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Review

Thermoelectric Generators Applied as a Power Source in CubeSats: State of the Art

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Abstract: This systematic review outlines the application of thermoelectric generators (TEGs) as energy sources in CubeSats. While CubeSats currently rely on solar cells with efficiencies between 16.8% and 32.2%, their performance diminishes with increased distance from the Sun. TEGs, although used in radioisotope thermoelectric generators (RTGs) for satellites, remain underutilized in CubeSats. A literature review revealed 33 relevant articles, with 21.2% employing simulation software to evaluate thermal behavior. Among 34 patents, only one mentioned micro-TEGs, with most focusing on structural improvements. Patent activity peaked between 2016 and 2020, emphasizing structural and thermal optimization, but no patents addressed TEGs as energy sources for CubeSats, highlighting a significant research gap. TEGs present a viable solution for harnessing residual heat in CubeSats.

Keywords: ProKnow-C; thermoelectric generators; TEG; energy source; mapping; CubeSat

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1. Introduction

Since the launch of the TIROS-M satellite in 1970, satellites have played a vital role in Earth observation, meteorology, and communication, providing essential services such as weather monitoring and connectivity in remote areas [1,2]. However, the high production and launch costs of traditional satellites have historically restricted their development to major space agencies like the National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) [3].

Since its inception in 1958, NASA has undertaken manned missions and launched communication satellites to enhance telecommunications and expand internet access. Similarly, ESA, founded in 1975, has contributed to global internet and telecommunications infrastructure through satellite launches and participated in scientific missions, such as the Cassini and Huygens probes, which provided valuable data on Saturn and its moons. The Soviet Union pioneered space exploration with the launch of Sputnik 1 in 1957, the world's first artificial satellite, marking the start of the space age and driving the development of subsequent communication satellites [4–6].

Advancements in Micro-Electronics and Microsystems Technologies have enabled the miniaturization of components, reducing costs and paving the way for SmallSats. These compact satellites maintain key functionalities while minimizing size and weight, making them an efficient and affordable option for LEO missions, significantly expanding access to space technology [7,8].

The CubeSat, developed in 1999 by professors Jordi Puig-Suari (California Polytechnic State University) and Bob Twiggs (Stanford University), is a standardized nanosatellite with dimensions of 10 × 10 × 10 cm, weighing up to 1.33 kg, as shown in Figure 1. One of its most notable advantages is the ability to be constructed entirely from COTS (Commercial Off-The-Shelf) components, which ensures adaptability to various mission requirements while maintaining low production costs. Additionally, its power consumption is minimal, estimated at only a few watts [7]. This standardization of size, mass, and capacity aimed to simplify satellite control and enhance payload flexibility, making it a popular choice for nanosatellite missions, with launch costs typically ranging from $50,000 to $200,000 [9,10].

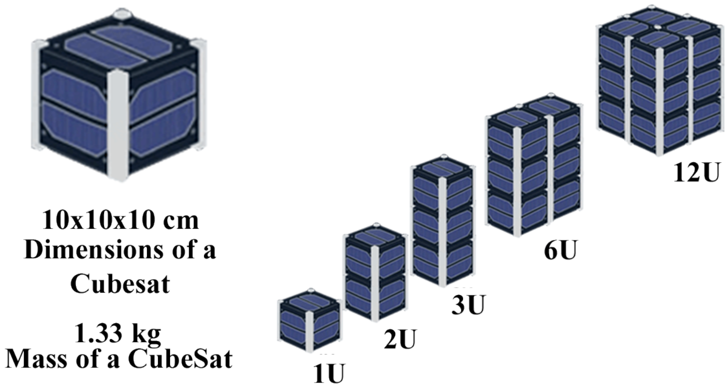


Figure 1. Standardized structure of a CubeSat. Adapted from [11].

In economic terms, the cost-per-kilogram ratio of payload has become the primary criterion for its transportation and launch, as the greater the amount of payload (in kilograms) to be launched into space, the higher its cost. This ratio has proven advantageous compared to traditional satellites, particularly for low-Earth-orbit missions, regarding construction and assembly time [10,12].

Focusing on the power supply for the systems and subsystems that make up the CubeSat, it is common to use photovoltaic solar cells as the main energy source, with efficiencies ranging from 16.8% to 32.2%, depending on their construction. Despite being widely implemented in space, these solar cells have the main disadvantage of specific power generated, measured in watts per kilogram (W/kg). This power decreases rapidly according to the $1/R^2$ relation, where R is the distance to the Sun [13,14].

Another possible unexplored solution to the use of solar cells is employing thermoelectric generators (TEGs) as a power source for CubeSats. Their application in satellites was already observed in [14]. Therefore, conducting research on the use of TEGs as a power source for CubeSats could reveal a promising application for low-Earth-orbit (LEO) space missions. Exploring this alternative could lead to significant advances in the feasibility of space missions with nanosatellites, expanding the technological and scientific capabilities of this sector.

TEGs and PVs are key energy sources for CubeSats, each with distinct advantages. TEGs efficiently convert temperature differences into electricity, leveraging waste heat from onboard systems and providing a reliable energy source in low-solar environments, such as deep-space orbits. Their compact, lightweight design suits CubeSats' weight constraints, although their conversion efficiency is relatively low (3.12–9.6%) [15,16]. PVs, on the other hand, achieve higher conversion efficiencies (16.8–32.2%) by directly harnessing solar energy, but their performance depends on consistent sunlight exposure and can be hindered by shading or orientation issues. Together, these technologies offer complementary solutions for diverse mission profiles. The comparative synthesis of the mentioned energy sources is presented in Table 1.

Table 1. Comparison between TEGs and PVs.

Characteristic	TEGs	PVs
Principle	Temperature difference conversion	Solar energy conversion
Efficiency	3.12–9.6%	16.8–32.2%
Weight	Lower in relation to generated power	Higher in relation to generated power
Dependency	Constant heat source	Solar exposure
Advantages	Operates without sunlight; utilizes residual heat; resistant to extreme conditions	High efficiency in energy conversion; greater performance in the presence of sunlight
Disadvantages	Low efficiency compared to PVs	Dependence on sunlight; reduced efficiency in shade or improper orientation

Preliminary Studies

A preliminary search identified eight scientific articles related to the research topic. Three focused on simulations using FEM software to analyze the thermal behavior of 1U CubeSats, specifically the operating temperatures of internal devices. One article explored the use of Thermoelectric Coolers (TECs) as temperature regulators for CubeSat hardware, while two investigated the application of micro-TEGs and conventional TEGs as energy sources for specific sensors in CubeSats. Additionally, two studies provided insights into advancements in thermoelectric systems: one highlighted recent progress in the modeling and simulation of thermoelectric power generation, emphasizing innovations in materials and multi-physics modeling approaches, while the other introduced a novel thermoelectric generator design incorporating stacked modules and dual heat pipes to enhance power density and efficiency.

Concerning this, the study proposed by [17] evaluated the energy generation potential of TEG modules using temperature gradients from solar panels. They conducted a numerical analysis to estimate temperature gradient variations in low Earth orbit, and the resulting data were used in an experimental test bench to map the real-time generated power. In conclusion, the experiment successfully reproduced the expected temperature gradients, but there were data discrepancies when the TEGs reached temperatures above 35 °C due to a limitation of the TEG itself.

In [18], the research addressed the development and verification of a conceptual model and an analytical model of the thermal controls of a 3U CubeSat, focusing on the study of an Orbital Satellite for Investigation of the Response of the Ionosphere to Stimulation and Space Weather (OSIRIS). The use of COMSOL Multiphysics to create FEM thermal models, along with analytical calculations, was essential to determine the worst-case temperature limits that the OSIRIS-3U might encounter during its mission. Additionally, a theoretical understanding was developed for applying different types of TEGs aimed at capturing residual energy in CubeSats. The results indicated that thin-film TEG devices provided a higher power density compared to traditional TEGs; however, due to the low expected temperature gradient in a CubeSat, the efficiency of these devices remained below 1%.

Therefore, with the mass and cost constraints of CubeSats, the current TEG technology did not seem viable for that application.

From this perspective, Ref. [19] presented a study evaluating the potential of using TEGs as an energy source to power an Assistance System, which was based on ensuring communication with a ground station or a service satellite, delivering data for maneuvers of inactive spacecraft. To achieve this, it was necessary to analyze the electrical characteristics of TEGs under space conditions to evaluate their potential for capturing residual energy in spacecraft, as commercial TEGs were developed for use on Earth. As a result, the analysis demonstrated that the proposed system was viable, with the necessary power being provided by TEGs utilizing the thermal loads present within a satellite.

In parallel, given the proposed research topic, it is extremely important to understand the thermal energy balance that occurs in a CubeSat, as the temperature distribution on the equipment's surface influences the TEGs' energy generation. Within this context, Ref. [20] focused on creating an accurate thermal model for the CubeSat MYSat-1, considering the effects of various thermal sources in orbit. A detailed model was developed using Ansys Workbench software and compared with CubeSatWizard, another MATLAB-based software The simulation results were compared with maintenance data, showing an acceptable difference of 0.45 °C in the CubeSat's average temperature between real data and the model results. However, on hot days, that difference was more significant, reaching 14 °C.

A study conducted by [21] involved the analysis of thermal simulations in a 1U CubeSat to ensure the electronic devices operated within their limits. Additionally, the study aimed to demonstrate that numerical simulations could be used to predict and optimize the temperature distribution of the space system before its construction. Ansys Icepak and Thermal Desktop software were used under LEO conditions. In conclusion, there was no overheating of the components under terrestrial hot-face conditions, as they were low-power devices. However, the study warns that in the near future, electronics were likely to continue developing while adding more power and functionality to devices. Therefore, thermal control would be necessary to ensure system reliability.

Another study proposed by [22] addressed the thermal simulation of a 1U CubeSat using COMSOL Multiphysics software Their objective was to simulate the impact of the inclination angle (beta angle) of the CubeSat on the temperature distribution of the nanosatellite, which describes the equipment's position relative to the solar vector. To investigate this parameter's effect, a set of simulations was performed for different beta angles. The simulations showed that the larger the beta angle, the greater the nanosatellite's exposure to prolonged solar heating, implying longer periods of both direct solar radiation and Albedo radiation.

In [23], the authors highlight significant progress in thermoelectric generator (TEG) systems, focusing on innovations in modeling techniques—analytical, numerical, and experimental—and advancements in materials like bismuth telluride, known for superior energy conversion properties. They explore the integration of Computational Fluid Dynamics (CFD), using COMSOL Multiphysics, with thermoelectric modeling to enhance simulation accuracy and presents practical applications, such as using TEGs to convert waste heat into electricity in automobiles, demonstrating improved energy efficiency even under variable conditions. Their research also addresses ongoing challenges, such as the need for more efficient materials and the integration of TEGs into complex systems, suggesting future investigations into novel thermoelectric materials and multi-physics models that account for phenomena like thermal conduction and electromagnetic conversion.

Lastly, Ref. [24] presents an innovative thermoelectric generator (TEG) design that utilizes stacked thermoelectric modules (TEMs) and dual heat pipes to significantly enhance power density, achieving up to 48.22 W/L in experiments, with a prototype output of 848.37 W. The use of dual heat pipes improves heat transfer efficiency between heating/cooling sources and the TEMs' hot/cold sides, enabling greater integration of TEMs in compact spaces. The study also highlights the adaptability of the design by modifying the number of layers in the stacked structure for diverse applications. Furthermore, it discusses the role of topological optimization and finite element modeling to simulate TEG performance, with experimental results validating the approach and demonstrating substantial efficiency improvements.

The data from the studies are essential for understanding the current limitations and future potential of TEGs. Advances in modeling combined with the development of new materials hold great promise for significantly enhancing the efficiency and applicability of thermoelectric systems. These improvements could make TEGs a viable option for various applications, including space exploration, where harnessing waste heat is critical for energy generation in resource-constrained environments.

This research aims to identify the application of TEGs as a power source for the Electrical Power System (EPS) of a 1U CubeSat operating in LEO. By mapping their application against existing technologies, the study seeks to address the gap in the use of TEGs in space missions and explore their potential for nanosatellite energy optimization. To achieve this, a systematic state-of-the-art review was conducted to identify the scientific literature and intellectual property (IP) related to EPS power sources, complemented by bibliometric analyses of the Bibliographic Portfolio (BP) and Patent Repository (PR). Connections between the datasets were further explored using Vosviewer software 1.6.20.

Initial research underscored the limited exploration of thermoelectric generators (TEGs) in nanosatellites, despite their widespread application in terrestrial industries such as automotive and manufacturing. This underutilization highlights a promising opportunity for LEO missions, particularly in leveraging TEGs as alternative power sources. Notably, the only prior use of TEGs in satellite applications involves radioisotope thermoelectric generators (RTGs). RTGs have been indispensable for NASA missions where solar power is impractical, such as in deep-space exploration. Often referred to as "nuclear batteries", RTGs have powered over 25 U.S. space missions since their debut in 1961, serving as a cornerstone of NASA's longstanding collaboration advancing space power systems [13].

A patent analysis identified only one direct application of TEGs for specific subsystems, neglecting geometric optimizations that could improve the watt-per-kilogram payload ratio of nanosatellites. The highlights of this study include:

- **Scientific and industrial impact**: TEGs can improve the energy efficiency of nanosatellites by increasing the W/kg payload ratio, enhancing power availability during low-Earth-orbit phases.
- **Unexplored technological approach**: the research addresses gaps in the application of TEGs as power generators for nanosatellites, utilizing temperature gradients from the space environment.
- **Utilization of waste heat**: TEGs harness waste heat generated by internal components or external space conditions, offering a novel approach to energy utilization in nanosatellites.
- **ProKnow-C methodology**: application of the ProKnow-C systematic method for mapping scientific and industrial developments related to TEGs as energy sources for CubeSats.

The study contributes to addressing this gap by investigating and analyzing key academic and industrial trends in the aerospace sector. While thermoelectric devices have primarily been used as temperature regulators for CubeSats, this research emphasizes their potential as energy sources, focusing on waste heat utilization and geometric optimization.

The results aim to enhance the performance of CubeSats, increase their power efficiency, and support future advancements in nanosatellite technology.

The article is structured into four sections. Section 1 contextualizes the topic, defines the general objective, and outlines the expected results and scientific contribution. Section 2 details the methodology, using the ProKnow-C method for a systematic review to select the Bibliographic Portfolio (BP) and Intellectual Property search, with a comprehensive bibliometric analysis of publications, patents, authors, and inventors, as well as the relevance of articles and patents. Section 3 provides a comparative analysis between the scientific portfolio and IP, utilizing Vosviewer software to examine the relationship between academic research and industrial patents. Section 4 concludes the study, summarizing the analyses and suggesting directions for future research.

2. Systematic Review

According to [25], a literature review aims to establish a line of reasoning that assists researchers in formulating hypotheses on the topic. Furthermore, a systematic review is essential for answering research questions, highlighting the main topics covered. This process aims to ensure a comprehensive and in-depth understanding of the subject.

In this context, the process of a systematic review is illustrated by the flowchart in Figure 2. Its organization involves a preliminary search for documents related to the topic to be investigated. These documents form a PDB, which should be studied to ensure alignment with the topic. Subsequently, the most common KWs should be extracted and combined, resulting in the main terms that will be used as references for creating the BP and PR. A general study of the obtained documents is conducted to ensure their relevance to the most pertinent information for investigating the proposed topic.

In this research, the scientific literature review addressing the utilization of residual heat for energy generation from TEGs as a power source for the EPS of a CubeSat was conducted using the ProKnow-C methodology, "Knowledge Development Process Constructivist".

According to [26,27], using this methodology as the primary tool to structure the BP aims to ensure its methodological foundation, based on the topic of interest, while considering the delimitations and restrictions of the articles that compose this portfolio. This establishes its scientific relevance and alignment with the research topic, based on the axes composed of combinations of KWs.

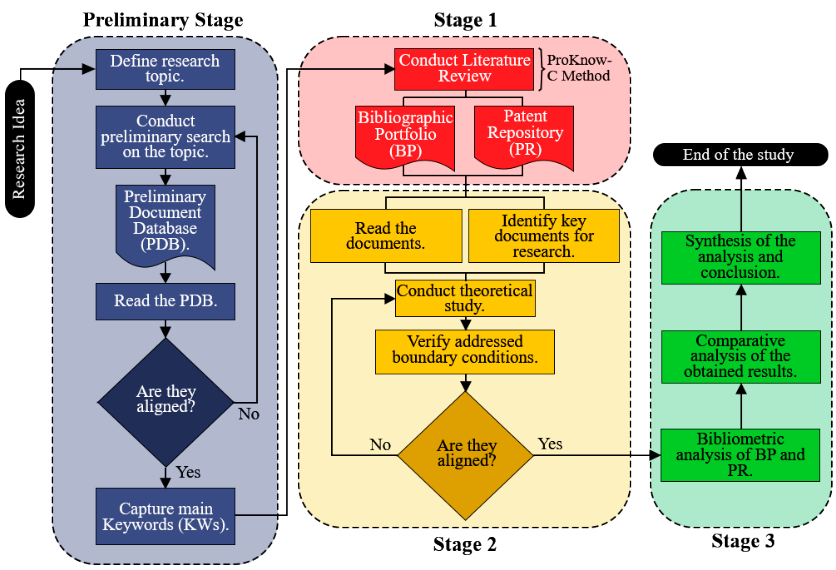


Figure 2. Basic process for conducting a systematic review.

The selected articles undergo a validation of the KWs through a verification of those present in the articles and are subsequently subjected to a bibliometric and systemic analysis. These steps form the primary stage of the ProKnow-C process, which consists of the following stages: selection of the BP; bibliometric analysis of the BP; Systemic analysis of the BP; and research question, as shown in Figure 3.

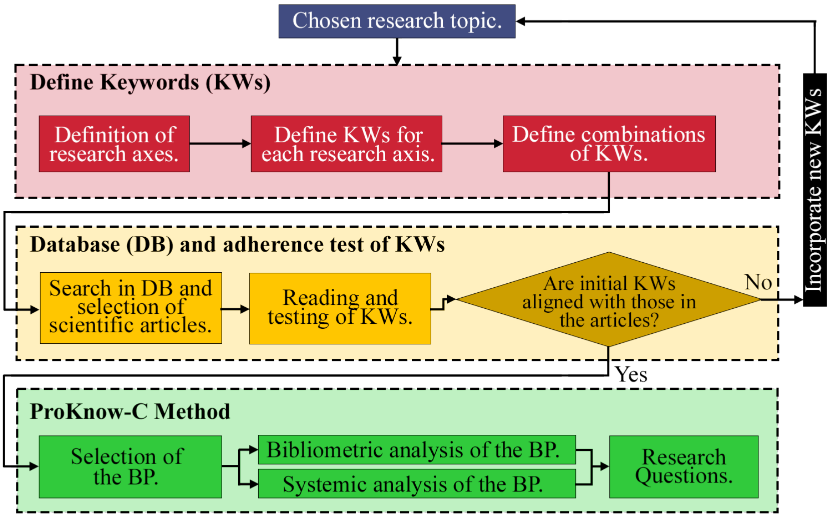


Figure 3. ProKnow-C methodology process.

2.1. Selection of the Bibliographic Portfolio

As an initial step in the execution of the ProKnow-C method, the selection of the BP is carried out through a systematic search for scientific materials, primarily in reliable databases [28]. For the present research, the chosen data sources were the WoS database, which generates the JCR and determines the impact factor of its journals, the Scopus database, which uses the SJR as its impact factor, and the SD database.

After selecting the DBs, the axes and KWs to be used for queries in these databases were defined. To clearly and comprehensively present the ProKnow-C procedures, the selection of the BP was organized into four axes within the proposed topic: Axis 1: internal and external temperature and structure of a nanosatellite; Axis 2: power sources and EPS of a nanosatellite; Axis 3: concepts of TEGs and their application in space; and Axis 4: thermal analysis in nanosatellites.

The combination of KWs for each axis was performed using logical expressions "and" and "or". Additionally, since the research area of this work focused on space conditions and the electronic systems of a nanosatellite, a category filter available in both DBs was applied, such as aerospace engineering, electrical/electronic engineering, mechanical engineering, and thermodynamics for WoS, and engineering for Scopus and SD.

The results of each query are displayed in Table 2, with a space–time delimitation over a period of 24 years. This time frame was defined based on the advancement of research that occurred from the year 2000 onward [1].

The PRAD, initially containing 1554 documents, was imported into the Mendeley bibliographic management tool [29]. After importing all the DBs into the software, it was verified whether all files from the export process were stored. This step was necessary because some titles may not have been exported due to unavailability in the desired format [30]. To address this issue, a manual search for the articles in the DBs can be performed. However, this process was not conducted at that stage.

Table 2. Results of the searches conducted in the DBs.

Database	WoS	Scopus	SD
Axis 1			
(CubeSat or Nanosatellite) and (Design or Structure)	312	157	10
(Temperature or Thermal) and (Internal or External) and (Nanosatellite or CubeSat)	27	8	80
("Finite Element analysis") and ("Thermoelectric Devices" or "Thermoelectric Generators" or "TEG") and (CubeSat)	1	0	0
Axis 2			
("Power Supply" or "Source") and (Nanosatellite)	188	156	90
Axis 3			
("Thermoelectric Generators" or "Thermoelectric Generator" or "TEG") and (Principles)	109	27	235
("Thermoelectric Generators" or "Thermoelectric Generator" or "TEG") and ("Space Applications")	26	25	50
Axis 4			
(CubeSat or Nanosatellite) and ("Thermal design" or "Thermal Modeling")	17	21	15
Preliminary Raw Articles' Database (PRAD)		**1554**	

As a result, the RAD contained 1309 titles, representing a loss of 15.76%. Subsequently, filtering actions were carried out to verify if the articles aligned with the proposed topic to obtain the K and P repositories, as described in the flowchart in Figure 4 [31]. At the end, 175 articles were obtained, whose citation numbers were verified on Google Scholar on 23 January 2024.

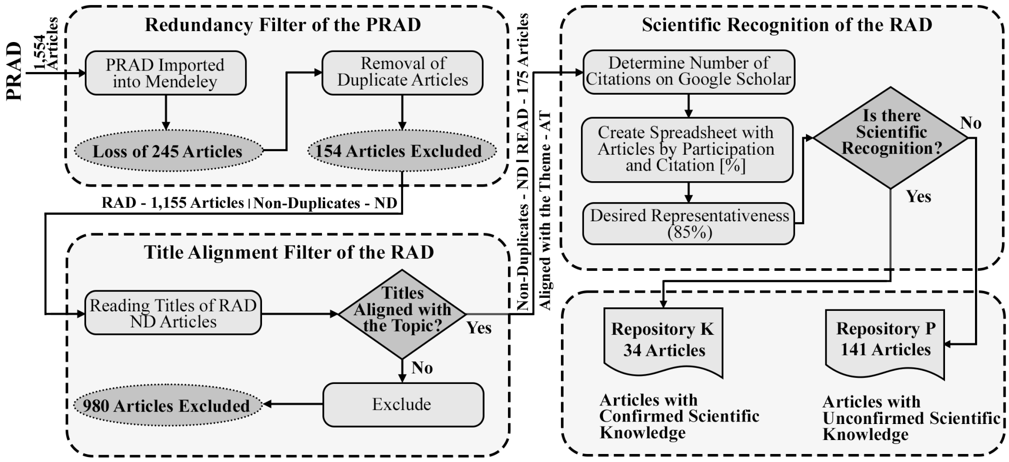


Figure 4. Initial filtering process for aligning titles with the proposed theme.

The organization of these articles was defined such that the citations were in descending order. Additionally, the minimum scientific representativeness criterion adopted followed the Pareto principle, which states that, in many phenomena, 80% of results or consequences are produced by 20% of their causes [32]. In this work, the adopted representativeness was 85%.

Using algorithms developed in Python, Repository K was composed of 34 articles with a cutoff value of 49, demonstrating proven scientific reliability. These articles represented

85% of the total citations, being cited 49 or more times. Conversely, Repository P consisted of 141 articles of lower academic relevance and without proven scientific reliability, divided between 104 journals with 1 to 48 citations and 37 without citations. Due to the number of articles in both repositories, the procedures established by [27] were automated using Python algorithms. These steps included verifying the thematic alignment of the articles, creating the AD, and validating it with articles from Repository P. Figure 5 illustrates a flowchart of the executed procedures, also presenting the final activity counts for the composition of Repository C.

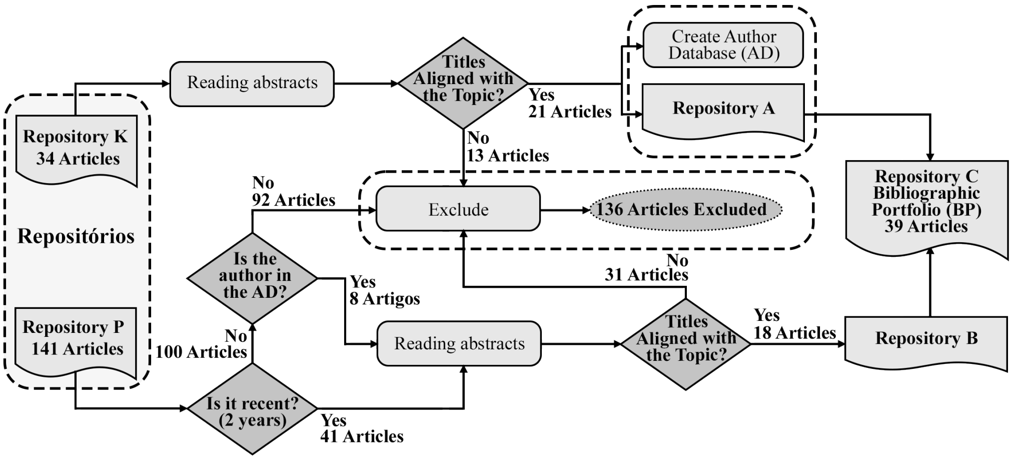


Figure 5. Process of analyzing Repositories K and P, resulting in Repository C.

In the end, Repository C was created by merging Repositories A and B, containing 39 articles that constituted the final BP, ensuring verified academic relevance and alignment with the researched topic. Each article in that portfolio was verified for availability through the CAPES portal or free access on the internet. As a result, 6 articles were excluded, totaling 33 articles in the BP. After these analysis procedures, the selection of that BP represented 2.12% of the initial 1554 articles. The 33 articles, ordered in descending order by the number of citations, are listed in Table 3.

Table 3. Presentation of the thirty-three articles that compose the Bibliographic Portfolio (BP).

Reference	BP Article	Citations
[33]	Thermoelectric generators: A review of applications. Energy Conversion and Management, 140, 167–181.	1185
[34]	Recent development and application of thermoelectric generator and cooler. Applied Energy, 143, 1–25.	762
[3]	CubeSat evolution: Analyzing CubeSat capabilities for conducting science missions. Progress in Aerospace Sciences, 88, 59–83.	534
[35]	Survey of worldwide pico- and nanosatellite missions, distributions, and subsystem technology. Acta Astronautica, 67, 854–862.	493
[36]	Safe radioisotope thermoelectric generators and heat sources for space applications. Journal of Nuclear Materials, 377, 506–521.	260
[37]	Review of wearable thermoelectric energy harvesting: From body temperature to electronic systems. Applied Energy, 258, 114069.	245

Table 3. *Cont.*

Reference	BP Article	Citations
[38]	Review of Micro Thermoelectric Generator. Journal of Microelectromechanical Systems, 27, 1–18.	219
[39]	Thermoelectric generator (TEG) technologies and applications. International Journal of Thermofluids, 9, 100063.	201
[15]	Thermoelectric Generators: A comprehensive review of characteristics and applications. Applied Thermal Engineering, 201, 117793.	151
[40]	Review of thermoelectric geometry and structure optimization for performance enhancement. Applied Energy, 268, 115075.	145
[41]	OpenOrbiter: A low-cost, educational prototype CubeSat mission architecture. Machines, 1.	109
[42]	A review of the state-of-the-art in electronic cooling. E-Prime—Advances in Electrical Engineering, Electronics and Energy, 1, 100009.	102
[7]	Small satellites and CubeSats: Survey of structures, architectures, and protocols. International Journal of Satellite Communications and Networking, 37, 343–359.	101
[43]	Thermal design and analysis of a nanosatellite in low earth orbit. Acta Astronautica, 115, 247–261.	96
[8]	CubeSat design for LEO-based Earth science missions. IEEE, 435–445.	95
[44]	Parametric study of a thermoelectric module used for both power generation and cooling. Renewable Energy, 154, 542–552.	85
[45]	Evolutionary design of a satellite thermal control system: Real experiments for a CubeSat mission. Applied Thermal Engineering, 105, 490–500.	66
[46]	Parametric study of heat-transfer design on the thermoelectric generator system. International Communications in Heat and Mass Transfer, 52, 97–105.	59
[47]	A review of battery technology in CubeSats and small satellite solutions. Energies, 13.	56
[48]	On-Orbit Thermal Design and Validation of 1U Standardized CubeSat of STEP Cube Lab. International Journal of Aerospace Engineering, 2016.	55
[49]	Analytical investigation of a nanosatellite panel surface temperatures for different altitudes and panel combinations. Applied Thermal Engineering, 75, 1076–1083.	49
[50]	Experimental Feasibility Study of Concentrating Photovoltaic Power System for CubeSat Applications. IEEE Transactions on Aerospace and Electronic Systems, 51, 1942–1949.	29
[12]	Enabling Science with CubeSats—Trends and Prospects. IEEE Journal on Miniaturization for Air and Space Systems, 3, 221–231.	8
[51]	Progress and perspectives in thermoelectric generators for waste-heat recovery and space applications. Journal of Applied Physics, 134. doi:10.1063/5.0166338	3

Table 3. *Cont.*

Reference	BP Article	Citations
[52]	Modelling CubeSat Structure for Thermal Analysis.	1
[53]	Chassis Optimization of a 1U CubeSat made in a developing Country. 2022-September.	0
[54]	Thermal modelling of a small satellite data processing unit aided by sensitivity analysis and uncertainty quantification. International Journal of Thermal Sciences, 193, 108514.	0
[55]	Numerical Simulation of Thermoelectric Based Temperature Control system for CubeSat in Space.	0
[56]	Project Irazú: Space and Ground Systems Engineering of a 1U CubeSat Store and Forward Mission for Environmental Monitoring. Transactions of the Japan Society for Aeronautical and Space Sciences, 66, 217–225.	0
[57]	Space missions in South America: Profile and evolutionary perspective of their development. Acta Astronautica, 206, 9–17.	0
[20]	Temperature Distribution of CubeSats Using Finite Element Method. 2022-September.	0
[58]	Thermal design and analysis of JZJ-5 CubeSat.	0
[59]	Morazán MRZ-SAT CubeSat: Thermal Modelling and Analysis Guide for Academic CubeSat Missions. Proceedings of the International Astronautical Congress, IAC, Vol. 2022-September.	0

Among the 33 articles that composed the BP, 7 (21.21%) were conference papers focused on the structure, designs, and missions of nanosatellites. Additionally, 18 (54.54%) aimed to present both the historical and scientific development of nanosatellites and their power systems, such as the EPS, as well as their numerical-computational modeling focused on thermal analyses at LEO altitudes, covering the range of 400 to 1500 km from Earth. Lastly, eight (24.24%) presented concepts and applicability of TEGs in terrestrial situations.

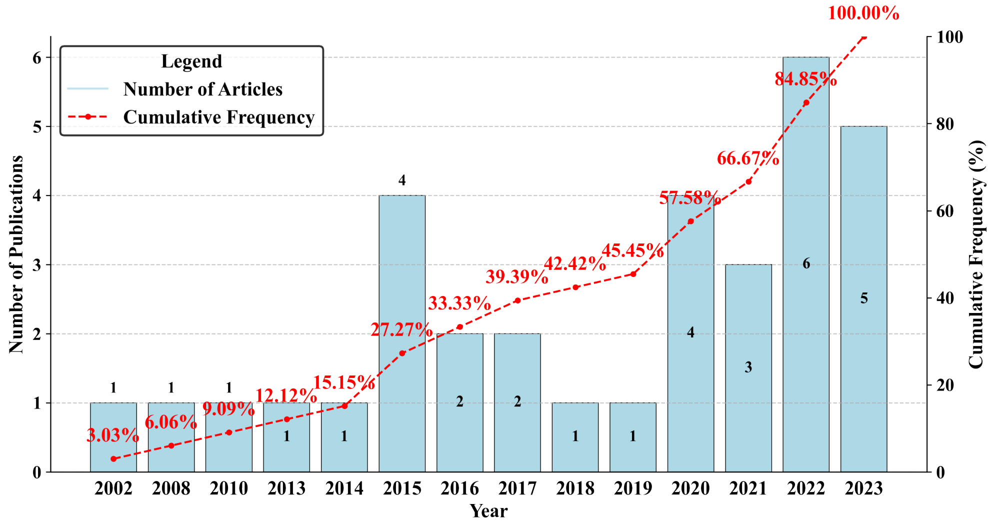
2.2. Bibliometric Analysis

The bibliometric analysis of the BP assists both in developing the theoretical framework on the topic and in accounting for the scientific recognition variables of the articles, authors, journals, and KWs [26,27]. Therefore, based on the data provided by the DBs, several combinations of the information that comprise each article are evaluated, such as the number of citations, author of each publication, year of publication, journal published, among others.

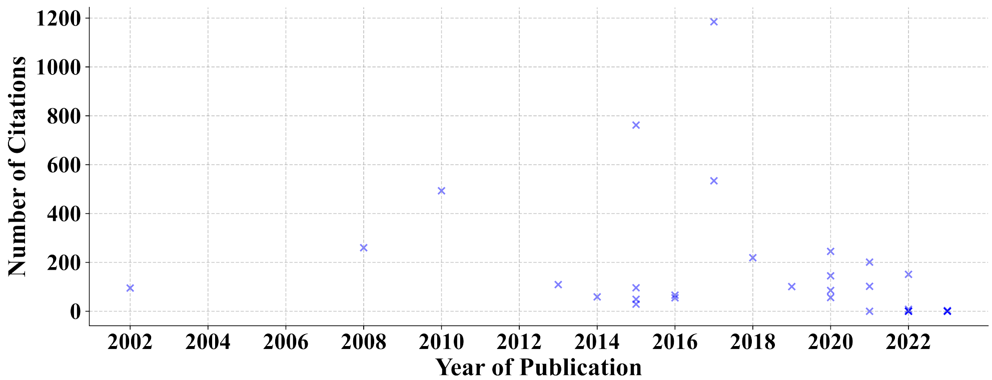
2.2.1. Citation Analysis of the Bibliographic Portfolio

The initial analysis of the 33 articles that composed the BP was structured according to the year of publication and academic relevance within the stipulated period. Figure 6a illustrates the historical distribution of the number of annual publications along with their cumulative frequency.

From this analysis, it is observed that more than half of the publications were concentrated between the years 2020 and 2023. This was confirmed by the graph presented in Figure 6b, which shows the number of annual citations that the BP contained and demonstrates the increase in the density of recent publications. Therefore, it was possible to assert that the proposed research topic was on the rise in recent years.



(**a**)



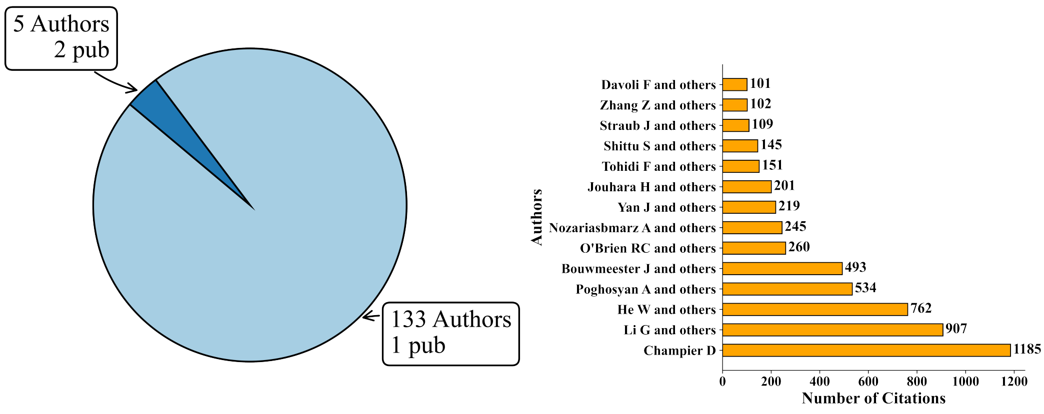
(**b**)

Figure 6. Distribution of (**a**) articles and (**b**) citations over the years.

2.2.2. Author Recognition

Another important analysis for determining the academic relevance of the BP, in addition to the annual publication of articles, is the recognition of the authors related to the proposed topic. In this case, a total of 138 authors were identified. Despite the number, it was found that 133 authors (96.38%) were present in only one publication, while only 5 authors (3.62%) had two publications. This distribution of the number of authors per article is illustrated in Figure 7a, which shows that even with the number of articles produced between 2020 and 2023, there were still not many branches of the proposed topic.

Furthermore, considering that the BP included both articles that studied TEGs in terrestrial conditions and in nanosatellites, Figure 7b shows the relationship of the most relevant authors to the BP research topic with 100 or more citations.



(**a**) (**b**)

Figure 7. Distribution of (**a**) the number of publications per author and (**b**) the number of citations per author.

2.2.3. Relevance of Articles and Keywords

The relevance of the articles, in terms of the publication medium and the manner in which they are presented to the academic community, whether through journals or conferences, aims to align both the articles that compose the BP according to the journal in which they were published and to present their publication frequency.

With a total of 33 articles, it was identified that 7 (21.21%) of these were conference papers presented in journals such as IEEE Journal on Miniaturization for Air and Space Systems, ResearchGate, and IOPScience. The remaining 26 (78.78%) were journal articles published in various journals, with Acta Astronautica, Applied Energy, and IEEE Journal on Miniaturization for Air and Space Systems being the most prolific, each representing 11.54% of the total articles. However, the journal Energies stood out as a promising venue for disseminating knowledge on the proposed topic, offering a suitable platform for advancing research in this field. The described results are illustrated in Figure 8.

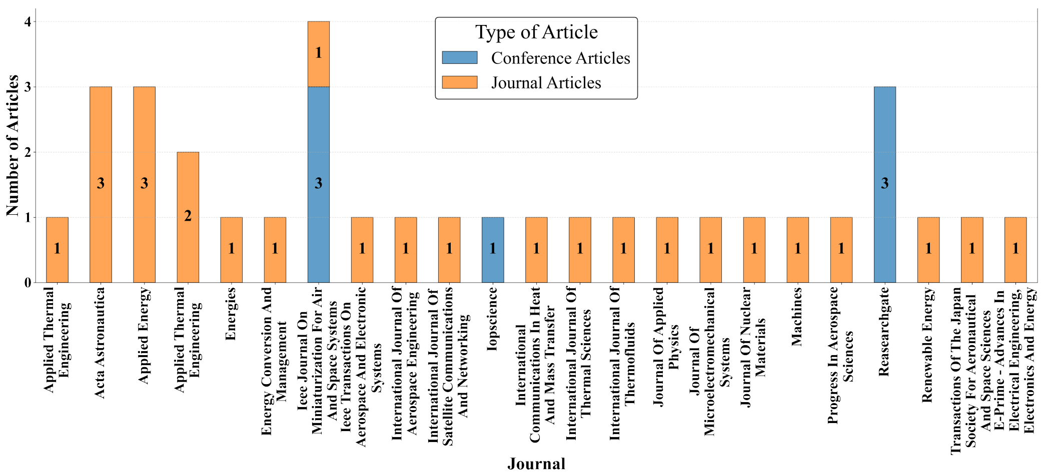


Figure 8. Scientific Relevance of the articles composing the BP and their published journals.

A total of 167 distinct KWs were identified in the academic works of the BP, with 112 (67.07%) observed only once, and 55 (32.93%) two or more times. The study of KWs helped identify which terms are most frequently used in the BP, ensuring their alignment with the proposed topic. The list of the top 30 most frequent KWs among the articles is presented in Figure 9.

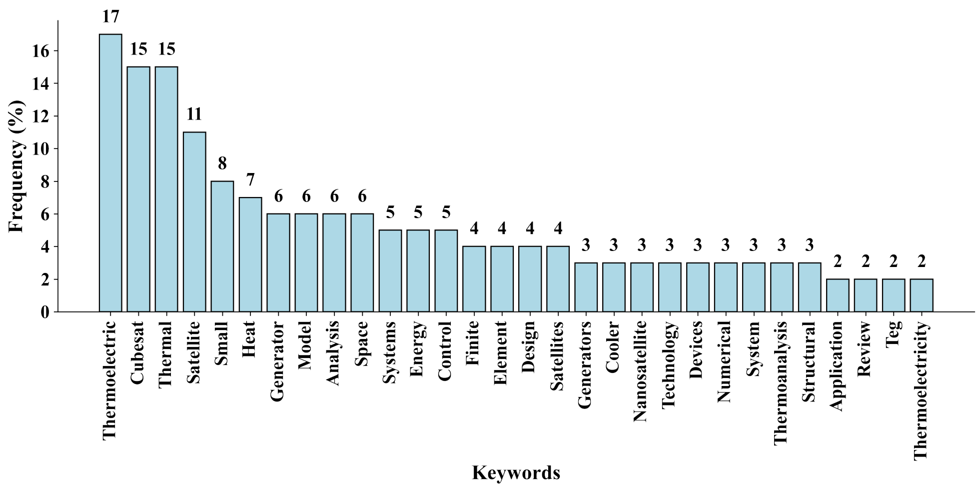


Figure 9. Representation of the 30 most frequently used KWs in the BP.

Even though the term "Thermoelectric" was the most frequently used in the BP, the terms "CubeSat" (second) and "Thermal" (third) held significant relevance in this KW analysis. Despite their individual positions, combined, they totaled 30 occurrences (17.96%), indicating their high usage in combination (or separately) for studies related to the proposed research topic. Additionally, among the 30 most cited KWs, terms like "Finite", "Element", "Numerical" and "Thermoanalysis" suggested the use of computational tools applied to the problem of thermal simulations in nanosatellites.

2.2.4. Analysis of the Bibliographic Portfolio

The BP consisting of 33 articles, it was essential to verify articles that reviewed the literature on the proposed topic, as well as those that aided in its development. These served as a basis for defining the connection between technological progress made in this area.

Therefore, to automate the process of capturing review articles, algorithms were developed in the Python programming language, along with Microsoft Excel spreadsheets, to identify the term "review" in the titles of the articles in the BP and separate them from the research articles. The distinction between research articles and review articles had to be made with the aim of identifying (i) if there had already been any review or application of TEGs within the proposed theme and (ii) if there were any research articles that had conducted an in-depth study on the application of TEGs in CubeSats as a primary energy source.

In total, seven (21.21%) review articles were identified, of which six (85.71%) presented reviews of concepts, applications, and innovations related to TEGs, while one (14.29%) presented a review of CubeSat batteries, as described in Table 4.

Table 4. Review Articles Ordered by Number of Citations.

Reference	Brief Description	Citations
[33]	Presents advancements in TEG production in terms of design and optimization, as well as classification and industrial applications. Additionally, it addresses improvements in the figure of merit (ZT), increased operating temperatures from high gradients, and the use of low-cost materials.	1185
[37]	Focuses on generally describing the use of TEGs to harness residual heat from the human body, highlighting the potential to power accessories and technological devices.	245

Table 4. *Cont.*

Reference	Brief Description	Citations
[38]	Explores the application of micro-TEGs as an economical and competitive alternative to traditional TEGs in areas such as medicine, electronic devices, and the Internet of Things (IoT).	219
[15]	Consists of a literature review on TEGs in the current energy market, aiming to present their potential and applications. Additionally, it delves into the development of TEGs using simulation software for various industrial sectors.	151
[40]	Discusses issues related to the geometry and optimization of thermoelectric device structures, focusing on enhancing their potential and mechanical performance under stress conditions.	145
[42]	Reviews current thermal management methods for electronic devices, highlighting active cooling. It covers techniques such as direct cooling, air jet, immersion, and contact. Additionally, it emphasizes the use of TEGs for contact cooling.	102
[47]	Conducts a review of battery technologies in CubeSats, illustrating the most commonly used types and their operating conditions. It also presents possible solutions to enable their use in space, considering environmental conditions, temperature, and mission requirements.	56

As identified, the set of review articles predominantly highlighted the advancements and applications of TEGs in terms of their design, optimization, and materials, as well as their widespread application in industrial and workplace environments, such as in electronic devices, IoT applications, and in the medical field, particularly for harnessing human residual heat for cardiac measurement devices, as highlighted by [33,37].

Other studies, such as those presented by [15], focused on literature reviews of the development and potential applications of TEGs, including the capture of residual heat from satellite dishes, hybrid systems with solar cells, heat sinks, and more. Notably, the text discussed the application of TEGs for deep space exploration missions, specifically describing the use of RTGs in satellites and their importance in thermal management.

There were discussions on structural challenges of thermoelectric devices under stress conditions, addressed by [40], and reviews of thermal management techniques in electronic devices, as mentioned by [42].

To conclude, Ref. [47] investigated the key technologies employed in CubeSats' batteries, identifying the main challenges associated with their use in space conditions and proposing possible solutions to optimize their efficiency given the limitations imposed by operational temperatures.

As presented, the review articles extracted from the BP indicated a gap in systematic review research regarding the application of TEGs as an energy source for CubeSats, with a primary focus on their implementation in terrestrial environments. Therefore, this work aims to fill this gap by detailing a systematic review of the scientific literature and recent industrial advancements in the aerospace sector concerning energy sources for nanosatellites.

The 26 research articles present in the BP were subdivided into three main themes: history, applications, and development of CubeSats, representing 8 (30.77%) articles; design and thermal analysis of CubeSats, comprising 13 (50.00%) articles; and finally, 5 (19.23%) articles that present studies and principles of TEGs. The articles are described in Table 5.

Table 5. Research Articles Ordered by Number of Citations.

Reference	Brief Description	Citations
[34]	Reviewed thermoelectric materials and their practical applications, highlighting existing technical barriers and proposing new research topics.	762
[3]	Reviewed CubeSats' state-of-the-art capabilities, focusing on scientific missions, and evaluated their potential for enabling high-quality, low-cost scientific missions.	534
[35]	Provided a detailed analysis of the most common technologies in nanosatellites and picosatellites, covering launch history, topologies, purposes, systems, subsystems, and applications.	493
[36]	Presented a historical review of radioisotope thermoelectric generators (RTGs) and their conversion mechanisms, providing information to enable a direct comparison with alternative isotopic systems.	260
[39]	Thoroughly analyzed the operating principles, applications, and materials used in TEGs. Additionally, it provided examples of simulations using software such as COMSOL Multiphysics and ANSYS.	201
[41]	Described the CubeSat OpenOrbiter's structural aspects and program objectives, focusing on requirements, constraints, high-level architecture, and design for small satellites.	109
[7]	Provided an overview of CubeSats, their systems and subsystems, main missions and objectives, and potential future challenges. Additionally, it classified topologies and protocols necessary for launches.	101
[43]	Presented the optimization process in the thermal analysis of a 1U CubeSat, setting boundary and environmental conditions. Developed and applied a MATLAB algorithm to compare results with ESTAN-TMS software.	96
[8]	Detailed the design and hardware/software architecture of internal systems for two 1U CubeSat missions: a combined probe/DC plasma impedance system on two satellites and two CubeSats for GPS scintillation measurements.	95
[44]	Developed a numerical model to predict the performance of a thermoelectric device as both a TEG and TEC, considering height, cross-sectional area, number of pairs, and ceramic plate's thermal conductivity.	85
[45]	Used a genetic algorithm to explore material combinations for 3U CubeSat coatings to meet operational temperature requirements, validated through FEM thermal simulation.	66
[46]	Described a high-performance platform combining heat transfer and thermoelectric conversion. Analyzed how different operating conditions affected TEG energy production using a metal pin array with forced convection.	59

Table 5. *Cont.*

Reference	Brief Description	Citations
[48]	Represented the development of the thermal design for the thermal control subsystem of the STEP Cube Lab and its validation through thermal vacuum tests, in order to estimate the thermal behavior of the components.	55
[49]	Conducted a thermal analysis of a 1U CubeSat in LEO, focusing on passive thermal control to ensure proper component operation using different surface coatings.	49
[50]	Proposed the use of a CPV system, or Concentrating Photovoltaic system, in a 1U CubeSat to improve energy generation efficiency by converting the energy provided by the Sun's light intensity and concentrating it onto the solar cells using lens arrays.	29
[12]	Provided an overview of CubeSats as scientific platforms, highlighting their potential and challenges, focusing on communication systems and efficient space utilization with integrated or shared components.	8
[51]	Discussed the current state and advancements in thermoelectric technology for use in next-generation RTGs and in waste heat recovery applications using TEGs, excluding the discussion of material property optimization strategies.	3
[52]	Analyzed different materials in transient and steady-state regimes of a 1U CubeSat to select the most suitable ones according to the specified temperatures.	1
[54]	Conducted a global sensitivity analysis to identify key elements limiting heat transfer in a 1U CubeSat's data processing unit, followed by an uncertainty analysis for the temperatures of crucial electronic components and the radiator surface.	0
[58]	Introduced the thermal control design of a 3U CubeSat, calculated the temperature field under various conditions using FEM, and compared in-orbit temperature data with thermal simulation results.	0
[20]	This study validated FEM models on the CubeSat using real data from MYSat-1, developing a thermal model in ANSYS to ensure safe CubeSat operation.	0
[57]	Proposed a comparative study of South American space programs using an adapted Wood and Weigel model, evaluating their evolution over the past three decades and providing a comparative view of ten regional programs.	0
[56]	Described the Irazú Project and its development, in a superficial manner, related to a 1U CubeSat for environmental monitoring, focusing on biomass estimation and carbon dioxide fixation in a fast-growing tree plantation.	0
[55]	Conducted a detailed simulation of a TEC-based thermal control system for a CubeSat in a 300 km circular orbit, evaluating the feasibility and performance of TECs under extreme conditions.	0

Table 5. *Cont.*

Reference	Brief Description	Citations
[59]	Explained the thermal environment in low Earth orbit for MRZ-SAT and described computational thermal modeling for this 1U CubeSat using finite element algorithms, serving as an initial guide for beginners in CubeSat thermal analysis and modeling.	0
[53]	Described the structural optimization of the Morazán Satellite (MRZ-SAT) chassis, an award-winning project for natural disaster early warning. Compared three structural patterns to achieve the lightest and most rigid design.	0

Several studies focus on the structure and development of CubeSats, covering topics from thermal analysis to system control and optimization. Works like [43], which presents optimization processes for thermal analysis in CubeSats, and [8], which details hardware and software architecture in specific missions, are fundamental for understanding key CubeSat concepts. Additionally, studies like [45] use genetic algorithms to explore different material combinations that meet the satellites' thermal needs, while [49] and [20] focused on both passive thermal control requirements and the validation of thermal models using real CubeSat data, demonstrating the practical application of theories and models in real operational contexts.

These studies, along with the analysis of specific projects like the Irazú Project detailed by [56], and the Morazán-Sat Project explored by [53,59], exemplify the structural optimization of nanosatellites intended for specific monitoring functions. These functions include verifying CO_2 emissions and implementing early warning systems for natural disasters.

For research on thermoelectric devices, notable works include those by [36,51], which offer a historical review of RTGs to compare them with alternative isotopic systems and discuss recent advances in the field, presenting new approaches to optimizing thermoelectric material properties for the next generation of RTGs. Ref. [39] delves into the operating principles of TEGs through simulations based on FEM analyses. Additionally, Ref. [44,46] develop models to predict the performance of thermoelectric devices under various conditions, highlighting the crucial role of these technologies in energy efficiency and the sustainability of space operations.

Studies by [12,57] describe the potential of space programs, focusing particularly on CubeSats and the evolution of space programs in South America, respectively. The first highlights the versatility of these nanosatellites as scientific platforms, emphasizing their challenges and potential for future space missions, with special attention to communication systems and the optimization of satellite internal space usage. The second study employs an adaptation of the Wood and Weigel model to conduct a comparative analysis of the progress of South American space programs over three decades, offering a comprehensive perspective on regional development and trends, illustrating how these initiatives have expanded and evolved in response to different technological and geopolitical challenges.

Lastly, it is important to note that, although 8 (30.77%) of the 26 research articles were not cited, they are highly relevant to this research due to their direct influence on the applicability of TEGs in CubeSats. For example, Ref. [55] present a study on the use of TECs in nanosatellites for temperature control under extreme conditions. Additionally, Ref. [20,58] focus on the modeling and thermal analysis of CubeSats to define temperature limits, directly influencing the operation of internal components. These studies are fundamental to this work, as the study of TEG application in nanosatellites depends entirely on the temperature gradient to which the satellite's face is subjected. Therefore, these studies cannot be disregarded.

In summary, the reviewed articles do not directly discuss the application of TEGs in nanosatellites, reinforcing a potential connection between thermoelectric technology and innovations in energy sources for small satellites. Future exploration in this field could open new avenues for space exploration and energy supply for nanosatellite missions.

Specifications and Boundary Conditions of CubeSats

This section aims to extract and present the main information that establishes both the specifications of CubeSats and the boundary conditions of the proposed topic, as found in the research articles of the BP. After reviewing the 26 articles, it was identified that the 13 articles focusing on the design and thermal analysis of CubeSats provided fundamental parameters for the research methodology, such as structural material, power source, number of PCBs, and others. Of these, only 11 are presented in Table 6, as they provide all the necessary information to establish the boundary conditions and appropriate structures for the application of TEGs as a power source in CubeSats.

Table 6. Structure, devices, specifications, and boundary conditions in CubeSats.

Reference	Structure and Devices	Specifications and Boundary Conditions	Software Used
[8]	1U CubeSat; structural material: AL 7075; solar cell: Tecstar Triple Junction; battery: LiPo	Circular orbit; LEO: 300 km and 60°; provides weights and consumed power	Not provided
[49]	1U CubeSat; structural material: AL6061T6; battery: LiPo; 5 PCBs	Sun-synchronous circular orbit; LEO: 600 km and 98°; transient and steady-state analysis; maximum and minimum temperatures provided	Not provided
[59]	1U CubeSat; structural material: AL6061; solar cell: GaInP2/GaAs/Ge	Circular orbit; LEO: 400 km and 51.65°; details angles and thermal analysis	GNU Octave; SINDA software
[52]	1U CubeSat; structural material: AL6061TE; 3 PCBs	LEO: 600 km and 67°; transient and steady-state analysis; operating temperatures provided	ANSYS
[55]	1U CubeSat; structural material: AL 7075; 4 PCBs; PCB material: FR4; solar cell: single crystal silicon; solar cell sizes provided; TE: CP1.031-17-06L	Circular orbit; LEO: 300 km with no inclination; period of 90.4 min; Earth represented as a sphere; satellite surface temperature: 6–60 °C; operating temperature: 0–40 °C	Not provided
[53]	1U CubeSat; structural material: 6061; solar cells and components: obtained from Endurosat 1U	Detailed component weights and consumed power provided	Autodesk Fusion 360 Education License
[50]	1U CubeSat; specifications of STEP Cube Lab; solar cells: polycrystalline single-junction silicon	LEO: 600 km, sun-synchronous; Period of 1 year	Solar Simulator
[58]	3U CubeSat; structural material: AL 7075; PCB material: FR4	LEO: 500 km, sun-synchronous; operating temperatures of components and their power provided	Not provided

Table 6. *Cont.*

Reference	Structure and Devices	Specifications and Boundary Conditions	Software Used
[43]	1U CubeSat; structural material: AL 6101T6 and AL7076T6 (plate); solar cells: gallium arsenide triple junction; reference to PiCPoT nanosatellite	LEO: 600 km and 98°; operating temperatures of components and power provided	MATLAB-ESATAN-TMS
[20]	1U CubeSat; structural material: AL 6061 and stainless steel 304; 5 PCBs; PCB material: FR4; battery: Li-Ion	LEO; operating temperatures and maximum and minimum temperatures obtained by the software provided	CubeSat Wizard with MATLAB-ANSYS
[48]	1U CubeSat; structure based on STEP Cube; structural material: AL 6061T6; battery: Li-Ion; solar cells: ITO-GaAs triple junction; 5 PCBs; PCB material: FR4	Sun-synchronous orbit; LEO: 600 km and 97.78°; period of 1 year; details components, their dissipated power, and operating temperature; provides temperatures in low and high operation; provides power generated by the solar cells	Thermal Desktop; RadCAD

Although all the presented boundary conditions are relevant for this research, the most notable ones are those that provide information about the space environment in which the nanosatellites operate. In this case, articles such as those by [20,48,53,55] provide essential data on ambient temperatures, inclination angle, weight, and internal component consumption to determine the feasibility of using TEGs as an energy source in CubeSats.

In more detail, parameters such as ambient temperature and solar incidence significantly influence the performance of TEGs in generating electrical energy. As highlighted in the reviews presented in Table 4, the operation of a TEG depends on a temperature gradient, created by a hot source on one face and a cold source on the other. Simultaneously, the weight and energy consumption of TEGs directly impact their ability to provide sufficient power for the CubeSat's operation. These factors are crucial to ensure a good watt/kg ratio of the payload, guaranteeing that the satellite operates efficiently and effectively.

2.3. Intellectual Property

The identification of registered products and patents within a research theme is extremely relevant for verifying existing technologies in the area, as they represent an indicator of technological advancement resulting from RD activities in universities [60]. Therefore, to verify the relationship between patent development and RD, steps similar to those applied for the selection of the BP were carried out.

2.3.1. Selection of the Patent Repository

The identification of patents was carried out using the Google Patents and Patentscope search engines. These tools are essential for a global search of patent data, including those registered in Brazil [61]. To optimize the search, combinations of KWs encompassing the investigated theme in both English and Portuguese were established, as shown in Table 7.

Table 7. Results of the patent searches conducted.

English	Portuguese	Google Patents	Patentscope
("Thermoelectric Generator" OR "TEG" OR Seebeck OR Thermoelectric) AND (Cubesat OR Nanosatellite OR Nanosat OR "Small spacecraft")	("Gerador Termoelétrico" OR "TEG" OR Seebeck OR Termoeletricidade) AND (Cubesat OR Nanossatélite OR Nanosat OR "Pequeno satélite")	93	101
("TEG") AND (Cubesat OR "Small spacecraft")	("TEG") AND ("Cubesat" OR "Pequeno satélite")	13	11
("Eletrical Power System" OR "EPS") AND (Cubesat OR Nanosatellite OR Nanosat OR "Small spacecraft")	("EPS") AND (CubeSat OR Nanosatellite OR Nanosat OR "Small spacecraft")	33	131
("Power System" OR "EPS") AND (Cubesat OR Nanosatellite OR Nanosat OR "Small spacecraft")	("Sistema de potência" OR "EPS") AND (Cubesat OR Nanossatélite OR Nanosat OR "Pequeno Satélite")	261	356
("Thermoelectric Generator" OR "TEG") AND (Cubesat OR "Small Spacecraft" OR Nanosatellite)	("Gerador Termoelétrico" OR "TEG") AND (Cubesat OR "Pequeno Satélite" OR Nanossatélite)	29	31
Raw Patent Database (RPD)		**1059**	

Subsequently, using the search data exported to Excel, data processing of the RPD containing 1059 patents was carried out, ensuring that the identified patents were aligned with the research. The process and treatment were performed using the structure shown in the flowchart in Figure 10. The initial filtering, called a correction filter, identified duplicate titles and codes within the patents in the RPB, resulting in 632 exclusions (59.68%). The patents represented in the PD were processed with an alignment filter, which involved reading all titles aligned with the research theme. At that stage, 385 patents (90.16%) that were not aligned were excluded, leading to two patent repositories: Google Patents Repository and Patentscope Repository, containing 32 and 10 patents, respectively. A check for duplicate titles between the repositories was performed through a check filter. As a result, the final PR contained 34 patents aligned with the investigated theme, representing 3.21% of the RPB.

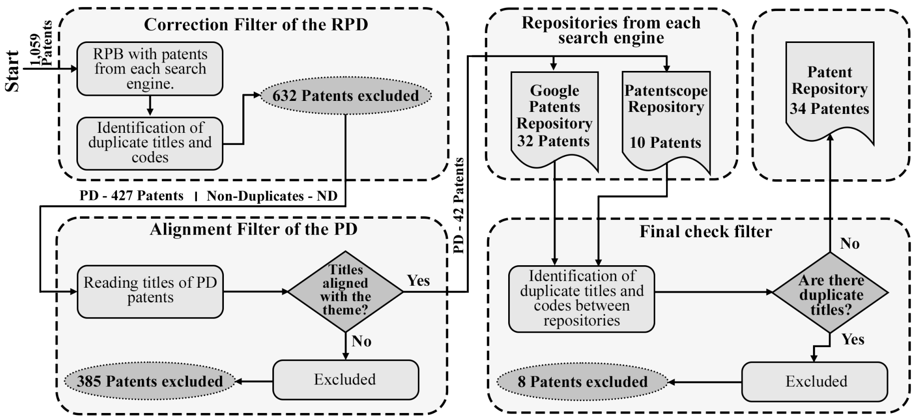


Figure 10. Flowchart representing the filtering of products and patents.

The patents from the Patent Repository (PR) are presented in Table 8, in ascending order. These patents include detailed information about the inventors, their titles and respective codes, country of origin, and a brief description of each invention. The evaluation of the relevance of these patents within the proposed theme was based on the following criteria: (i) verifying if the patented technology was directly applied to satellites or nanosatellites; (ii) assessing the impact on energy generation in the satellite or nanosatellite; and (iii) using residual heat for electricity generation.

Of the 34 patents belonging to the PR, 5 patents (14.70%) (numbers 1 to 5) met all the mentioned requirements, demonstrating a significant influence on the research. Another 26 patents (76.47%) (numbers 6 to 31) had a lesser influence, partially fulfilling the requirements. Finally, three patents (8.83%) (numbers 32 to 34) were discarded for not meeting the established criteria.

Table 8. Presentation and selection of patents that comprised the Patent Repository.

Reference (Number)	Title: Code	Brief Description
[52] (1)	A kind of device for generating electricity using satellite external surface temperature gradient: CN-106208814-B	The invention proposes a method for generating electricity by utilizing the temperature gradient on the external surface of satellites. This is achieved through a series of thermal insulation layers, a heat-conducting layer, and thermoelectric devices, which is especially useful for micro- or nanosatellites.
[62] (2)	Magneto-thermoelectric generator for energy harvesting: US-9793829-B2	The invention consists of a device called a magneto-thermoelectric generator (MTG), capable of converting residual thermal heat from a photovoltaic cell into mechanical energy and, ultimately, into electrical energy. The embodiments operate based on the principle of thermally induced switching between open and closed states of a ferromagnetic switch, aiming to generate mechanical oscillations that cause deformation in a piezoelectric material, resulting in the generation of electrical energy.
[63] (3)	Nano-engineered thin-film thermoelectric converter for photovoltaic applications: US-2022285571-A1	The patent describes systems, devices, and methods for manufacturing nano-engineered thin-film thermoelectric converters (NETT) with photovoltaic applications. These devices utilize the cold of space for satellites or improve the efficiency of terrestrial solar photovoltaic systems. Examples of methods include mounting a thin-film thermoelectric device to a photovoltaic device, followed by the assembly of a heat sink and, optionally, a radiator or heat exchanger.
[64] (4)	Nanostructured material-based thermoelectric generators: US-2009044848-A1	These are electric power generators that utilize the thermoelectric effect in arrays of nanostructured materials. A thermoelectric device is described, consisting of p-type and n-type elements made of carbon nanotubes, and it is capable of operating at high temperatures, generating considerable output power despite being lightweight. A method for manufacturing this device is also presented.
[65] (5)	Radioisotope thermoelectric generator: WO-2016138389-A1	The present invention pertains to radioisotope thermoelectric generators, focusing on miniaturized versions to provide power in space-constrained situations. These generators incorporate radiological heat sources and are designed to operate in high-temperature, high-pressure, and high-vibration environments, such as in drilling probes.
[66] (6)	A power supply: AU-2019262087-A1	The invention describes a power supply for an autonomous device with multiple power supply units, each having an input for source power, an output to a common power rail, an energy storage device, and control to manage the energy flow.

Table 8. *Cont.*

Reference (Number)	Title: Code	Brief Description
[67] (7)	Compact nuclear power system applied to space environment and working method: CN-110043338-B	A compact nuclear power system is proposed for the space environment. Using carbon dioxide as the working fluid, the system is capable of operating stably for decades or even centuries, increasing efficiency by more than 10%. It can be used as a power source in space probes for long-term missions.
[68] (8)	CubeSat system: US-11021274-B1	The invention consists of the introduction of small, ready-to-use, low-cost CubeSat systems that are more accessible, reliable, and easier to use compared to conventional CubeSats. It provides a complete solution, including a satellite, ground station, and remote field units, which can be assembled and deployed quickly.
[69] (9)	Extendable solar array for a spacecraft system: US-9856039-B2	The patent addresses a set of systems applied to a 2U CubeSat nanosatellite, focusing on generating electrical power from solar energy. These systems may include aluminum honeycomb structures or composites with glass covers, as well as rigid crystalline photovoltaic cells and rigid or flexible deployment mechanisms.
[70] (10)	Flexible thin-film solar cell: US-6410362-B1	A transparent thermal film is applied directly onto thin-film solar cells, creating a flexible solar panel. This panel can be installed on a substrate during the manufacturing process to allow illumination and heat dissipation on both sides, making it ideal for building a solar array on curved surfaces, such as spherical nanosatellites. The current inventions involve thin-film devices and processes, especially solar cells and flexible circuit boards, and their manufacturing methods.
[71] (11)	Integrated solar power module: US-6300158-B1	The invention focuses on the presentation of thin-film devices and processes, particularly thin-film solar cells and flexible circuit boards, and their manufacturing methods. An exemplary configuration involves multiple layers of transparent polyimide with metallization between them, forming a three-dimensional flexible printed circuit board. This allows for the direct deposition of thin-film solar cells, creating flexible electronic modules. These boards are ideal for electronic systems on curved surfaces, such as spherical energy nanosatellites.
[72] (12)	Integrated thin-film battery and circuit module: US-7045246-B2	The invention pertains to thin-film batteries embedded in thin-film printed circuits to provide localized power to electronic devices. These batteries are integrated into multi-layer flexible circuit boards, supporting devices such as power regulators, forming an integrated battery and circuit module.
[73] (13)	Micro–nanosatellite power system based on super capacitor: CN-106602694-A	The invention reveals a power system for micro and nano satellites based on a supercapacitor, comprising a supercapacitor and a power input module. The power input module includes an array of solar cells that charge the supercapacitor.
[74] (14)	Modular electrical power subsystem architecture: US-2022158477-A1	The present application provides an electrical power subsystem (EPS) with a dual-battery configuration that enables sufficient power supply for a spacecraft bus and a payload module carried by the spacecraft.

Table 8. *Cont.*

Reference (Number)	Title: Code	Brief Description
[75] (15)	Modular solar cell and solar cell array: US-2023299610-A1	The present invention pertains to power management in spacecraft, particularly in the context of modular solar cells and solar cell arrays that can be deployed on different types of spacecraft. Examples of the invention include modular solar cells, arrays, and energy management systems designed for use in satellite systems and constellations.
[76] (16)	Power supply module for spacecraft: WO-2017177301-A1	The present invention pertains to power converter circuits or devices, specifically power modules based on solar cells for power subsystems in spacecraft. These modules provide power to an unregulated electrical bus of the spacecraft, using a solar cell and a power converter mounted on it to convert solar energy into a DC output voltage determined by the voltage of the spacecraft's electrical bus.
[77] (17)	Satellite modular power supply: US-10536107-B1	The invention presents simplified concepts for improved power supply configurations for satellite devices. An example discussed involves power units, i.e., batteries, in the form of polygons arranged around a power control module within the satellite's chassis.
[78] (18)	Satellite storage battery system: CN-113422423-A	The invention illustrates a battery system for satellites, enabling the conversion of solar energy into electricity, the storage of that energy, and its use when solar energy is unavailable. It includes a solar energy production device, a storage device, and a set of batteries that work together to provide power as needed.
[79] (19)	Solar array remote acoustic sensing (SARAS): US-10078328-B1	The invention relates to sensing technologies, specifically systems and devices that utilize solar arrays, photovoltaic cells, or photodetectors to obtain or provide acousto-optic signatures. These devices act as remote acoustic sensors, detecting fluctuations in the intensity of optically modulated light at audio frequencies.
[80] (20)	Solar battery and the integrated device of slot antenna: CN-106711576-B	The invention presents a device that combines a slot antenna and a solar battery into a single system. This resolves space competition issues in micro- and nanosatellites, reducing the satellite's volume and weight while increasing the light capture area of the solar battery.
[81] (21)	Solar energy conversion and transmission system and method: US-9815573-B2	The present invention relates to systems and methods for converting solar energy into microwave electrical energy and transmitting it to Earth.
[82] (22)	Solar panel and flexible radiator for a spacecraft: EP-3239057-B1	The invention relates to a combination of a solar array and a flexible radiator for a spacecraft.
[83] (23)	Solar panel array: US-9882330-B2	The invention relates to methods and devices for interconnecting a set of solar panels composed of elongated PCBs, each with solar cells mounted linearly and connected in series to form a panel. There are also hinge assemblies consisting of hinge pieces, support plates, a spring, and a hinge pin, which are mounted between the panels to allow them to be folded in an accordion arrangement or deployed up to 180 degrees.
[84] (24)	Space vehicles including multijunction metamorphic solar cells: US-2021202777-A1	The document addresses spacecraft with multijunction solar cell panels and their manufacturing, focusing on the design and specification of bandgap ranges in four- or five-junction solar cells to optimize efficiency in orbit and ensure performance over an operational lifespan of five to fifteen years.

Table 8. *Cont.*

Reference (Number)	Title: Code	Brief Description
[85] (25)	Space-based radioisotope production and methods of use: US-20220367077-A1	The text describes a system for producing radioisotopes in space and its methods of use. It highlights the acceleration of a propellant by decay energy and the possibility of recharging radioisotope rocket thrusters at an orbital charging station. Additionally, it mentions that activated isotopes can be used to generate electricity and irradiate other items in space for various purposes.
[86] (26)	Spacecraft solar cell monitoring system: US-2009119060-A1	The invention deals with monitoring the characteristics of a solar cell array in small spacecraft. A method is used to determine the current and voltage of the solar cells, allowing the determination of the cells' orientation relative to the sun. This is useful for monitoring the degradation of the solar cells over time in picosatellites.
[87] (27)	Thermoelectric rocket propellant tank pressurization system: US-10495028-B1	The text describes advanced rocket engine systems, where one system uses TEGs to produce electrical power for the pump, based on the temperature difference between the liquid propellant and the heat produced in the combustion chamber. This pressurizes the propellant tanks to feed the engine.
[88] (28)	CubeSat system, method, and apparatus: US-9248924-B2	It addresses a satellite system consisting of a chassis with an avionics package in the upper portion. This package includes various boards, such as the main board, payload interface board, daughter board, and battery board, all arranged in parallel planes. They are connected through stackable connectors. The method of operating the satellite is also described.
[89] (29)	Power distribution system: US-6396167-B1	The present invention relates to power distribution systems that manage the distribution of electrical power between power sources and energy storage elements on a regulated bus in micro- and nanosatellites. The system allows the coupling of multiple power sources and energy storage devices to the bus, with individual regulators and chargers for each device.
[90] (30)	Power supply and distribution module applied to CubeSat: CN-106059266-A	The invention relates to a power and distribution module designed for CubeSats, offering 3.3 V and 5 V converters connected in parallel to a power distribution unit. This compact and highly integrated module is developed to meet the high-reliability, high-performance, and high-integration power requirements of CubeSat equipment.
[91] (31)	Satellite-constructor, training-demonstration model: RU-2693722-C2	The invention relates to the design and equipment of small modular CubeSats, including models for training. The CubeSats feature a basic modular platform, internal network, central processor, control and communication module, and service systems for selecting and replacing elements. A service connector allows access to the internal network, the debugging of programmable devices, and external power supply.
[92] (32)	Satellite thermal control: WO-2024003013-A1	The invention pertains to a satellite with a body containing a radiative surface to emit heat into space, and an attitude control system to orient the satellite in Earth's orbit. This system can adjust the satellite's orientation relative to the sun, switching between a position where the radiative surface points away from the Sun and one where it is exposed to the Sun. The goal is to control the satellite's heat transfer.

Table 8. *Cont.*

Reference (Number)	Title: Code	Brief Description
[93] (33)	Scenario-based method for testing software: US-11138100-B2	The present invention pertains to the field of software testing, specifically a method for testing software, such as that used in satellites, using scenario-based programming. The method involves testing the operational software of a system with various internal subsystems, operating in an environment controlled by a hardware board using electronic signals and operational software.
[94] (34)	Spherical mobility system: US-11420777-B1	The text describes a lunar exploration rover designed to detect subsurface ice and traverse varied terrains in extraterrestrial environments. The rover features a spherical structure that houses an avionics core. The avionics core contains components for data acquisition and motor assemblies that enable the rover to rotate the spherical shell for locomotion.

Description:
US—United States; CN—China; AU—Australia; RU—Russia; EP—European Patents Official; WO—World Intellectual Property Organization.

2.3.2. Analysis of the Patent Repository

The initial analysis of the PR focused on identifying the countries with the most patents related to the theme. As a result, Figure 11 shows the number of patents from each country, indicating that 64.71% of the total patents in the PR originated from the United States, followed by China with 17.65%, patents administered by WIPO with 8.82%, and countries like Russia, Australia, and the EP institution each representing 2.94%.

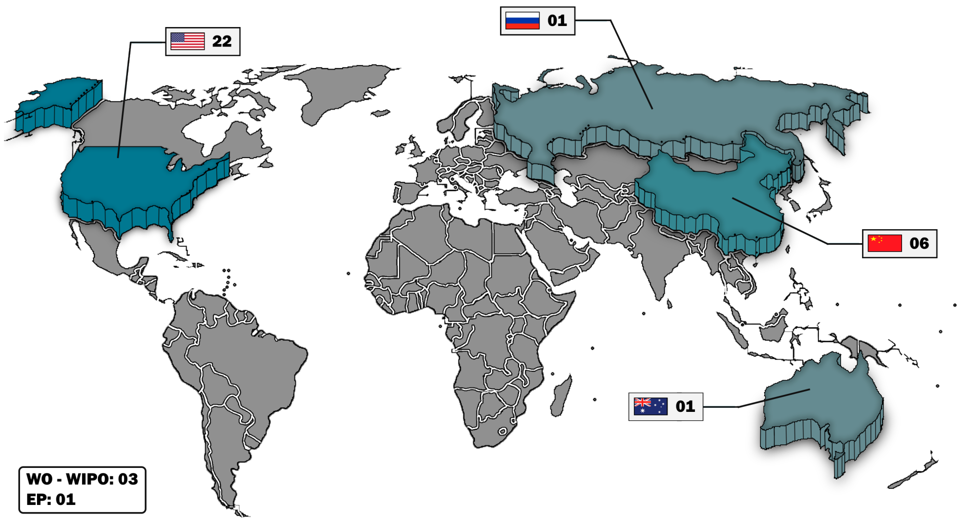


Figure 11. Number of patents registered by country.

Using The Lens Patent Search mechanism provided by The Lens site allowed us to capture legally characterizing information about the patents in the PR. Data such as annual patent publications, most cited patents, discontinued, inactive, expired, or active patents, main inventors and institutions, among others, are made available for free by the platform. Thus, analyses of the patents and the inventors/institutions were carried out to verify their industrial relevance within the proposed theme.

By adding the codes of each patent in the PR to the platform, a "Dynamic Collection" was formed. This guide allowed access to the associated legal records. Of the patents analyzed, 29 patents (85.29%) referenced other inventions, totaling 335 citations, highlighting their importance for conceptual and innovative development.

Additionally, 12 patents (35.29%) included citations of non-patent literature documents, providing additional context and aiding in defining the state of the art in the relevant field. Concurrently, 21 patents (61.76%) served as a foundation for developing new inventions.

Figure 12 illustrates the evolution in the number of patents created over the past 20 years, according to their year of publication, classified into two categories: granted patents, referring to those approved by a licensed office, and patent applications, referring to inventions that have entered the patenting process [95]. In this case, a significant increase in the production of patents related to the theme was observed starting from 2016.

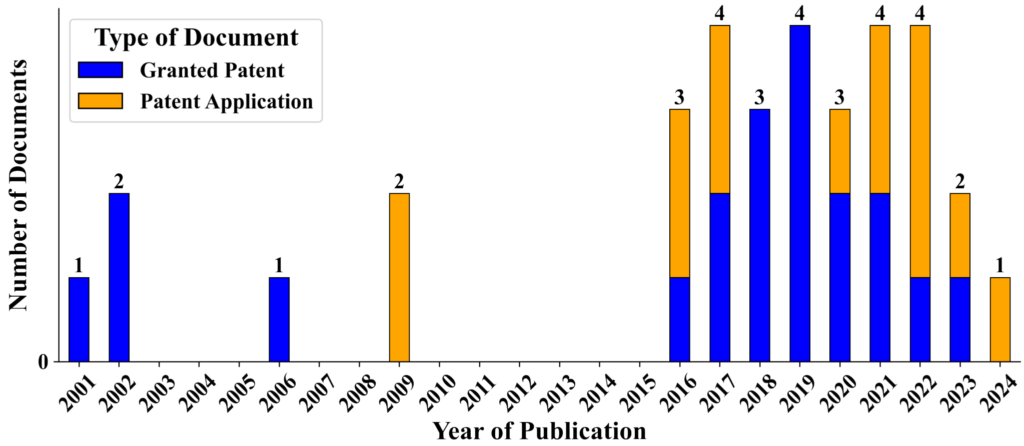


Figure 12. Number of patents registered per year.

In parallel, it was essential to identify the legal conditions associated with each patent, considering their year of registration. This process involved determining the current legal status of the patent, which can vary between active, inactive, expired, discontinued, pending, patented, or unknown. Additionally, it was important to quantify the number of citations each patent had received to highlight the relevance of the previously selected ones in the field of study.

Thus, Figure 13 shows the number of citations per patent for each year of registration, accompanied by Table 9, which presents the number of documents by legal status. This analysis indicated a significant growth in the production of new patents starting from 2016, showing increased interest from companies and inventors in the aerospace sector. Furthermore, 52.9% of the total patents remained active, while 26.4% represented patents that had been discontinued, expired, or were inactive, and 20.6% were pending approval by an accredited office.

Table 9. Number of patents by legal status.

Legal Status	Quantity	
Active/patented	18	(52.9%)
Pending	7	(20.6%)
Expired	3	(8.8%)
Inactive	3	(8.8%)
Discontinued	3	(8.8%)

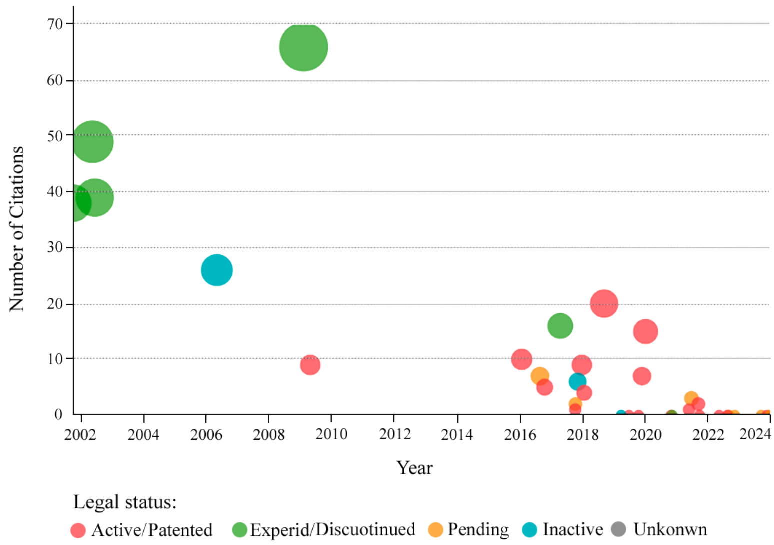


Figure 13. Number of citations per patent by year of publication. Adapted from [96].

In view of this, Table 10 describes the legal information of the patents that met all the requirements influencing the research, briefly described in Table 8.

Table 10. Description of the legal status of the filtered patents.

Reference	Code	Legal Status	Citations per Patent
[64]	US-2009044848-A1	Discontinued	66
[65]	WO-2016138389-A1	Pending	7
[62]	US-9793829-B2	Active	1
[97]	CN-106208814-B	Inactive	0
[63]	US-2022285571-A1	Pending	0

The analysis of the filtered patents revealed the legal status and citation impact of each. Among the patents, one was active (US-9793829-B2), two were pending (WO-2016138389-A1 and US-2022285571-A1), one was inactive (CN-106208814-B), and one was discontinued (US-2009044848-A1). Notably, the discontinued patent had the highest number of citations (66), while others had significantly fewer or none.

With this analysis, it was possible to identify the inventors with the highest number of registered patents in their names, as well as their involvement in other patents. Figure 14 presents the top 20 inventors in the PR, organized by the number of patents produced. It shows that inventor Edward Simburger had the highest number of produced patents, followed by Paul Gierow, Frank Jeffrey, and James Matsumoto.

Similar to the analysis of patent production by inventor, it is advisable to identify which institutions focus on the research theme. Additionally, it is important to determine the purposes for which the patents were designated to ensure their relevance to the present work.

Using the same procedures as before, the number of patents registered by company was obtained through a heat map, illustrated in Figure 15a, and the top 20 codes related to CPC are presented in Figure 15b. The CPC is a classification system developed by the USPTO and the EPO. This system has a designation letter for each study area, detailed in [98].

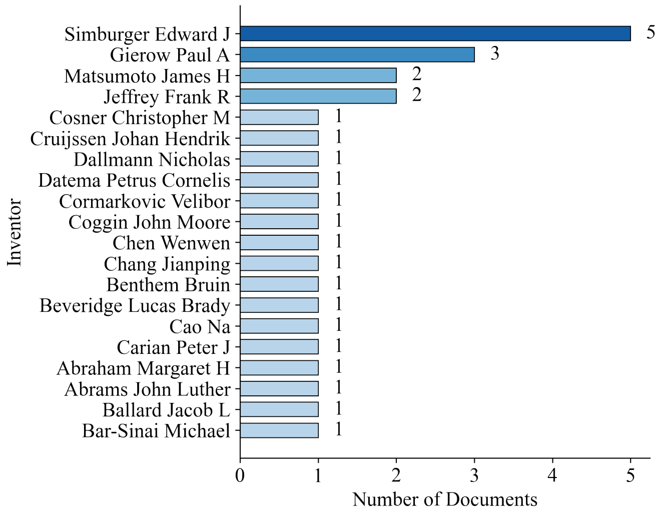
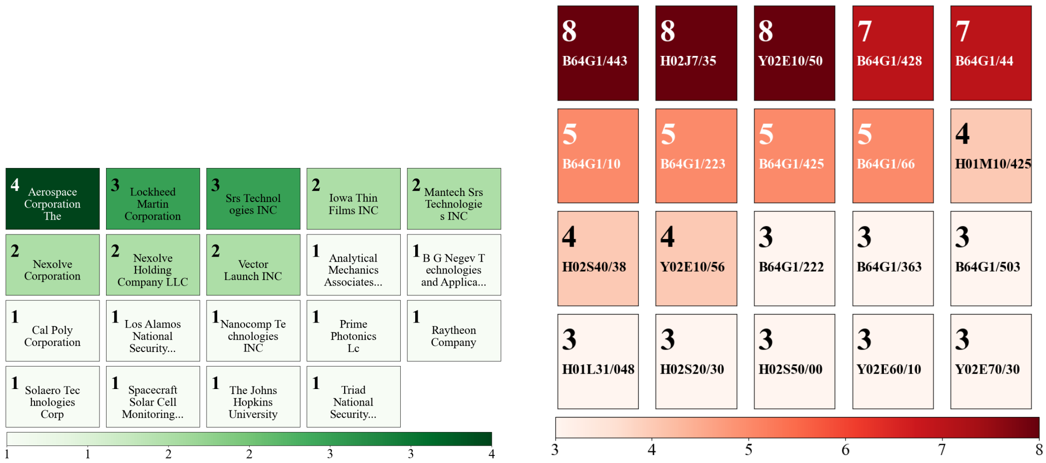


Figure 14. Number of patents produced by inventor. Adapted from [96].



(**a**) (**b**)

Figure 15. Number of documents by (**a**) institutions and (**b**) according to CPC classification.

In some cases, a patent may have more than one CPC classification. This occurs because the invention can cover multiple technical areas, making it relevant to different aspects of classification. For the PR, which contained 34 patents, some documents may also have had multiple categories.

Thus, out of a total of 31 documents registered by companies, it was noted that Aerospace Corporation had the highest number of patents, with four patents (12.90%), followed by Lockheed Martin Corporation and Srs Technologies INC with three patents each (9.68%), Iowa Thin Films, Mantech Srs Technologies INC, Nexolve Corporation, Nexolve Holding Company LLC, and Vector Launch INC with two patents each (6.45%), and other institutions with one patent each (3.23%).

Regarding the CPC classification, it was identified that a large portion of the patents were related to the code B64G1, which is classified under Performing Operations Transporting. More specifically, they focused significantly on energy and communication systems for space applications. Patents classified under codes H02J7, H01M10, H01L31, H02S50, and H02S20 were directed towards the development of structural components, energy storage systems, and photovoltaic system testing. Lastly, those with codes Y02E10, Y02E60, and Y02E70 were related to the development of batteries and photovoltaic systems.

2.3.3. Most Relevant Patents

In the context of the research, Ref. [97] describes the use of micro-thermoelectric devices, composed of thermoelectric materials with high ZT values at low temperatures and high-thermal-conductivity ceramic plates, to generate electricity using the temperature gradient on the external surface of the nanosatellite. Positioned centrally on the six faces of a CubeSat (Figure 16a), the structure of the invention is shown in Figure 16b. Other details are presented in [97].

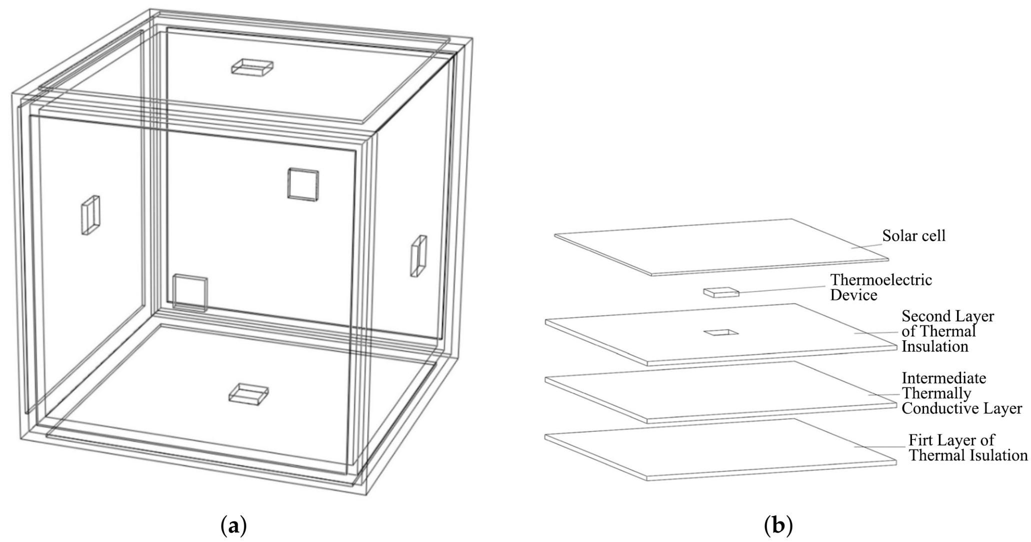


Figure 16. Drawing of the (**a**) three-dimensional schematic and (**b**) layer structure of the invention [97].

The approach presented in [62] describes a device capable of converting residual thermal heat from a photovoltaic cell into mechanical energy and, ultimately, into electrical energy. Called the MTG, this invention operates based on the thermally induced change in magnetic moment within a magnetic material due to the thermal transition between a heat source and a heat sink. This requires the use of a medium to force the nonlinear restoration of motion, exemplified by the use of a spring coupled to a ferromagnetic material. Its construction is observed in Figure 17, from top to bottom, where (10) details the MTG device.

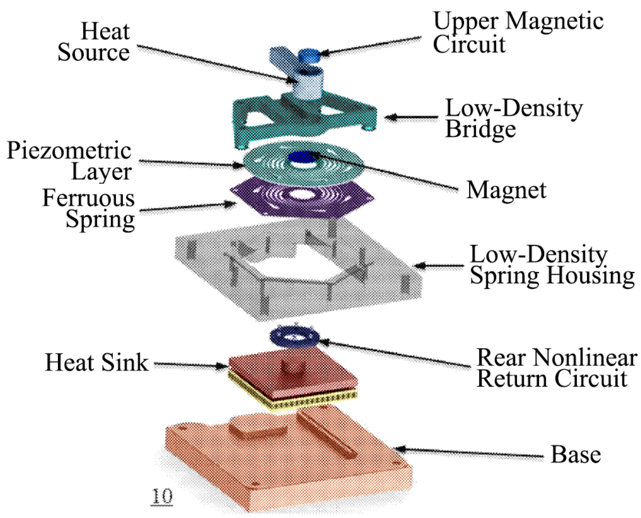


Figure 17. MTG device. Adapted from [62].

In the cold state, the magnetic material is in the closed position, i.e., in thermal contact with the hard magnet on the hot side. As heat from the source is conducted to the magnetic material, it approaches its transition temperature and experiences a change in the magnitude or direction of its magnetization. With the opposing magnetic force weakened, the means for the nonlinear restoring force return the magnetic material to the cold side of the device. After sufficient heat transfer to the cold side, the magnetic moment returns to its original state, moving the material back to the hot side. The movement of the magnetic material between the hot and cold sides causes mechanical oscillations, which are a form of nonlinear restoring force. Electrical energy is generated by coupling the means for the nonlinear restoring force with a piezoelectric material, resulting in the electromechanical production of electrical energy. Its operation and methodology are presented in [62].

Meanwhile, Ref. [63] describes methods for the fabrication of NETT devices for MJPV applications. Focusing on space employment, their use in satellites is appreciated in terms of harnessing residual energy, optimizing size, weight, and power. In certain cases, NETT devices can be used between the thermal blankets used by satellites, providing distributed energy to various sensors without reliance on the solar panel array. This means that the residual thermal energy output can be considered as the sum of the total incident solar power minus the energy output of the photovoltaic solar panels and minus the energy output of the NETT. The structure of the MJPV-NETT device is shown in Figure 18, where (190) shows the fabrication of the MJPV-NETT device. Additional details are available in [63].

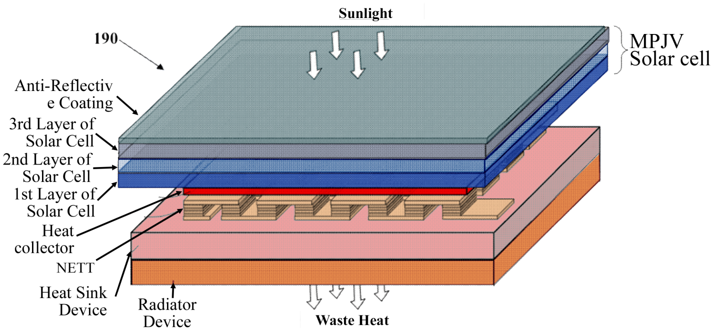
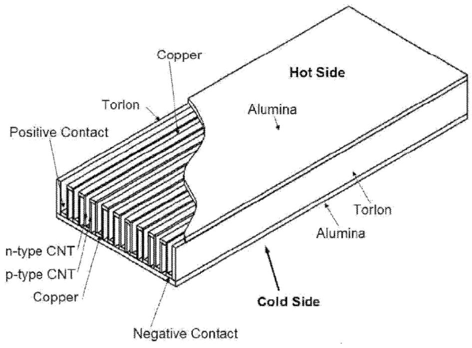


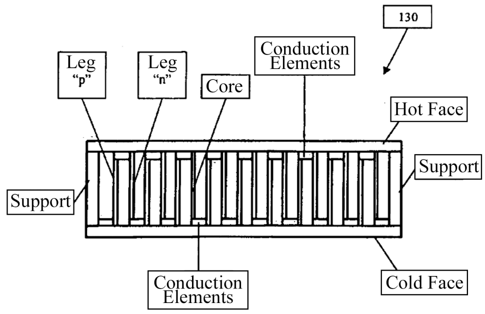
Figure 18. MJPV-NETT device. Adapted from [63].

In parallel, Ref. [64] conducted studies on the changes in geometry, material, and weight of TEGs for space applications. As a result, they patented a thermoelectric device consisting of (i) a first element designed to collect heat from a heat source, (ii) a second element spaced from the first element to dissipate heat from the first element, and (iii) a core positioned between the first and second elements to convert heat into useful energy. The core was composed of a carbon nanotube that exhibited a relatively high Seebeck coefficient, which increased as the temperature rose. Additionally, it had a relatively high transition temperature, allowing the coupled elements to operate in a substantially high-temperature range. Its construction is shown in Figure 19a, and detailed in Figure 19b, where (130) shows the device.

In summary, Table 11 addresses the main characteristics identified in the PR. It highlights that the only patents that closely aligned with the proposal of using TEGs as an energy source for CubeSats were those by [62,97]. However, these patents differed mainly because they integrated a hybrid TEG system with solar cells (or another type) and did not provide power for the entire nanosatellite. Additionally, [62] discussed thermoelectric devices to regulate the temperature of specific sensors and subsystems, rather than providing power for the entire system.



(**a**)



(**b**)

Figure 19. Schematic drawing of the thermoelectric device composed of carbon nanotube cores: (**a**) three-dimensional and (**b**) two-dimensional [64].

Table 11. Mapping of the main characteristics addressed in the topic.

Analyzed Characteristics	IP Publications					
	[97]	[62]	[63]	[64]	[65]	Proposal
Study of thermoelectric devices as electrical power generators	✓	✗	✗	✓	✓	✓
Presents modification in the standard structure of TEGs	✗	✓	✗	✓	✓	✓
Has space applications	✓	✓	✓	✓	✓	✓
Utilizes only residual heat from ambient conditions	✓	✓	✓	✓	✗	✓
Forms a hybrid system with solar cells or another type	✓	✓	✓	?	✓	✗
Application in CubeSats	✓	✓	✓	?	✓	✓
Impact on energy supply to CubeSat subsystems	✓	✓	?	?	?	✓
Uses only TEGs for the integral power supply of CubeSats	✗	✗	?	?	?	✓

Complies: ✓ **Does Not Comply:** ✗ **Not informed/Not identified:** ?

The proposed research distinguishes itself from existing studies by exclusively focusing on the use of TEGs as the primary and integral power source for the EPS of a CubeSat, in contrast to prior works that predominantly explore hybrid systems or specific subsystem applications. Furthermore, the proposal introduces structural modifications to TEGs to optimize their functionality in space environments, an aspect not addressed in previous references. While many existing studies provide limited or unclear assessments of the impact of TEGs on nanosatellite subsystems, this research offers a comprehensive evaluation of their integration into the entire power system, thereby addressing significant gaps in the current literature.

3. Comparative Analysis of the Scientific and Patent Portfolio

This section aims to establish the relationships between the BP identified through the ProKnow-C methodology and the IP search conducted, resulting in the PR. It evaluates the connections between the authors and inventors of each repository, as well as the progress of RD in relation to the advancement of industrial innovations on the researched topic.

3.1. Relationship Between Scientific and Industrial Advancement

The importance of the comparative analysis between the BP, which comprised the most academically relevant articles, and the PR, constructed from the most relevant patents in the industrial sector, lay in establishing the main relationships regarding the production and development of new technologies applied to the energy supply for a CubeSat's EPS. This analysis structured the evaluation of scientific and industrial advances derived from the bibliometric analysis and compared the connections between authors and inventors, keywords, and the annual production history of works.

Thus, the evaluation of the annual production of works based on the existing relationship between scientific articles and patents related to the proposed research topic was conducted, aiding in the evolutionary diagnosis of documents and their possible historical links. The result is illustrated by Figure 20, where, for a better behavior analysis, rectangular regions with performance criteria are defined. These are red rectangles indicating the intervals between years in which there were no publications for both documents and green rectangles emphasizing the years in which the total number of both documents was greater than one.

The analysis indicated an increase in the production of works related to the topic studied in this research starting from the year 2014, with at least a total of two publications per year. Additionally, periods without publications were observed in the years 2002 to 2005, 2006 to 2008, and 2010 to 2013. This pattern suggested growing interest in the topic investigated by articles linked to both RD and the industry over the past 10 years.

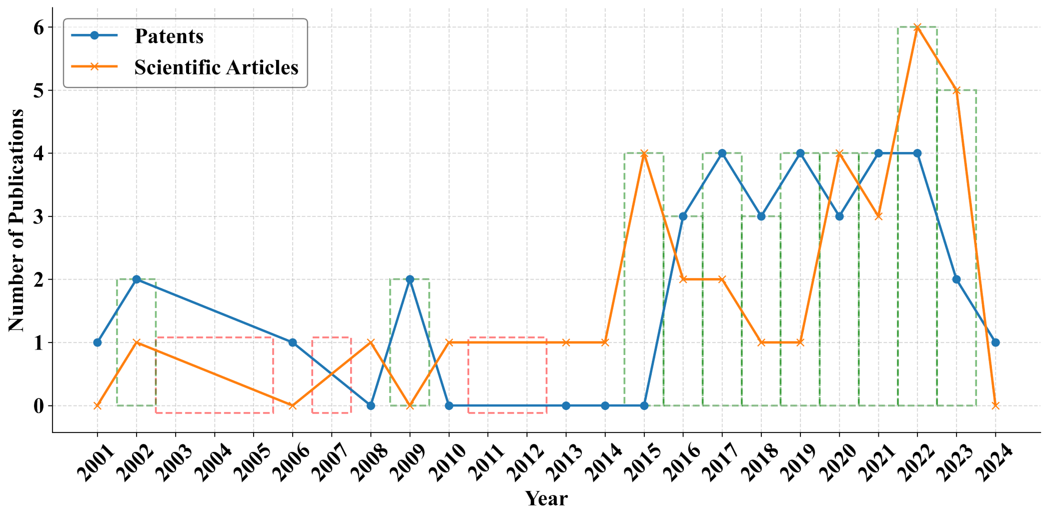


Figure 20. Number of scientific articles and patents over the years.

3.2. Interrelations of the Bibliographic Portfolio and Patent Repository

In order to explore the interrelationships among both the authors and KWs of the BP articles and the inventors of the PR patents, a robust analytical approach was adopted using the open-source software Vosviewer. This analysis focused on mapping the main connections between the authors and inventors, aiming to identify the key influencers in the scientific and industrial fields and contribute to a deeper understanding of RD trends. Additionally, it sought to highlight collaboration networks that may influence future academic work.

For the patents, detailed mappings of authors and co-authorships were obtained, illustrated in Figure 21. A total of 32 isolated and unrelated groups of inventors were identified, with a particular highlight on inventor Edward Simburger. He showed the highest density of interconnections among inventors, which supports the analysis conducted in the previous section (Figure 14) and confirms his relevance in inventions within this industrial sector. Additionally, the publication years of the related patents were highlighted and linked to their inventors, revealing a trend of emerging new inventors such as Stephen David, Jacob Ballard, and others after 2016.

An additional analysis revealed the lack of connection between the 32 groups of inventors. This suggested that despite the progress in patent inventions related to the research, there was no direct correlation between the inventions of each subgroup. This indicates possible confidentiality and restrictions when it comes to sharing information among inventors from different institutions. As result, Table 12 presents patents related to the main connections of each inventor, subdivided into low, medium, and high density.

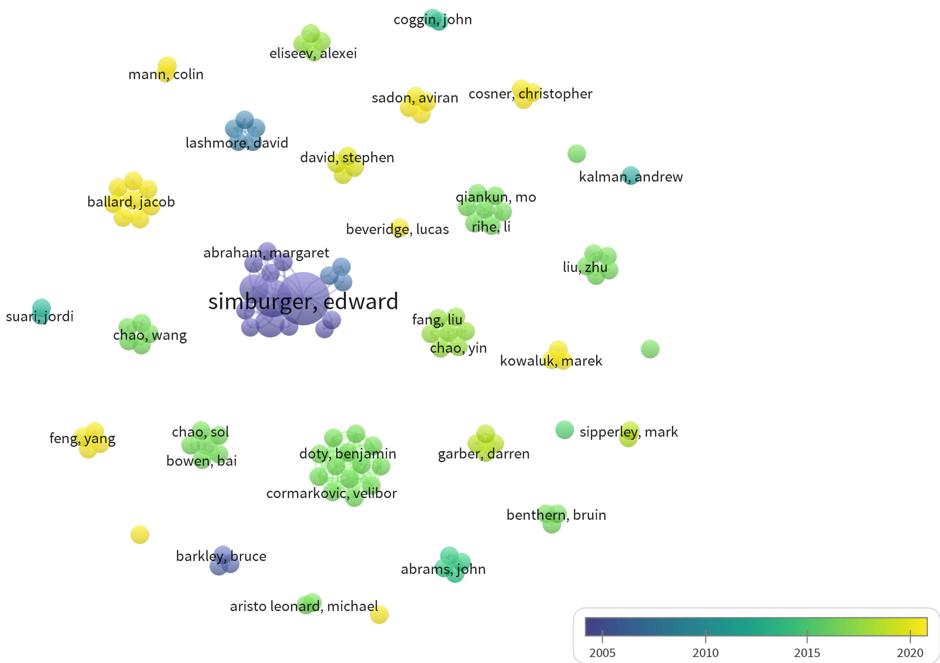


Figure 21. Mapping the existing connections between the inventors.

High-density patents indicate studies related to solar cells and energy storage systems, such as flexible thin-film solar cells and the integrated thin-film battery and circuit module. Medium-density patents present variations in innovations such as thin-film thermoelectric generators and the application of RTG. Low-density patents address both storage and energy supply systems for CubeSats, utilizing batteries, solar cells, and RTG modifications, as well as communication systems. Examples include power distribution modules applied to CubeSats and compact nuclear energy systems for space environments.

Table 12. Relationship between patents and the degree of connection density.

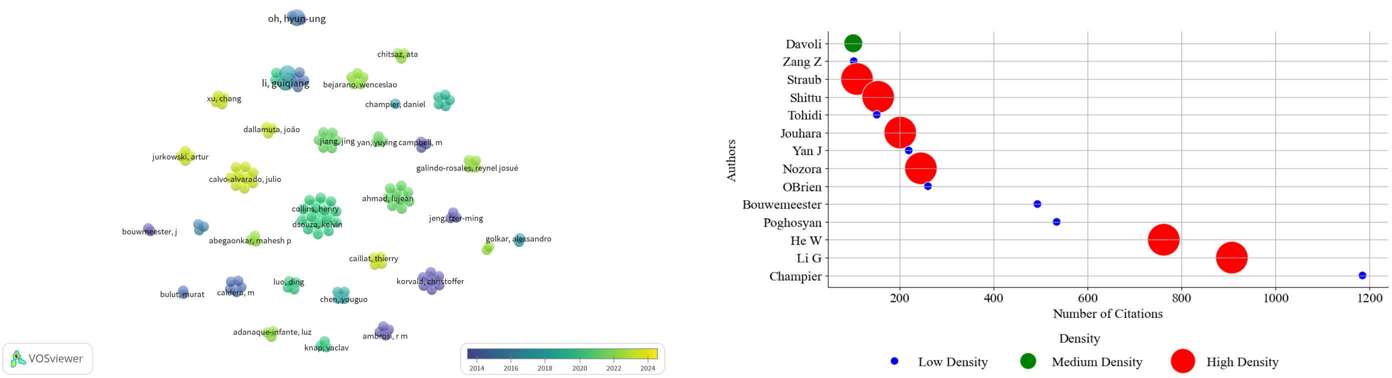
Density	Title
High density	Flexible thin-film solar cell. Integrated solar power module. Integrated thin-film battery and circuit module. Power distribution system. Spacecraft solar cell monitoring system.

Table 12. *Cont.*

Density	Title
Medium Density	Nano-engineered thin-film thermoelectric converter for photovoltaic applications. Radioisotope thermoelectric generator.
Low Density	Micro–nanosatellite power system based on supercapacitor. A power supply. Power supply and distribution module applied to CubeSat. Compact nuclear power system applied to space environment and working method. Solar battery and the integrated device of slot antenna. Satellite-constructor, training-demonstration model.

Regarding the scientific articles, similar to the previously adopted criteria, the density map is illustrated in Figure 22a, presenting a total of 31 isolated and unrelated groups of authors, with existing links between authors for specific articles. By evaluating the density of each group, it was possible to determine its intensity degree according to the number of citations per author presented in Figure 7b.

As a result, Figure 22b was obtained, demonstrating that, in this study, the citation relationship was not directly proportional to the connection density. For example, Champier D, who had 1185 citations, exhibited a low density, whereas Sratub et al. and Shittu et al., with 109 and 154 citations, respectively, exhibited a high density. Similarly, the same pattern of isolation observed with the patents was evident, highlighting the isolation of each scientific article concerning the academic development related to the research topic.



(**a**) (**b**)

Figure 22. Representation of (**a**) density mapping and (**b**) the relationship between the number of citations per author and density.

At the end, Table 13 presents the density levels of scientific articles based on the existing connections between the authors, categorized into low, medium, and high densities. Based on the distribution of the titles of scientific articles within these density categories, articles classified as "High Density" focus on technologies related to CubeSats, suggesting a detailed technical discussion on the development and capabilities of these nanosatellites. Additionally, they highlight the optimization of geometry and applications of TEGs, reflecting a deep exploration of how to maximize the efficiency of these devices.

The article classified as "Medium Density" presents a slightly broader scope, covering an overview of CubeSats structures, architectures, and protocols. Articles addressed as "Low Density" discuss both the various applications of TEGs more generally and studies dealing with the global analysis of nano- and picosatellite missions and the use of RTG in space missions.

Table 13. Relationship between scientific articles and the degree of connection density.

Density	Title
High density	OpenOrbiter: A low-cost, educational prototype CubeSat mission architecture. Review of thermoelectric geometry and structure optimization for performance enhancement. Thermoelectric generator (TEG) technologies and applications. Review of wearable thermoelectric energy harvesting: from body temperature to electronic systems. CubeSat evolution: analyzing CubeSat capabilities for conducting science missions. Review of thermoelectric geometry and structure optimization for performance enhancement.
Medium density	Small satellites and CubeSats: survey of structures, architectures, and protocols.
Low density	A review of the state of the art in electronic cooling. Thermoelectric generators: a comprehensive review of characteristics and applications. Review of micro thermoelectric generator. Safe radioisotope thermoelectric generators and heat sources for space applications. Survey of worldwide pico- and nanosatellite missions, distributions and subsystem technology. CubeSat evolution: analyzing CubeSat capabilities for conducting science missions. Thermoelectric generators: a review of applications.

3.3. Keyword Analysis

This section aims to establish the relationships between the BP, identified through the ProKnow-C methodology, and the search conducted by the IP, resulting in the PR, through the existing relationships between the KWs of each article. The objective is to identify the most relevant terms associated with CubeSats, focusing on their subsystems and energy sources. Additionally, it seeks to diagnose the connection between the application of TEGs and thermal analysis in the structures of this category of nanosatellite.

As a consequence, Figure 23 illustrates that the term “CubeSat” is prominently associated with branches in thermal analysis, boundary conditions, communication and distribution technologies, and energy storage and consumption.

In conclusion, no direct relationships were identified with the application of TEGs as the main energy source, but rather as temperature regulators for these subsystems. Nevertheless, this analysis corroborated the combination of KWs initially used and presented both in Table 7 and in the graph shown in Figure 9, demonstrating that they were coherently aligned with the proposed research theme.

Another important highlight is the absence of the “Keywords” topic in patent documents, indicating the recommendation to synthesize the documents to identify the main words that describe them. This synthesis would enable a comparison with the most frequent words in the BP, to verify the relationship between the axes established by ProKnow-C and those identified in the IP search.

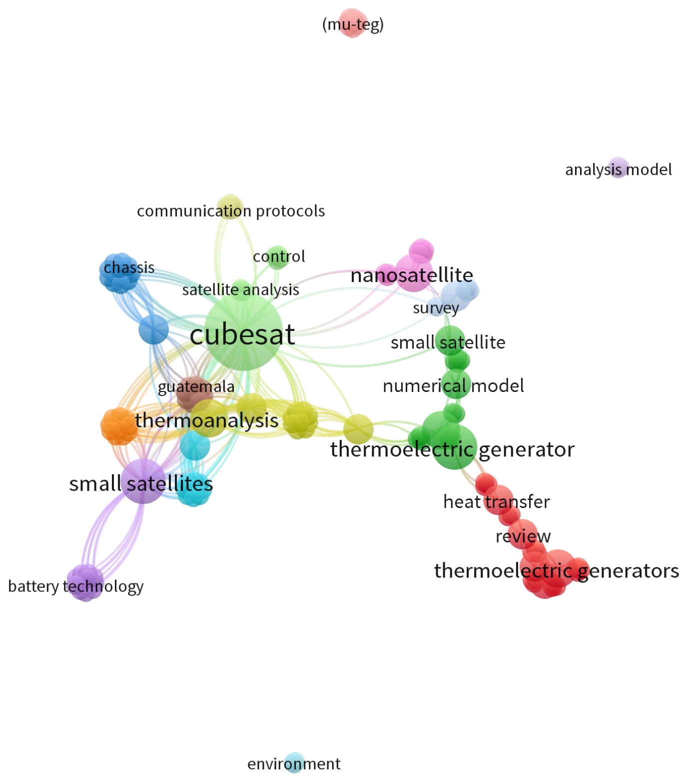


Figure 23. Mapping the existing connections between the inventors.

4. Final Considerations

This review aimed to recognize the application of TEGs as the main energy source in nanosatellites, particularly CubeSat models, identifying the impacted structures and systems under space conditions. The study highlighted the absence of TEG application, prompting the use of the ProKnow-C methodology for a state-of-the-art search. This search identified 33 relevant scientific articles and, after filtering, defined the necessary conditions to evaluate TEGs in CubeSats.

A similar patent search resulted in 34 patents, with only 5 meeting the criteria and 2 closely aligning with the research proposal. Initial assessments showed extensive use of simulation software like ANSYS and Matlab in 63.63% of the reviewed articles to evaluate CubeSat thermal behavior, considering construction specifications and enabling TEG application evaluation based on a CubeSat's face temperatures. However, there was a notable absence of studies directly addressing the use of TEGs as energy sources in nanosatellites, with existing research predominantly focused on terrestrial applications. Both internationally and in Brazil, the scientific literature and patent production on this topic remain limited, with the field being notably dominated by North American contributions.

The patent analysis revealed a predominance of U.S.-origin inventions, indicating a lack of incentives for this topic in Brazil and internationally. Only one patent addressed micro-TEGs, while others suggested structural modifications without direct applications in nanosatellites. The analysis of patents and scientific articles highlighted a peak in patent creation between 2016 and 2020, with a decline in scientific article production during the same period, but an increase since 2019, suggesting industry influence on academia.

Since 2020, the focus shifted to CubeSat structural and thermal optimization, crucial for potential TEG applications. Patents were mostly classified under "Execution of Transport

Operations", focusing on space application energy and communication systems, structural development of electronic components, energy storage, and photovoltaic system testing. No patents were specifically for TEG application in CubeSats, highlighting an industrial innovation gap in nanosatellite energy supply systems.

The methodology used facilitated a detailed bibliometric analysis of scientific articles and patents, leading to key conclusions. TEGs were identified more as thermoelectric temperature regulators rather than energy sources for CubeSats, highlighting the importance of comprehensive state-of-the-art reviews. Among identified review articles, none directly addressed TEGs in CubeSats, indicating pioneering research. The 33 scientific articles did not show TEG applications as energy sources in CubeSats, instead focusing on temperature regulation. The analysis of the relationship between academic research and industrial sector patents revealed increased patent production since 2015, with a decline in the scientific literature until 2019, when it began to correlate more with patent development, indicating a connection between research and industrial progress.

The use of TEGs in CubeSats presents both opportunities and challenges. On the one hand, TEGs offer unique advantages, such as their ability to harvest waste heat from internal components and external space conditions, providing a supplementary power source that complements solar cells. Their compact and lightweight design aligns well with the constraints of nanosatellites, and their lack of moving parts ensures high reliability in the harsh space environment. In hybrid systems, TEGs could enhance the overall performance of the EPS, particularly during orbital eclipses or periods of reduced solar exposure.

On the other hand, significant limitations remain in the use of TEGs for CubeSats, particularly their low power output and reliance on thermal gradients, which are challenging to achieve on small satellite surfaces. A potential solution lies in modifying the geometry of TEGs to better adapt to the 10×10 cm dimensions of a 1U CubeSat's faces. By optimizing their design to conform to specific face orientations—such as those exposed to higher thermal flux—TEGs could improve heat absorption and dissipation, enhancing power generation. This geometric optimization would enable better integration into the CubeSat structure without compromising payload space or mass constraints, making TEGs a more viable option for hybrid energy systems or even as standalone power sources in the future.

Future work should consider modifying procedures to include lost relevant articles, using new criteria like journal impact factors, and reading abstracts of excluded articles for valuable information. Additionally, numerical-computational simulations to describe TEG properties when optimally applied to CubeSats could reveal innovative methods for using thermoelectric devices in space missions, enhancing both temperature distribution analysis and power systems.

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Abbreviations

The following abbreviations are used in this manuscript:

NASA	National Aeronautics and Space Administration
ESA	European Space Agency
LEO	Low Earth orbit
COTS	Commercial Off-The-Shelf
TEGs	Thermoelectric generators
RTG	Radioisotope thermoelectric generator
FEM	Finite Element Method
TECs	Thermoelectric Coolers
KWs	Keywords
BP	Bibliographic Portfolio
PR	Patent Repository
EPS	Electrical Power System
IP	Intellectual Property
RD	Research and Development
PDB	Preliminary Database
WoS	Web of Science
JCR	Journal Citation Report
SJR	SCImago Journal Rank
SD	Science Direct
DBs	Databases
PRAD	Preliminary Raw Articles' Database
RAD	Raw Articles' Database
AD	Author Database
PCBs	Printed circuit boards
RPD	Raw Patent Database
PD	Patent Database
CPC	Cooperative Patent Classification
USPTO	United States Patent and Trademark Office
EPO	European Patent Office
MTG	Magneto-thermoelectric generator
NETT	Nano-engineered thin-film thermoelectric
MJPV	Multiple Junction Photovoltaic
IoT	Internet of Things
CNPq	Brazilian National Council for Scientific and Technological Development
FACEPE	Fundação de Amparo a Pesquisa de Pernambuco
PPGIES	Programa de Pós-Graduação Interdisciplinar em Energia e Sustentabilidade

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