

Refrigeración solar de edificaciones. Un estado del arte

Solar cooling in buildings. A state of the art

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Abstract

Context: The use of solar energy, rather than an alternative, is the viable solution to the energy demands of our planet for sustainable development. Given the population increase and the quality of life at a global scale, it is very reasonable to forecast an increase in global energy demand. In this context, solar cooling systems are a viable and timely strategy to follow.

Methods: This work offers a state of the art on the different methods of obtaining solar cold. The review is generated by using the tools offered by the Scopus directory and using the VOSviewer bibliometric analysis software.

Results: Solar thermal cooling in buildings is shown as a trend within these energy practices, followed by photovoltaic solar cooling. Today, the United States of America, Italy, and China are the nations that lead this field. The most fertile research areas in this subject matter are engineering, energy and materials science.

Conclusions: The next few years will be decisive for the development of solar cooling technologies since they depend on the incentives and promotion plans offered by those responsible for formulating environmental and energy efficiency policies for buildings.

Keywords: Renewable energy source, photovoltaic solar cooling, thermoelectric solar cooling, thermo-mechanical solar cooling, solar thermal cooling

Resumen

Contexto: La utilización de la energía solar, más que una alternativa, es la solución viable a las exigencias energéticas de nuestro planeta de cara al desarrollo sostenible. Dado el incremento poblacional, y calidad de vida a escala global, es muy razonable pronosticar un aumento en la demanda energética mundial. En este contexto los sistemas de refrigeración o climatización solar se muestran como una viable y oportuna estrategia a seguir.

Métodos: Este trabajo ofrece un estado del arte sobre los diferentes métodos de obtención de frío solar. La revisión se genera utilizando las herramientas que ofrece el directorio Scopus y empleando el software de análisis bibliométrica VOSviewer.

Resultados: La refrigeración solar térmica de edificaciones se muestra como una tendencia dentro de estas prácticas energéticas, seguida por la refrigeración solar fotovoltaica. Estados Unidos de América, Italia y China son las naciones que hoy lideran este campo. Las áreas de investigación más fértiles en esta temática son la ingeniería, la energética y la ciencia de materiales.

Conclusiones: Los próximos años serán decisivos para el desarrollo de tecnologías de refrigeración solar, pues dependen del estímulo y planes de promoción ofrecido por los encargados de formular las políticas ambientales y de eficiencia energética para edificios.

Palabras clave: Fuente de energía renovable, Refrigeración solar fotovoltaicos, Refrigeración solar termoeléctrica, Refrigeración solar termo-mecánica, Refrigeración solar térmica

1. Introduction

The global warming occurs when carbon dioxide, caused mainly by the burning of fossil fuels (oil, natural gas, and coal) and other gasses, such as methane and nitrous oxide, is accumulated in the lower atmosphere (Gibon et al., 2017; H. Sun et al., 2018; Worsoe-Schmidt, 1980).

Chlorofluorocarbons (CFC) and hydrochlorofluorocarbons (HCFC), which are widely used in cooling and heating, are gasses that have a strong negative impact on the ozone layer. As a result of the rapid growth of the global population, the total consumption of energy and heating and cooling has increased. It is expected that the polluting emissions to the environment increase by 71 % from 2003 to 2030 (Antoci et al., 2018; Hwang et al., 2008).

The main consumption of electric power in non-industrial buildings is associated with cooling and heating of spaces. This consumption can range from 40% to 60%, depending on the geographical position of the installation, its structure and its purpose (Ahmadzadehtalatapeh, 2018; Jing et al., 2018). Hence, the use of solar energy in cooling installations is an alternative to conventional cold generation techniques. An alternative that contributes to alleviating environmental pollution problems and decreasing the demand for electric power associated with the benefits of artificial heating and cooling. In addition, the advantage is that the peak hours of operation of the buildings generally match the hours of sunlight availability (Bravo Hidalgo, 2015b; Valladares-Rendón et al., 2017).

The weather conditions in the Central American and the Caribbean region, with an average temperature of 26°C and sustained temperatures over long periods of time during the summer above 32°C, require the use of air conditioning

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systems to meet the thermal control conditions (Lara et al., 2015).

Solar heating and cooling stand out as a timely and feasible solution to the global environmental and energy situation, for the following reasons: it represents significant savings in primary energy consumption and a reduction of CO₂ emissions. Solar heating and cooling do not work with environmentally hazardous refrigerants, such as chlorofluorocarbons (CFC) and hydrochlorofluorocarbons (HCFC). Noises and vibrations are reduced compared to the mechanical refrigerant vapor compression technologies (Díaz Torres et al., 2015; Nkwetta & Sandercock, 2016).

This research shows an analysis of the most researched solar-powered cooling technologies and the future trends. Therefore, it is based on a literature review of the most cited documents in this area of knowledge.

2. Materials and methods

The paper is focused on literature research on solar powered cooling technologies. It is developed by using the tools offered by the Scopus directory since this directory represents many journals of greater impact and visibility that project the results in research and advances in this type of energy practice. Furthermore, the VOSviewer analysis and bibliometric mapping tool is used. This software was used for:

- a) Creating maps based on network data.
- b) Visualizing and exploring maps.

The data collected from the Scopus academic directory were exported as CSV files, in order to be processed in the aforementioned bibliometric analysis tool.

The exploration analyzes works from 2013 to February 16, 2018, under the search criterion of solar cooling in buildings, which was applied to the title, the abstract and the keywords of the contributions. The search showed a total of 1,873 related articles and 18,069 registered patents in the aforementioned period. From this search, the contributions with a higher Hirsch index (H Index) were selected. These specifically referred to the solar cooling technologies, such as photovoltaic solar cooling systems, thermoelectric solar cooling, thermo-mechanical solar cooling, and solar thermal cooling techniques.

3. Results

Research related to solar cooling in buildings showed a strong growth in recent decades. As shown in Figure 1, the trend curve displayed presents growth since the engineers and researchers see in the solar cooling technology a fertile way to reach the conditions of thermal comfort in indoor areas through the use of clean and abundant energy. It is important to mention that in order to obtain this chart, a period from 1995 to 2017 was considered. The aforementioned search criterion was used as well as the other conditions mentioned in the Methods section of this study.

So far, the research areas showing more results in this subject area are engineering and energy. As shown in figure 2, this is a consequence of the strong presence of solar-powered heating and cooling technologies in industrial, residential and commercial buildings. The areas of research shown in this chart were detected in the Scopus directory and under the search criteria and conditions set out in the Methods section.

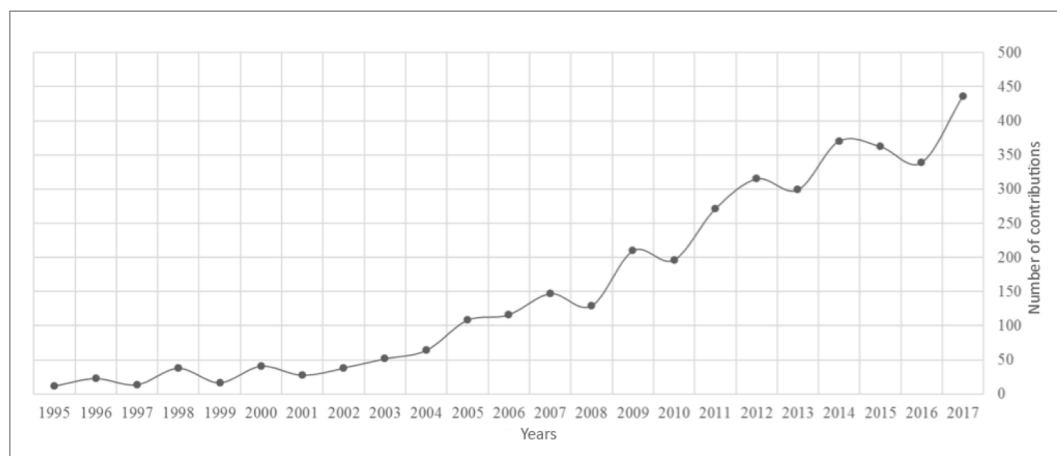


Figure 1. Behavior of the number of investigations related to solar cooling in buildings in recent decades

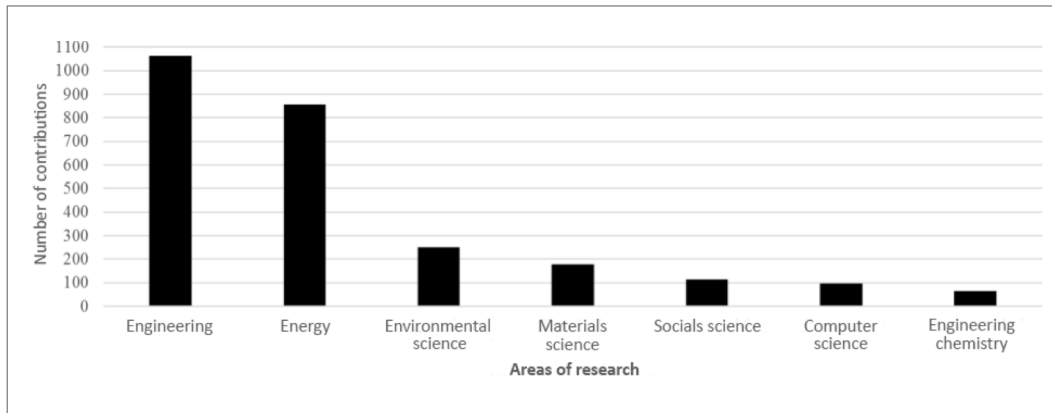


Figure 2. Number of contributions as per areas of research in solar cooling in buildings

The author with more contributions in this subject area is Anna Laura Pisello, professor of University of Perugia, Italy, with a total of 25 works in journals registered in the scientific directory under analysis.

The last state of the art article written with regard to this subject was (Kim & Infante Ferreira, 2008), which aims at a review of the state of the art of the different technologies available in that moment to provide cooling from solar energy. The main results of this research highlight that the photovoltaic and thermo-mechanical systems are more expensive than the absorption and adsorption systems. Likewise, these last two are comparable in terms of performance, but the adsorption coolers are more expensive and larger than absorption coolers.

Research on solar cooling in buildings in the directory under analysis is led by a group of authors who are related as

shown in figure 3. This figure was generated through the VOSviewer software. There is evidence of the existence of two focal points. To the left of the chart, there are a greater number of authors mainly from Asian countries, while to the right of the chart the relationship between authors mostly from Europe and the United States of America is shown. It can be seen that there is little connection between these research groups and the widespread interest among the different Asian authors in this subject matter.

Figure 4 was generated through the VOSviewer software. This figure shows the relationship between the nations with more findings presented in investigations on the subject matter. The United States, Italy, and China are the leading nations. Noticeably, the world economic powers see in solar cooling in buildings an effective, safe and practical alternative.

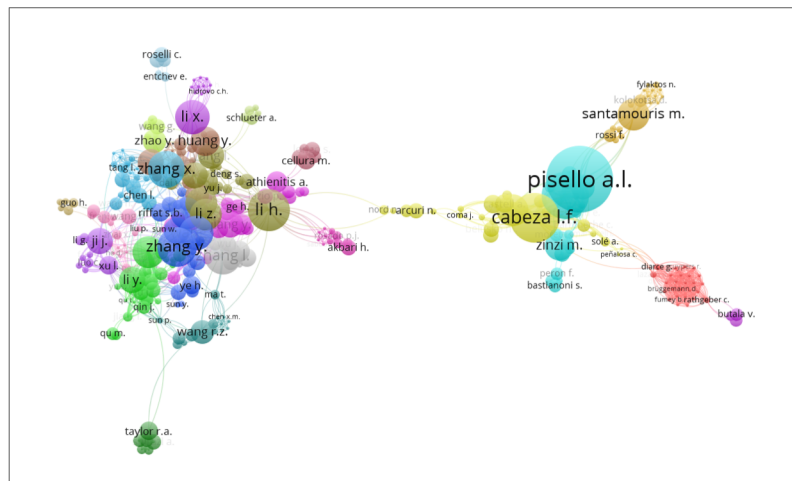


Figure 3. Correlation network among the authors with the greatest impact on the research of solar-powered cooling for buildings



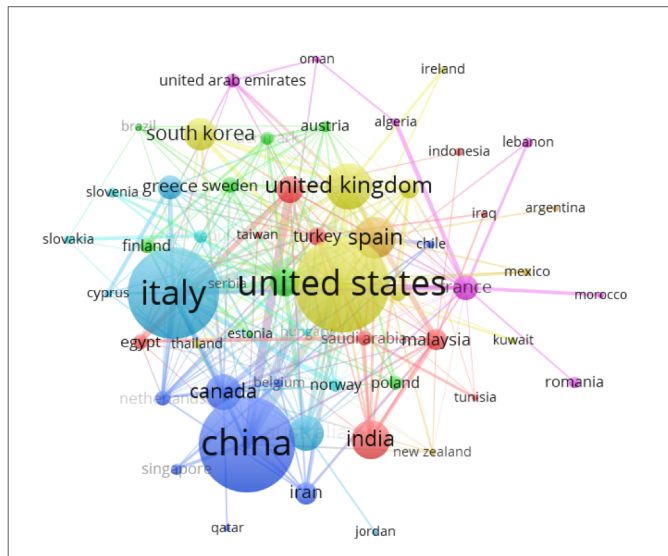


Figure 4. Nationwide research interaction network of solar cooling in buildings

Figure 5 was obtained through the aforementioned software. This figure shows a map of terms related to the field of solar powered cooling in buildings. The colors show the density of the terms that delimit the investigations on solar cooling in buildings. They go from blue (the lowest density)

to red (the highest density). The bottom right side of the chart shows that the term building envelope, thermal performance, and thermal comfort represent a group of terms strongly related to the investigations in the field of solar cooling in buildings.

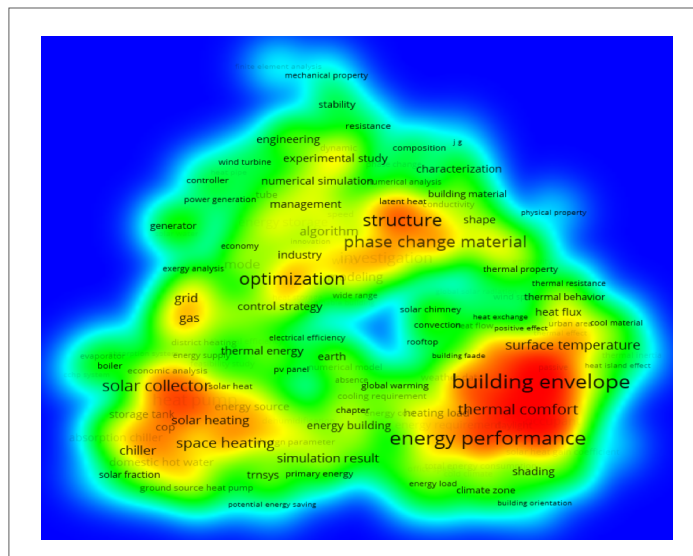


Figure 5. Map of terms in the field of active solar cooling in buildings

Table 1 shows a summary of the most cited investigations by solar-powered cooling technologies. This table shows the general objectives of these investigations and

their main findings, as well as their number of quotations and their H index.

Table 1. Summary of the most cited investigations as per cooling technologies

Solar powered cooling technologies	Title	Author/s	Year	Published in:	Type of publication	H Index	Number of quotations	Objective	Bibliographic reference
Photovoltaic solar cooling	<i>A review on photovoltaic / thermal hybrid solar technology</i>	T.T. Chow	2010	<i>Applied Energy</i>	Article	685	460	<i>This article shows a state of the art of thermal photovoltaic technologies from the 1970's to the first decade of the 21st Century.</i>	<i>(Chow, 2010)</i>
	<i>A review of solar photovoltaic technologies</i>	Bhubaneswari Parida S. Iniyank Ranko Goic	2011	<i>Renewable and Sustainable Energy Reviews</i>	Article	620	394	<i>This article reviews the photovoltaic technology, its power generation capacity, the different light absorbing materials used, its environmental aspect and a variety of applications.</i>	<i>(Parida, Iniyank, & Goic, 2011)</i>
	<i>Hybrid photovoltaic /thermal solar systems</i>	Y. Tripanagnostopoulos Th. Nousia M. Souliotis P. Yianoulis	2002	<i>Solar Energy</i>	Article	417	306	<i>This article presents the results of the tests in hybrid solar systems, composed of photovoltaic modules and thermal collectors (hybrid systems PV/T).</i>	<i>(Tripanagnostopoulos, Nousia, Souliotis, & Yianoulis, 2002)</i>
	<i>Cooling, heating, generating power, and recovering waste heat with thermoelectric systems</i>	Lon E. Bell	2008	<i>Science</i>	Article	1917	1456	<i>The thermoelectric materials are solid-state power converters whose combination of thermal, electrical, and semiconductor properties allows them to be used to convert residual heat into electricity or electric power directly into cooling and heating. These principles are illustrated by several proven</i>	<i>(Bell, 2008)</i>



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Thermoelectric solar cooling	<i>Thermoelectrics: a review of present and potential applications</i>	<i>S.B Riffat Xiaoli Ma</i>	2003	<i>Applied Thermal Engineering</i>	Article	872	536	<i>and potential applications and thermoelectrics. The thermoelectric devices are solid-state devices. They are reliable power converters and do not make noise or vibrate since there are no mechanical moving parts. In this work, the basic knowledge of thermoelectric devices is given, as well as a general overview of these applications. The perspectives of the applications of thermoelectric devices are also discussed.</i>	<i>(Riffat & Ma, 2003)</i>
	<i>Development and applications of solar-based thermoelectric technologies</i>	<i>Hongxia Xi Lingai Luo Gilles Fraise</i>	2007	<i>Renewable and Sustainable Energy Reviews</i>	Article	172	104	<i>This work presents a study of solar powered thermoelectric technologies and their applications. Typical applications of thermoelectric cooling and the scope of other applications. The areas of application described in this document show that the solar-powered thermoelectric technologies could be used in a wide variety of fields.</i>	<i>(Xi, Luo, & Fraise, 2007)</i>

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Thermo-mechanical solar cooling	<i>Solar refrigeration options – a state-of-the-art review</i>	<i>Kim, D. S. Infante Ferreira, C. A.</i>	2008	<i>International Journal of Refrigeration</i>	Article	381	224	<i>A review of the state of the art of the different technologies available to provide cooling from solar energy is presented. This review covers solar electric and solar thermal power and some new emerging technologies. Solar thermal systems include thermo-mechanical, absorption, adsorption and desiccant solutions. A comparison is made among the different solutions both from the point of view of energy efficiency and economic viability.</i>	<i>(Kim & Infante Ferreira, 2008)</i>
Solar thermal cooling	<i>Solar thermal collectors and applications</i>	<i>Soteris A. Kalogirou</i>	2004	<i>Progress in Energy and Combustion Science</i>	Article	1676	974	<i>This article presents a study of the different types of solar thermal collectors and their applications. Initially, an analysis of environmental problems related to the use of conventional energy sources is presented and then the benefits of renewable energy systems are described.</i>	<i>(Kalogirou, 2004)</i>



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Solar thermal cooling	<i>A review of solar collectors and thermal energy storage in solar thermal applications</i>	Y. Tian C.Y. Zhao	2013	<i>Applied Energy</i>	Artículo	380	264	<i>This article focuses on the latest developments and advances in applications of solar thermal energy, providing a review of solar collectors and thermal energy storage systems.</i>	(Tian & Zhao, 2013)
	<i>Perspectives of solar cooling in view of the developments in the air-conditioning sector</i>	A.M. Papadopoulos S. Oxizidis N. Kyriakis	2003	<i>Renewable and Sustainable Energy Reviews</i>	Artículo	112	25	<i>The analysis discussed in this article is focused on the state of the art of the use of solar thermal systems and in the possibility of combining them with cutting-edge technologies in sorption cooling to meet the cooling demand of residential and commercial buildings.</i>	(Papadopoulos, Oxizidis, & Kyriakis, 2003)
	<i>Review on sorption materials and technologies for heat pumps and thermal energy storage</i>	Cabeza, L. F. Solé, A. Barreneche, C.	2016	<i>Renewable Energy</i>	Artículo	2	1	<i>Adsorption and absorption cooling systems, as well as their integration with thermal storage systems, are the topics covered in this review. This is the first review in which research on both applications is shown together.</i>	(Cabeza, Solé, & Barreneche, 2016)

Considering the dependence of solar energy production on time and weather conditions, the successful use of all these cooling systems depends to a large extent on the capacity on the accumulation system or energy storage used (Bravo Hidalgo et al., 2017). Table 2 shows the different technologies of the solar heating or cooling with energy storage (Chidambaram et al., 2011).

In comparison with conventional systems of mechanical refrigerant vapor compression, an important saving of electrical power can be expected from solar cooling systems. Thus, the energy demand for heating and cooling is lower. Therefore, the ecological footprint of these processes is reduced (Bravo Hidalgo, 2015a).

Solar cooling can be achieved through four basic methods: photovoltaic solar cooling, thermoelectric solar cooling, thermo-mechanical solar cooling, and solar thermal cooling. The first method consists in a solar energy collection system using photovoltaic panels, in which solar energy is converted into electric power which is used to run the electric motors of the systems of mechanical refrigerant vapor compression (Chen et al., 2017; Florides et al., 2002). The second method consists of the cold production through

thermoelectric processes (Zhao & Tan, 2014). The third method is comprised of a system where the thermal energy is converted into mechanical energy. Then, the mechanical energy is used to produce the cooling effect (Papadopoulos et al., 2003). The fourth method consists in the activation of a thermal compression system, where a solar collector directly heats a working fluid running the generator of an absorption machine, thus causing the refrigerant effect (Díaz Torres et al., 2015; Z. Sun et al., 2017; Thirugnanasambandam et al., 2010). The performance of cooling systems is determined based on the energy indicators of these systems. The coefficient of performance (COP) can be calculated as follows as expressed in the equation (1) (Arora, 2010):

$$COP = E_u/E_c \quad (1)$$

Where:

E_u is the cooling effect obtained, E_c is the energy consumed by the system to achieve such an effect.

Table 2. Solar cooling systems

Power supply source	Power Conversion	Heat storage system (hot fluid)	Operation principle of the cooling machine	Thermal storage system (cold fluid)	Application
Solar power	*Photovoltaic solar power		<ul style="list-style-type: none"> Mechanical refrigerant vapor compression Thermoelectric 		<ul style="list-style-type: none"> Air conditioning in: <ol style="list-style-type: none"> Hotels Buildings Offices Industrial Processes: <ol style="list-style-type: none"> Pharmaceuticals Chemistry Dairy Cold storage plants: <ol style="list-style-type: none"> Meat and fish Fruit and vegetables
	Solar thermal power <ul style="list-style-type: none"> Flat plate collectors Tubular collectors Parabolic collectors 	<ul style="list-style-type: none"> Sensible heat Latent heat Thermochemistry 	<ul style="list-style-type: none"> Ejector Desiccant Absorption: <ol style="list-style-type: none"> Single acting Dual acting 	<ul style="list-style-type: none"> Sensible heat Latent heat Thermochemistry 	

*Note: The use of photovoltaic solar energy in air conditioning handles energy storage technologies through different types of alternating current batteries. These vary in shape, size and composition material according to the storage capacity for which they are designed.

4. Contributions in the different solar powered zcooling technologies

Figure 6 shows the behavior of the contributions of each of these solar powered cooling technologies in the Scopus directory. There is a noticeable trend towards the increase in research related to solar thermal cooling in the

last decade, followed by a modest takeoff in the research of photovoltaic solar cooling. The most recurrent topics treated in the different solar powered cooling technologies are modeling and efficiency optimization, investigations on working fluids and optimization of operating costs (Fan et al., 2007; Haller et al., 2012).



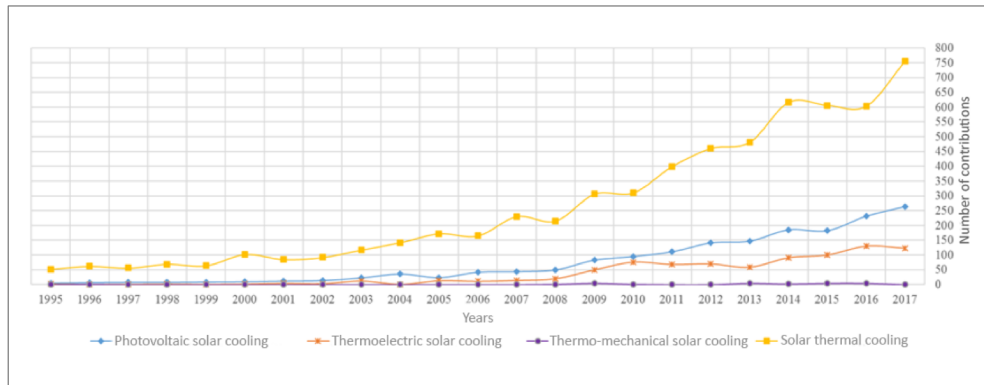


Figure 6. Number of publications as per different solar powered cooling technologies

5. Discussion

Although these solar cooling technologies are considered mature, they have a discreet representation at a global level. This is due to a group of barriers or limitations that have slowed down, and are holding back, the establishment of these technologies in the market of cooling of spaces. The main limitations are described as follows:

- Currently, solar-powered cooling systems are more expensive if we compare them with the prices of conventional chillers. This condition is more pronounced in the case of low power chillers, commonly used in houses and small shopping centers.
- The use of solar thermal powered chillers generally requires cooling towers. These items are subject to specific legislation in order to prevent the possibility of dangerous *Legionella* bacteria from emerging in the ducts. Apart from that, the maintenance of the cooling towers is relatively expensive.
- Currently, the existing market for machines with low cooling capacities is very limited (Ajib, 2010).
- Tax reduction and other financial incentives for the development of solar cooling are limited and insufficient to promote this technology.
- A guide for solar-powered cooling systems is necessary at the government level. These installations are often forgotten in the financial incentive schemes not only for producers but also for consumers. The financial incentives must be aimed at mitigating the high initial costs of this type of investments (Bravo Hidalgo, 2015a; Mokheimer et al., 2017).

Despite the fact that adopting solar technology is recognized as a realistic response to the energy and environmental problems calling the attention of engineers and architects, the economic assessments are often unfavorable. The critical factors that will ensure the extension of solar cooling systems are the technological maturity and the improvement of their economic viability.

Despite the fact that adopting solar technology is recognized as a realistic response to the energy and environmental problems calling the attention of engineers and architects, the economic assessments are often unfavorable. The critical factors that will ensure the extension of solar cooling systems are the technological maturity and the improvement of their economic viability.

The economic analyses of the solar cooling systems show that these systems will not be competitive compared to the conventional cooling systems taking into account the current price of electricity.

There are 156,325 more licenses related to conventional cooling than those related to solar cooling. There is an urgent need of incentives for the investment and the setting of taxes that reflect the total environmental cost of conventional fuels in order to overcome the constraints to the development of sun-powered cooling technology. The works of (Boopathi Raja & Shanmugam, 2012; Dickinson et al., 2010; Testi et al., 2016) highlight the costs of implementing and using this type of technologies, even making comparisons between them.

With regard to the future direction of solar cooling development, a focus on low-temperature sorption systems will be convenient. This is because, first of all, the cost of a solar collector system tends to increase faster with working temperature than the Coefficient of Operation (COP) of a sorption machine. And secondly, high-temperature chillers will not be compatible with the solar collection systems originally designed to produce domestic hot water that are very common in houses, schools, shopping centers, etc. Figure 8 of the publication of (Kim & Infante Ferreira, 2008; Linjawi et al., 2017) sets costs according to operating powers and activation temperatures of these thermal machines that support the above.

Solar cooling systems can be used either as stand-alone systems or with systems integrated with conventional techniques for obtaining cold in order to improve the indoor air quality of several types of buildings. Along with the photovoltaic systems, solar thermal powered cooling systems are increasingly being used in various regions, with a trend towards an increase in these practices. (Hashe, 2017; van Straaten, 1977; Worsoe-Schmidt, 1980).

Finally, it is important to mention that the solar cooling systems are more environmentally friendly both in the production period and in the operation period than the conventional cooling systems because of the use of unpolluted working fluids, such as lithium bromide, water and ammonia instead of chlorofluorocarbons (Toppi et al., 2016; Weber et al., 2014).

6. Conclusions

The final considerations of the investigation put forward conclusively are detailed as follows:

- a) The investigations related to solar cooling present a growing trend since the engineers and researchers see in the solar cooling technology a fertile path to achieving the thermal comfort conditions in interior spaces, through the use of clean and abundant energy.
- b) The majority of the investigations on solar cooling are focused on the engineering, energy, and materials science of these processes.
- c) The future energy practices are aimed at solar thermal cooling technologies. This condition is given by the thermal storage potential of this practice.
- d) Researchers of the United States of America, Italia, and China lead these investigations. The investigations in Europe and America are concentrated on productive research, but there are not so many researchers. In China, research in solar cooling in buildings is a topic addressed by a large number of authors.
- e) Building envelope, thermal performance and thermal comfort represent a group of strongly related terms or more likely to occur in the investigations in the field of solar cooling in buildings.
- f) The next few years will be decisive for the success and the development of better technologies in solar cooling systems, which depend on the incentives and promotion plans provided by the people in charge of formulating environmental and energy efficiency policies.
- g) Research in thermo-mechanical cooling for heating and cooling of buildings is an area with very few works. Materials science and control and thermal efficiency of the process are research opportunities in this type of cooling in buildings.

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