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SOLAR-POWERED THERMOELECTRIC REFRIGERATION: AN ANALYSIS OF TECHNOLOGICAL EVOLUTION

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Abstract. *The pursuit of sustainable refrigeration solutions has driven significant interest in thermoelectric refrigeration, a technology that operates without the use of environmentally harmful refrigerants. This study aimed to evaluate the technological advancements in thermoelectric refrigeration systems powered by solar energy. A patent search was conducted using the Espacenet database, employing targeted keywords and followed by a manual screening to exclude patents that were not relevant to the topic, resulting in 109 patents meeting the criteria. The findings highlight the potential of Peltier-effect-based refrigeration systems for eco-friendly climate control, despite the low coefficient of performance, and reveal a promising upward trend in patent activity over recent years, especially in 2017 when it reached its peak. The research identified China as the leading country in patent filing and a balance between independent researchers, companies and universities as the leading institutions in patent filing. A comparison of recurring technologies was conducted, and the primary application areas of these technologies were evaluated. Notably, small-scale applications such as vehicle interiors, residences and personal cooling emerged as prominent areas of focus. These findings can guide future investments in eco-friendly refrigeration technologies, contributing to the reduction of environmental impact in the refrigeration sector.*

Keywords: *Peltier, thermoelectricity, solar energy, cooling, technology prospecting.*

1. INTRODUCTION

High temperatures can cause discomfort for people, especially in enclosed environments such as automobiles or homes. It is also important to note that elevated temperatures are harmful to health as they accelerate the degradation of materials like plastic (Zitting, 1998), leading to an increase in the number of toxic particles present in the air. To prevent these issues, refrigeration is used in enclosed spaces through air conditioning systems that employ refrigerant fluids, such as R410A (a zeotropic mixture of difluoromethane and pentafluoro ethane) and R134A (tetrafluoroethene). Although these are hydrofluorocarbons (HFCs) and do not damage the ozone layer, HFCs are still considered greenhouse gases (Aljolani *et al*., 2024) due to their high Global Warming Potential (GWP). Furthermore, according to Bentrcia *et al*. (2017), systems that use compression for air conditioning consume large amounts of energy.

Thus, it is of great interest to develop more sustainable refrigeration techniques by investing in cleaner technologies, such as thermoelectric devices based on the Peltier effect. This phenomenon occurs when an electric current flows through N-type (negative) and P-type (positive) semiconductor junctions, cooling one end while heating the other (Ramzy *et al*., 2025), however, as acknowledged by Kaiprath and Kumar (2023), the coefficient of performance (COP) of thermoelectric refrigeration system is quite low when compared to compressor-based refrigeration system. Despite this limitation, such systems do not use refrigerant gases with high Global Warming Potential (GWP). Moreover, it is possible to supply the necessary energy to these devices by converting solar energy

into electricity through the photovoltaic effect, as Nadimuthu *et al*. (2025) already showed with their work, consequently reducing the consumption of conventional electrical energy in climate control systems.

Technological prospection studies are of great importance, as according to Teixeira (2013), these types of studies make it possible to predict trends in the evolution of technologies, which enables investments to be made in the creation of innovations. Due to the need for advancements in the field of solar thermoelectric refrigeration, this study aims to analyze the evolution of solar-powered thermoelectric refrigeration systems through technological prospecting of the European patent database (Espacenet). The study examined the growth rate of these technologies, the main countries and applicants responsible for patent development, as well as the primary types of climate-controlled environments.

2. METHODOLOGY

The technology foresight process began with the use of the search bar, applying filters to search only within “titles or abstracts” on the European patent database Espacenet, which was chosen for its global coverage and robust search tools. A set of keywords relevant to the topic of thermoelectric cooling powered by solar energy and associated with air conditioning applications was used, resulting in the following query: ("peltier" OR "thermoelectric" OR "thermo electric") AND "air condition*" AND ("solar*" OR "photovoltaic*"). This query was formulated using Boolean operators such as AND OR, along with the truncation operator (*), as shown in Figure 1. According to Lara-Bertrand *et al*. (2024), a well-constructed research query with Boolean and truncation operators is important when conducting a technology foresight, as it helps encompass all possible patents relevant to the study. However, despite this careful approach, some important patents may still not be retrieved by the query.

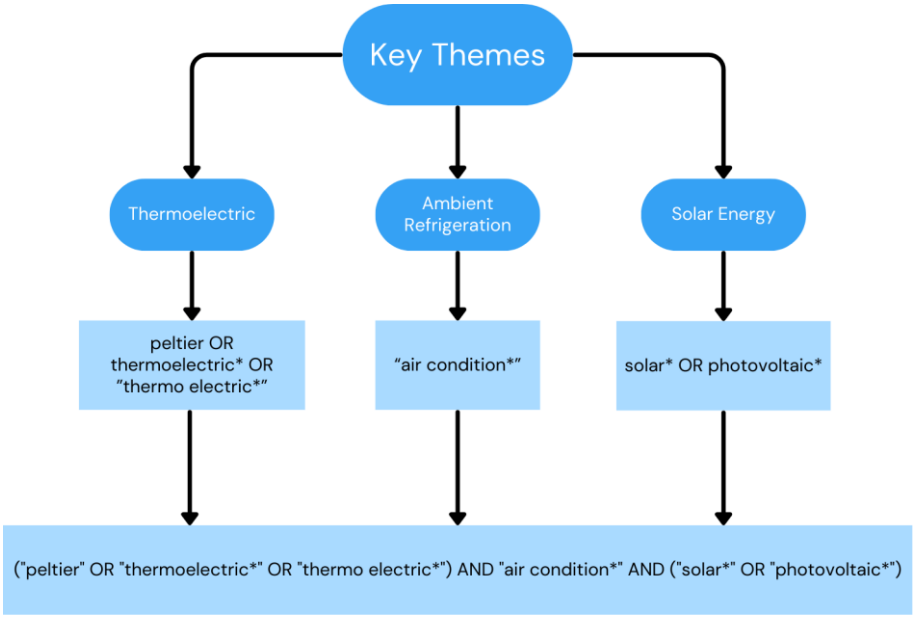

Figure 1. Research query

A total of 199 search results were exported from the patent database in spreadsheet format and manually filtered by reading their abstracts. Systems that were not powered by solar energy or that made use of compressors or high-GWP refrigerant liquids during the thermoelectric cooling process were excluded. However, systems that employed thermoelectric cooling to lower the temperature of a refrigerant gas after it exited a compressor were considered valid, as they did not interfere with the thermoelectric cooling itself. Additionally, patents that diverged from the main topic in any other way were also discarded. It is worth noting that this manual screening process represents a limitation of the study, as the evaluation depends on the interpretation of the abstracts and may have led to the unintentional exclusion or inclusion of patents with ambiguous or unclear descriptions.

The steps of this methodological process are summarized in Figure 2. Using the spreadsheet and Microsoft Excel, scripts were written in the Visual Basic for Applications (VBA) compiler to extract data such as the publication year, responsible country, assignee (applicant), and IPC code along with its subclasses for each approved patent. The extracted data were then analyzed by filing year, country of origin, assignees, and IPC codes. Patterns in the annual growth of patent filings, leading countries in terms of filings, major assignees, the most frequent technological applications, and the primary types of cooled environments were identified. Furthermore, all selected patents were read in full, and a qualitative analysis was conducted, considering the invention descriptions, claims, and drawings to identify technological trends, similarities, and differences among the proposed solutions and the types of climate-controlled environments.

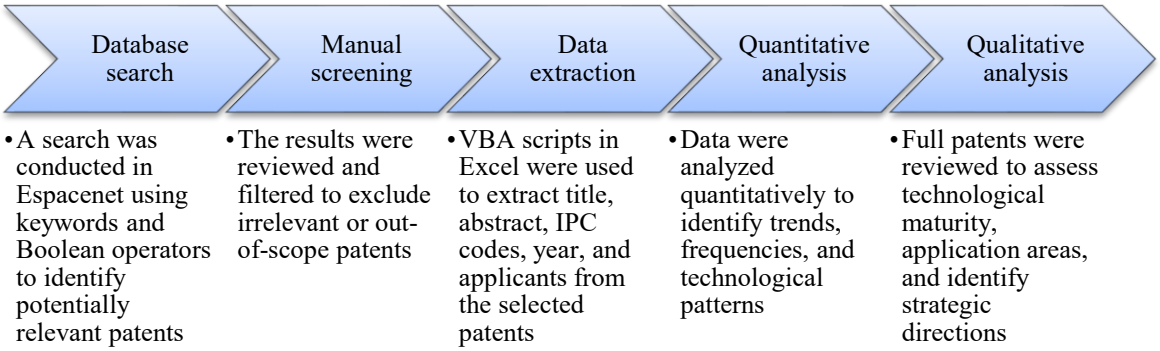

Figure 2. Steps to the methodological process

3. RESULTS AND DISCUSSION

After individually analyzing the 199 patents, it was found that 90 of them did not fully address the chosen research topic. The main reasons for excluding these 90 patents included: the use of refrigerant fluids and/or compressors during the thermoelectric cooling process; the use of the thermoelectric effect merely to improve the energy efficiency of systems by converting residual thermal energy from other components; and the absence of the Peltier effect in the climate control process. Additionally, some systems patented as invention patents had slightly modified and simplified versions registered as utility models. In such cases, only the invention documents were approved due to their strong similarity to the variants. As a result, 109 patents were considered suitable for the selected research topic. Notably, since the studied patents were obtained from only one database, it is likely that there are other patented systems meeting the prospection criteria in different databases that were not analyzed in this research.

3.1 ANNUAL PATENT DEPOSIT

Regarding the annual filing of patents that are truly relevant to the topic studied, it was observed that the first patent related to the theme was registered in 1985, as illustrated in Figure 3. Initially, patent publications were very sparse, with only one patent being published in the years when filings occurred. However, the intervals between these filings gradually decreased over time, becoming more frequent from 1999 to 2006 and again from 2008 to 2020. It is worth noting that starting in 1999, the number of annual patent filings began to increase, with only the years 2005 and 2006 recording a single patent each. In addition, it was concluded that the highest peak in filings occurred in 2017, with a total of 13 patents filed.

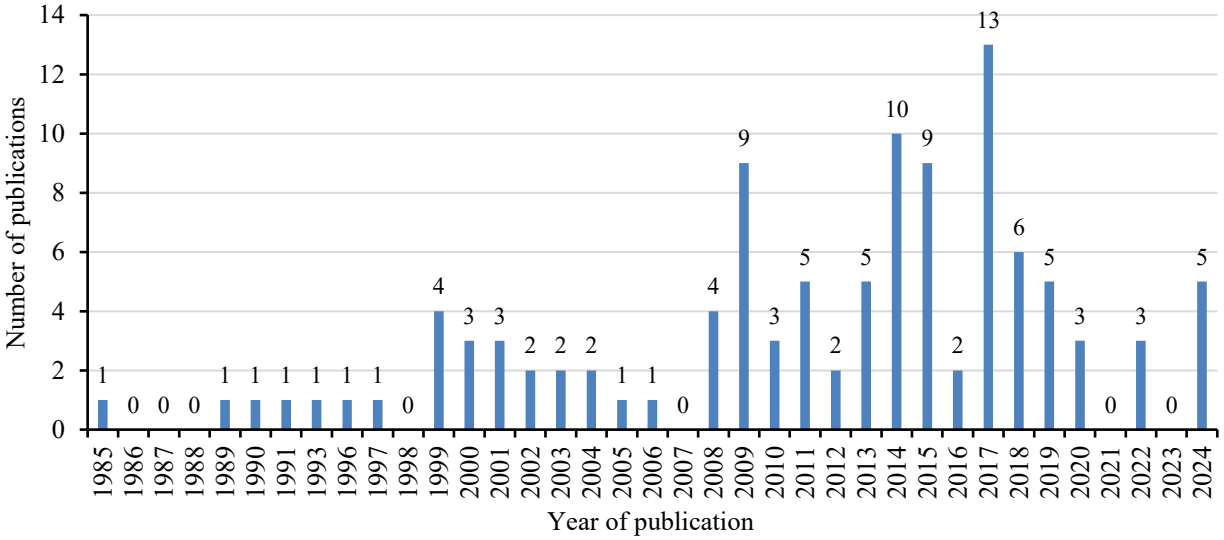

Figure 3. Patents published by year

3.2 PATENTS DEPOSIT PER COUNTRY

It was observed that China was responsible for the largest number of patent filings, totaling 60 — approximately 55% of the total — highlighting the country's strong research efforts in thermoelectric materials (Ibn, 2024). South Korea ranked second with 20 filings, representing around 18%, followed by Japan with 14 patent filings, accounting for approximately 13% of the total. These data are presented in Figure 4, along with information on other countries responsible for the remaining filings. It is important to note that during the data extraction process regarding the country of origin for each patent, it was not possible to determine the origin of the patent with the code EP3418087A1 (Djidjan, 2018). This is because the European Patent Office (EPO) was responsible for its publication, allowing the patent to be validated in multiple European countries. Additionally, the entity responsible for the invention, AGCO Corporation, is an international company, which makes it impossible to assign a specific country of origin to this document.

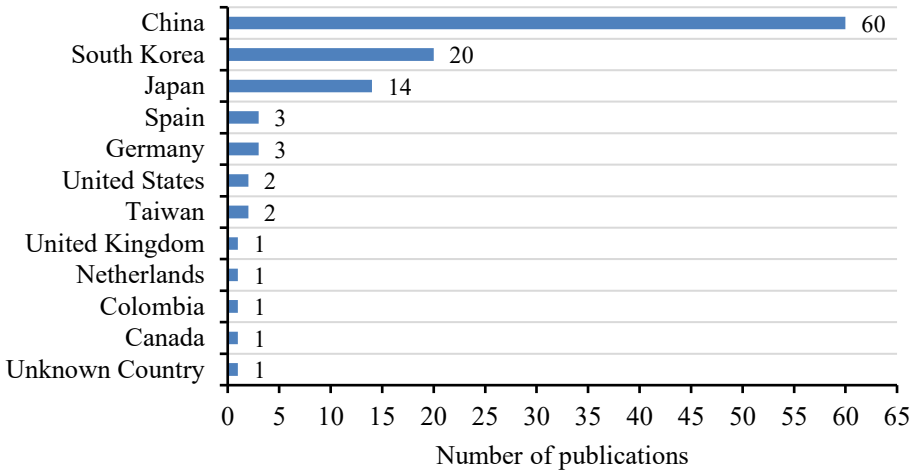

Figure 4. Publications by country

3.3 TYPE OF PATENTS HOLDERS

Regarding the ownership distribution of the analyzed patents, the data revealed that independent inventors were responsible for the highest number of filings related to the topic, accounting for 40 patent applications, which corresponds to approximately 37% of the total. Among them, a Chinese man named Wu Peng stood out, having filed three patents. In second place, private companies had a significant share, with 36 patents filed, around 33% of the total. Mazda Motor, with just two patents, was the private company with the highest number of filings. Academic institutions represent the third and final major group, with 33 patent registrations, about 30% of the total. It is worth mentioning that within this category, Wuhan Tech University, located in China, had the highest number of filings in this field, with three patented systems. As can be observed, the difference in the number of filings among the ownership groups is small, which highlights the broad interest in developing more environmentally friendly climate control solutions. The data mentioned are presented in Figure 5.

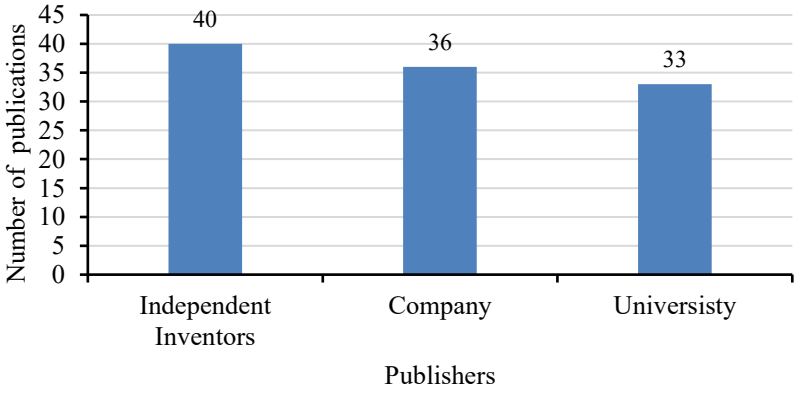

Figure 5. Patents by publisher

3.4 TECHNOLOGICAL AREAS AND SUBCLASSES

To investigate the applications of each patent system, the IPC (International Patent Classification) codes were analyzed. It is worth noting that, depending on the capabilities of the registered system, it may fall under more than one macro category. The most frequent classification during the study was Class F – "Mechanical Engineering, Lighting, Heating, Weapons, and Blasting", with an emphasis on heating, due to the need to dissipate the heat absorbed during the thermoelectric effect. This classification appeared 65 times. This can be exemplified by patents such as CN117433080A (Ming *et al*., 2024) and KR20170025540A (Jeong *et al*., 2017), which, during operation, use water as a cooling fluid to dissipate heat from the thermoelectric cooler and transfer this thermal energy in the form of heated water to another part of the system. In the first case, the water is used for consumption, while in the second case, the absorbed energy is dissipated, and the fluid is recirculated.

Next is Class B – "Performing Operations and Transporting", with a strong focus on transportation due to the various systems aimed at cooling the interior of a vehicle. Examples include patents CN106379139A (Chen *et al*., 2017) and CN101134450A (Chul, 2008), which propose an auxiliary cooler responsible for maintaining the interior temperature of a vehicle at a comfortable level while it is turned off and parked in areas with high solar incidence. IPC code B appeared 45 times. In third place is Class H – "Electricity", related to the conversion of solar and, in some systems, thermal energy into electricity. An example is patent CN103383123A (Qu *et al*., 2013), which combines photovoltaic devices and additional thermoelectric devices to convert heat from a solar-heated water tank into electricity for the system. IPC code H was found 32 times. Finally, Class E – "Fixed Constructions" with patent such as CN204343483U (Liu and Luo, 2015) and KR20140146692A (Park, 2014) that modifies the structure of a residential building to integrate an air conditioning system by making a hollow wall with a cooling semiconductor device inside facing aluminum plates both indoor and outdoor like the first patent or integrating a thermoelectric module on a window frame like the second patent. A – "Human Necessities" tied in fourth place with Class E, each with 12 occurrences, this class was the focus of patents like CN103750587A (Dai *et al*., 2014) that suggest a helmet with a refrigerating capability for workers on open fields. These data are illustrated in Figure 6.

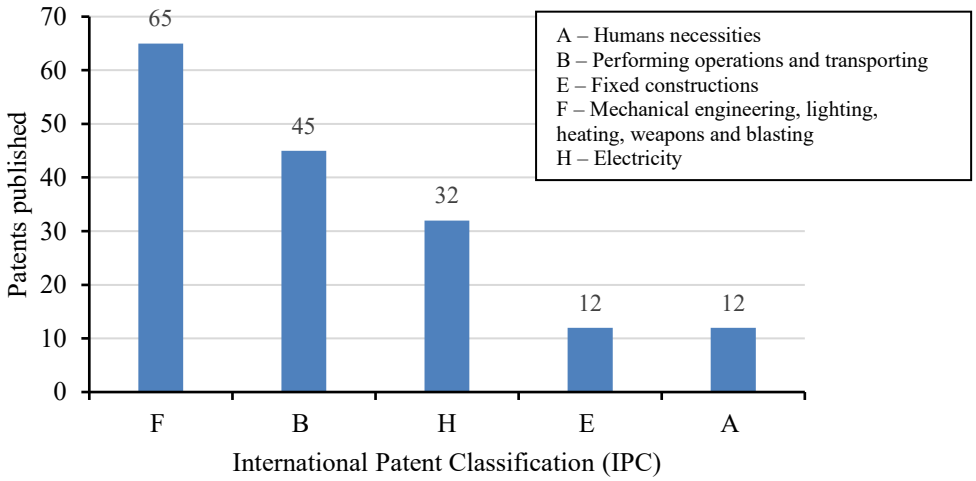

Figure 6. Patents published by IPC

Regarding the subclassifications of the macro areas, it was noted that the code F24F – "Air-conditioning; Air humidification; Ventilation and use of air currents for filtration" had the highest number of occurrences, with a total of 45. Closely following was subclass B60H – "Arrangements or adaptations of heating, cooling, ventilating, or other air-treatment devices specially adapted for passenger or goods spaces in vehicles" with 43 occurrences. In third place was code F25B – "Refrigeration machines, plants or systems; Combined heating and refrigeration systems; Heat pump systems" appearing 32 times. With a significant drop in frequency, the code that ranked fourth was H02S – "Generation of electric power by conversion of infrared radiation, visible light, or ultraviolet light", for example, using photovoltaic modules which appeared only 11 times. In fifth place, two subclasses tied with 10 occurrences each: H01L – "Semiconductor devices not covered by class H10", and H02J – "Circuit arrangements or systems for the supply or distribution of electric power; Systems for storing electric energy". In total, 37 different subclassifications were identified; however, only the 11 most frequent ones were illustrated in Figure 7. It is worth noting that the definitions of the IPC codes and their subclassifications mentioned and/or illustrated can be found in Table 1.

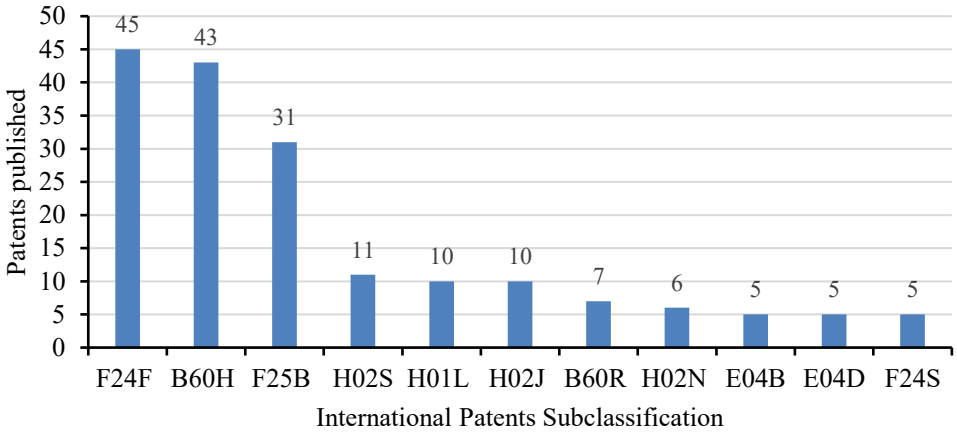

Figure 7. Most repeated patent subclassifications

Table 1. Classes and subclasses found in the studied patents according to the international patent classification (IPC)

IPC Classes		IPC Subclasses	
A	**Human necessities**	A01G	Horticulture; Cultivation of vegetables, flowers, rice, fruit, vines, hops or seaweed; forestry; watering
		A42B	Hats; Head coverings
B	**Performing operations; Transporting**	B60H	Arrangements of heating, cooling, ventilating or other air-treating devices specially adapted for passenger or goods spaces of vehicles
		B60R	Vehicles, Vehicle Fittings, Or Vehicle Parts, Not Otherwise Provided For
E	**Fixed constructions**	E04B	General building constructions; Walls, e.g. partitions; Roofs; Floors; Ceilings; Insulation or other protection of buildings
		E04D	Roof coverings; Skylights; Gutters; Roof-working tools
F	**Mechanical engineering; Lighting; Heating; Weapons; Blasting**	F24F	Air-conditioning; Air-humidification; Ventilation; Use of air currents for screening
		F25B	Refrigeration machines, Plants or systems; Combined heating and refrigeration systems; Heat pump systems
H	**Electricity**	H01L	Semiconductor devices not covered by class H10
		H02J	Circuit arrangements or systems for supplying or distributing electric power; Systems for storing electric energy
		H02N	Electric machines not otherwise provided for
		H02S	Generation of electric power by conversion of infrared radiation, visible light or ultraviolet light

3.5 FREQUENCY OF PATENTS BY TYPE OF REFRIGERATED ENVIRONMENT

In the process of patent development, inventors usually conceptualize the system with a specific environment intended for conditioning. An analysis of these targeted environments is illustrated in Figure 8. Upon analyzing the documents, it was noted that the type of environment with the highest number of cooling systems was the interior of vehicles, totaling 45 systems. Some patents aim to prevent the heating of a vehicle's interior when parked under the sun with the engine off, as in patent CN204472487U (Liao, 2015), or, in more specific cases, to save electrical energy in electric vehicles by using a thermoelectric system with solar energy conversion, such as in patent CN203974472U (Yang *et al*., 2014). Next are residential environments, with a total of 34 dedicated systems. An interesting example is the system JPH0510543A (Kikuchi, 1993), which includes a thermal storage component responsible for gradually absorbing heat. Farther behind, but in third place with 8 systems, are patents aimed at providing personal climate control, i.e., for individual use only, such as CN204245776U (Tang, 2015), which presents a thermoelectrically cooled sleeping bag, and CN217826888U (Sun *et al*., 2022), which proposes a cooling hat for hot days Also in third place, with 8 cases, under the category named "others," are all patents for environments that appeared at most three times, such as patent CN221258985U (Zhang *et al*., 2024), which shows a system to cool the interior of military tents used during army expeditions in remote locations. Tied for fourth place, with 5 occurrences each, are multi-environment patents, those suggesting systems capable of being easily adapted to more than one type of environment, such as system

KR20100100350A (Joo, 2010), which suggests conditioning the interiors of vehicles or greenhouses, and outdoor climate control systems like CN101435611A (Yan *et al*., 2009), which presents a parasol capable of cooling users seated around it. Lastly, in fifth place, with 4 occurrences, are patents that did not specify a particular environment for conditioning.

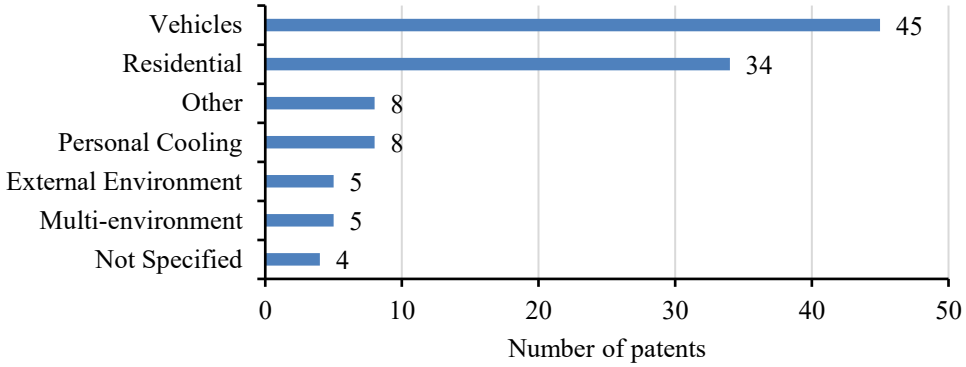

Figure 8. Frequency of patents by type of refrigerated environment

Based on the documents analyzed, it is evident that it is possible to design thermoelectric cooling systems powered by solar energy. Furthermore, it is noticeable that most patents aimed to provide greater comfort to users in a direct manner, whether by cooling environments such as vehicle interiors and residences or through wearable items like hats. Only a few patents pursued goals other than human comfort, such as system JP2002115926A (Hayashi *et al*., 2002), in which thermoelectric modules are used to cool the condenser of a refrigeration system in an aircraft in order to improve the efficiency of air conditioning within the vehicle. Systems like this, which aim to cool a working fluid, appeared only three times. Thus, it becomes clear that even with the annual growth in patent filings, there are still specific areas where thermoelectric cooling powered by solar energy is not widely utilized. This is the case in fields such as cooling of central processing units (CPUs) and laser sensors, for which no patents were found using the query applied in this study.

4. CONCLUSION

Despite the limitations of thermoelectric cooling systems, such as their low COP, the study conducted on Espacenet shows that there is significant interest in the technological advancement of solar-powered thermoelectric cooling systems, particularly from independent inventors, as a sustainable alternative to traditional cooling methods since they do not require refrigerants or compressors. It was noted that there is a trend toward applying this type of system on smaller scales, such as in vehicle interiors and residences. Over the years, the number of filed patents has increased, with China being the leading country in total developed patents. However, this research did not retrieve any documents originating from Brazil.

Moreover, the number of patents meeting the study criteria may be higher than what was found, since the subjective process of manual filtering and the restriction to a single database may have restricted the number of systems identified. In the future, it is possible to deepen the presented study by replicating the same methodology in different patent databases or by conducting technological prospection on other themes, such as electrical power generation with thermoelectric devices. Overall, the findings from this study provide a basis for guiding future research and investments in areas with a low number of patents, highlighting opportunities for innovation.

5. ACKNOWLEDGEMENTS

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