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Review

Investigation of the thermoelectric potential for heating, cooling and ventilation in buildings: Characterization options and applications

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A B S T R A C T

Researchers have spent decades exploring strategies for reducing energy consumption in buildings worldwide, proposing passive solutions and optimizing active systems. However, no breakthrough technology has been developed. The use of thermoelectricity in buildings for heating, cooling and ventilation has been proposed as an alternative solution to many systems anchored in our day-to-day. This paper seeks to classify, analyze and summarize the possibilities of the thermoelectric technology integration in buildings. The results obtained from the search were divided into two main groups: systems that are integrated in the building envelope and non-integrated systems that operate independently. Among the analyzed parameters, on the one hand the characteristics of the prototypes' components needed for the construction were described. On the other, the thermoelectric specific parameters required for optimization under the operating scenarios' conditions were studied. The results of most of the studies showed that even though the technology can provide the comfort conditions, still the performance of these systems is not competitive compared to conventional vapor compression systems. However, the advantages of thermoelectricity such us the non-use of refrigerants or the high durability, makes this technology an alternative solution to consider, of which interest is growing in line with recent studies.

Contents

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Abbreviations

ATI	Active Thermal Insulator
ABE	Active Building Envelope
ASTRW	Active Solar Thermoelectric Radiant Wall
BITE	Building Integrated Thermoelectric
BIPV	Building Integrated Photovoltaics
BIPVTE	Building Integrated Photovoltaic Thermoelectric
CCP	Ceiling Cooling Panel
COP	Coefficient of Performance
CTE	Código Técnico de la Edificación/Spanish Technical Building Code
ESMVS	Exhaust/Supply Mechanical Ventilation System
HVAC	Heating Ventilation and Air Conditioning
IEA	International Energy Agency
PCM	Phase Change Materials
PV	Photovoltaic
STACHWS	Solar Thermoelectric Air Conditioner with Hot Water Supply
STCC	Solar Thermoelectric Cooled Ceiling
TE	Thermoelectric
TE-AD	Thermoelectric Air Duct
TEG	Thermoelectric Generator
TEM	Thermoelectric Modules
TE-RCP	Thermoelectric Radiant Ceiling Panel System
TERP	Thermoelectric Radiant Panel System
TCHU	Thermoelectric Cooling and Heating Unit

1. Introduction

It is well known that buildings are responsible for the 40% of the total energy consumption according to the United Nations Environmental Program. Thus, the concern around energy usage in buildings had been under focus in the last decades and it is expected to keep this way in the future. Besides, being fossil fuels still the world's most used energy sources, alternatives to their usage are among the main policies.

In this context, applying thermoelectricity in buildings emerges as a significant alternative for indoor thermal comfort requirements. The thermoelectric (TE) effect is the conversion of temperature differences into an electrical voltage (Seebeck effect) or the opposite, temperature difference generation when an electrical current is applied (Peltier effect). The Peltier effect is produced when an electrical current flows through a junction between two different types of semiconducting materials. The electrical current initiates a heat transfer from one union to the other: while one union is getting cooler the other starts to heat up. Changing of the applied current direction results in changing of the heat transfer direction, hence Peltier cells can be used as heat pumps.

Many applications utilizing the Seebeck effect are applied in the industry, automobile and aerospace fields mainly, while using waste heat to generate electricity. The Peltier effect is also being used mostly for cooling purposes of small microelectronic devices, but also for space probes, solar power, military clothing, etc. However, these applications are always focused in small scale devices. Thus, the use of thermoelectricity in buildings' energy systems is a barely developed area, yet with a remarkable potential.

There are several advantages that thermoelectric modules (TEM) bring to buildings. These modules have a long operative life without affecting the performance [1]. This high reliability leads to low maintenance requirements, which is an important part of the life cost of a building. The versatility of the modules makes possible to have both heating and cooling in the same device. Besides, the physical characteristics of the modules ease the design of a decentralized system, reducing the space occupied by conventional HVAC systems, as shown in Fig. 1. The modules work with direct current, which simplifies the connection to photovoltaic cells offering the possibility to work off the grid with a renewable source. The TEMs allow an excellent temperature precision, which assures very accurate thermal comfort conditions.

Furthermore, the main advantage is the non-use of working fluids, such as refrigerants, for heating and cooling of buildings, as opposed to conventional vapor compression refrigeration systems. The concern about the use of refrigerants is increasing day by day [2,3] due to their negative impact on the environment. Some researches analyze and compare the adverse effects of different refrigerants [4,5] in order to raise awareness of the problem. Other efforts are focused on finding natural alternatives [6], such as, water [7–9] and carbon dioxide [10,11]. Thermoelectricity can also be a possible solution to this major problem.

This paper seeks to classify, analyze and summarize the state of the art of the TE technology integration in buildings. Specifically, the last decade studies dealing with applying the Peltier effect in buildings are gathered. Even though the number of studies related

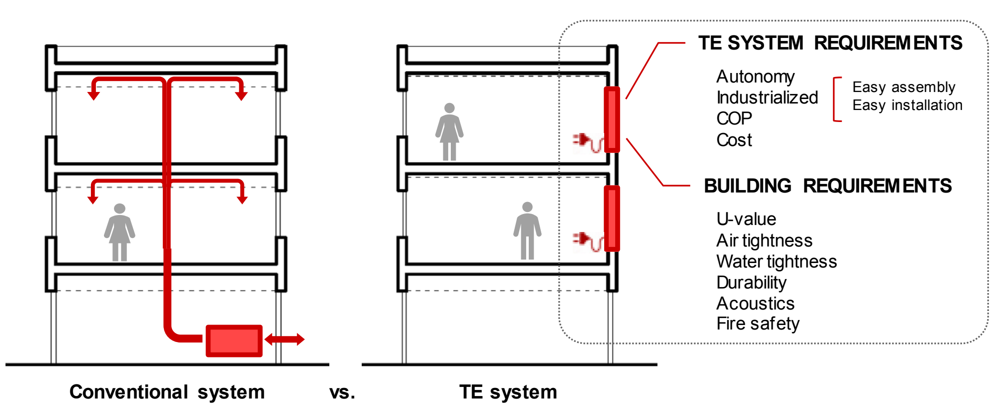

Fig. 1. Concept vision of conventional HVAC system solution (left) vs. TE solution (right). The requirements that a TE system integrated in a building must fulfill come from both disciplines, thermoelectricity and buildings.

with the use of thermoelectricity in buildings is increasing, still the performance of these systems is not competitive compared to conventional vapor compression systems. The coefficient of performance (COP) of conventional TE air conditioners is typically about 0.4 in the cooling mode and 1.4 in the heating mode [12]. The performance of TE systems depends on many operation parameters [13], such as the temperature of the TEM sides [14], thermal and electrical conductivities of the TE elements [15], thermal resistance of the heat sink [16] and the applied electrical current [17]. This paper analyses all of these parameters in most of the prototypes and investigated systems developed during the last ten years, including their relation with constructive solutions.

2. Method

All of the cited references in this review were found under certain search parameters and were analyzed and classified. The specified below classification criteria were developed by the authors and considered as necessary since so far, no systematic investigation analyzing the integration of thermoelectricity from an architectonical or construction perspective was reported.

2.1. Search queries: framework of search parameters

In order to gather the main research experiences within the scope of the study, two online journal databases were consulted: Web of Science (WoS) and Scopus. The search parameters used are shown in Table 1. Crossing the results from both databases, the initial total amount of results was 274. The query string for Scopus was "(TITLE-ABS(thermoelectric* OR peltier) AND TITLE-ABS-KEY(building* OR façade* OR envelope* OR indoor)AND TITLE-ABS-KEY(heat* OR cool* OR ventilation OR "air conditioning" OR hvac)) AND PUBYEAR > 2006 AND PUBYEAR < 2018" and for Web of Science "TS=(thermoelectric* OR peltier) AND TS=(building* OR envelope* OR façade* OR indoor) AND TS=(heat* OR cool* OR ventilation OR HVAC OR air conditioning)".

All of these publications were analyzed and filtered. Regarding the type of publications, conference reviews and notes were excluded. Regarding the topics of the researches, only the technologies involving the Peltier effect were selected, thereby eliminating studies about TE generators. Besides, the system had to be directly related with buildings, which leaves out of the scope TE coolers for photovoltaic cells or advances in TE materials to improve the performance of the TEMs, among others. A few studies about thermoelectricity in cement composites were also removed, since even though they are associated with construction, they are not directly related to building services. There were two applications about TE dehumidifiers that were eliminated from the classification [18,19], since the state of the researches was far from considering it as a technology to be integrated in buildings. This filter left a final sum of 72 publications.

2.2. Classification criteria

As the literature research showed (Fig. 2), the studies concerning thermoelectricity integration in buildings have been increased considerably in the last years, likewise, two main review papers were published referring to the TE technologies in buildings. The first one, reviewed the applications of solar TE cooling technologies for zero energy buildings and possible applications were discussed [20]. The other study analyzed four technologies based on thermoelectricity to be applied in buildings: two of them were based on Peltier effect (a radiant ceiling and a primary air handling unit), and the other two, were based on the Seebeck effect (a solar photovoltaic-TE generation hybrid system and a solar hot-water TE generation hybrid system) [21].

Since the previous investigations are limited either to cooling or to some limited specific technologies, the authors of this review deem necessary to gather, analyze and classify the thermoelectricity use in buildings in a more holistic view and from a building integration perspective. Thus, the classification of the studies made in the following sections is divided into two groups: integrated TE systems in the envelope of the building and non-integrated systems, which are independent of the building envelope. The second group also includes additional researches of TE in buildings in an early stage of the development or in the simulation phase. (see Tables 2–5)

Among the integrated systems, another classification is made following construction parameters. Then, the studies are divided into those related to windows, to walls and to roofs or ceilings. The diagram in Fig. 3 represents these classification criteria in a graphic representation. Besides, some tables are added to the study that gather, on one hand, the physical configuration of the prototypes analyzed in each investigation and, on the other hand, the TE characteristics of each research.

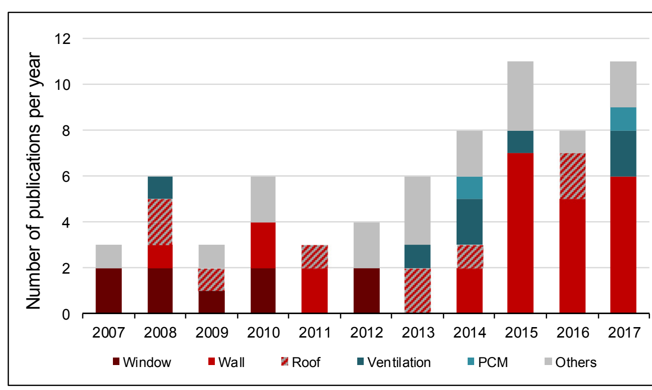

Fig. 2. Number of publications with the search queries over the last 10 years. The classification presents the same order as the structure of this paper.

Table 1
Search conditions.

Publication date >2006, <2017	Type of Search or Field	
Keywords	Scopus	WoS
thermoelectric* OR Peltier	Title/Abstract	Topic
AND		
building* OR façade* OR envelope* OR indoor	Title/Abstract/Keywords	Topic
AND		
cool* OR heat* OR ventilation OR "air conditioning" OR HVAC	Title/Abstract/Keywords	Topic
Matches found	**238**	**197**

Table 2
Physical characteristics of the prototypes of TE systems integrated in the building envelope (ordered by publication date).

	Ref	Heat sink		Ventilation		Heating	Cooling	PV system	Test environment and scale
		Indoor	Outdoor	Indoor	Outdoor				
Windows									
Xu et al.	[25] [26]	Aluminum tubes filled with water	Aluminum fins	Natural convection	Natural convection	X	X	X	Real outdoor conditions Small scale testing room
Van Dessel et al.	[28]	Glass	Glass	–	–	X	X	–	Lab test. Small scale prototype Validated model, parametric study
Harren-Lewis et al.	[29]	Aluminum fins	Aluminum fins	Natural convection	Natural convection	–	X	X	PV panel size window Validated model
Zhang et al.	[30]	Aluminum fins	Aluminum fins	Fans	Fans	X	X	–	Window size prototype Simulations
Walls									
Gillott et al.	[31]	Aluminum fins	Aluminum fins	Centrifugal fan	8 Fans (3 W)	–	X	X	Small room Lab environment tests
Martín-Gómez et al.	[40]	Aluminum fins	Heat pipes	Tangential fan	Axial fan	X	X	–	Room size Real conditions
Ibañez-Puy et al.	[42]	Aluminum fins	Aluminum fins	Tangential fan	Tangential fan and natural convection	X	X	–	Room 2.1 × 3.2 x 2.04 Real conditions
Irshad et al.	[43]	Aluminum fins	Aluminum fins	Axial fan	Axial fan	–	X	–	Room 2.8 m × 2.7 m x 2.5 m Real conditions (north façade)
Irshad et al.	[45]	Aluminum fins	Aluminum fins	Axial fan	Axial fan	–	X	X	9.45 m^3 Real conditions (north façade)
Liu et al.	[32]	Aluminum panel	Heat pipes	Natural convection	Fans	–	X	X	Room 3 × 3 × 3m Real conditions
Liu et al.	[36]	Aluminum fins	Water source	Fan	–	X	X	X	Lab environment test and validated model
Piantanida	[47]	Aluminum fins	Aluminum fins	Natural convection	Natural convection	–	X	X	Lab room 1m^3 Small scale system
Wang et al.	[46]	Aluminum fins	Aluminum fins	Tangential fan	Tangential fan	X	–	X	Real conditions 1m^3 Case study simulations Small scale
Roof and ceilings									
Lertsatitthanakorn et al.	[51]	Aluminum plate	Water	Fan	–	–	X	–	Lab conditions, controlled chamber Room 2.25m^2
Cheng et al.	[13]	Copper plate	Copper water channel	Natural convection	Natural convection	–	X	X	Lab, no model Small prototype
He et al.	[53]	Cooling coil	Heat pipe	Fan	–	X	X	X	Lab, real conditions 0.125m^3
Liu et al.	[54]	Aluminum panel	Heat pipes	Natural convection	Fan	X	X	X	Lab conditions, controlled chamber Room, 2.5m^2

3. TE systems integrated in the building envelope

This section presents the studies that have been developed during the last ten years that comprise the integration of the TEMs in the building envelope. In this review, the definition of "building envelope" is taken from Ref. [22], where is defined as the integrated elements of building which separate its interior from the outdoor environment. The term "integration" is mostly defined in the field of solar energy systems. The International Energy Agency (IEA) conveys that the "architectural integrability" should be considered at the three basic architectural levels: functional, constructive, and formal. The main recommendation for the functional integration is to consider multi-functionality, i.e. finding envelope function(s) compatible with the considered technology [23]. In this same direction, the Spanish Technical Building Code (CTE in Spanish) defines the architectural integration for solar systems as the disposition of the collectors in which they fulfill a double function, energetic and architectural (coating, enclosure or shading) and, in addition, they replace conventional constructive elements or are essential elements of the architectural composition. There are three different options for integrating thermoelectricity in the building envelope: in the windows, in the external walls and in the roof or ceilings.

3.1. Windows

Active windows are the systems that integrate the TE technology in the window's frame or glass. Some of the first studies have been carried out by Xu and Van Dessel, where they define the technology as Active Building Envelope (ABE) systems. In this case, the TEMs were mounted on two aluminum tubes in both sides of the window. The experiments determined the coefficient of performance (COP) for the TEMs upon operation under different voltage conditions and different electrical connection diagrams, were also analyzed in the laboratory [24]. An outdoor prototype was also built to be tested in real conditions [25] and a steady state model of this prototype was afterwards validated in Ref. [26]. A similar study was proposed in Ref. [27], were the TEMs installed in the window compensated the heat flow through the window panes, for obtaining a COP greater than three.

Van Dessel and Foubert used the concept of Active Thermal Insulators (ATI), for applying solar energy to compensate passive heat losses or gains in building envelopes. The system was composed by Building Integrated Photovoltaics (BIPV) that provided electrical energy to power the TEMs that were integrated into the wall assembly. In this case, the TEMs were integrated in two glass panes in a window and a finite element model was developed to assess the performance [28].

Following the ATI concept, Harren-Lewis et al. [29] analyzed an

Table 3
Thermoelectric equipment description of TE systems integrated in the building envelope.

	Ref.	TEM type	Connection type/array[a]	Q_{max}[b] [W]	Tests	COP
Windows						
Xu et al.	[25,26]	CP1.4-127-045L PT4-12-40	4 S x 2 P	68.8 W x 8 32 W x 8	3 V, 5 V and 7 V	Cooling: 1.5 Heating: 2.5
Van Dessel et al.	[28]	Variable	One TEM	Variable	1.2 and 2.4 A	Cooling: 0.32–0.95 Heating: 0.44–1.1
Harren-Lewis et al.	[29]	CP1.4-11-045, Melcor 195 different TE units	110 S x 2 P	27.5 W x 112	I = 0,32 A V = 0,39 V	Cooling: 3.7
Zhang et al.	[30]	Melcor (model not specified)	Not specified	–	Different climates, 0.68–3.16 V	Not specified
Walls						
Gillott et al.	[31]	UltraTEC UT8-12-40-RTV	2 S x 4 P	69 W x 8	4.8 A for each module	Cooling: 0.46
Martín-Gómez et al.	[40]	Marlow RC12-8	Not specified	78 W x 84	Not specified	Heating: 0.6
Ibañez-Puy et al.	[42]	Marlow RC12-8	4 groups of 2 S x 2 P	78 W x 32	7.2 and 12 V	Cooling: 0.62–0.78 Heating: 0.8–1.3
Irshad et al.	[43]	Heibei TEC1-12730	8 S x 3 P	25 W x 24	Six levels of I (2–7A) Opt = 6A and 5 V	System: 0.392 to 0.679 Cooling: 0.6–0.9
Irshad et al.	[45]	TEC 1-12730	5 S x 3 P	25 W x 15	Six levels of I (2–7A) Opt = 6A and 5 V	Cooling: 1.15
Liu et al.	[32]	9500/127/060 B Ferrotec	5 S x 2 P	57 W x 10	1–6 A Iopt = 1.2–2.2 A	Cooling: 0.5–1.7 Heating: 2.3 [33]
Liu et al.	[36]	9500/127/060 B Ferrotec	Not specified	Not specified	Variable	Cooling: 2.59 Heating: 3.01
Piantanida	[47]	Not specified	Not specified	33.4 W x 4	Not specified	–
Wang et al.	[46]	TEC1-12706	3 P	50 W x 3	4–9 V in the lab 6–9 V outdoors	Heating: 1.80–2.22 (outdoors) 2.01–3.92 (lab)
Roof and ceilings						
Lertsatitthanakorn et al.	[51]	TEC1-12708, China	Series (Not specified)	48 W x 36	I opt = 1,5A	0.75
Lertsatitthanakorn et al.	[50,52]	TEC1-12708, China	Series (Not specified)	48 W x 36	1A	0.82
Cheng et al.	[13]	Not specified	2 S	Not specified	0.7 A	Cooling: Up to 1.2
He et al.	[53]	127–03	–	25.7 W	12 V and 3A	0.45
Liu et al.	[54]	Ref 9500/127/060 B Ferrotec	5 S x 2 P	57 W x 10	4–5 V	Cooling: 0.9 Heating: 1.8

[a] Number of TEMs in series (S) x number of TEM in parallel (P).
[b] Cooling capacity per module (in W) x number of TEMs.

Table 4
Physical characteristics of the prototypes of TE systems non-integrated in the building envelope (order by publication date).

	Ref	Heat sink		Ventilation		Heating	Cooling	PV system	Tests and scale
		Indoor	Outdoor	Indoor	Outdoor				
Ventilation systems									
Le Pierrès et al.	[57]	Aluminum bonded fin	Water	Air flow of 8.17 m^3/s	Not specified	X	X	X	Model and experiments
Kim et al.	[58] [59]	Aluminum bonded fin	Aluminum bonded fin	Fan 780 m^3/h	Fan	X	–	–	Simulations of a house
Han et al.	[60]	Heat pipes	Heat pipes	2 fans 60 m^3/h	2 fans	X	X	–	Validated model with experiments
Meng et al.	[61]	Heat pipes	Heat pipes	Fan 128 m^3/h	Fan	–	X	–	Simulations
Liu et al.	[62]	Heat pipes	Heat pipes	Fan 21 W and air flow of 0.03 kg/s	Fan	–	X	X	Experimental and simulations
Phase change materials									
Zhao et al.	[64]	Aluminum fin	Finned coil	Fan	Not specified	–	X	–	Lab conditions, chamber of $1.2 \times 0.9 \times 1.9$ m
Skovajsa et al.	[65]	Not specified	Coils	Not specified	Not specified	–	X	X	Lab conditions

active window concluding that "*The ATI design is a significant improvement over the state of the art energy efficient windows. It can reduce the heat gained through a window by as much as 67% and is powered only by the incident solar radiation. The reduced resulting load on traditional HVAC systems will reduce the economic and environmental cost associated with building energy consumption*". Even though they only evaluated the cooling option on summer, they deliberated the option of including a battery to make winter heating a viable option. However, they didn't consider the aesthetics in this prototype and they considered that a closer examination of the heat sinks design would lead to a more commercially viable element.

Zhang et al. proposed an Active Thermoelectric (ATE) window design [30], which was an evolution of triple pane windows. TEMs were integrated between the inner and middle panes in order to regulate the heat transfer through the windows. In this case, surrogate models were developed to represent the optimal modes of operation as a function of the ambient temperature, wind speed and solar radiation. The ATE windows were operated at appropriate trade-offs between the minimal power consumption and the minimal allowed heat transfer through the window.

Table 5
Thermoelectric equipment description of TE systems non-integrated in the building envelope (order by publication date).

	Ref.	TEM type	Connection type/array[a]	Q_{max}[b] [W]	Tests	$COP_{PELTIER}$
Ventilation systems						
Le Pierrès et al.	[57]	CP2-127-06 Melcor	4 P modules (exp.) 2 S x 4 P (simul.)	134.4 W x 8	16 V 1–5 A	Cooling: 0.5–4 Heating: 1.1–3.2
Kim et al.	[58,59]	9501/242/160 B Ferrotec	In parallel	289 W x (40–50)	3 scenarios to find optimal TEM num. and current	Cooling: 1.7 Heating: 2.0 (max.)
Han et al.	[60]	9500/127/120 B	12 S	114 W x 12	1–2.1 A	Cooling: 4.78 (max) Heating: 4.16 (max)
Meng et al.	[61]	TEC1-12706 Hebei	11 S x 3 P	50 W x 33	Not specified	Heating: 2.6 (max.)
Liu et al.	[62]	9500/127/060 B	Not specified	57 W x 20	Not specified	Heating: 2.9–3.35
Phase change materials						
Zhao et al.	[64]	RC12-8-01LS Marlow	15 P	71 W x 15	0–5 A	Cooling: 0.87 average $Cooling_{max}$: 1.22
Skovajsa et al.	[65]	Not specified	Not specified	Not specified	Not specified	Not specified

[a] Number of TEM in series (S) x number of TEM in parallel (P).
[b] Cooling capacity per module (in W) x number of TEMs.

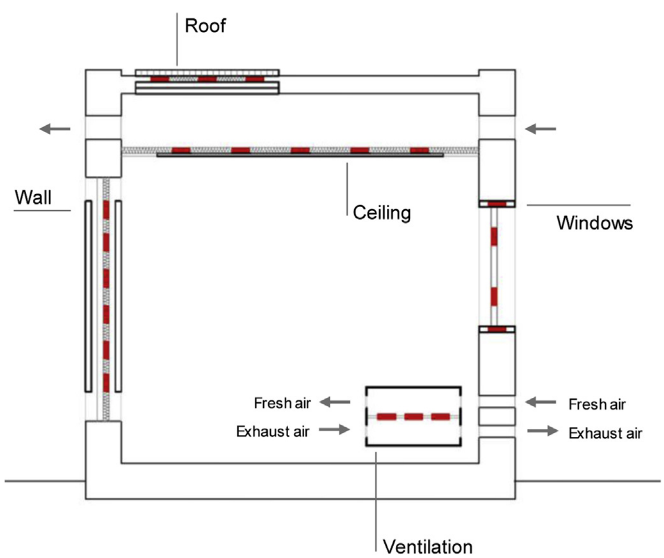

Fig. 3. Diagram of the different technologies studied.

3.2. Walls

A significant amount of application possibilities was focused on the integration of TE modules in the envelope of the buildings for heating and cooling. Guillot et al. proposed a compact TEC to supply comfort cooling for small scale buildings [31]. A theoretical analysis was made under standard working temperature conditions of modules taking into account the net energy received at the cold side. Then, an experiment was set up with 8 TEMs. The theoretical results showed that a lower current input has a higher maximal COP but lower cooling capacity. The experiments showed that practical COP could reach 0.40–0.45 when the input current was chosen at the level of 4.8A to maintain the maximal cooling capacity.

A group of researchers from Hunan University in China has carried out the most complete studies regarding the application of thermoelectricity in buildings. Their experiments included TEMs in the building façade started with [32], where they presented the technology as Active Solar Thermoelectric Radiant Wall (ASTRW), which integrated TE radiant cooling with photovoltaic (PV) technologies. The PV module was integrated in the façade as an external layer. The main goal of this element was to control the heat flux through the building envelope in summer conditions, however, the results showed that it was not only possible to minimize the heat flux but also to provide certain cooling capacity. The same prototype was tested also in winter conditions [33]. In this case, the outdoor air cavity of the façade also controlled the opening and closing of the louvers. Three different scenarios were tested, (1) opened louvers and PV system connected, (2) opened louvers and DC power supply and (3) closed louvers and DC power supply (night-time operation mode). They determined that, in sunny days, the mean interior surface temperature of the ASTRW system was strongly influenced by the solar irradiation intensity. The COP achieved was high compared to other studies (reaches 2.3 in mode 1 and 2.0 in mode 2), however, the operating conditions only control the heat flux through the envelope, and the indoor comfort conditions were not met. A model of this system was developed and validated in Ref. [34]. In this study, they concluded that the effect of the thickness of the air duct (the external air cavity) can be neglected in the entire test. This was a relevant conclusion, also mentioned in Ref. [35], when integrating the system in the façade.

In a further study, they proposed a Solar Thermoelectric Air Conditioner with Hot Water Supply (STACHWS) [36]. In this case, the system was developed in order to reduce indoor cooling and heating load and to provide a continuous hot water supply for householders. A water tank was included in the rig, which helped the heat dissipation of the hot side of the TEMs when working in the cooling mode. It was tested under different operating modes; (1) space cooling and water heating, (2) only heating and (3) only cooling modes. In the heating and cooling modes, the system worked as a water source TE heat pump. The results showed that the system worked more efficiently with lower water inlet temperature in the cooling mode and higher water inlet temperature in the heating mode. The performance of the STACHWS system was strongly influenced by the water temperature. It was tested under constant room temperatures (26 °C in summer and 18 °C in winter).

Besides of experiments, several studies have been carried out by the same group regarding the dynamic model of the system. In Ref. [37], a dynamic heat transfer model of the Thermoelectric Radiant Panel (TERP) was developed. In order to calculate the average surface temperature of the TERP, a dynamic model was established combining an analytical system model and artificial neural networks, as well as, the dynamic calculation functions of the internal parameters of the TEM. This model provided a solid foundation for modelling of the whole Building Integrated Photovoltaic Thermoelectric (BIPVTE) wall system. Thus, in Ref. [38], a non-uniform time step model was proposed and validated. This system has been recently compared to a simple PV wall integrated in a massive wall [39]. They conclude that in general, the cooling and heating loads are lower with the BIPVTE wall system, however, the thermal bridge created by the TEMs is the main weakness, being a problem at nights in winter.

All of these previous studies describe some of the most advanced investigations on this topic, however, the constructive integration of the system is not solved. A first approach to the constructive integration of TEMs in building facades was made by Martín-Gómez et al. [40] where a prototype with 84 TEMs was built in a testing cell that simulated a room. The working principle was similar to [33]. This experience served to raise several constructive parameters to consider for future prototypes. Besides, even though the COP was low, it demonstrated that it was possible to cool or heat a 6.7 m^2 room using thermoelectricity.

Regarding the constructive requirements of a TE façade, Ibañez-Puy et al. presented in 2014 a theoretical design of a TE wall and all of the requirements that it should fulfill, based on the Spanish Building Code: acoustic protection, energy saving and thermal insulation, fire safety, health, protection against humidity, risk of impact, maintenance and structural security [41]. Later, the proposed prototype was built and examined in Ref. [42]. This Thermoelectric Cooling and Heating Unit (TCHU) was completely integrated in the façade. It used the outdoor air cavity of the façade to dissipate the heat of the TEMs. It was one of the few studies that considered the aesthetics of the building while integrating the thermoelectricity in the wall.

Other real scale prototype was built by Irshad et al. to heat and cool a testing room in Malaysia. The system, named Thermoelectric Air Duct (TE-AD), was composed by twenty four TEMs that provided up to 600 W while being located in the building façade [43]. The heat dissipation was ensured through air ducts in both sides of the façade. They concluded that the heat sinks and the fans played an important role in maintaining, as lower as possible, the temperature difference between the hot and the cold side of TEMs. The maximal intensity was found at 6 A, above it the performance was reduced as heat starts transferring from the hot to cold sides.

In a second study, they analyzed the thermal comfort of the occupants in this space [44]. The thermal response of the occupants shifted from (+2) warm to neutral (0), as the input current supply increased from 2 to 5 A, regarding the ASHRAE 7-point scale. With the system running at input supply of 6 A and 5 V the thermal, air quality and humidity met the ASHRAE standard criteria.

The latest study of this research group included a PV system to supply power to the TE-AD and a validation of the simulation model [45]. The TE-AD system was north oriented, and the PV system was south facing, then, it was not integrated in the same system. However, the installation of the PV modules as a ventilated façade component reduced the cooling demand of the chamber and the electrical power installed in the TE-AD. In general, the COP was increased from 0.67 to 1.15 compared to the previous study.

Most of the studies thus far used the TEMs only for cooling or for both, heating and cooling. However, a recent study developed in the UK [46] proposed a TE heat exchange module as a solution for domestic indoor space heating whilst using renewable electricity and that satisfies UK thermal comfort levels. A cubic meter test cell was built and tested in lab environment and winter environment outdoors under different current conditions. Using the results from the experiments, a case study of a mid-terrace house was simulated. In the case study, all of the electricity was powered by renewable sources (PV and wind turbines).

Another study was presented by Piantanida in Ref. [47] where experimental results of TEMs integrated in a ventilated façade and powered by PV modules were analyzed. This study proposed a constructive integration of the TEMs on which the aesthetics was highly considered. The aim of this prototype was to contain the over-heating of the inner layers of the façade in summer.

Oliveira proposed a theoretical description of a TE system integrated in façade with PV system [48]. The setup is similar to that built by Ref. [49] or [32], but the constructive solution differs to some extent. In this case, the design of two chambers in the outside façade layers instead of one was proposed. In a cooling mode, this solution would help the heat dissipation of the TEMs, since the middle chamber would have a lower temperature than the chamber facing outside, which would be covered by the PV modules. In a heating mode, the outside air would be preheated in the first chamber, so when it reaches the second chamber, the temperature difference with the indoor would be lower than while just having one chamber.

3.3. Roof and ceiling

In this section the vertical elements or those integrated in a roof (flat or sloped) are studied, whether in a direct contact with the outdoor conditions or in indoor ceilings.

The Thermoelectric Ceiling Cooling Panel (TE-CCP) system integrates TEMs in the ceiling to cool the air of a room. Lertsatitthanakorn et al. studied the performance of this system in Refs. [50] and [51]. The outside heat sink was connected to a constant temperature bath, meaning that the heat dissipation conditions were constant. When the water temperature decreased, more heat was released at the hot side of the TE modules, leading therefore to a better cooling performance. In a second analysis the thermal comfort of the chamber was also analyzed [52]. The corresponding cooling capacity was 289.4 W with a COP of 0.75 and an average indoor air temperature of 27 °C [51].

Cheng et al. developed a similar experiment; in this case they included a solar cell for water heating. The TEMs were connected to a constant temperature bath in the outside heat sink, which was a copper water channel. The indoor heat dissipation was made by a copper plate. The water channel was covered by a copper plate and this was the direct support of the solar cell [13]. The COP decreases when the temperature entering the channel increases. At a certain point when the temperature of the hot side of the TEM (indoor) was higher than the ambient temperature, there was no cooling, (the intensity was always constant at 0.7 A).

He et al. presented a TE cooling and heating system, which was also integrated in a ceiling, however only the summer mode results were studied. The system model was developed and validated with a small-scale prototype tested in the lab. The system could get hot water using heat pipes and solar photovoltaic and thermal modules (PV/T) while cooling the room in summer using the PV/T modules power. In winter it could heat the room with the TEMs, while using the PV/T modules, the power and the heat source simultaneously [53].

Liu et al. developed a more sophisticated system including the TEMs not only in a chilled ceiling but also in a dehumidified ventilator equipment, or more precisely a displacement ventilation system [54]. The system was also powered by PV modules and they referred to it as Solar Thermoelectric Cooled Ceiling (STCC). The displacement ventilation system is a room air distribution strategy where conditioned outdoor air is supplied at a low velocity from air supply diffusers located near the floor level and extracted above the occupied zone, usually at the ceiling height [55]. The results showed that the main parameters affecting the performance were the operating voltage, ambient temperature and indoor temperature. The total heat flux of the STCC system in cooling mode was higher than 60 W/m^2 and the system COP could reach 0.9 under operating voltage 5 V. In a heating mode, the total heat flux of the STCC system under operating voltage of 4 V was higher than 110 W/

m^2 and the COP of the system can reach 1.9. To conclude, and as many other studies, they emphasized that the performance of the system could be improved by improving the module's contact resistances and thermal interfaces. The model for estimating of the surface temperature of the radiant ceiling panel was afterwards developed by part of the same team in Ref. [56], where the system in was referred as Thermoelectric Radiant Ceiling Panel system (TE-RCP).

4. TE non-integrated systems

Among the studies that analyze the applicability of TE as building HVAC system, some of them do not integrate the TEMs in the building construction but rather as an independent system. Those investigations are mainly divided into four groups: (1) the ones that use TE in ventilation systems or ventilation system components, such as ducts, (2) those that couple the TE systems to Phase Change Materials (PCM) (3) the investigations about the use of TE as dehumidifiers and (4) other related developments, most of them are simulation approach studies.

4.1. Ventilation system

This section gathers the studies for applying thermoelectricity in ventilation systems either as air pre-cooling or pre-heating heat exchangers or as TE heat pumps.

In Ref. [57] the integration of TE in air ducts to pre-heat or pre-cool the air before entering the building was suggested. The temperature difference between the air taken from the outside and the air inside domestic buildings is lower than 15 °C for moderate climates. Thus, optimal performances can be obtained for air pre-heating or pre-cooling, since the lower the temperature difference between the sides, the higher the COP of the TE element. In the frame of the research a model was developed and a simplified experiment in a small scale was used to find the convective heat transfer coefficients under typical conditions that can be found in ventilation air ducts.

The group headed by Kim [58] developed a simulation study to determine the optimal number of TE modules and the optimal electrical current of a thermoelectric heat pump (THP) coupled to an energy efficient building. They defined three configuration options for a THP, (1) the THP coupled to an exhaust/supply mechanical ventilation system (ESMVS), (2) the THP coupled to an ESMVS and to an air-to-air heat exchanger and (3) the THP installed with an ESMVS and an earth to air heat exchanger. It was demonstrated that an optimal number of modules is driven by the dissipated heat flux and the temperature difference between both sides of the TEM; which affects the optimal electrical current. This optimal number of modules corresponds to the minimal electrical power consumption required to meet the demand. This conclusion was also achieved in Ref. [59] where they carried out a deeper study in the same scenarios. They added that, the performance forecasted by the manufacturer (nominal COP) was not representative of the performance reached by the user when the THP is coupled to the building.

The research group from China mentioned in section 3.2 also investigated the integration of TE in ventilation systems. Han et al. [60] found that the TE ventilator can provide sufficient energy for fresh air handling and heat recovery from exhaust air. They proposed an integrated design method which avoids the estimation of temperature difference between the faces. The method was afterwards validated by an experimental setup. They found that the TE ventilator can provide sufficient energy for fresh air handling and heat recovery from exhaust air. Besides, the TE ventilator is more adequate for mild weather conditions and further studies were proposed to reduce the heat transfer resistance, especially on the hot side of the TEM.

In a later study, Meng et al. [61] investigated a TE Warm Air Heater. Following the previous study, an experiment of a TE ventilator in a bathroom was carried out. In this study again, the optimal operating conditions were found when the operating voltage was varied from 6 V to 8 V. In addition, the supplied air temperature was of a little contribution to the COP. As concluded in the previous study, in this case also, it was noted that optimizing other parameters such as the system's thermal resistances could achieve a significant improvement in the TE COP. Upon increasing of the indoor temperature, the temperature difference between the cold and hot side decreases, improving the performance.

The latest research of this group analyzed the same ventilator coupled to a photovoltaic module in a brief study [62]. The outdoor fresh air was firstly pre-heated in an air channel disposed behind the PV module, and then heated up further when it flowed through the hot side heat sink of the thermoelectric ventilator, TEV. At the same time the exhaust air cooled down the heat sink on the other side. The results showed that the COP and the fresh air temperature supplied indoor increased as the solar radiation intensify increased. The electrical power storage from the PV was used to power the TE ventilator through a voltage controller.

4.2. Phase Change Materials

PCMs can be applied for thermal energy storage. These materials store a large amount of energy during the phase change process. Thus, thermal energy storage realized by PCM exploits not only sensible, but especially latent heat [63]. This section presents the studies that have analyzed the performance upon coupling the TEMs with PCM.

In Ref. [64], Zhao et al. proposed a TE cooling unit integrated with a PCM heat storage that would carry, partially, the cooling load during a cooling operation. The storage unit consisted of an inner tube, an outer tube and a well-insulated rectangular shell envelope. The annulus space between the inner and outer tubes was filled with a PCM. The system was tested under two operation modes, always under the same cooling load, since the room temperature was maintained constant. Thus, if the outdoor air temperature was relatively low (early morning or late afternoon), the first working mode would represent an operation in which the heat generated by space cooling would be dissipated to the outdoor environment through an air-water heat exchanger. However, when the air temperature is high, the system would operate in the second mode in which the PCM heat storage unit would be activated. This PCM heat storage system is suitable for locations that have large temperature differences between day and night, since it is a short-term diurnal thermal storage application.

Another study used PCM based accumulation panels coupled to a TEC system [65–67]. Several modes of heating or cooling of PCM panels were analyzed. In this case, the focus of the investigation regarding thermoelectricity was the performance of the PCM panels for cooling using TEC as a cooling source. Since the TEMs can cool the PCM panels, one of the disadvantages concerns the waste heat produced in the hot side of the modules. The usage of this heat for hot water preheating was suggested but it was not examined in the study.

4.3. Related developments

There are some studies that do not suggest any physical prototype or integration possibility of TE in the building but simulate the TE effects for cooling and heating purposes.

This is the case of Allouhi et al. [68], whom carried out a theoretical analysis of a TE heating system installed in an office building in Morocco. Three cases where simulated, January, March and October, corresponding to high, medium and low heating demands. The hourly simulation results showed that among the studied calculation nodes, the COP was found as between 2 and 3 in 42% cases for January 13–14 and 59% cases for March 11–12. The COP exceeded a value of 3 in 26% cases for the simulated period of October 26–27. The optimal number of TEMs to achieve a COP of 2 was 12 modules. It was concluded that this system could reduce up to 64% of energy consumption in an office room as compared to a conventional electric heater.

Another study analyzed the usage of TEMs based on two functions, as a heat pump or as a thermoelectric generator (TEG) when space heating and cooling are not required, and incident solar radiation is sufficient, coupled to an evacuated solar collector [69]. The hot water from the collector can act as the heat source for the TEG. Regarding the heat pump mode, an 18 TEMs system was simulated. The results showed a variability of the cooling mode's COP between 0.38 and 2.35 and the heating mode's COP in the range of 1.26 and 3.8.

5. Discussion and conclusions

This paper classifies and analyzes the different applications of thermoelectricity for heating, cooling and ventilation in buildings that have been published during the last decade. Currently, the introduction of this technology in the building environment is far from the market, however, this study demonstrates that there are several possible options of implementing TE systems for this purpose. Regardless the low COP compared to vapor compression systems, the very high potential of TE for buildings has been demonstrated.

The classification presented in this study is made from an architectural, constructive and building services design point of view, which is the perspective of the prescribers and end users of the technology. The analysis has eased the definition of the state of the art and the identification of the main key points for the future development of the technology in this field.

As with any other HVAC system in buildings, the main goal of a thermoelectric system in buildings is to achieve the indoor thermal comfort conditions. The literature review showed that still further development must be made to reach the point of analyzing the thermal comfort for any specific system. It is also notable that, even though the final application is the heating and cooling of buildings, only one research examined the thermal comfort achieved in the room [44] and only a few considered the importance of achieving comfort conditions in the room.

Regarding the TE systems integrated in the building envelope, the integration in the façade is the most investigated option and the studies about it are rising during the last years. The case of the window integration differs, since during the last years no studies could be found about it. One of the reasons could be the difficulty of commercializing the product or a low interest from the market, but it can also be attributed to the fact that several studies have been carried out, but few with prototype experiences in real buildings. This case is in general translatable to all of the examined systems. One of the advantage of the wall integration is the decentralization. It is a system without easements. However, the weakness of the thermal bridge that is caused when the system is not working still is not solved [35,39].

The studies about non-integrated systems are fewer than the integrated systems, but in general, they show higher COP. The use of mechanical ventilation is necessary in near zero energy buildings, hence, introducing TE in ventilation systems fits for this application since the consumed power could be utilized for pre-heating or pre-cooling the air. In the case of PCM, even though it is considered a very efficient energy storage system, still is not exploded in the market probably due to the poor performance in case of fire of some PCMs.

Therefore, the technology still needs to be developed, but the main improvements should go through the following points:

- Regarding the construction and architectonical integration, a few studies consider the parameters that affect the integration of a TE system in the envelope of a building. Concepts such as the heat losses through the façade, durability, acoustic performance, aesthetics or the behavior of the elements in case of fire must be further analyzed for implementing this kind of technology in the future market.
- Referring to the performance of the whole system, the TE system optimization process is basically to find the best balanced point between the cooling capacity and the COP [64]. The low COP of the TE systems compared to conventional vapor compression systems is one of the factors hindering the development of this implementation. In this context, an application of this technology in low energy consumption buildings can be understood as the most logical application [70]. However, in practice, the constructive integration of the system in the envelope is not developed sufficiently to cope with the thermal bridge that is generated in the façade or roof. Thus, this application weakens the theoretical continuous envelope needed by the near to zero energy buildings.
- Most of the studies also remark that the performance of the system can be improved by selecting high performance TEMs. This conclusion depends on the improvement of the figure of merit of the TEMs, and on the development of thermoelectric materials.
- Even though this review does not include an analysis of the control system, this issue is one of the key factors towards an optimal performance. In general, the studies about the operation and performance of TEMs are based on the temperature of the cold and hot sides, however, in a building application, the reference temperature is the ambient temperature of the room. Al-Nimr et al. [71] developed a simulation model based on the room temperature. In addition, Bermejo et al. [72] presented the scenario of installing several BIPVTE systems in façades and made a theoretical proposal of a decentralized control system for all these autonomous components.
- It must be also highlighted that the level of interest about the inclusion of a DC line in the buildings of the future is growing [74]. The use of PV systems as energy sources, together with many other electrical devices that are commonly being used in residential buildings, requiring converters, raise the question as whether a DC line installation in household will be convenient in the future. There are already studies that evaluate the feasibility of this distribution system, such as [75].
- The future solutions will have to struggle against the inertia of the market, while transforming a widely optimized technology in the military, aerospace or health sectors into applications in the building sector, which has been accommodated in the use of vapor compression systems for years.

Finally, we would like to bring up four additional considerations about the future of this technology in buildings:

1. After this revision, the effort to unify the nomenclature seems necessary. Each study uses their own terms. The role of professional societies, such as the International Thermoelectric Society may be decisive.

2. The final solution is expected to contain a high degree of prefabrication, could it be related to the 3D printing in the future? [73].
3. Peltier cells in addition to DC lines and photovoltaic systems looks like a powerful and robust solution, but this sum also requires taking into account the location of accumulation batteries, so that they have really independent elements. But, in these moments, and given the COPs and the necessary power in the starting of the equipment, they are still too large for their direct inclusion in facades.
4. Aesthetics must be considered by end users or industry prescribers. It is a difficult to measure concept, but decisive for the end user, especially in the case of housing.

Most of the described studies rely on the improvement of the thermoelectric materials' figure of merit. This fact raises the requirement of optimizing novel thermoelectric compositions for the specific temperature and heat transfer conditions applied in practical building applications.

Technology has advanced exponentially over the last two decades, leading to plentiful techniques and products which were unimaginable years ago. Likewise, a future is outlined that even now is challenging to imagine. In this context, the technology applied to the ventilation, heating and cooling systems has advanced, but far from generating a radical change in society. Hence, energy systems in the built environment need the development of cutting-edge technologies accompanying the current spearhead fields.

It must be recalled that certainly, there are cheaper solutions, but none that provide such high durability, almost non-existent maintenance, the possibility of combination with photovoltaic systems and without using fluorinated gases. Possibly this last point is the one that best allows to argue in favor of the development of the thermoelectric technology in the near future.

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