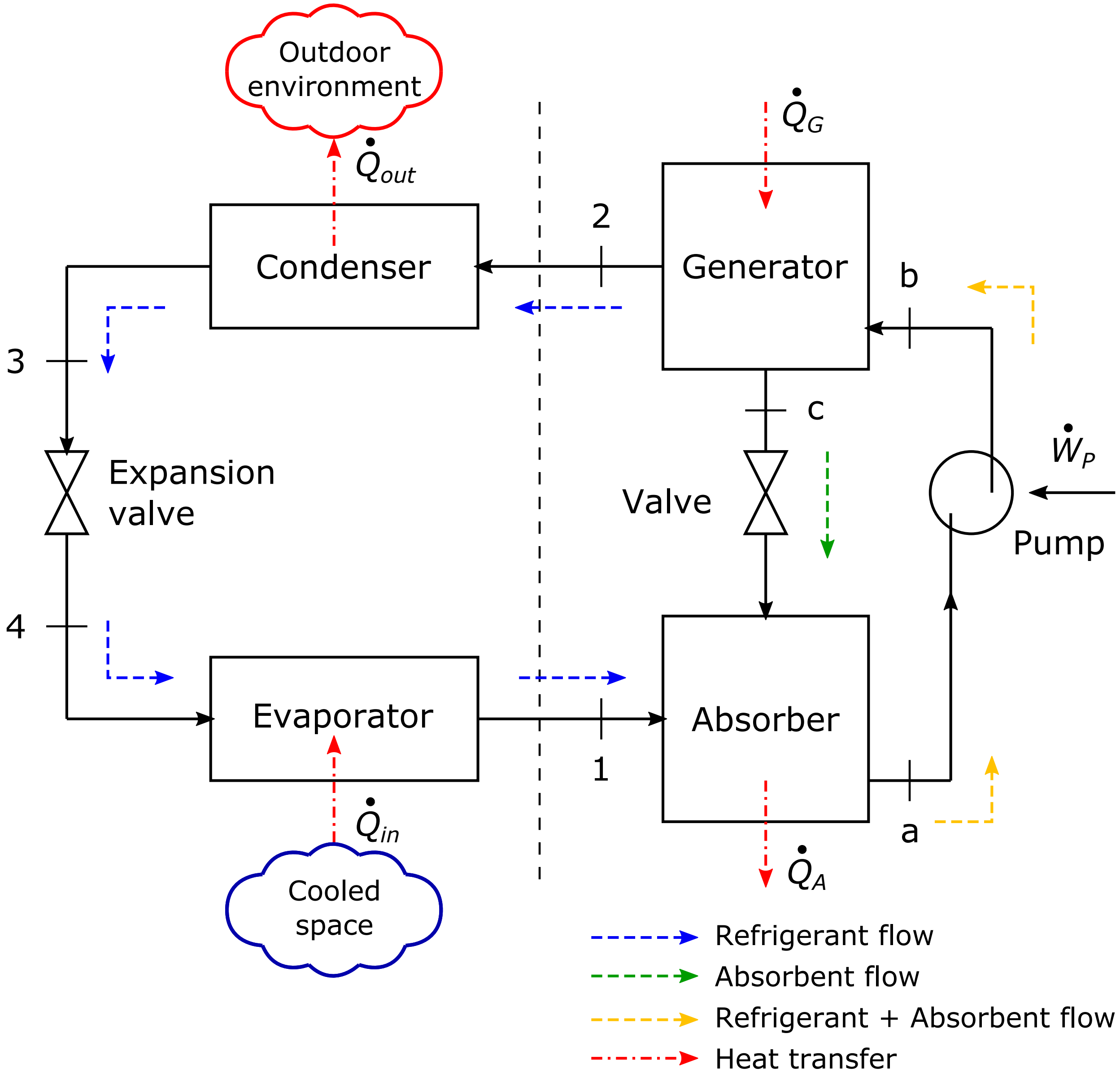

Figure 4: A simplified illustration of an absorption cycle.

3.1. Identification

In the identification phase, we searched the Derwent Innovation Platform in March 2020 for patents with the earliest priority year of 1998–2017. The selection of 2017 as the end year is due to the 18 months lag between application and publication of a patent, while the 20 years period corresponds to the time horizon validity of a patent.

Patent searches of the cooling technologies were performed using patent classification codes and keywords. International Patent Classification (IPC) codes considered in the search are shown in Table 1. The IPC codes

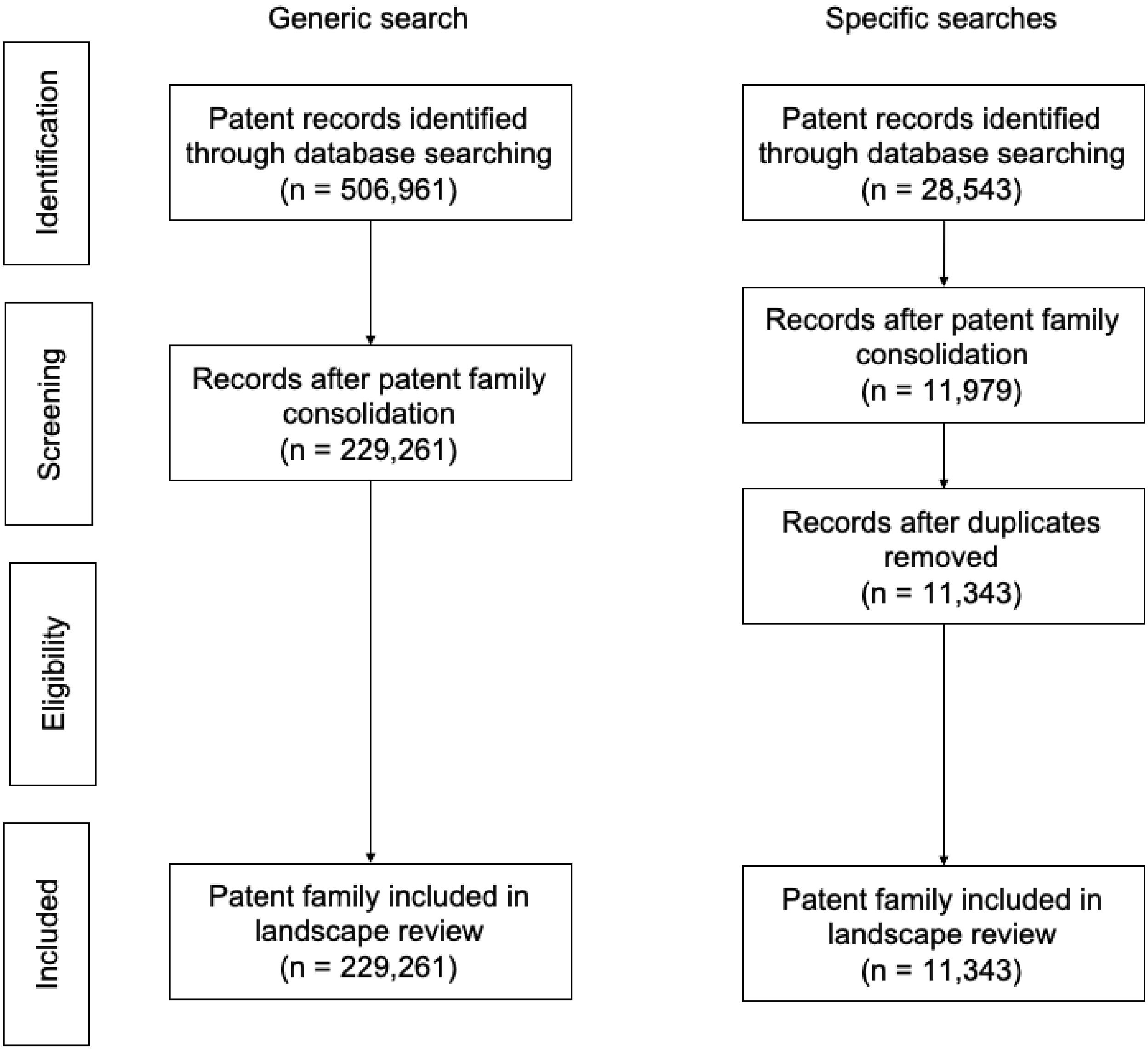

Figure 5: Workflow of the patent search: generic (left), and specific (right).

selection was based on the main technological interest of producing a cooling effect through air-conditioning and refrigeration. As such, dedicated air-humidification and ventilation equipment, for instance, are not included in the selected IPC codes. The search keywords were divided into technology-specific and generic cooling terms, as shown in Table 2. Keywords were searched in the title and abstract of patent documents.

3.2. Screening

In the screening phase, we consolidated the identified patent records by identifying patent family and duplicates. To avoid multiple counting of the same innovation, a patent family count is used in this study

Table 1
IPC codes used in the patent search

IPC Code	Description
F24F 1/00	Room units for air-conditioning, e.g. separate or self-contained units or units receiving primary air from a central station
F24F 3/00	Air-conditioning systems in which conditioned primary air is supplied from one or more central stations to distributing units in the rooms or spaces where it may receive secondary treatment; Apparatus specially designed for such systems
F24F 5/00	Air-conditioning systems or apparatus not covered by group F24F 1/00 or F24F 3/00
F25B	Refrigeration machines, plants, or systems; Combined heating and refrigeration systems; Heat pump systems
F25D	Refrigerators; Cold rooms; Ice-boxes; Cooling or freezing apparatus not covered by any other subclass

Table 2
Search terms in patent data collection

Cooling technology	**Technology-specific keywords**	**Cooling-generic keywords**
vapour-compression cycle	vap*r compressi*	
Not-in-kind technologies		
Solid-state		
Magnetocaloric	(magnetocaloric OR magnetic) ADJ (cool* OR refrigerat* OR chill* OR air condition*)	
Elastocaloric/Thermoelastic	(elastocaloric OR thermoelastic) ADJ ADJ (cool* OR refrigerat* OR chill* OR air condition*)	
Electrocaloric	electrocaloric ADJ (cool* OR refrigerat* OR chill* OR air condition*)	
Thermoelectric	thermoelectric ADJ (cool* OR refrigerat* OR chill* OR air condition*)	
Thermionic	thermionic ADJ (cool* OR refrigerat* OR chill* OR air condition*)	
Thermotunneling	thermotunnel*	
Electro-mechanical		
Bernoulli heat pump	bernoulli heat pump	
Brayton cycle	brayton cycle	
Pulse-tube refrigeration	pulse tube ADJ (cool* OR refrigerat* OR chill* OR air condition*)	cool*
Thermoacoustic	thermoacoustic ADJ (cool* OR refrigerat* OR chill* OR air condition*)	refrigerat*
Vortex-tube refrigeration	vortex tube ADJ (cool* OR refrigerat* OR chill* OR air condition*)	air condition*
Critical flow cycle	critial flow	chill*
Evaporative cooling	"evaporative" ADJ (cool* OR refrigerat* OR chill* OR air condition*)	
Membrane heat pump	membrane heat pump	
Thermally driven		
Liquid dessiccant	liquid desiccant	
Solid desiccant	solid desiccant	
Absorption cooling	absorption ADJ (cool* OR refrigerat* OR chill* OR air condition*)	
Adsorption cooling	adsorption ADJ (cool* OR refrigerat* OR chill* OR air condition*)	
Duplex-Stirling	duplex stirling	
Vuilleumier	vuilleumier	
Ejector cooling	ejector ADJ (cool* OR refrigerat* OR chill* OR air condition*)	

instead of a patent record count. Patent family corresponds to a single entry for one innovation, while patent record count includes multiple patents for a single innovation, i.e. registration of one innovation in multiple patent offices. The Derwent World Patent Index (DWPI) patent family criteria were used as the family definition in this study.

3.3. Eligible patents

In the eligibility phase, the consolidated patent family data were checked for duplicity. Specific searches could produce duplicated observations due to the occurrence of more than one technology-specific keywords in a patent document. For example, the keyword "adsorption" could be mentioned in an absorption cooling patent due to the similarities between the two technologies. Two-tier methods were used to remove these duplications. First, an automated categorisation was performed based on the order of occurrence of the keywords in a patent title and abstract. For instance, if both the word "absorption" and "adsorption" were present, the patent was categorised into the keyword that came first in the title, abstract or description. Second, the remaining duplicates were assessed manually to determine their appropriate category.

3.4. Included patents

Finally, eligible patent family datasets were included in the post-processing. In addition to the patent family count, other relevant variables in the patent landscape are the priority country and assignee. The priority country refers to the location of the patent office where a patent application was first submitted. This variable can be used to indicate the country of origin of a patent. The assignee corresponds to the entity that has the legal right to the patent. This entity may be an individual or, most prevalently, a company. Here we used the "Optimized Assignee" variable from Derwent Innovation platform to reveal patent assignees names. Furthermore, patent data from Derwent Innovation platform includes the legal status of a patent: alive, dead, and indeterminate. This information allowed us to observe the legal status trends of the identified patents.

4. Results and discussion

By post-processing the results of patent searches, we present the visualisations and trend analysis of generic and specific patent data to describe the patent landscape of active cooling technology in the last 20 years. Top countries and assignees are illustrated for the four technology categories. The legal status of the dominant cooling technologies is discussed further to illustrate the relative values of their patent applications. Finally, a comparison between patent family count and a qualitative measure of technical maturity is given to show the benefit of the patent landscape in quantifying technological maturity.

4.1. Patent application trend

4.1.1. Generic search

The generic patent search (without technology-specific keywords) produced over 500,000 patent counts, which corresponds to approximately 230,000 patent families. This reduction of more than 50% indicates the

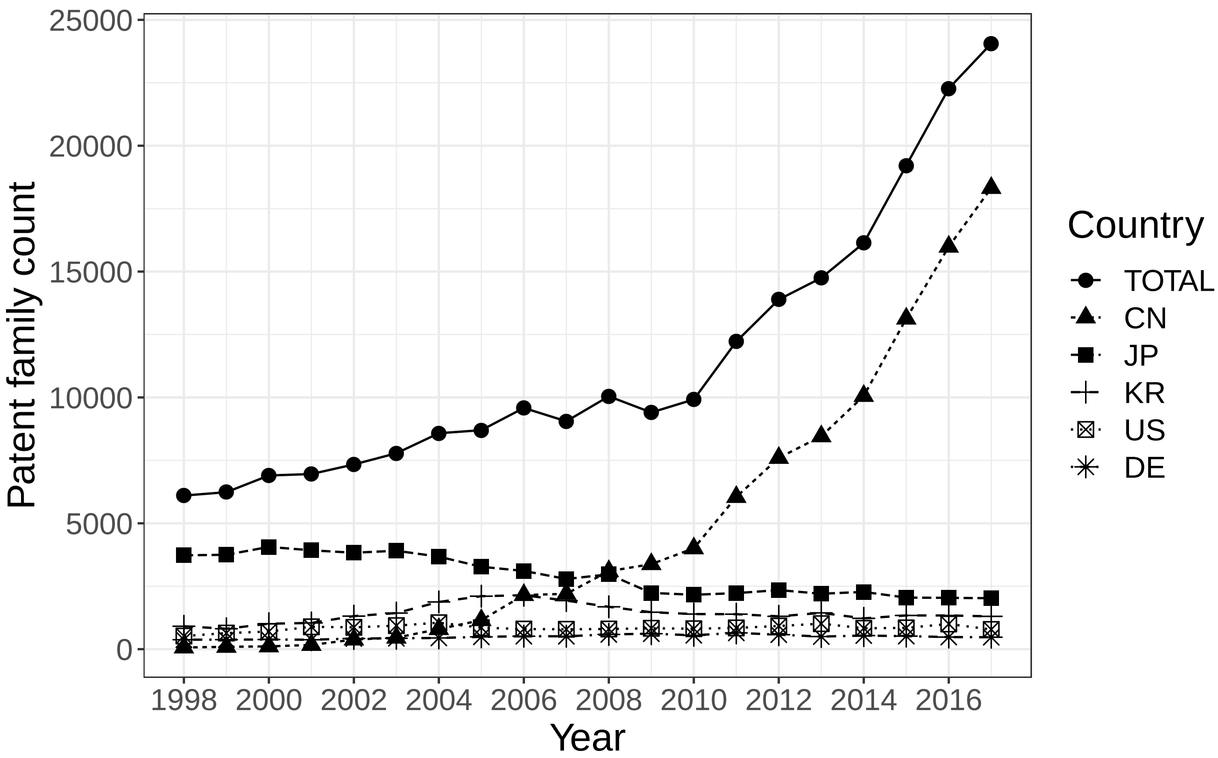

Figure 6: Patent application trend based on the generic search. CN: China, JP: Japan, KR: South Korea, US: United States, DE: Germany

benefit of using patent family, rather than patent count, as a proxy for innovation. The application trend of these patent families over the period is illustrated in Fig. 6. The increasing trend is observed over the past 20 years, with a significant surge in application rate after 2010.

The top five priority countries of these patents are China (46%), Japan (28%), South Korea (13%), United States (8%), and Germany (5%). As shown in Fig. 6, while applications from the US, South Korea and Germany have been relatively stable over the past 20 years, it is interesting to note the difference in trend between China and Japan. Patent applications with Japan as the priority country had a declining trend between 2003 and 2010 from around 4000 to 2000 patents per year and have been levelling at the lower annual patent counts since then. On the contrary, patent applications from China started to emerge in around 2002 before ascending from 2010 onwards. The latter also explains the post-2010 trend in Fig. 6.

The declining trend in Japan patent applications in general, which can be related to reduction in innovation activity, has been attributed to the country's economic crisis in the early 1990s (Yamashita, 2020). The crisis was found to have prolonged adversed effects on Japanese patents landscape even a decade after the crisis. Furthemore, the decline of Japan's and the rise of emerging Asian economies of South Korea, Taiwan, and China have been observed in overall patent applications and quality (Kwon et al., 2017). The surge of patent applications from China in the last two decades has been significantly driven by government patent subsidy programs, among other aspects such as increasing investment and supportive legal changes (Li, 2012; Prudhomme, 2015; Boeing and Mueller, 2019). However, such programs have been found to foster the applications of low-quality patents (Dang and Motohashi, 2015; Chen and Zhang, 2019). Although external influencing factors, such as economic growth and policy instruments, are outside the scope of this landscape review, they have to be considered in interpreting the technological landscape.

In terms of patent assignees, companies from China (CN), Japan (JP), and South Korea (KR) are dominating the top ten with a combined share of approximately 28% of the total patent family count. These companies are: 1) LG (KR), 2) Midea (CN), 3) Panasonic (JP), 4) Daikin (JP), 5) Mitsubishi (JP), 6) Gree (CN), 7) Samsung (KR), 8) Haier (CN), 9) Sanyo (JP), and 10) Huawei (CN). It is interesting to note that when we modified the counting based on the total patent record count, the list changes slightly with the addition of BSH (DE) and Carrier (US). The latter is often credited for inventing the modern air-conditioning in the early 20^{th} century (Biddle, 2008). These shares of total patent application indicate that East Asian manufacturers have become the driving force in active cooling technology innovation in the last 20 years. This fact is key to the global efforts of increasing the efficiency of cooling technologies in the market. For instance, the importance of China in global air conditioning policy has recently been highlighted (Phadke et al., 2020). Our finding here stresses this further by providing evidence on how East Asian manufacturers hold a significant number of patent families, which are not limited to the incumbent technology and well extended to the not-in-kind cooling technologies, as will be described further later in the paper.

4.1.2. Specific searches

The patent family dataset of the specific searches (with technology-specific keywords) is significantly smaller (n = 11,343) than in the generic search. Furthermore, because individual technology searches were performed to build the dataset, patent application trends are constructed for the four main cooling technology categories: vapour-compression, solid-state, electro-mechanical, and thermally-driven cooling, as shown in Fig. 7. It also includes the trends of non-dead patents, which illustrate patent maintenance trends of the four categories.

In Fig. 7.a, the publication trends of all patent families regardless of their legal status have varying degrees of increment depending on the technology type. Electro-mechanical cooling technology has the largest growth in the past 20 years, while vapour-compression and solid-state technology have relatively similar patent application trend. A different picture emerges when dead patents are excluded, as illustrated in Fig. 7.b. All technologies have a similar patent application trend in the first half of the 20 years. Thermally-driven technology has the highest average patent family count per year while vapour-compression and solid-state technology have a similar increasing trend in the last 10 years. It should be noted that the relatively small numbers of patent family between 1998-2000 can be attributed to the 20-year expiration of granted patents at the time of our search (March 2020).

In terms of retention percentage, i.e. the ratio between the number of non-dead and all patents, vapour-compression technology has the highest percentage at 58%, followed by the solid-state (52%), electro-mechanical (46%), and thermally-driven technology (42%). For vapour-compression, this indicates the market maturity of the technology, i.e. there is a higher possibility for an innovation to be financially beneficial for the assignee. It is interesting to note that despite their low technical and market maturity, as reported in the literature (Brown and Domanski, 2014; Goetzler et al., 2014), solid-state technology has higher retention percentage than electro-mechanical and thermally-driven technology. This could be an indication that solid-state patents assignees have higher confidence in the economic potential of their patents.

Figure 7: Patent application trends between 1998 and 2017 showing yearly patent family count for patents with the legal status of: (a) Alive, Dead, and Indeterminate, and (b) Alive and Indeterminate. The legal status was based on DWPI data as of March 2020.

For electro-mechanical and thermally-driven technology, the larger percentage of dead patents could be attributed to either more unsuccessful applications or fewer patent renewals. During the lifetime of a patent, maintenance or renewal processes are typical and associated with further fees. Therefore, maintaining a substantial number of patents could carry high costs, especially for smaller organisations and individuals. On the other hand, regularly maintained patents indicate a higher value of the innovation and a better outlook for financial return.

In terms of priority countries, patents from China, Japan, and the US dominate the top three in most cooling technology categories, as shown in Fig. 8. The higher number of patents from the US and Japan in the case of vapour-compression technology can be explained by the relative maturity of the technology which was developed by the US and Japanese manufacturers in the past decades. In both electro-mechanical and thermally-drive category, the number of Chinese patents is significantly higher than the next country, even after disregarding the dead patents. The gaps between the top three countries are less prevalent in the solid-state category, with the US and China have similar patent family counts.

Top patent assignees in all category are dominated by organisations from China and Japan, as illustrated in Fig. 9. Similar to the trend in priority country, top filing organisations in vapour-compression

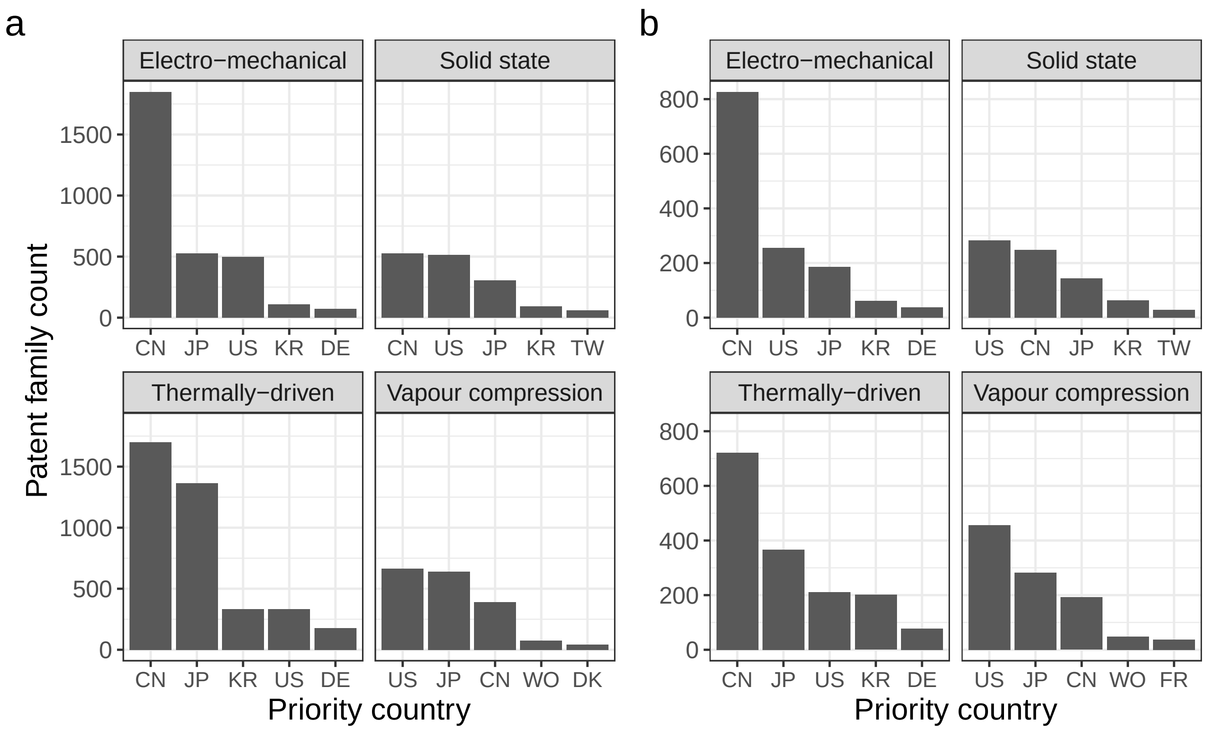

Figure 8: Top priority countries of specific searches patents with the legal status of: (a) Alive, Dead, and Indeterminate, and (b) Alive and Indeterminate.

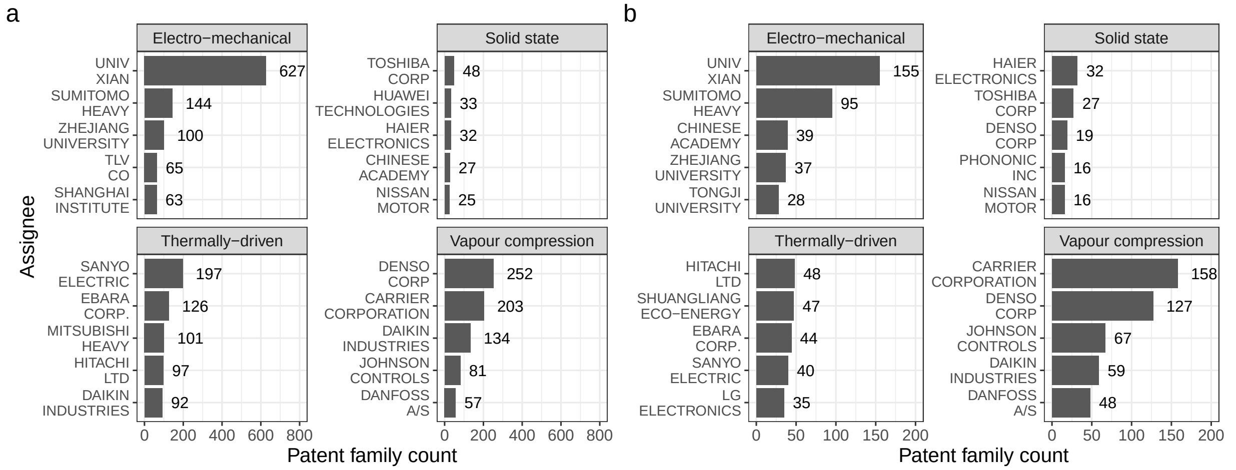

Figure 9: Top assignees of specific searches patents with the legal status of: (a) Alive, Dead, and Indeterminate, and (b) Alive and Indeterminate.

technology are Japanese and US manufacturers. Unlike in other categories, there is a significant presence of research organisations in electro-mechanical technology, such as Xian Polytechnic and Zhejiang universities in China. This will be discussed further in Section 4.2.2. Furthermore, the composition of the top five assignees for vapour-compression technology does not change between the two figures, which reflects the main technological focus of the companies.

4.2. Not-in-kind patents

In this section, the patent application trends for not-in-kind cooling technologies are examined further based on their individual technology. Vapour-compression cycles were excluded in this analysis due to their high maturity as the incumbent cooling technology.

4.2.1. Solid state

The patenting trends of solid-state cooling technologies are depicted in Fig. 10. Thermoelectric (n = 1098) and magnetocaloric cooling (n = 611) have significantly larger patent family counts than other technologies. In the past ten years, other technologies that appear to be in the early phase of growing patenting activity include elastocaloric (n = 8) and electrocaloric cooling (n = 20), although with orders of magnitude lower counts than the top two technologies.

Looking at the trend of all patents (Fig. 10.a), patent applications for thermoelectric are relatively stable over the years, while magnetocaloric cooling experienced a notable increase after 2010. Furthermore, more magnetocaloric patents (64%) have been maintained in the past 20 years as opposed to thermoelectric patents (44%). These retention percentages imply that more magnetocaloric patents are foreseen as more valuable

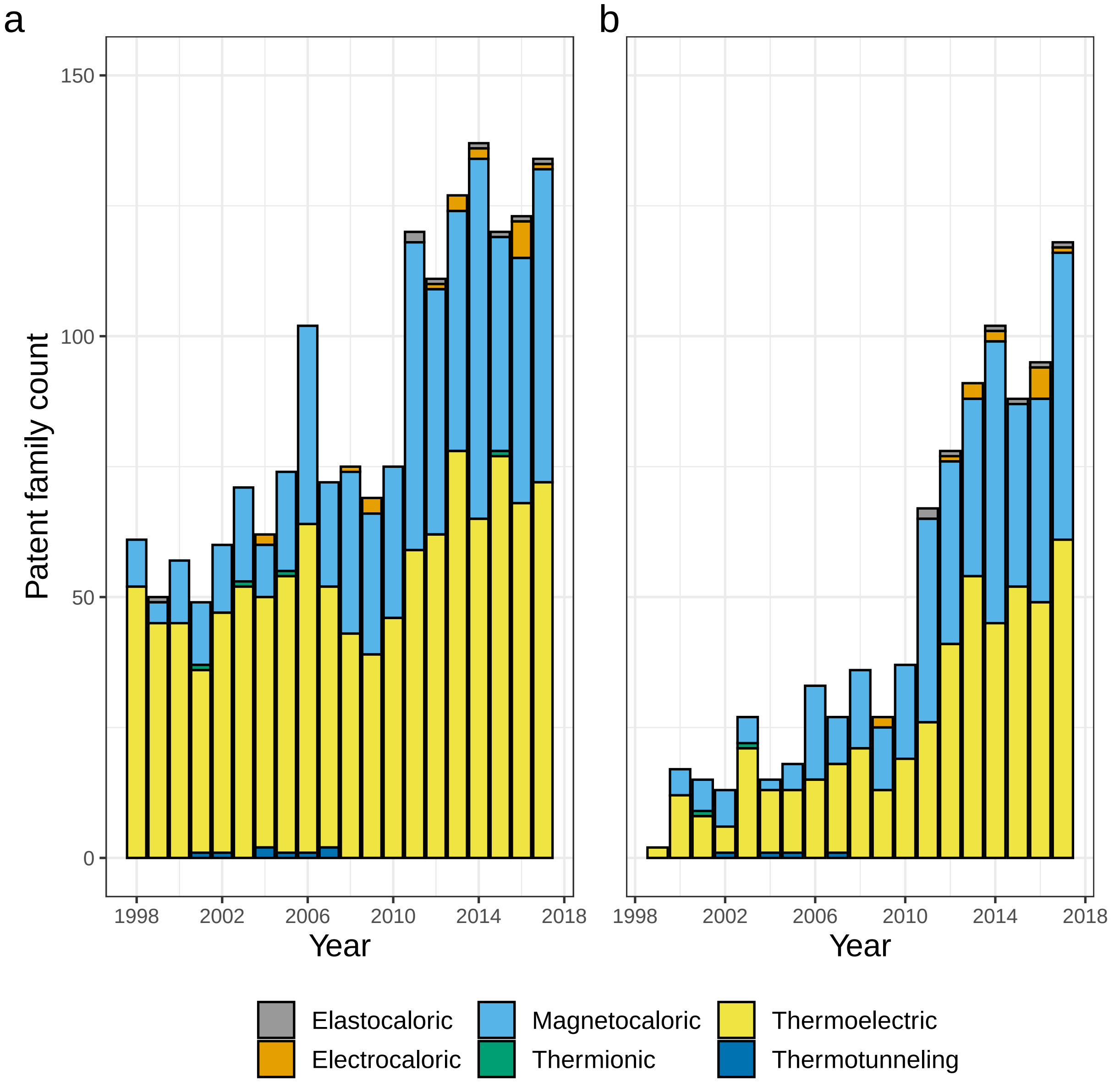

Figure 10: Solid state cooling patents with the legal status of: (a) Alive, Dead, and Indeterminate, and (b) Alive and Indeterminate. The legal status was based on DWPI data as of March 2020.

than thermoelectric ones. Furthermore, the relatively large numbers of patents on these two technologies are inline with assessments in the literature that foresee their high potential (Bansal et al., 2012; Goetzler et al., 2014; Brown and Domanski, 2014).

The top ten assignees for both technologies are shown in Fig. 11. The fields in which assignees operate can be seen as more diverse in magnetocaloric technology with the inclusion of Nissan Motor, South China University, Chinese Academy of Science, and Astronautics Corp among electrical and electronics manufac-

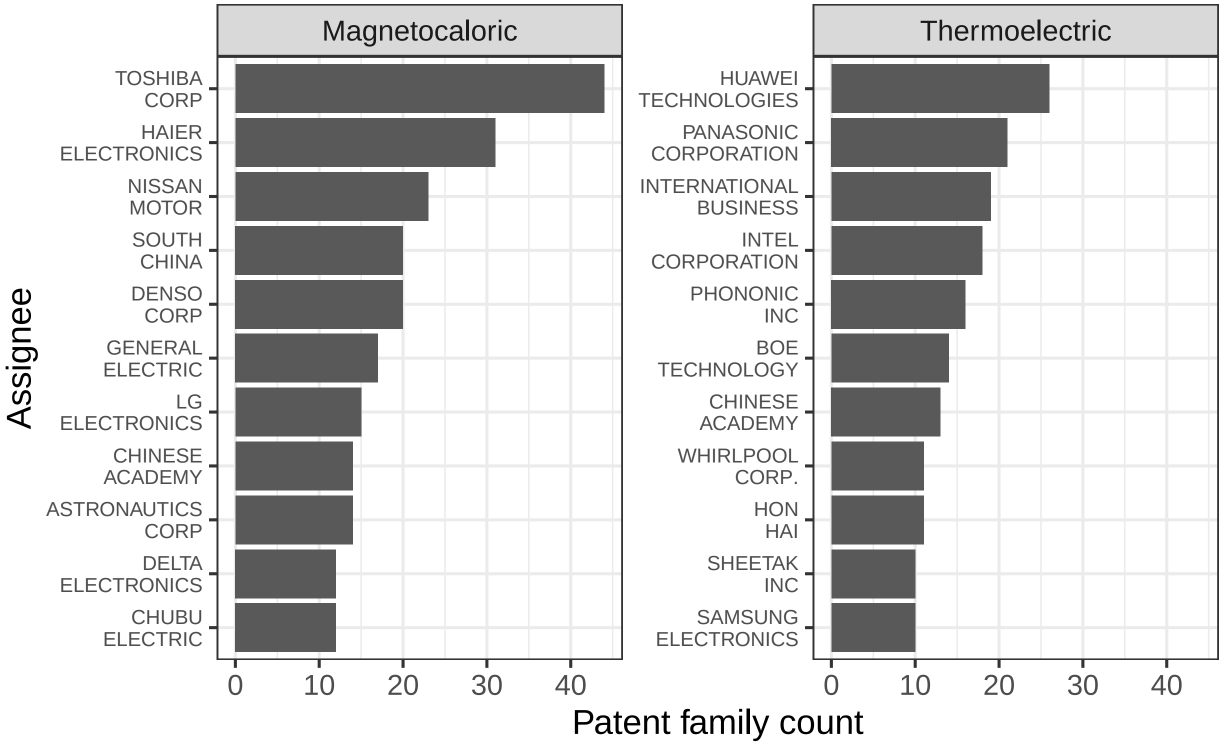

Figure 11: Top ten assignees for magnetocaloric and thermoelectric cooling for patents with all legal status.

turers. The latter dominates the top ten assignees in the case of thermoelectric technology. The type of assignee also illustrates the typical or potential applications of the technology. For instance, thermoelectric cooling has a prevalence in consumer products and thermal management for electronics equipment (Zhao and Tan, 2014), while magnetocaloric cooling is foreseen to have potentials in commercial refrigeration equipment (Greco et al., 2019).

Technological progress of magnetocaloric and thermoelectric cooling over the past decades are well documented in the literature. As the most developed solid-state cooling technology, numerous magnetocaloric cooling devices have been constructed, mostly as experimental apparatus and prototypes, since the first design in 1976 (Brown, 1976; Yu et al., 2010; Greco et al., 2019). The discovery of the giant magnetocaloric effect materials in 2005 has accelerated the development of this technology (Gschneidner Jr et al., 2005; Yu et al., 2010). This acceleration is corroborated by the increase in annual patent applications in magnetocaloric cooling since 2006 (Fig. 10). Research efforts on this technology have been focused on materials and prototypes development; thus, reported data are mostly centered around cooling power, temperature lift, and magnetic systems. Performance-related values, e.g. COP, have to be carefully interpreted since they are highly dependent on the aforementioned variables (Kitanovski, 2020). Interested readers are referred to review article available in the literature (Yu et al., 2010; Greco et al., 2019; Kitanovski, 2020).

Advancement of thermoelectric cooling in the past two decades has been occured around improving the materials performance (ZT) and development of cooling devices (Riffat and Ma, 2004; Bell, 2008; Zhao and Tan, 2014; Mao et al., 2020). Performance improvements have been focused on Bi_2Te_3 alloys, although these improvements have not yet incorporated into applications (Mao et al., 2020). This contributes to the relatively stagnant COP on device level and has confined thermoelectric cooling in niche applications, such as portable cooler, medical devices, electronic cooling, and automobile air conditioners (Zhao and Tan, 2014). Despite this missing link between materials research and device development, the combination of these two activities are contributing to the relatively stable patent applications rate in thermoelectric cooling (Fig. 10.)

4.2.2. Electro-mechanical

The top two electro-mechanical cooling technologies based on patent family counts are evaporative (n = 2280) and pulse-tube cooling (n = 779), as shown in Fig. 12. It can be seen that the increasing number of patent application in electro-mechanical cooling after 2010 has been driven mainly by evaporative cooling-related patents. However, pulse-tube cooling patent applications have been relatively stable in the past 20 years. As for the other technologies, thermoacoustic cooling has a notable number of applications (n = 113), while vortex-tube refrigeration patents have started to grow in the past ten years (n = 80).

Several electro-mechanical cooling technologies have been deemed unlikely to challenge vapour-compression cycles in the foreseeable future due to combinations of low efficiency and operating temperature. These include Brayton cycle, pulse-tube, vortex-tube, evaporative cooling, Bernoulli heat pump and critical-flow cycle (Brown and Domanski, 2014; Goetzler et al., 2014; El Fil et al., 2021). The inclusion of evaporative cooling on this list refers to its potential in replacing a vapour-compression cycle in an application. Its large number of patents illustrates the wide application of the technology, including as a sub-system in space conditioning systems.

On the other hand, thermoacoustic and membrane heat pumps have been shown to have competitive charasteristic in exergetic efficiency and energy savings potentials, respectively (Goetzler et al., 2014; El Fil et al., 2021). Thermoacoustic cooling is third in patent family count in Fig. 12, while membrane heat pumps cooling is the last. Potential explanations on the latter are given in Section 4.3.

In terms of patent assignees, the top two technologies have a significantly different composition of organisations and relative number of patent family counts, as depicted in Fig. 13. The number of patent family from universities is significantly higher in evaporative than pulse-tube cooling. This is due to the unusually

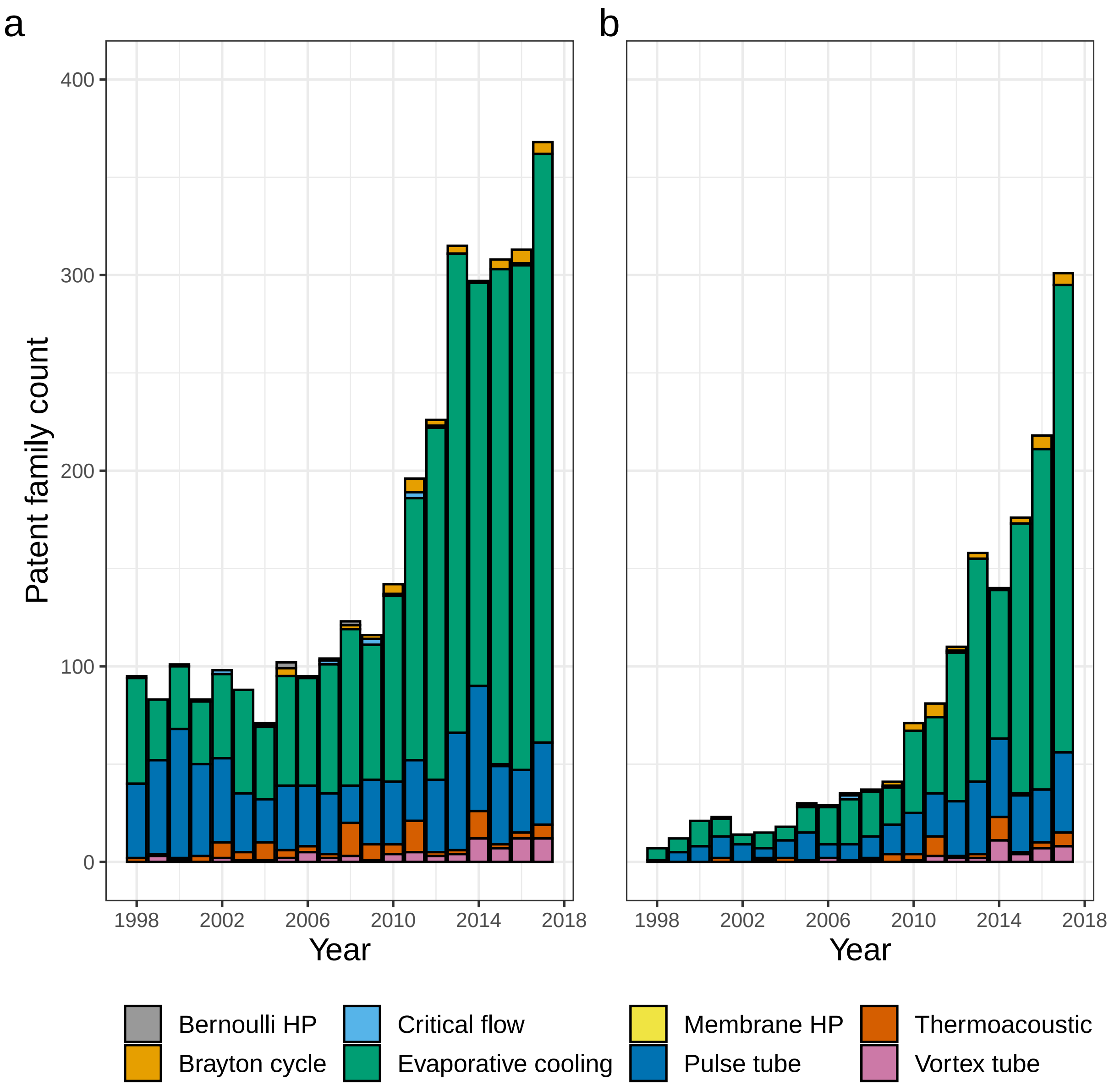

Figure 12: Electro-mechanical cooling patents with the legal status of: (a) Alive, Dead, and Indeterminate, and (b) Alive and Indeterminate. The legal status was based on DWPI data as of March 2020.

high patent family count from Xian Polytechnic University in evaporative cooling technology, with close to an order-of-magnitude difference to the next largest assignee. The University has been actively patenting in this technology since 2007 (2 applications) and submitting 133 applications in 2017. Furthermore, its patent applications have been exclusive to the Chinese patent office.

The high number of evaporative cooling patent applications from Chinese universities can be explained by considering the following two factors. First, evaporative cooling technology has been widely investigated

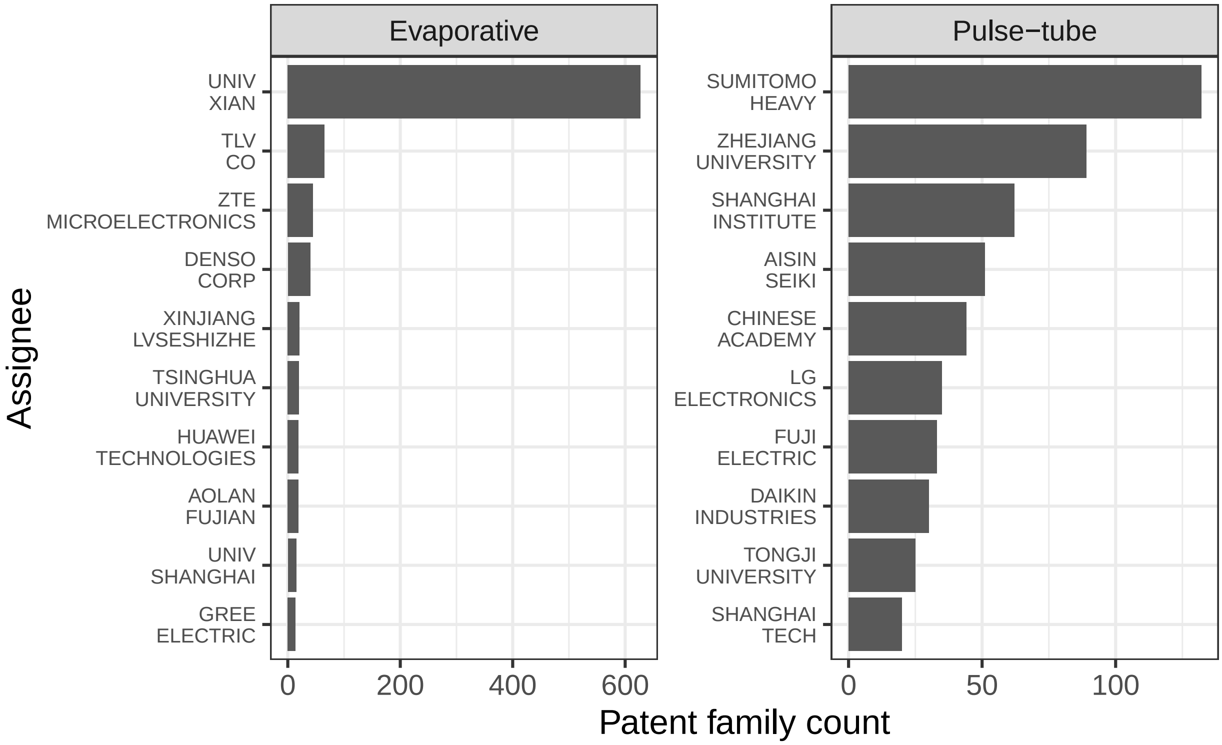

Figure 13: Top ten assignees for evaporative and pulse-tube cooling.

in the country (Xuan et al., 2012a,b). It was reported that evaporative cooling research in China has been expanding since the 1980s; however, most of these works were published in Chinese (Xuan et al., 2012a). Second, as discussed in Sub-section 4.1.1, government subsidy programs on national and province-level have been introduced in the last decades to promote patenting at Chinese universities. These have been shown to contribute significantly to the rapid increase in patent applications from Chinese universities (Li, 2012; Fisch et al., 2016; Chen et al., 2016).

The large number of evaporative cooling-related patent family counts and their assignees also reflect the wide range applications of the technology. For example, the concept can be used in a water fountain-based passive cooler and a hybrid air conditioner with the vapour-compression cycle (Cuce and Riffat, 2016; Xuan et al., 2012b). The range is relatively narrower for pulse-tube refrigeration, which is mainly used in a cryogenic application (Brown and Domanski, 2014).

Evaporative cooling has been widely used in industrial process, built environment, and microclimate cooling (Cuce and Riffat, 2016; Yang et al., 2019). Due to their well known physical mechanism (Fig. 3), progress in evaporative cooling has been oriented more towards applied improvements, such as the combination with other cooling technologies to increase the overall efficiency (Yang et al., 2019). The significant overlap between active and passive cooling classification for evaporative cooling can also contribute to the constantly increasing patent applications in the last two decades.

4.2.3. Thermally-driven

Sorption cooling technologies, both absorption (n = 3528) and adsorption (n = 419), have dominated the patent applications for thermally-driven cooling (Fig. 14). They are followed by liquid desiccant (n = 131) and ejector cooling (n = 110), while the rest have relatively minor patent family counts. In the past 20 years, absorption cooling patent applications have dipped between 2003-2006 before increasing again up to around 250 patent applications per year in the last seven years. Both absorption and adsorption cooling have similar patent retention percentage at 40% and 44%, respectively.

The top ten assignees of absorption and adsorption cooling technology are shown in Fig. 15. Major manufacturers dominate the absorption cooling landscape, while several research organisations have a significant presence in adsorption cooling. The difference in the type of assignees and patent family count are reflections of the technical maturity of the two technologies, with adsorption still in the earlier research stage than absorption cooling.

The result of absorption cooling with the largest patent share in this category is in line with previous assessments that argue for its high potential (Bansal et al., 2012; Brown and Domanski, 2014). The performance of absorption cooling is also considered to be relatively competitive among other not-in-kind technologies (El Fil et al., 2021). Furthermore, the technology also has significant market share within the thermally-driven cooling technologies (Keppler, 2018). Nevertheless, the share of absorption cooling in the overall cooling technologies remains relatively low. Keppler identified several factors that influence the diffusion of absorption cooling technology, such as the relatively high investment costs, high space requirements, lower efficiency than VCC, and relative energy costs (electricity and thermal) (Keppler, 2018). Indeed, the particular combination of cost of electricity, gas, and subsidies has been attributed to the widespread use of absorption cooling in Japan (Brown and Domanski, 2014). This trend can also be observed through the strong presence of Japanese manufacturers in absorption cooling (Fig. 15).

Interestingly, most of the top assignees in absorption cooling are also manufacturers of VCC technology, e.g. Sanyo, Hitachi, Daikin, and LG. The presence of these established manufacturers is not surprising due to the natural extension from their core business in cooling technology. However, there is a concern that since absorption cooling is an additional business stemming to user demands for a green image, the established manufacturers would have less interest in promoting the technology as a serious alternative to their main products (Keppler, 2018).

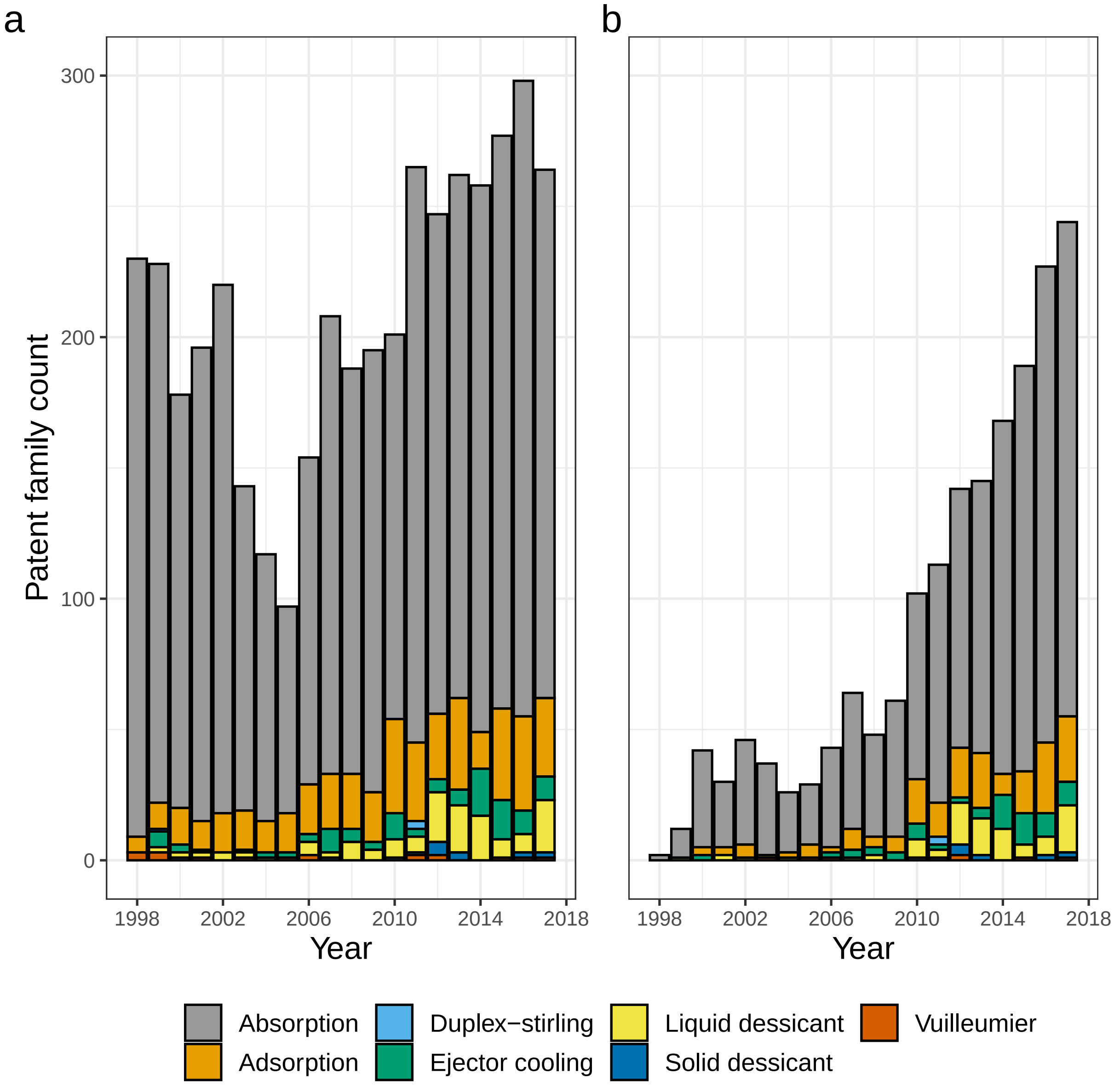

Figure 14: Thermally-driven cooling patents with the legal status of: (a) Alive, Dead, and Indeterminate, and (b) Alive and Indeterminate. The legal status was based on DWPI data as of March 2020.

Progress on absorption and adsorption cooling technology in the past two decades have occured on various fronts, including working fluids, adsorbent/adsorbate pairs, number of effects, system design, control strategy, and low-temperature heat input (Wu et al., 2014; Herold et al., 2016; Alahmer et al., 2019). The latter has been driven by increasing interest in solar thermal cooling (Shirazi et al., 2018). A recent comparative study has shown that vapour absorption cycle has significant potential to compete with vapour compression cycles (El Fil et al., 2021).

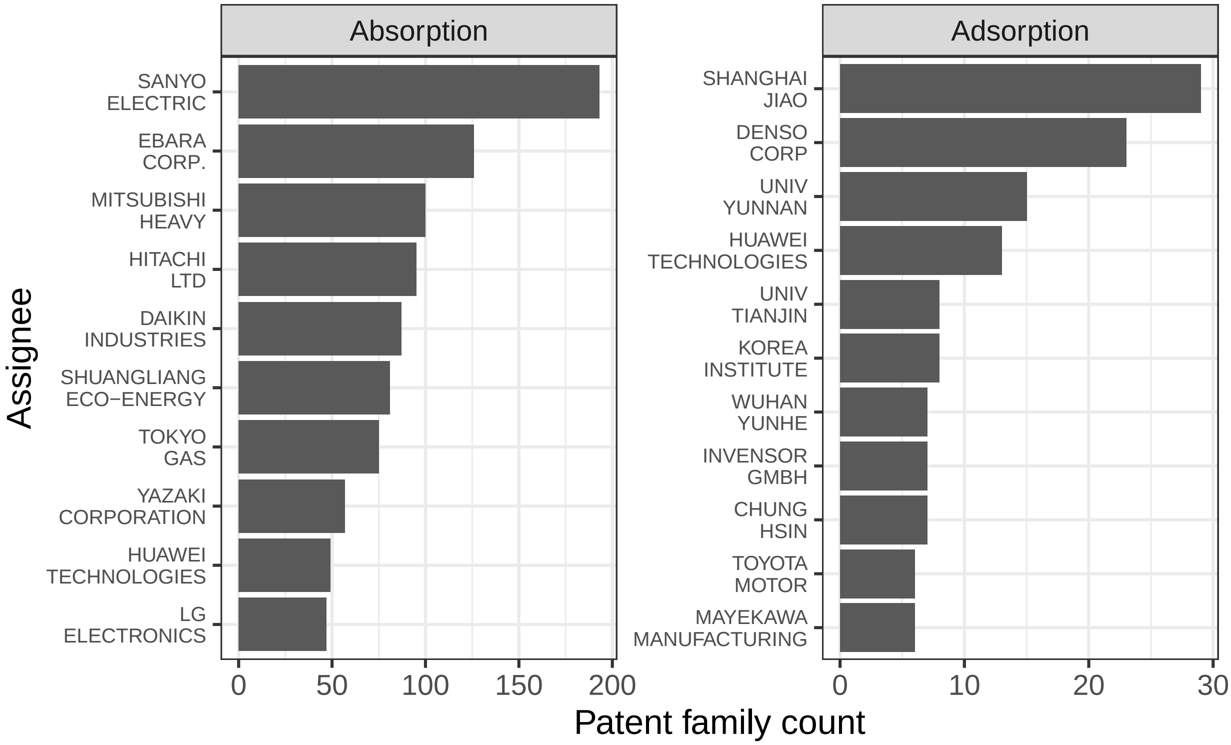

Figure 15: Top ten assignees for absorption and adsorption cooling.

4.3. Patent count and technical maturity

Patent counts can provide a quantitative indication of the technical maturity of a technology. This is illustrated in Fig. 16 where patent family counts of cooling technologies are plotted against three levels of technical maturity (Low, Moderate, and High). The technical maturity levels are based on qualitative evaluations of the technology, e.g. prototype development stage and availability of commercial products in the market (Goetzler et al., 2014). Intuitively, the clusters of cooling technologies are expected to follow a diagonal trend across the figure, i.e. low-maturity technologies will have lower patent counts, and vice-versa. In Fig. 16, this is true for most cases with approximately an order of magnitude threshold between technical maturity level, with low-maturity technologies having patent count at the 10^1 order while high-maturity technologies having patent count at the 10^3 order. However, there are several notable exceptions: membrane heat pump, Duplex-Stirling, solid desiccant, and vortex tube cooling.

For the membrane heat pump, it was reported that only one company was developing the technology (Goetzler et al., 2014). Furthermore, based on the patent search, we found one membrane heat pump patent from State University of New York (Owejan and Demario, 2019). Given the typically generic description of a patent, it is also possible that the membrane heat pump technology is described with other combination of keywords. However, a recent thermodynamic modelling study of the technology found that there are significant practical challenges before commercialisation of the technology (Bukshaisha and Fronk, 2019). Therefore, we argue that membrane heat pump needs to be categorised as having a low technical maturity

In the case of Duplex-Stirling heat pump, products are currently available mostly for low-temperature refrigeration applications (Doğan et al., 2018). The technology is based on the Stirling-cycle which arguably has a relatively high technical maturity. Thus, the low patent family count may be a reflection of the rather restrictive technology-specific keywords.

For solid desiccant, the resulting patent family count for the technology might be too conservative because of the selected IPC codes in the patent search which exclude a dedicated humidification/dehumidification equipment. Another possible explanation is the division between solid and liquid desiccant technology in the search. This may have excluded overly generic patent descriptions that do not specify the type of desiccant.

The vortex tube is considered to have a high technical maturity due to its widespread use in industrial processes (Goetzler et al., 2014). Despite of this, it has a relatively low patent count compared to other mature technologies. The relatively straightforward design of the technology might contribute to the low patent count. The vortex tube is a device with no moving parts that separates a compressed gas into hot and cold streams and was discovered in 1930s (Xue et al., 2010). This simple design and relatively mature technology explain the relatively low patent count of the technology in the past 20 years.

Overall, patent family count provides a good indication on the technical maturity of cooling technologies. Furthermore, by using a quantitative indicator like patent family counts, we can assess the relative maturity of technologies within a single qualitative indicator. For example, based on Fig. 16, thermoelectric, magnetocaloric, and adsorption cooling have higher potentials for near-future deployment than thermoacoustic cooling within technologies with moderate technical maturity. Finally, the historical development of the technology and the patent landscape timeframe have to be considered in extracting technical maturity information from the patent landscape.

4.4. Implications of the study

The patent landscape can support the effort of understanding and shaping the global development of active cooling technology. Three potential implications have been identified: First, the key priority countries and assignees of active cooling patents are valuable information in developing global and national cooling policies. In the past 20 years, patent applications in active cooling technology have been steadily increasing. A more rapid upward trend was observed after 2010, which was mainly driven by patent activities from China. Large manufacturers from China, Japan, and South Korea have approximately 28% share of the

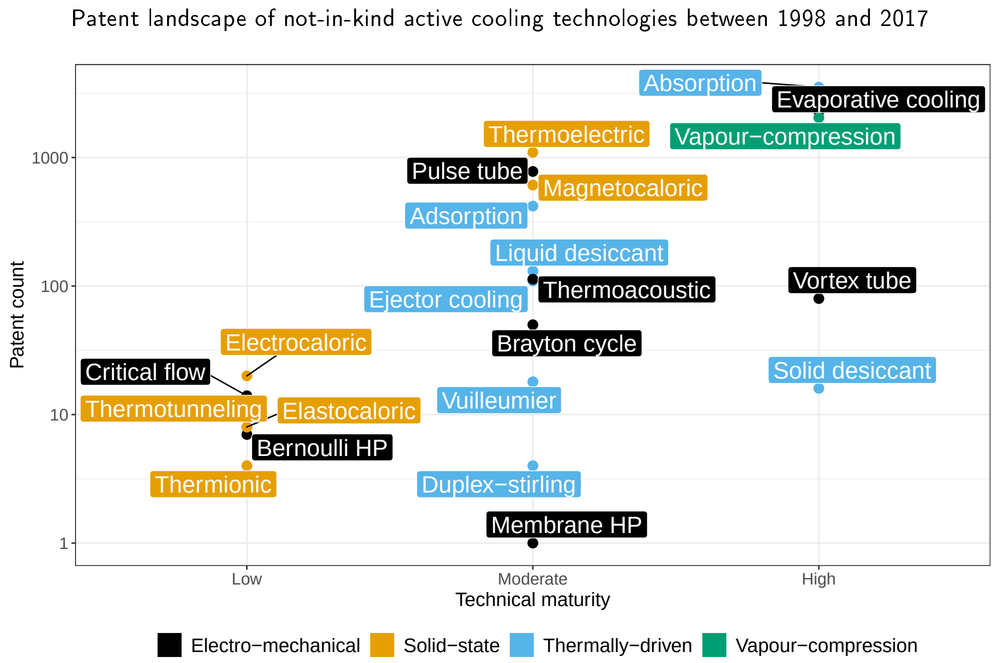

Figure 16: Technical maturity level and patent count. The information on technical maturity were taken from Goetzler et al. (2014). The *y*-axis (patent count) is in logarithmic scale.

total patent family count.

Second, the relative technical maturity between technologies could inform research funding policy towards a better share of support. As shown in this paper, the patent family count can add an extra dimension to the typically used maturity level. Emerging technologies with lower patent counts, e.g. thermoacoustic, may need further support on more fundamental research, while those with higher patent counts, e.g. adsorption cooling, may benefit from applied research support.

Finally, the patent landscape can provide useful information for designing a deployment-oriented policy for alternative cooling technologies. Relatively mature options, such as absorption and evaporative cooling, could be promoted further by providing support to reduce the burden of investment and operational costs. This type of policy should be implemented in addition to the more widely adapted efficiency improvement policies for cooling appliances, e.g. energy labelling and minimum energy performance standard.

4.5. Limitations and recommendations

Limitations of the study have to be considered in interpreting the resulting patent landscape. The inherent characteristic of broad language and terminology used in patent applications could mean that deriving information such as the field of application impractical. Furthermore, patenting activities could also be driven by governmental incentive policies which could significantly inflate the number of patent applications. In order to limit the potential bias, we have included the patent legal status (Alive, Dead, and Indeterminate) in our analysis with the assumption that patents with higher innovation value would be continuously maintained over the legal period. Finally, the landscape should be treated as one of several information sources that could help in R&D or policy-related decision making. It provides a viewpoint of innovation trend and supplements other tools, such as recent market data, systematic literature reviews, and qualitative reviews.

Several directions can be recommended to advance the technological landscape of active cooling technologies. First, a patent landscape on the improvement of vapour-compression cycles would provide further insights into the development in the field. This could include methods to increase its coefficient of performance and the development of alternative refrigerants. Second, combining patent data with historical market and policy data could also provide insights into how they potentially influence each other. This information would be useful in efforts to foster the development of not-in-kind cooling technologies.

5. Conclusions

A patent landscape of active cooling technology has been presented, which accounts for the global patenting activities in vapour-compression and not-in-kind cooling technology over the last 20 years (1998-2017). The patent landscape provides a broader scope of active cooling technologies based on global patent application data.

Two key findings are derived from the patent landscape review. First, China, Japan and South Korea are the dominating priority countries in the past two decades. Manufacturers from these countries also have significant presence based on patent assignees data. Therefore, it is important to positively engage with these identified stakeholders in the efforts to shape the future cooling supply and minimise the potential negative impacts on increasing global cooling demand.

Second, not-in-kind cooling technologies with a high number of patent applications are thermoelectric, magnetocaloric, evaporative, pulse-tube, absorption, and adsorption cooling. Among these, only pulse-tube technology has little relevancy with near-room temperature cooling, while the rest have the potential to complement and replace the vapour compression technology. Identifying these technologies is crucial to help focusing future research efforts and developing supportive policies for increasing level of deployment.

The growing global cooling demand would have significant negative consequences to climate change mitigation efforts if the current practice of fulfilling this demand were left unchecked. To minimise the negative impacts of cooling, improvements on both active and passive cooling technologies are necessary. The assessment of the current technological landscape is a vital step towards developing better active cooling solutions. The developd active cooling patent landscape can help researchers, technology developers, and policymakers in identifying, shaping, and influencing the technological interventions required to deliver sustainable cooling.

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CRediT authorship contribution statement

Renaldi Renaldi: Conceptualization, Methodology, Investigation, Writing - Original Draft, Visualization. **Nicole D. Miranda:** Investigation, Writing - Review & Editing. **Radhika Khosla:** Writing - Review & Editing, Supervision, Funding acquisition. **Malcolm D. McCulloch:** Writing - Review & Editing, Supervision, Funding acquisition.

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