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Thermoelectric Modules: Applications and Opportunities in Building Environments for Sustainable Energy Generation from Biomass, Municipal Waste, and Other Sources

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Abstract

In the constant search for alternative energy sources, thermoelectric modules have emerged as a crucial technology for power generation. This study provides a comprehensive review of their applications in the building environment, an area that has become increasingly important. Despite their lower efficiency, thermoelectric modules are very useful for capturing and converting waste heat from waste gas decomposition into valuable energy sources. The paper is structured into five categories: power generation, sustainable building practices, heating and cooling systems, software simulations, and hybrid systems. Ultimately, this research analyzes the opportunities and prospects for thermoelectric applications in buildings, offering valuable insights into the current energy recovery landscape, especially in the context of biomass and municipal solid waste decomposition.

Keywords: Thermoelectric; Waste heat recovery; Circular economy; Sustainability; Biomass; Solid waste.
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1. Introduction

Given that buildings account for 32% of global energy consumption[1] and are responsible for over 60% of CO_2 emissions from operational processes,[2] it is imperative to employ diverse methods and strategies to construct energy-efficient structures and transition towards net-zero energy buildings (ZEBs).[3] Numerous countries have either adopted or are contemplating the establishment of ZEBs as a future energy target to combat environmental degradation.[4] These strategies for improving building performance encompass reducing energy demands, particularly for heating and cooling, and incorporating renewable energy and other technologies.[5] Such strategies offer a promising arena for the application of thermoelectric (TE) technology. Energy-efficient measures must encompass not only building service systems[6] but also building envelopes[7] to facilitate energy and environmental conservation. TE technology is currently in high demand, aligning with global initiatives for recycling,[8] green energy,[9] and circular economies.[10]

Presently, TE systems can be integrated into civil buildings[11] where they serve as TE generators (TEGs)[12] or heating/cooling devices.[13] Despite their relatively lower TE efficiency and the substantial surface area required for installation, they offer notable advantages over competing technologies, including the absence of noise and vibration, compact dimensions, lightweight construction, simplicity, and the absence of hazardous or environmentally significant gases.[14] Opportunities abound in TE development, spanning circular economy projects,[15,16] the advancement of new materials and devices,[17] and the optimization of technology,[18] among other areas.

Thus, the adoption of TE technology in buildings emerges as a significant solution for indoor thermal comfort requirements.[19] TE can convert temperature differentials into electrical voltage through the Seebeck effect,[20] with electricity generation contingent on the temperature disparity between the two sides of the TE generator module,[21] or conversely, the generation of temperature differentials when an electrical current is applied due to the Peltier effect.[22] Meeting the escalating energy demands of buildings is an

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imperative that must go hand in hand with energy and environmental conservation efforts. Consequently, TE technologies can play a pivotal role in enhancing energy efficiency while mitigating climate change. Furthermore, another pressing issue lies in the continued reliance on fossil fuels, which emit environmentally harmful gases,[23] and in municipal solid waste facilities, which release polluting gases during the decomposition of municipal waste.[24] The year 2020 witnessed a significant shift in global pollution levels due to the COVID-19 pandemic, attributed to reduced fossil fuel use in vehicles and airplanes, leading to improved air quality in many cities worldwide.[25] To address this problem, renewable energy adoption has been promoted to reduce harmful gas emissions.[20] A comprehensive pollution mitigation plan has been developed, encompassing air quality analysis, research into pollution mitigation technologies, investigations into the environmental impact of pollution, and the development of holistic solutions on a global scale, see Fig. 1a.[26] A modern solid waste management plant must target the minimum impact on emissions and environment, see Fig. 1b; with strategies as minimizing the heat pollution using thermoelectric cells, integrated with other systems such as infrastructure, cars, and industrial emissions, Fig. 1c, targeting a sustainable planet.

In municipal waste treatment plants, the decomposition of waste often produces exhaust gases containing sulfur compounds, nitrogen, acids, hydrocarbons, and other pollutants.[24] This emission of noxious gases is primarily due to inadequate gas circulation or insufficient temperatures for waste decomposition. Consequently, the major challenge in this process is gas leakage.[27] The focus is on improving system efficiency and harnessing the heat generated by these gases. The potential for energy generation in municipal waste plants is substantial, as they release significant heat through gases like CO_2 and CH_4.[28]

Therefore, TE devices can be strategically placed at heat-rich locations to maximize energy extraction. Chimneys stand out as prime candidates, as they typically maintain temperatures between 55 °C and 180 °C, well within the operating range of TEGs.[29] This research comprises an inclusive review across five categories: power generation, green building, heating and cooling systems, software simulations, and hybrid systems, drawing upon data sourced from the Scopus database.

To address the challenges and limitations of thermoelectric technology, interdisciplinary collaborative efforts in materials science, engineering and economics are essential. Continued research and development play a key role in advancing this promising field and unleashing its full potential for sustainable energy solutions. Thermoelectric technology faces significant hurdles and constraints that must be overcome to fully exploit its capabilities in a variety of applications, ranging from power generation to cooling. In this context, we present the main challenges identified by recent studies and highlight ongoing research efforts within this field.

One of the main challenges in thermoelectric technology is

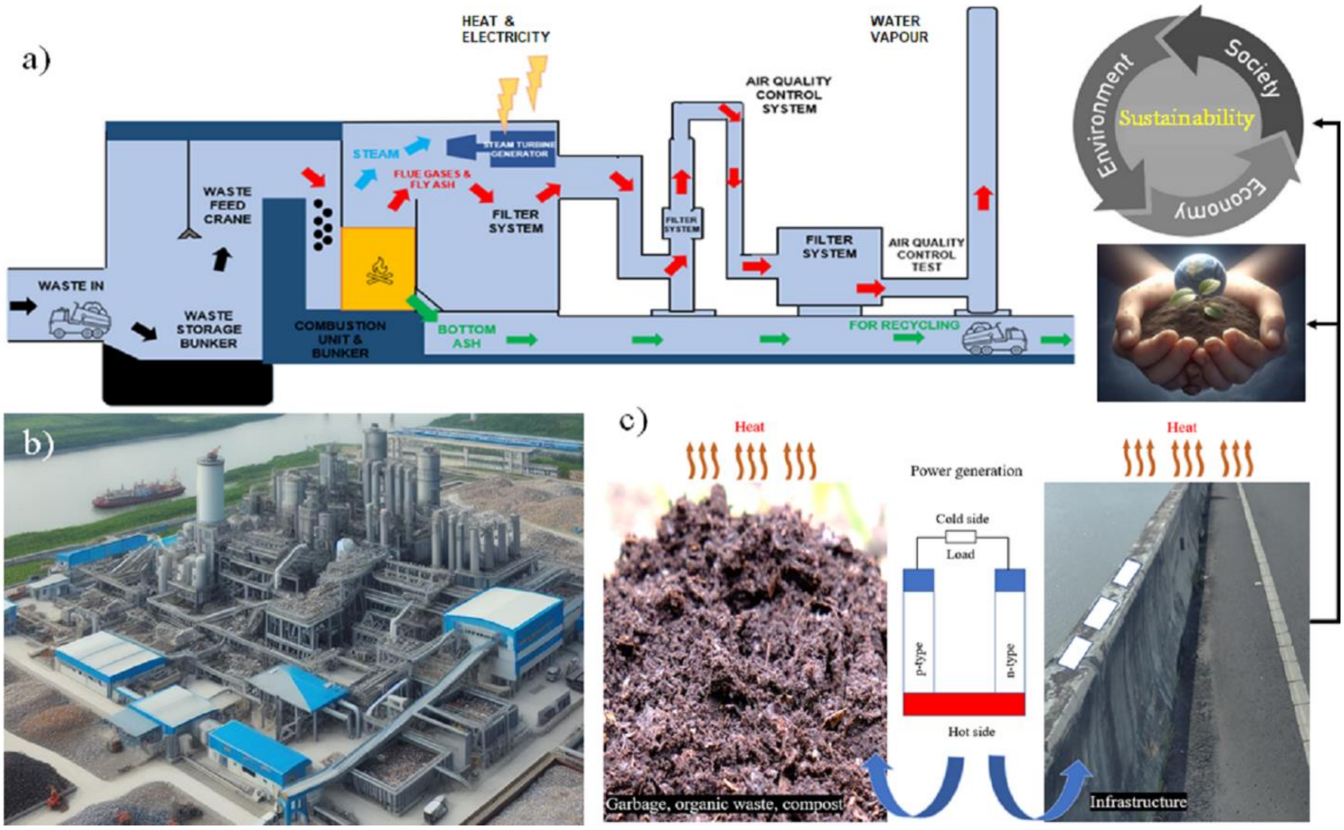


Fig. 1 a) Municipal Solid Waste Combustion process; b) representation of a modern plant concept with near zero emissions; c) representation of thermoelectric cells recovering part of the released heat.

to find materials with high efficiency in converting heat into electricity. The efficiency of thermoelectric modules is highly dependent on the choice of materials, which underlines the importance of selecting abundant, non-toxic, lightweight and cost-effective materials. In addition, ensuring mechanical flexibility for applications such as portable electronics and managing thermal conductivity to reduce heat loss are crucial aspects.[30]

The long-term stability and reliability of thermoelectric materials are vital to their commercialization and widespread use. Mechanical properties, such as flexibility, and electrical stability under various conditions are critical considerations to ensure the durability of thermoelectric devices.[30]

The cost-effectiveness of thermoelectric devices is hampered by the high cost of materials and complex fabrication methods. Rare and expensive materials such as bismuth (Bi) and tellurium (Te) increase the overall cost of thermoelectric devices. The development of economically viable production methods with low-cost materials is essential for widespread adoption.[30]

Optimizing the performance of thermoelectric devices and their integration into various applications requires innovative design approaches. This includes addressing design complexity, selecting suitable materials for flexible and transparent requirements, and developing novel module designs that balance flexibility with power requirements. Achieving large-scale production and commercialization while ensuring long-term stability remains a considerable challenge.[30]

Thermoelectric generators (TEGs) currently exhibit lower efficiency than other renewable technologies such as solar panels. Intrinsic material limits and design optimization are critical factors contributing to this challenge. Innovative approaches, such as material segmentation and non-uniform cross-sections, are being explored to overcome efficiency limitations.[31,32]

The environmental impact of thermoelectric materials, especially those containing toxic elements, is a concern for sustainability. Developing environmentally friendly materials without compromising performance is essential to reduce the environmental footprint of thermoelectric technology.[33]

2. Methods

2.1 Exclusion Criteria

Following the described methodology, specific exclusion criteria were applied to refine the results of the systematic search and ensure alignment with the main objective of the review. This step-by-step approach allowed the selection of articles that closely matched the objectives of the review and the scope of the research. The following exclusion criteria were applied during the data analysis process:

2.1.1 Relevance to primary focus

Articles that were found not to directly relate to the primary focus areas of the review, such as thermoelectric applications in building technology, were excluded. This criterion aimed to eliminate studies that did not align with the specific scope of the review.

2.1.2 Publication date

Only articles published within the defined timeframe (2010-2020) were considered. This criterion ensured that the selected literature was current and reflected recent advancements and trends in thermoelectric technology applied to buildings.

2.1.3 Article type

Only articles categorized as "article type" were included in the analysis. Other document types, such as conference papers, reviews, and editorials, were excluded to maintain consistency in the data analysis and focus on peer-reviewed research articles.

2.1.4 Title and summary relevance

Articles that did not demonstrate relevance to the primary focus based on the title and summary were excluded. This criterion helped to filter out studies that were peripheral to the main topics of interest.

2.1.5 Full article review

Articles that, upon reading the full text, were found not to contribute substantially to the review's primary focus areas were excluded. This step ensured that only high-quality, relevant studies were included in the final analysis.

2.2 Heat recovery in buildings: data analysis using Scopus database

The data analysis was conducted using the Scopus database. Initially, the search employed the keywords "Thermoelectric" AND "Building," resulting in 1,935 hits when additional search terms like article titles, abstracts, and keywords were considered. Subsequently, these results were narrowed down to the last 10 years, from 2010 to 2020, and filtered by article type, yielding 1,620 and 892 results, respectively. However, upon reviewing the titles and keywords of this initial systematic search, it became evident that many of the entries were not directly related to the primary focus of the review.

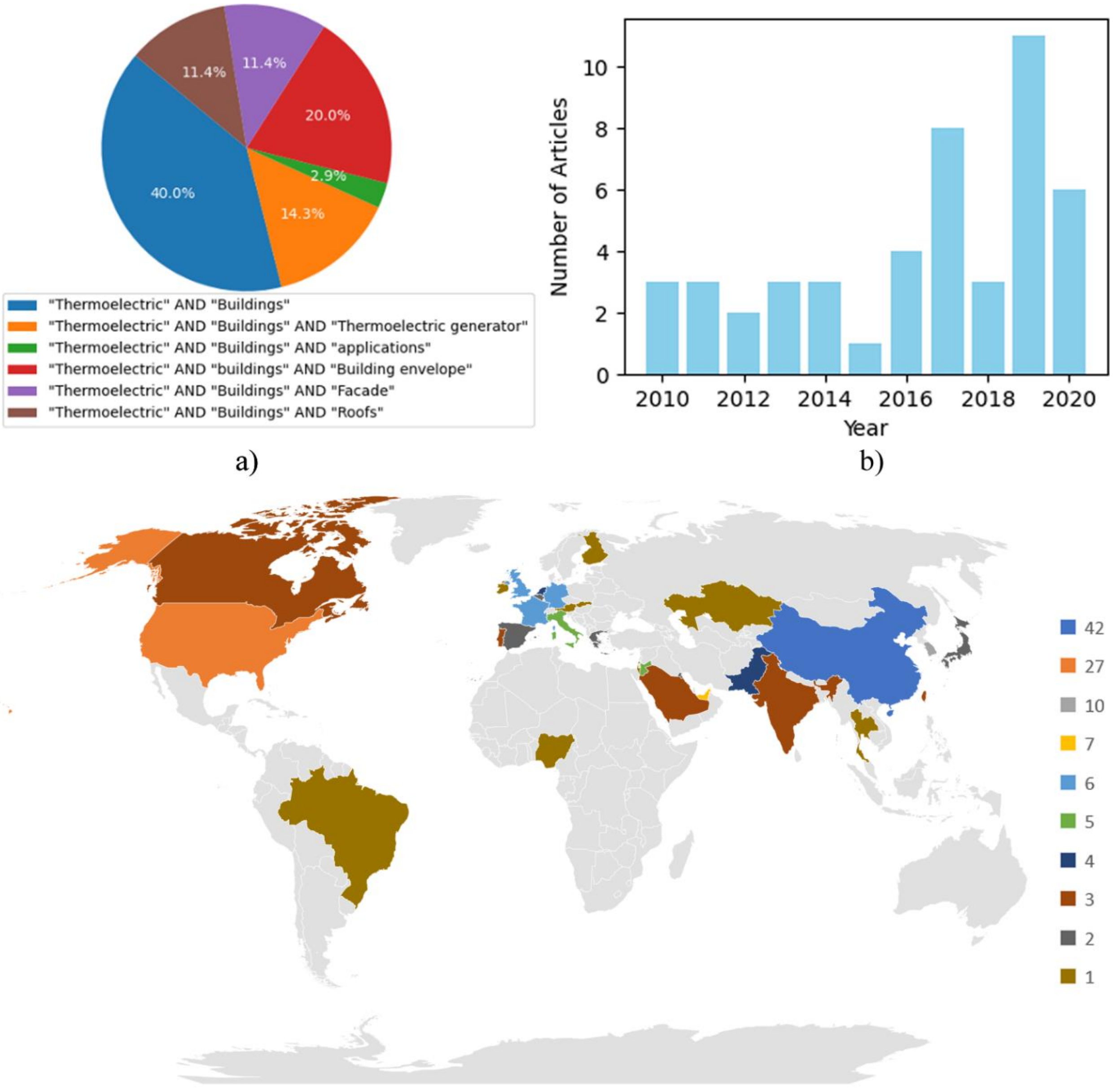
To refine the systematic search, the following search strings were utilized, using only article titles and keywords as additional search terms. Furthermore, the identified papers were subjected to sequential filtering: first by the last 10 years, then by document type, followed by a review of the title and summary, and finally, by reading the full articles. The results of this refined systematic search are presented in Table 1, and Fig. 2 illustrates the number of articles discovered per search string, the distribution of articles by year, and the geographical distribution of documents by country.

In addition to filtering papers, they were also categorized into five primary areas of focus for the review. Table 2 displays the classification of papers into the following categories: Power Generation, Green Buildings, Heat and Cooling

Table 1. Search strings and filters employed in the systematic search.

Search strings	Number of articles found				
	Unfiltered	Filter 1	Filter 2	Filter 3	Filter 4
"Thermoelectric" AND "Buildings"	21	21	17	14	14
"Thermoelectric" AND "Buildings" AND "Thermoelectric generator"	67	57	26	5	5
"Thermoelectric" AND "Buildings" AND "applications"	135	113	56	12	1
"Thermoelectric" AND "buildings" AND "Building envelope"	39	25	12	9	7
"Thermoelectric" AND "Buildings" AND "Facade"	18	18	11	4	4
"Thermoelectric" AND "Buildings" AND "Roofs"	32	27	13	4	4

Filter 1: Year of publication of the article from 2010 to 2020, Filter 2: type of document "article type", Filter 3: reading of title and summary, Filter 4: reading the article.



a) b)

c)

Fig. 2 Analysis of article distribution: a) Search string results, b) Yearly distribution, and c) Geographic origins.

Systems, Simulation, and Hybrid Systems.

Filter 1: Year of publication of the article from 2010 to 2020, Filter 2: type of document "article type", Filter 3: reading of title and summary, Filter 4: reading the article.

In addition to filtering papers, they were also categorized into five primary areas of focus for the review. Table 2 provides a classification of reviewed papers into key focus areas related to TE technologies. The categories include power generation, green buildings, heat and cooling systems, simulation, and hybrid systems.

The results presented in Table 2 reveal a wide spectrum of studies covering various aspects of TE technologies, showing their potential in different areas.

Table 2. Classification of reviewed papers into key focus areas.

Ref.	Power generation	Green buildings	Heat/Cooling systems	Simulation	Hybrid system
[34]		x		x	
[35]				x	
[36]		x		x	
[5]			x		
[14]					x
[37]		x	x		
[38]		x			
[39]			x		x
[40]					x
[41]				x	x
[42]				x	
[43]					x
[44]	x			x	
[45]	x	x			x
[46]	x				
[47]	x	x			
[48]		x			
[6]			x	x	
[49]		x	x		
[50]		x			
[51]		x			
[52]			x	x	
[53]			x	x	
[54]		x	x		
[55]		x	x		x
[56]			x		x
[57]		x			x
[58]			x	x	
[59]			x	x	
[7]		x	x		
[60]		x	x		x
[61]		x	x		
[62]		x	x		x
[63]		x			x
[64]		x			x
[65]		x			x
[66]		x			
[67]			x		
[68]		x	x		
[69]		x			
[70]		x	x		x
[71]		x	x		
[72]		x	x		x
[73]		x	x		x

2.2.1 Patent research

A comprehensive patent investigation was conducted to gain insights into the current state of TE technology development. The search strings were formulated using keywords extracted from the papers identified in the Scopus systematic search. Only patents published within the past 20 years were considered.

The search strings employed, along with the corresponding count of patents retrieved from US Patent Applications in the Free Patents Online database, encompass combinations such as "thermoelectric AND buildings AND generation AND power AND structures AND wall system AND building envelope AND generator" and "applications AND power generation AND thermoelectric applications." This yielded a total of 194 patents identified through these search criteria.

To showcase the patent developments in the realm of TE technologies for building applications, three noteworthy patents are examined and detailed in Table 3, along with their respective citations.

Table 3. Relevant patents identified from US patent applications.

Match	Document	Document Title
1	US20100132818	Thermoelectric power generation device[74]
3	US20180205343	Systems and methods for building-integrated power generation[75]
4	US20130340969	Energy exchange building envelope[76]

2.3 Waste heat recovery

In this review, comprehensive bibliographic searches were conducted within the Scopus database, focusing on TE-related topics. The research information was gathered using keywords such as TE, Bi_2Te_3, Waste, Garbage, Municipal, and Biomass. The search encompassed documents published within the timeframe of 2010 to 2020. Table 4 provides an overview of the documents obtained, with detailed data analysis presented below.

Two filters were applied to select the papers for inclusion in this study. The first filter restricted the documents to those published from 2010 to 2020, resulting in an initial pool of 601 documents. After the application of this filter, 507 documents remained. Subsequently, a second filter was applied, focusing on the specific application areas relevant to this review. As a result of the second filter, a total of 13 documents were identified, from which the pertinent information for this review will be extracted.

Initially, the identified documents were categorized according to their specific application areas. This categorization was carried out to provide a broader overview of the subject matter and to facilitate the structured exploration of the topics to be addressed within the review. This approach aids in the systematic examination of the subject matter by establishing a well-organized framework for addressing various aspects of the research.

Figures 3 and Table 5 show the distribution of documents according to their geographical origin and year of publication. This analysis aims to identify the most important contributions in this field and to highlight the periods in which this topic has been the subject of great attention and relevance.

Table 4. Keywords and search queries in the review.

Keywords	Unfiltered	Filter 1 (Years 2010 - 2020)	Filter 2 (Applications)
"Thermoelectric" AND "Bi2Te3" AND "Waste" AND "Heat recovery"	72	62	2
"Thermoelectric" AND "Municipal Waste"	85	70	2
"Thermoelectric" AND "Garbage"	10	6	1
"Thermoelectric" AND "Municipal Garbage"	2	2	1
"Thermoelectric" AND "Biomass"	432	367	7

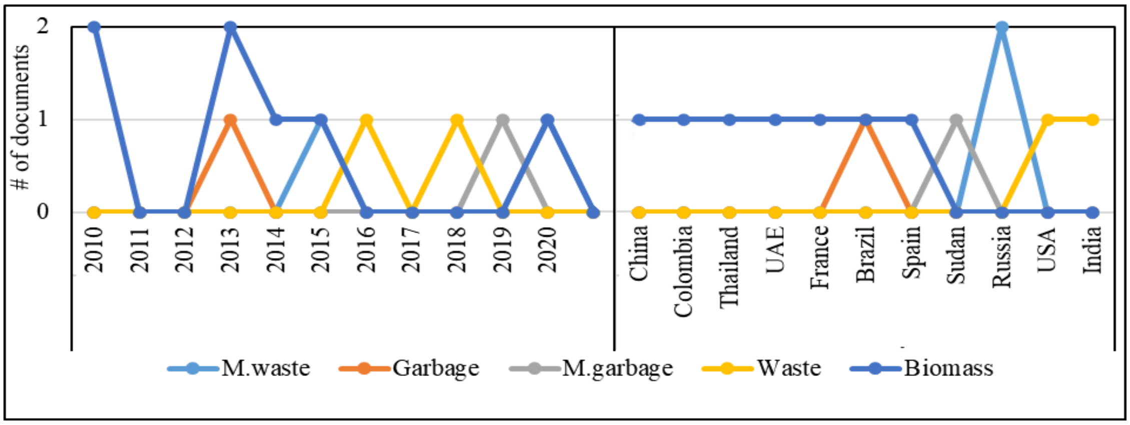


Fig. 3 Publication trends by year and geographic region since 2010.

Table 5. Review paper sources and their application areas.

Ref.	Year	PG	HR	PT	AE	CE	Source
[77]	2020				x		Energies
[78]	2020			x			Journal of Cleaner Production
[79]	2019				x		International Conference on Computer, Control, Electrical, and Electronics Engineering (ICCCEEE)
[80]	2018			x			International Journal of Energy Research
[81]	2016		x				15th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)
[82]	2015				x		Thermal Engineering
[83]	2015	x					Ingeniería y Universidad
[84]	2014	x					Advanced Materials Research
[85]	2013					x	Fuel
[86]	2013			x			Journal of electronic materials
[87]	2013	x					Journal of electronic materials
[88]	2010	x					Energy
[89]	2010		x				Journal of electronic materials

PG: Power generation, HR: Heat recovery, PT: Performance of TE, AE: Alternative Energy, CE: Circular economy.

Figure 4 illustrates the classification of documents based on publication type and the materials under study. Predominantly, the materials explored in TE research include those composed of Bi_2Te_3, along with some investigations involving waste materials and TE that have surpassed their useful lifespan.

Bi_2Te_3 TE modules are commonly employed in this system due to their high deformability, which enables easy accommodation within the tubes through which the gas flows. Additionally, these modules can withstand the temperatures at which the system operates, ranging from 25 °C to 250 °C.[89]

3. Results and discussions

3.1 Power Generation

In the present era, with the escalating global energy demand, a shift towards non-conventional energy generation technologies becomes imperative. Consequently, the utilization of TE technology for energy generation within buildings emerges as a noteworthy trend aimed at enhancing construction efficiency. Buildings demand substantial energy to ensure occupant comfort and habitability. This energy requirement encompasses factors such as energy losses, as well as the energy necessary for lighting, ventilation, and various building systems, as depicted in Fig. 5.[90]

A building's envelope serves as a thermal barrier, separating the temperature-controlled indoor environment from the external surroundings. This barrier establishes a temperature differential across its boundaries. In regions with high irradiance levels and hot climates, daytime solar

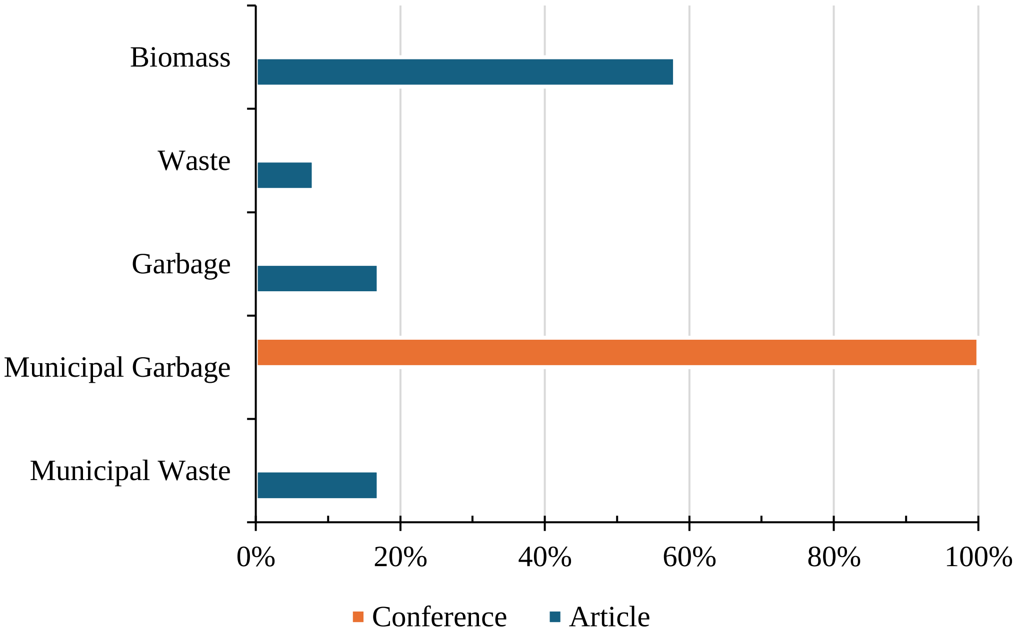


Fig. 4 Publication trends since 2010, categorized by type.

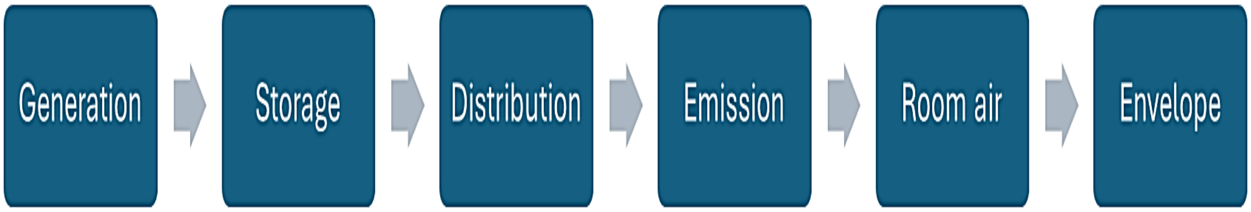


Fig. 5 Energy dispersion in a building.

radiation exposes the external surfaces of building envelope components to elevated temperatures. This temperature contrast creates a thermal gradient that can be harnessed to generate electricity, particularly for small-scale applications.[91] TEGs can leverage this temperature difference and serving as power generation systems. TEGs directly convert the temperature gradient across semiconductor blocks into electricity through the movement of holes and electrons, a phenomenon known as the Seebeck effect.[92]

Numerous researchers have been actively engaged in the study of TEGs and their practical applications in real-world conditions. Table 6 illustrates the endeavors directed toward enhancing TEG performance in realistic settings and exploring their adaptability to varying seasonal and environmental conditions.

TEGs find diverse applications in power generation, primarily focusing on the recovery of energy losses and the utilization of temperature gradients. As previously mentioned, energy dispersion is inherent in meeting various inhabiting needs within a building. TEGs have the potential to recapture some of this energy and can be integrated into facades, windows, HVAC systems, and even solar photovoltaic generators.

Table 6. TE Generator (TEG) systems and their applications.

Ref.	Generation [V]	Operating conditions	Uses
[3]	The winter season contains all the months with average temperatures lower than 18 °C and summer season higher than 26 °C. The rest belongs to transition season. The energy accumulation curves for PV + TE, PV + Grid + TE and Grid +T E are sharing with similar shapes.	The results showed that the “first zero” goal can be fully achieved across those regions under the default system setting. Even with the unoptimized battery capacity, the PVTEB can realize 72–92% energy saving in cold region, 88 100% energy saving in mixed zone, and totally 100% energy reduction in cooling dominant zone.	HVAC systems.
[44]	The experimental findings showed that the TEG was able to generate about 22 mW of electrical power at matched load resistance.	The temperature difference between hot and cold side is 10 °C. The test was realized at different points of the TEG but always maintaining a constant ΔT.	Extreme climate and air-conditioned spaces, where exist a temperature gradient among the controlled space indoor and the extreme outdoor climate.
[45]	The power output for concentration ratio C = 5 firstly increases before C is no more than 967 W/m^2 and then decreases with further increase in the solar irradiance. The maximum power output of CPV-TEG system could be achieved at 58.85 W, 103.04 W, 133.18 W, 149.98 W and 154.29 68 W separately for the concentration ratio varying from 1.0 to 5.0. The performance of the concentrated photovoltaic-TE generator (CPV-TEG) system highly depends on operations as well as physical parameters such as solar irradiation, concentration ratio, number of TEGs and environment air temperature.	When the values of solar radiation G vary from 100 W/m^2 to 1000 W/m^2, energy efficiency and exergy efficiency decrease respectively from 0.104 to 0.093 and from 0.112 to 0.1 for C = 1. The power output of CPV system is boosted by 14.22% when the TEG is installed to the back of solar cells. The exergy destruction of CPV-TEG increases with increase in solar radiation and concentration ratio, and the maximum Exd could be found to be much higher than the power output of CPV-TEG.	The performance of the CPV-TEG system highly depends on operations as well as physical parameters such as solar irradiation, concentration ratio, number of TEGs and environment air temperature.

[46]	For the solar TE generator studied in this paper; results showed that the daily power generation varied in a range of [-69.2%, 0.6%] over the electrical load. And the electrical loads for achieving the maximum daily power generation (i.e. 6.588 kWh/day) and maximum daily power generation efficiency (*i.e.* 2.657%) were both equal to 5.8Ω	Then, the daily performance of Solar TE generator STEG under real meteorological conditions is studied, and approaches obtaining the optimal daily performance are proposed.	House's energy harvesting and facades in large surface buildings.
[47]	The material purchased was $Bi_{0.4}Sb_{1.6}Te_3/Bi_{1.75}Te_{3.25}$. The prototype TE window is a large (132.25 cm^2) plexiglas panel with 144 holes integrated with 72 pairs of complementary TE pillars. The series connection is completed by connecting the complementary pillars by using custom made dog-bone-shaped copper interconnects. The output power from the large panel integrated with two materials was 0.16 mW for a temperature difference of 22.5 °C between the hot and the cold.	With meticulous engineering, 300 W of power can be generated from a 9 m^2 window for a temperature gradient of 20 °C, which is typical in hot climates. A TE window can be a supplementary power source for waste heat recovery in green building technology.	Thermoelectricity generating window.

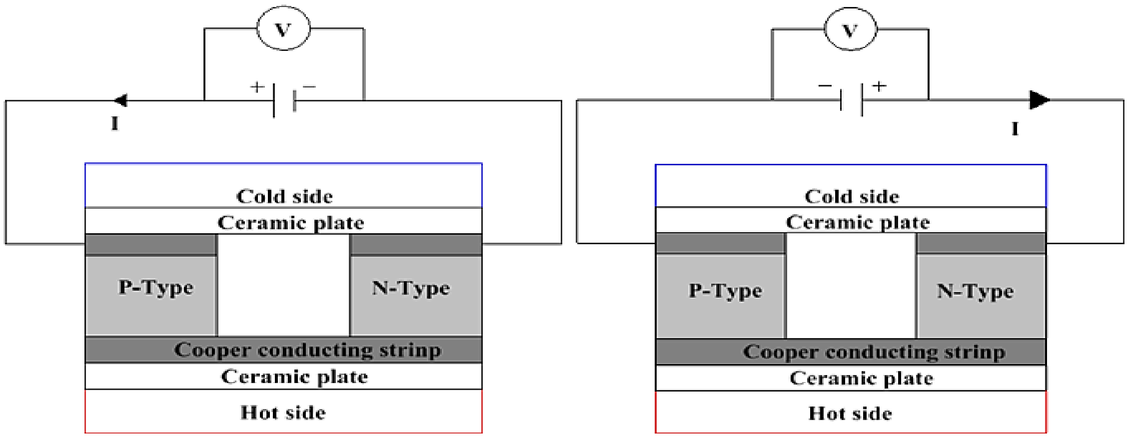
3.2 Green buildings

In the contemporary context where energy needs are on the rise rather than diminishing, the construction industry is embracing the concept of green buildings, which leverages energy waste for generation. The integrated development of net-zero energy buildings is driving the integration of TE technology and systems to curtail energy losses within structures. The approach to architectural design is transitioning towards energy conservation and efficiency. In this context, TE technologies offer substantial advantages: they require minimal maintenance, produce no noise, have minimal environmental impact, and consume low levels of energy.

While efficiency remains a pivotal parameter in the adoption of TE technology, the aesthetic aspect of building facades also assumes significance in the application of these technologies. Balancing the cost-benefit equation, architectural considerations undoubtedly emerge as a crucial design factor.

3.3 Heat and cooling systems

TE systems are employed in heating and cooling systems, capitalizing on the Peltier effect that arises when an electrical current flows through a junction between two dissimilar semiconductor materials.[22] This electrical current induces heat transfer from one junction to the other, causing one junction to cool while the other heats up. Reversing the direction of the applied current leads to a reversal in the direction of heat transfer, allowing Peltier cells to function as heat pumps. Fig. 6 presents a schematic representation of a TE System, demonstrating both its Heating Mode (a) and Cooling Mode (b) configurations.



a) b)

Fig. 6 Schematic representation of a TE system: a) Heating mode; b) Cooling mode.

Numerous researchers have harnessed the Peltier effect to create more efficient structures, reducing heat losses in ventilation and air conditioning systems. For instance, Trancossi *et al*.[34] conducted an analysis of an innovative TE heating and cooling system implemented in an energy-efficient container house. Their study focused on designing and thermodynamically evaluating a TE heat pump that leverages the junction box of photovoltaic modules and Peltier cells as heat sources. Additionally, Gondal[38] introduced a novel concept: a compact integrated solar-TE module that becomes an integral part of the building envelope. In this setup, the heating and cooling modes utilize photovoltaic electrical current to power the heat pump. Table 7 provides an overview of variables, operating conditions, and applications of TE technology in cooling and heating systems.

It is possible to say that TE can make part of our common life, making a big difference among several HVAC systems, due to buildings having great areas where this technology can be installed and the lower maintenance cost, as well as can take advantage of theirs both behavior because depending on the seasonal climate can be used for energy generation or heating and cooling the indoor facilities.

3.4 Simulation

Due to the high cost of TE materials and the development of projects for the application of this technology on a macro scale, simulation from the operating conditions of these tools appears as a good option to predict the feasibility and possible improvements that can be made before getting fully on track in the implementation of this technology. Table 8 provides an overview of the simulation models and applications for TE systems.

Table 7. Heating and cooling systems: applications and use cases.

Ref.	Variables	Operating conditions	Uses
[5]	A TE radiant panel ceiling is set up inside a solid, conductive material such as aluminum, and it is powered by an electric current source. A TE air duct system has been put into operation. The integration of a TE cooling façade with a photovoltaic system is in place.	Environmental and temperature difference between the duct and indoor space.	TE technology in air condition systems.
[37]	Evaluate the effect of gender difference on sleeping comfort and energy utilization in a test chamber with TE air- cooling systems.	The research revealed that female occupants reported feeling comfortably cool when the TE cooling system was operating at a capacity of 600 W, while male occupants generally expressed satisfaction with the system when it was running at a cooling capacity of 720 W.	Chamber with TE air-cooling systems
[62]	The most efficient material commercially available is bismuth telluride (Bi_2Te_3). ZT values ~1.5 for heat pump/cooling applications	Besides ZT, the COP of a TEHP depends on the value of the operating temperature difference (hot-cold sides) and on the electric current input.	TE heat pump. Building façade used for electricity generation.
[68]	The air-conditioning equipment is made up of 84 Peltier cells RC12-8, which are placed in groups of two TE cells, 70 W each, connected in series. This makes a total of 42 TE systems that are added to the base sheet2. The connection of the TE equipment is made in groups of two which are connected in series. Four Peltier cells are connected in series to form a group. All these groups are connected in parallel. Altogether 21 groups need a voltage of 50 V DC.	In a hot day $\Delta T = 5$ °C, in a cold day is $\Delta T = 15.73$ °C and the electrical consumption is respectively 2.5 and 2.75 kWh. Peltier systems generate a large amount of heat that, unless it was effectively evacuated, would damage the installation. This means that heat-dissipation elements must be used.	Active façade envelopes.

Table 8. TE simulating models and applications.

Ref.	Generation [V]	Simulating method	Uses
[34]	The adoption of a VT-199-1.4-0.8 Peltier cell ensures a maximum cooling power of 172 W and heating power of 278 W. Consequently, the maximum heating power reaches 2.7 kW, while the maximum cooling power is rated at 1.7 kW. A round pin heat sink has been preferred over a flat plate heat sink for its superior heat transfer efficiency.	Efficiency, voltage consumption, and ΔT generated by TE devices were determined through the application of the first and second laws of thermodynamics. The calculation involved a comprehensive analysis of factors such as monthly average solar radiation, environmental conditions, and the thermal properties of the building's construction materials.	Heating and cooling systems.
[39]	In terms of instantaneous heat gain during the summer, both the PV wall and massive wall act as heat barriers, reducing the heat flux and lowering the cooling load on the building envelope to approximately 12—20W/m^2. However, the BIPVTE wall stands out by providing nearly 45W/m^2 of cooling energy for the indoor space at noon. It's worth noting that the thermal bridge effect of the BIPVTE wall leads to slightly higher heat gain at night. In a broader context, when considering the daily heat gained, the PV wall and massive wall accumulate 318.7Wh/m^2 and 379.5Wh/m^2, respectively. In contrast, the BIPVTE wall exhibits a negative value of -9.9Wh/m^2, indicating a net reduction in heat gain. Comparing BIPVTE to the reference massive wall, the PV wall reduces daily heat gain by 16%, but the BIPVTE wall achieves remarkable energy savings, potentially offsetting about 102.6% of the energy consumed by the indoor air conditioning system on the hottest day.	The model establishment involved the utilization of several methods, including the Lambert W function, the state-space method, and an analytic model of the radiant panel. In terms of temperature, the coldest day is expected to reach approximately -3 °C, while the hottest day could soar to around 39 °C.	Photovoltaic and TE systems were simulated and evaluated.

The quality of a simulation is inherently linked to the quality of the data used as input. Simulations serve as powerful tools, enabling us to closely approximate and conclude the performance and efficacy of TE materials in construction applications. Even as costs are minimized, simulations necessitate rigorous sampling and comprehensive characterization of the specific location or case under study. Remarkably, the data generated from simulations often closely align with and are comparable to results obtained from entirely experimental systems.

3.5 Hybrid systems

Despite the abundant and versatile nature of solar energy, it remains underutilized in directly powering human activities. Solar electricity currently contributes to a mere 0.015% of global electricity production, while solar heat accounts for just 0.3% of heating for both space and water.[93] Therefore, there is a pressing need to enhance the energy conversion efficiency of materials, which currently falls short of 30%.[94]

Commonly, solar systems are designed to incorporate photovoltaic cells, TE modules, and hot water systems within a multi-layered building envelope. The actual energy conversion efficiency of such systems depends on factors like solar irradiation, ambient temperature, and water flow temperature, varying with the material properties of each layer.[65] In contrast to traditional solar panels, this design offers the potential for superior overall efficiencies, resulting in increased electrical power output and enhanced utilization of thermal energy.

The implementation of this technology can lead to the production of cost-effective assemblies. For example, Kumpeerapun *et al*.[95] investigated the performance of an innovative attic ventilation concept utilizing low-cost TE modules. This approach allows TE modules to harness energy from the temperature differentials generated by solar radiation on roofs and windows, as well as the internal temperature of controlled spaces with specific temperature and humidity requirements.

Indeed, the integration of TE technology into buildings is imperative, given their substantial energy consumption. TE modules have the potential to recover a percentage of this energy, depending on the scale of implementation.

3.6 Patent applications in building heat recovery

Patents offer valuable insights into ongoing developments within the field, providing a snapshot of the current state of TE technology advancement. Prominent patents highlight significant efforts aimed at optimizing TE materials and their applications in devices designed for measurement and variable control.

In the context of building heating systems, where steam and fluid piping are commonly employed, there is a critical need for monitoring and controlling variables such as temperature without compromising system integrity or endangering personnel conducting measurements. This necessity gave rise to the concept of utilizing TE technology to create a tool capable of reducing energy consumption. These tools effectively operate as direct current (DC) sources, powering temperature controllers on hot surfaces.

The potential for power generation lies in the temperature differential present in hot spots, allowing for the creation of integrated TE assemblies. For example, Dell R. *et al*.[74] devised a TE-based power generation system designed to be clamped onto the exterior of steam pipes or other heating pipes. This system can comprise multiple assemblies affixed to the pipe's sides, with each assembly comprising a hot block, an array of TE modules, and a cold block system. The hot block establishes a thermal pathway to the modules' hot plates, while the cold block incorporates a heat pipe equipped with fins.

N. G. Perego *et al*.[75] integrated energy generation and storage devices into roofing elements. These integrated roofing elements feature components capable of both generating energy (e.g., photovoltaic cells and TE devices) and storing energy (e.g., batteries and supercapacitors). Additionally, they may incorporate microinverters, such as three-phase microinverters, for energy transmission and reception with the grid. The elements also include controllers for directing the generated or stored energy within each integrated roofing element and between them, as well as to various alternating current (AC) and direct current (DC) loads. Moreover, these integrated roofing elements can be interconnected to form a roof structure that does not require continuous solid support beneath each integrated element.

J. Vollen *et al*.[76] introduced a material capable of adjusting at least one surface property in response to varying climatic conditions to influence energy exchange between the exterior and interior of a structure. This material is integrated into a building's façade envelope and associated materials.

3.7 The current landscape of waste processing for power generation

In 2015, Tsunatu *et al*.[29] described the gasification process as a method to generate energy from solid materials by subjecting them to heat in the absence of ambient oxygen, resulting in the production of a gas primarily composed of carbon monoxide (CO_2) and hydrogen (H_2). This process is primarily geared towards converting solid municipal waste into electricity. There are several thermal processes employed for power generation, including pyrolysis, gasification-pyrolysis, and conventional or plasma arc gasification. Each of these processes exhibits varying efficiencies, with Plasma Arc Gasification being one of the most efficient, producing approximately 816 kWh/ton of municipal solid waste (MSW) compared to about 685 kWh/ton MSW for conventional gasification technology.

Municipal solid waste comprises both organic and inorganic components, and the energy recovery typically focuses on the organic waste (as depicted in Fig. 7). Energy can be harnessed from these wastes through two main processes: thermochemical conversion or biochemical conversion. These processes generate thermal energy in the form of gas through the decomposition of waste materials.[96]

In 2016, Scarlat *et al*.[96] reported a total of 1,618 waste processing facilities worldwide that convert waste into energy. These facilities were distributed across different regions as follows: 512 in Europe, 822 in Japan, 88 in the United States, and 166 in China. Japan and Europe emerged as pioneers in energy generation from waste (see Fig. 7c). Currently, the most widely used method for energy generation from municipal solid waste is incineration due to its efficiency. However, alternative methods, such as anaerobic digestion, pyrolysis, and gasification, are also employed.[97]

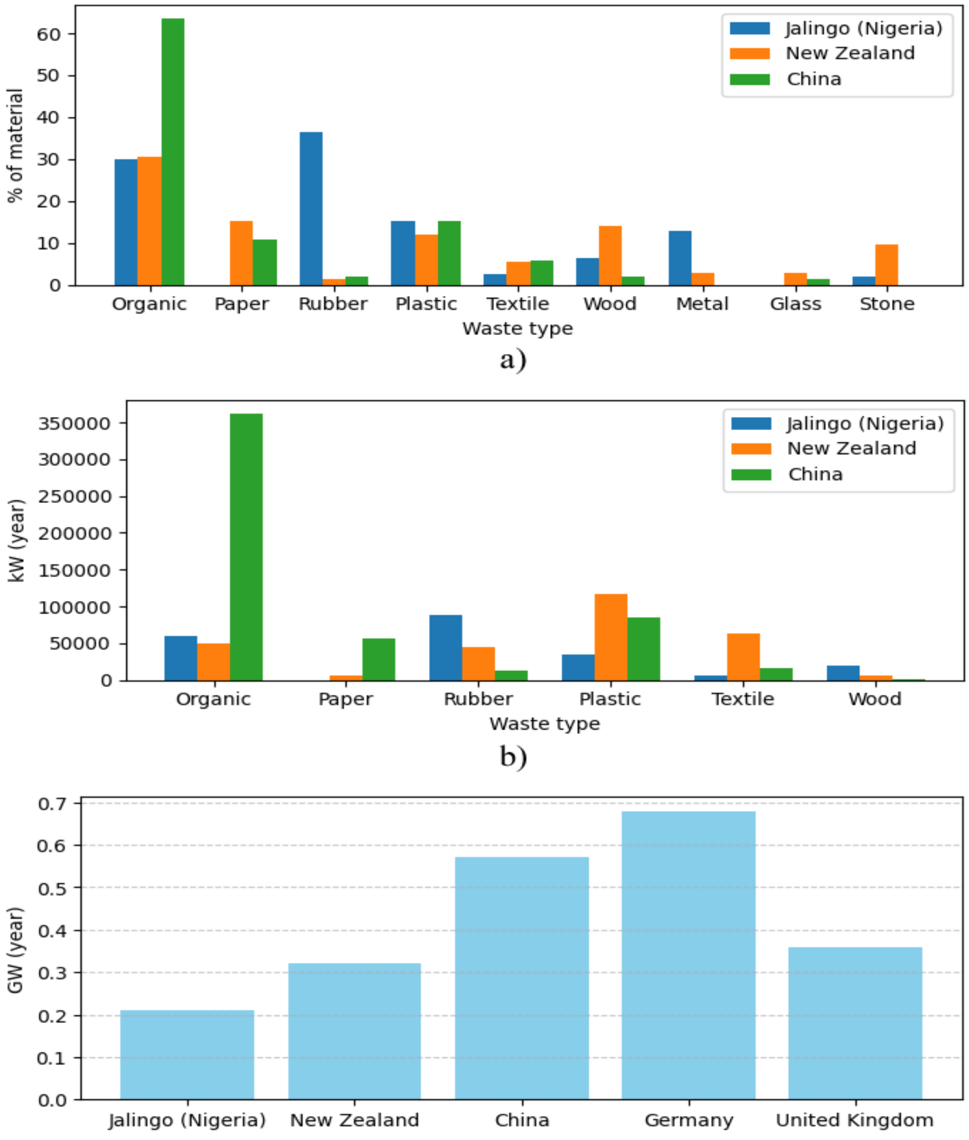
The authors Perrot[97] and Cheng[98] note that for heat recovery in municipal solid waste plants, the waste collected and processed, including bulky waste, primarily originates from homes, businesses, offices, educational institutions, and small markets. Consequently, as depicted in Figs. 7a and 7b, most of the obtained waste is organic in nature, given its prevalence in communities as a common source of consumption. It's worth noting that this process excludes materials that are eligible for recovery, recycling, or reuse, as they necessitate a more intricate management process tailored to their respective purposes.[97]

3.8 System development and structure

In 2020 Ishaq[78] introduced a comprehensive system that integrates cryogenic gas separation subsystems for the extraction of oxygen from nitrogen, a flow gasifier for biomass gasification, the Brayton cycle for power generation, and the utilization of TE devices for electricity generation. Within this system, TEGs play a pivotal role in converting heat extracted from the outlet of the Brayton cycle into electrical energy. The exhaust gases exit and are directed toward the generator's hot side, while the Rankine cycle is incorporated on the low-temperature side to further harness energy.

These systems encompass a cryogenic air separation subsystem responsible for oxygen-nitrogen separation, a flow gasifier designed to collect gas from municipal waste containers, and TEGs for electricity production. Power generation in this setup is achieved through the Brayton cycle, which involves energy generation via gas turbines employing an internal combustion system that imparts heat to the working fluid. This cycle comprises four key stages.[99]

- Isentropic heat compression
- Addition of heat to the working fluid at a constant pressure.
- Isentropic expansion of the turbine



a)

b)

c)

Fig. 7 Analysis and insights into waste classification and power generation a) percentage of waste classification by material, b) power generation according to waste classification by material, c) power generation by territory.

- Discharge of heat from the working fluid at constant pressure

An additional crucial cycle in this process is the Rankine cycle, primarily focused on heat preservation and operating in a manner akin to the Brayton cycle. The Rankine cycle serves as the working cycle for recovering waste heat from the TE generator, thereby generating electricity.[78]

In 2009, Maneewan elucidated that TEGs are employed within the system to convert heat extracted from the turbine's outlet into energy. The generator operates based on the Seebeck effect, which leverages temperature differences to convert heat flow into electrical energy.[89] The hot gases emanating from the turbine enter the generator's hot side, with the Rankine cycle integrated on the low-temperature side to maximize energy production.[78]

3.9 Efficiency, costs, and system recovery rate

Understanding the performance of TEGs compared to other energy recovery technologies involves critical considerations of efficiency, cost, and system recovery rate. This analysis addresses several studies, highlighting both the challenges and opportunities associated with thermoelectric modules (TEMs) when compared to alternative systems. Although TEMs offer a distinctive method of energy recovery through the Seebeck effect, their efficiency and cost-effectiveness require evaluation in comparison to other energy recovery technologies. The inherent advantages of TEMs, such as environmental sustainability and reliability, must be carefully weighed against efficiency and cost factors to determine their optimal applications in various energy recovery systems.

3.9.1 Efficiency and temperature differential

Wang *et al*. (Wang *et al*., 2014) emphasized the correlation between temperature differentials and output power in TE devices, highlighting the significance of temperature in determining the efficiency of TEGs. Higher temperature gradients generally contribute to improved efficiency, a factor inherently tied to the performance of TEGs.[89]

3.9.2 Power generation and electrical properties

Illustrative cases of TEGs demonstrate power generation levels at varying temperatures.[87] These generators typically operate at temperatures below 250°C, which can limit their power output compared to other systems.[87] Furthermore, specific design aspects, such as resistor utilization, can significantly impact the efficiency and energy generation of TEGs.[88]

3.9.3 Electrical properties and cost-effectiveness

TEGs predominantly composed of Bi_2Te_3 exhibit diverse electrical properties and power output capabilities, often operating at lower temperatures to ensure commercial viability and cost-effectiveness.[86,87] The cost of these modules can range between 10 USD and 23 USD, influenced by factors like temperature conditions and material selection.[100]

3.9.4 Thermoelectric module cost factors

The cost of thermoelectric modules (TEMs) varies based on temperature conditions, materials, and manufacturing processes.[100] Factors influencing cost include material efficiency, system-level considerations, and market trends. Specific applications and configurations can lead to significant price variations.[101]

Two cases of TEGs (see Fig. 8) illustrate their power generation levels (W/h) at varying temperatures. These generators exhibit relatively low power generation levels since waste decomposition systems typically do not reach temperatures exceeding 250 °C, significantly lower than other systems[87] Additionally, Case 2 demonstrates lower efficiency compared to Case 1, attributable to the utilization of a 2-ohm resistor, impeding current flow and thereby reducing energy generation.[88]

Various types of TEGs are employed in this system (see Table 9), predominantly composed of Bi_2Te_3, each exhibiting distinct electrical properties and power output capabilities. These generators operate at relatively low temperatures, rendering them commercially viable and cost-effective, with prices ranging between 10 USD and 23 USD.

Table 9. TE output power.

Ref.	Year	Output Power (W)	Model
[86]	2013	1.2	ENERKIT SC-127-10-15
[87]	2013	1	TEG-127-230-32e
[88]	2010	0.1	TEP1-12656-0.8.
[89]	2010	0.58	TEP1-1264-3.4
[89]	2010	0.49	TEG1-1260-5.1

3.10 Comparison with other technologies

A comparable system is the internal combustion system, which operates at relatively low temperatures like those of the decomposition system. However, unlike the decomposition system, it has lower energy generation levels even at equivalent or higher temperatures. This lower generation is attributed to the lower gas concentrations, resulting in lower gas flow and, consequently, an inability to achieve the heat concentration required to generate equivalent levels of energy at these temperatures (see Fig. 9).[102,103]

Compared to other energy recovery technologies, TEMs excel in applications where quiet operation, reliability, and the ability to operate with small temperature differences are critical. They also offer advantages in remote or hazardous locations where maintenance is complicated. However, for applications requiring high power and efficiency, other technologies may be more suitable.

While TEMs may not consistently offer the most efficient or cost-effective option for energy recovery, they offer clear advantages in terms of reliability, environmental impact, and suitability for specific applications. Ongoing research aims to improve efficiency and reduce the cost of TEMs, which could broaden their applicability in the future.

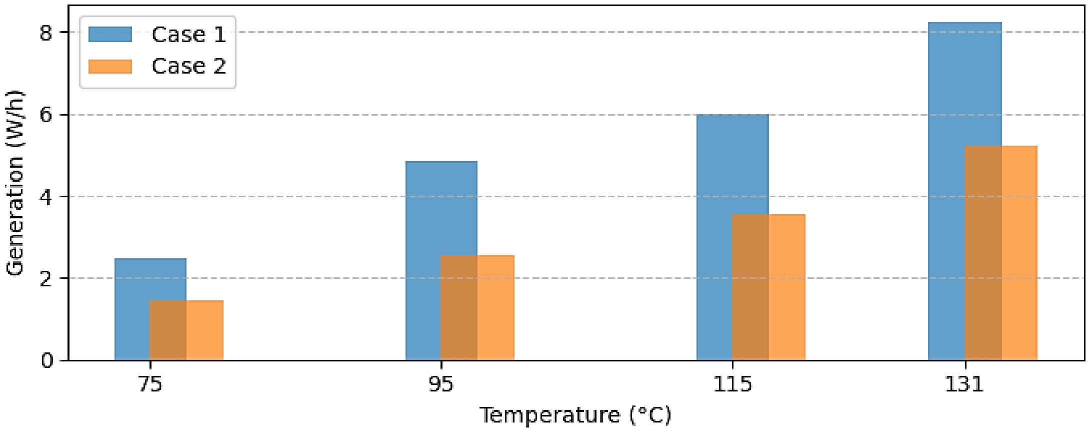


Fig. 8 Power *generation* of Bi_2Te_3 TEGs: Case 1[87] and Case 2[88]

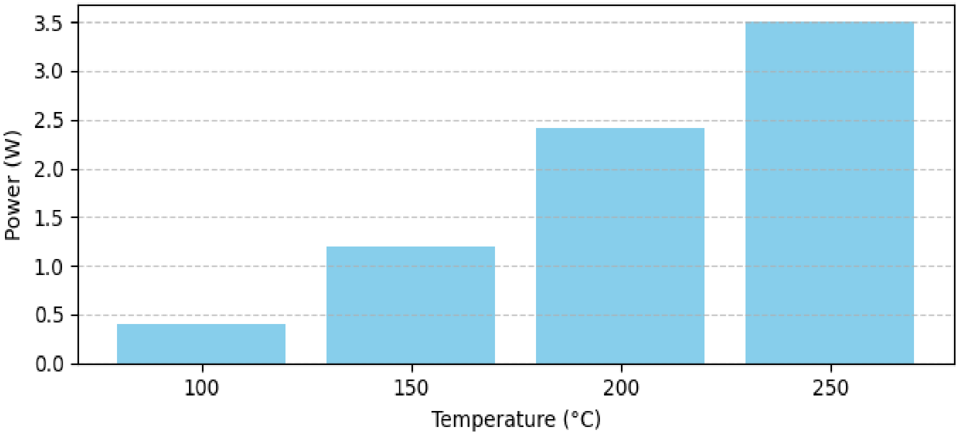


Fig. 9 Power generation in internal combustion engines.

3.11 Environmental impacts and circular economy considerations

In terms of environmental impacts, this process will primarily be assessed in relation to climate change, human health effects, and the generation of airborne particulates affecting air quality. In 2019, González-García and Bacenetti[104] outlined potential consequences of employing TE devices in biomass disintegration plants for energy production. Regarding climate change, González-García and Bacenetti explained that the changes resulting from this technology are unlikely to be significant. However, the process enables waste separation, allowing for alternative uses of these materials, thereby contributing positively to waste reduction and resource reuse. Moreover, this eco-friendlier process produces fewer greenhouse gas emissions compared to conventional combustion systems used in forestry machinery, further benefiting the environment.

In 2020, Moliner *et al.*[105] described the generation of unwanted materials, particularly ash, during the solid waste disintegration process, particularly from biomass. Embracing the principles of the circular economy, efforts have been made to ensure that nothing goes to waste, as doing so would entail unnecessary costs for the plant. Consequently, innovative applications for this ash have been sought post-disintegration. These ashes, predominantly organic in nature, can serve multiple purposes, such as soil fertilization and absorption of pollutants from liquid or gaseous streams in proximity to production sites (see Fig. 10).

In 2014, Genon *et al.*[106] emphasized that the future of energy derived from biomass decomposition hinges on the availability of biomass for biofuel and thermal or electrical energy production. To harness the full potential of this energy source in the future, it is essential to implement effective forest biomass management. Proper management can significantly contribute to environmental improvement by enhancing the control of carbon emissions, particularly in comparison to current conventional decomposition methods. If successful, it is anticipated that by 2050, forest biomass could account for 18% of global primary energy consumption.[107] Furthermore, it is projected that by 2050, bioenergy from greenhouse gases could contribute to the production of 100-200 EJ (exajoules) of energy.[108] The realization of this substantial energy production is contingent upon the efficient management of forest biomass resources.

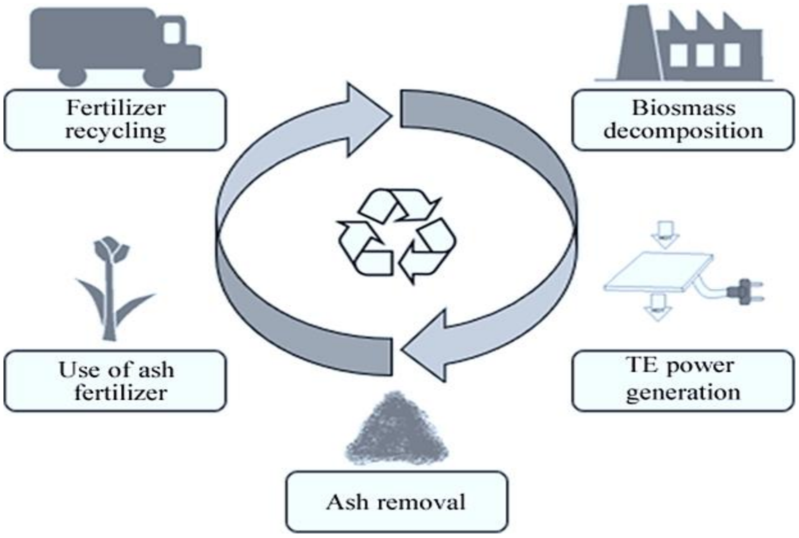


Fig. 10 Circular economy framework for biomass disintegration process.

4. Opportunities and prospects

The potential applications of TE technology in buildings offer significant opportunities. These applications extend beyond outdoor heat recovery from areas exposed to varying climatic conditions and can encompass indoor hot spots such as furnaces, extractors, heating ducts, and gas heaters. TE systems have advantages over other heat recovery systems, notably their low maintenance requirements, minimal noise output, and suitability for integration into the ample available spaces within buildings. By implementing large-scale TE solutions in modern constructions, it becomes conceivable to create self-sufficient buildings. Given that buildings account for a substantial portion of energy consumption, the energy recovery potential of TE technology holds great promise.

Furthermore, TE systems not only enable energy generation but also facilitate space conditioning, allowing their versatile use depending on environmental and climatic conditions. Representing a versatile and adaptable system, TE technology can usher in a transition toward more energy-efficient buildings, a crucial aspect of the global energy transition.

However, as a relatively new technology, the cost of TE materials may pose a limitation to their widespread adoption. Therefore, the development of more cost-effective and efficient TE materials remains a significant challenge.

From the new materials perspective, several proposals need to be fully implemented and further investigated, to improve the thermoelectric performance, the ZT maximum.[109] Materials such as SnSe,[110,111] $Cu_2(Se,Sn,Te)$,[112–114] Pb(Te,Se,S),[109,115–117] Bi_2Te_3 nanowires,[118] can have all ZTmax bigger than 2.0, which shows a line of research for further improvements. Perhaps a combination of the higher volumetric TE materials presented before with these nanowires could be a solution to move forwards the performance of a new generation of TE devices. For polymers, flexible TE materials are an intense area of research.[119,120] Polymers such as polyacetylene, polyaniline, polythiophene, polypyrrole, Poly(3,4-ethylenedioxythiophene), and Poly(styrenesulfonate) are examples of them, with ZTmax values even reaching up to 1 in some cases.[120] In ceramics, there are excellent materials for TE[121] because of it is high thermal and mechanical stability, but in some cases limited by the high temperature processing and costs. One emerging area to solve this problem is the porous ceramics.[122] The TE fabrication is being revolutionized by additive manufacturing, also known as 3D printing.[123] Sustainability,[124] nanocomposites,[125] and design,[126] are some of the areas that could be improved. Diverse additive manufacturing technologies are being used for the fabrication of TE devices: fused deposition modeling,[127] laser-based,[128] direct energy deposition,[129] and materials jetting.[130] are some of the examples. All these areas are willing to further improve the efficiency of TE and decrease their manufacturing costs.

5. Conclusions

Heat losses in buildings present a significant opportunity for small-scale power generation and energy utilization systems. TE technology demonstrates its potential in reducing energy consumption, whether applied to ventilation and air conditioning systems or incorporated into heat sinks for photovoltaic panels.

The application of TE technology is closely intertwined with advancements in materials science, aiming to make this technology more cost-effective for widespread adoption. Emerging fields like nanotechnology hold promise for the development of highly efficient and affordable TE materials. While large building areas can be leveraged for TE installations, the architectural design of buildings must also be considered to align with aesthetic and technological innovations. Striking a balance between efficient TE materials and modern construction aesthetics presents a noteworthy challenge.

This research has primarily focused on information gathered from 2010 to 2020, offering insights into recent developments in the field. The central focus of this study has been on power generation through TEGs in waste decomposition facilities, highlighting the utilization of this energy source as an alternative means of electricity production. Although TEGs exhibit relatively low power output, this research has provided a comprehensive understanding of their energy generation capabilities. While information on the costs associated with this process is limited, it is evident that the integration of TEGs into the system may incur expenses, which are offset by the considerable energy output achieved in these systems, considering their relatively modest size.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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