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Article

Ultra-Low-Power Energy Harvesters for IoT-Based Germination Systems: A Decision Framework Using Multi-Criteria Analysis

Daniel Aguilar-Torres [1,2], Enrique García-Gutiérrez [1], Omar Jiménez-Ramírez [3], Eliel Carvajal-Quiroz [3] and Rubén Vázquez-Medina [1,*]

[1] Instituto Politécnico Nacional, CICATA-Querétaro, Cerro Blanco 141, Colinas del Cimatario, Santiago de Querétaro, 76090, Querétaro, Mexico
[2] Secretaría de Ciencia, Humanidades, Tecnología e Innovación, Insurgentes Sur 1582, Crédito Constructor, Benito Juárez, 03940, CDMX, Mexico
[3] Instituto Politécnico Nacional, ESIME Culhuacan, Santa Ana 1000, San Francisco Culhuacan, Coyoacán, 04440, CDMX, Mexico
* Correspondence: ruvazquez@ipn.mx

Abstract

The ongoing miniaturization of electronic systems and the increasing demand for sustainable, autonomous technologies driven by the Internet of Things (IoT) highlight the importance of efficient, ultra-low-power energy harvesting devices. This study evaluates fifteen such devices manufactured by five of the eight industry leaders. The study assesses the technological suitability of these devices for small-scale, intelligent, autonomous seed germination systems. The evaluation is based on a flexible, practical, multicriteria analysis framework that incorporates a broad set of criteria related to the context of the case study system. The framework also considers the functional and operational limitations of the low-power energy harvesters under analysis. The findings suggest that a comprehensive and transparent methodological approach can generate a prioritized list of energy harvesters aligned with the case study system. This list facilitates selecting the most suitable energy harvesters for IoT-based, small-scale seed germination systems. The analysis demonstrates the feasibility of systematically and structurally selecting the analyzed energy harvesting devices while considering conflicting technical, economic, and environmental priorities. Finally, the study emphasizes that distinct device prioritization lists can emerge when the scope or objective of the project changes because these alterations impact the set of evaluation criteria, their ranking, and weighting. This study outlines a structured evaluation framework that can be adapted to different contexts to facilitate technology selection. Technology researchers and practitioners can use this replicable, auditable tool to identify the advantages and disadvantages of incorporating technology into specific projects.

Keywords: energy harvesting; ultra-low-power devices; multicriteria decision-making; sustainable electronics; smart agriculture

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1. Introduction

Unlike previous studies, which focused on energy storage technologies [1], this study focuses on energy harvesting technologies. These technologies aim to eliminate the costs and practical issues associated with replacing or recharging batteries by harvesting ambient energy. Apparently, these technologies extend the life of electronic devices, including IoT devices, wireless sensors, medical devices, consumer electronics, smart locks, wearables, smartphones, and low-power devices. For a more in-depth understanding, review the study by Bhatt *et al.* (2024) [2], which provides a comprehensive evaluation and comparative analysis of these technologies. The study considers various factors, including energy sources, energy availability, conversion mechanisms, required infrastructure, and production costs. In addition, it provides information on production rates, application areas, and

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aspects related to overall energy efficiency, potential limitations, and commercial viability. It is also advisable to review the study by Citroni *et al.* [3], which focused on analyzing the importance of reducing power consumption and increasing energy efficiency to improve the autonomy and longevity of sensor devices. Furthermore, this study analyzes advances, challenges, and future directions in designing ultra-low-power devices, efficient energy storage, energy management units, wireless communication protocols, and energy harvesting techniques. A key element of this study is the integration of these techniques within the framework of remote device monitoring and IoT. This study aims to promote the development and application of robust and environmentally friendly technological solutions for long-term practical use in real-world scenarios.

Ultra-low-power devices for energy harvesting are essential for providing long-term power to low power electronic systems. These devices convert small amounts of energy captured from various environmental sources into useful electrical energy. As electric vehicles primarily rely on a main battery to power the drive system, energy harvested from other sources could power accessories such as air conditioning, interior lights, and the radio. Ultra-low-power energy harvesting devices primarily function through transducers that convert specific types of environmental energy into electrical energy. These devices also have energy management circuits that regulate and store harvested energy to ensure efficient use in powering the intended device. In this regard, it is also recommended to review the study by Citroni *et al.* [3], which provides a technology review that focuses on analyzing the importance of reducing power consumption while simultaneously increasing energy efficiency. This approach aims to enhance the autonomy and longevity of sensor devices within the framework of remote device monitoring and the IoT. In this context, it is essential to consider ultra-low-power devices, efficient energy storage, energy management units, wireless communication protocols, and energy harvesting techniques. Additionally, the study by Citroni *et al.* [3] examines the advances, challenges, and future directions of design techniques for these technologies to encourage the development and application of robust and eco-friendly technological solutions for practical and sustainable use in real-world scenarios.

Therefore, in this study, a multicriteria decision-making methodology based on a simple additive scoring and weighting approach was used to technologically compare ultra-low power devices for energy harvesting, considering their competitiveness when used in energy harvesting systems. The most appropriate method of multicriteria analysis varies depending on the specific problem, the nature of the data, the number of alternatives and criteria, the level of stakeholder involvement, and the desired level of rigor and complexity.

In most cases, decisions are made based on economic factors to optimize time, space, money, energy, raw materials, labor, and other resources to achieve innovation, profitability, competitiveness, and environmental sustainability. However, optimal decision-making is not always feasible. In such cases, the multicriteria decision-making approach can be considered. This approach, as outlined by Alvarez *et al.* [4], can be used as a sorting and selection method. Its application has been documented in the evaluation and selection of mobile phones [5], industrial suppliers [6], software engineering practices [7], transportation based on the idea of shared mobility [8], IoT applications [9], sites for renewable energy systems [10,11], on-demand energy technology [12], nanomaterials for energy harvesting systems [13,14], or alternative materials based on nanogenerators as wearable devices [15]. It has also been applied to the management of electrical and electronic waste in the supply chain [16]. However, applications of this approach in ultra-low-power devices for energy harvesting have not been identified.

Although there are several methods with specific variants, the stages of a multicriteria analysis generally include six aspects: i) structuring the decision problem, ii) specifying the analysis criteria, iii) developing a strategy to measure the performance or quality of the alternatives, iv) scoring the alternatives and weighting the criteria to rank the alternatives, v) performing sensitivity and robustness analyzes of the results, and vi) reviewing, justifying, and documenting the results. There are many multicriteria analysis methods. Each method has its own strengths and weaknesses and is suited to

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different types of problems and data. Many schemes use multicriteria analysis, each with its own strengths and weaknesses. This makes them more or less suitable for certain types of problems and data. Despite this diversity, these schemes are grouped into three basic categories: value-based, outranking, and simple methods. Value-based methods construct a function that represents the preferences of decision-makers regarding various criteria. Three sub-classes are defined in this category. The first subclass consists of strategies based on the analytical hierarchy process. This process organizes and analyzes complex decisions in a structured way, considering mathematics and psychology, as well as pairwise comparisons to determine relative weights and scores. The second subclass includes strategies based on the technique of ranked preference by similarity to the ideal solution. In this technique, alternatives are ranked according to how close they are to an ideal solution (the best) or a negative ideal solution (the worst). The third subclass is based on optimization and compromise strategies that focus on assessing and selecting a set of alternatives with conflicting criteria. The goal is to find an ideal compromise. In contrast, outranking methods determine which alternative is better by comparing pairs based on a set of preference criteria and thresholds. There are two main approaches in this category. One approach establishes an outranking relationship based on indices of concordance (agreement) and discordance (disagreement). This approach delegates the decision-making process of eliminating and selecting alternatives to achieve the best possible outcome. The other approach uses preference functions to establish a partial or complete ranking of alternatives. Finally, for simple multicriteria analysis methods, three basic approaches have been developed. The first is to program by objectives, aiming to minimize deviations from conflicting desired objectives. The second approach is fuzzy analysis, which uses fuzzy set theory to address uncertainty and imprecision in criteria and preferences. The third approach is the simple additive scoring and weighting method.

Consequently, this paper is organized as follows. Section 2 presents a concise overview of key concepts related to multicriteria decision making, competitive profile matrices, critical success factors, and competitive technology factors. Additionally, it provides an overview of fundamental concepts related to ultra-low power devices in the context of energy harvesting techniques and IoT. Section 3 describes the methodology used to identify the critical technological factors for the success of energy harvesting systems when applied to electric vehicles. Then, Section 4 demonstrates how the methodology should be applied to a specific case study that considers ultra-low power devices for energy harvesting from two manufacturers. It includes context, competing technologies, technological competitive factors, and a competitive profile matrix. Thus, based on the competitive profile matrix of the systems considered, a technological comparison is made. Finally, Section 6 is devoted to the conclusions.

2. Background

This section covers four topics. First, it provides a concise overview of prominent companies that are developing energy harvesting technology. Second, it examines the most notable ultra-low-power energy harvesters currently available in the market. Third, it offers an extensive overview of the primary applications of ultra-low-power energy devices. Finally, it presents a comprehensive description of the multicriteria analysis used to compare these devices and determine the most suitable option for IoT applications.

2.1. Leading Companies

Several companies are at the forefront of developing ultra-low-power ICs and energy harvesting solutions. These include:

1. **Texas Instruments** is another company at the forefront of this technology, offering products such as the TPS62200 and TPS62201 devices. Texas Instruments is renowned for its ultra-low-power microcontrollers (MSP430 family) and power management ICs for energy harvesting. Examples include the BQ25504 and BQ25570 devices.

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2. **Analog Devices** offers a wide range of ultra-low-power energy harvesting devices and power management solutions. These products convert energy from vibration (piezoelectric), photovoltaic, and thermal sources into regulated electrical power. The company also offers boost converters, ultra-low quiescent current linear regulators, and components for stand-alone systems. Examples include the ADP5090 and LTC3330 devices.
3. **STMicroelectronics** offers low power management devices for IoT applications, wearables, and remote sensing, including ultra-low-energy harvesters and battery chargers, solar energy harvesters optimized for outdoor conditions, ultra-low-power microcontrollers, development tools and evaluation tools, as well as solutions geared primarily towards harvesting energy from photovoltaic, thermoelectric, and RF energy.
4. **Microchip Technology Inc.** is a leading provider of microcontrollers and semiconductor solutions. The company has a strong market presence in energy harvesting systems and offers ultra-low-power microcontrollers (XLP family) and power management devices designed for energy harvesting. Instead of selling energy harvesting devices as standalone units, Microchip Technology Inc. provides a complete set of components, development kits, and solutions for the implementation of energy harvesting systems.
5. **Silicon Labs** is actively developing and promoting energy harvesting solutions for the IoT, with a focus on battery-free or extremely long-life devices. The company offers microcontrollers (XLP family) and power management devices designed for energy harvesting. However, Silicon Labs specializes in low-power wireless system-on-a-chip (SoC) solutions for battery-powered and battery-less IoT devices, such as the EFR32BG22 series. These solutions support Bluetooth LE and Zigbee Green Power standards.

   Electronic Portable Energy Autonomous Systems (e-peas) is a company that focuses on ultra-low-power semiconductor technology for energy harvesting and processing solutions. This company provides high-efficiency environmental energy managers for energy harvesting that utilize diverse energy sources, including photovoltaic, thermal, radio frequency, and vibration. Its primary focus is on enabling devices to be energy autonomous, essentially giving them "infinite battery life", by harvesting ambient energy efficiently and significantly reducing power consumption. The ambient energy manager (AEM) family of power management integrated circuits (PMICs) is its core product line for energy harvesting.
6. **EnOcean GmbH** is a leading provider of wireless energy harvesting technology. The company offers self-powered, maintenance-free wireless sensors and switches for building automation and IoT. These products draw energy from their surroundings, eliminating the need for batteries and wires. This company produces the ECO200 kinetic energy harvester, which can be combined with wireless switch modules.
7. **Cymbet Corporation** develops thin-film and solid-state batteries (EnerChips) and related energy harvesting technology. This company combines these batteries with power management solutions to create "embedded energy" systems for low-power applications such as wireless sensors, medical devices, RFID systems, and industrial controls. However, discussions on forums suggest that its products may be discontinued or have limited availability.

These electronic boards enable the future of ubiquitous, self-sufficient electronic devices that require minimal or no maintenance, significantly reducing their environmental impact and expanding their deployment possibilities.

2.2. Ultra-Low Power Devices and Energy Harvesting

In the context of IoT, the main factor hindering the long-term, large-scale deployment of wireless devices is their current lack of energy autonomy. To address this issue, environmental energy harvesting and wireless power transfer techniques have emerged [17]. These techniques enable the design and deployment of battery-less wireless devices with self-sufficient and sustainable energy supplies [18]. This addresses the issue of traditional batteries, which have a limited lifetime and require frequent

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replacement. This has implications for maintenance costs, downtime, and environmental issues related to battery disposal. It is essential to associate these technologies with devices that adhere to standard communication protocols, have low power consumption requirements, and are designed according to energy efficiency and cybersecurity criteria. The rise of IoT has also led to the increased use of wireless sensor nodes [19]. These nodes are used indoors to control processes and collect data. However, since these devices typically rely on batteries, they are neither sustainable nor practical in the long term. To promote sustainability and extend their lifespan, battery-less sensor nodes must be developed and deployed. These ultra-low-power devices use ambient energy harvesting to convert energy into useful electrical energy.

Hence, when energy harvesting is considered, ultra-low-power devices are a relevant technology that enables low power electronic systems to be energy self-sufficient for long periods with minimal demand on traditional batteries. A wide variety of devices convert small amounts of energy from various environmental sources into useful electrical energy. It should be emphasized that achieving ultra-low power in energy harvesting systems requires careful design of the following:

1. Energy management units: These devices harvest, convert, store, and supply energy. They include maximum power point tracking, which optimizes power extraction from the energy harvester. This is especially important for variable energy sources, such as solar or vibration energy. The topic also includes voltage regulation, which provides stable output voltages to the load. This is often achieved using low-dropout regulators or DC-DC converters (buck/boost). The category includes energy storage management through storage devices, such as supercapacitors and thin-film batteries, as well as cold-start circuits. Cold-start circuits are essential for starting operation from a fully depleted state with very low input power.
2. Low-Power microcontrollers: These devices process data and control system operations while consuming minimal power.
3. Efficient rectifiers: They convert the alternating current (AC) output of some harvesters to direct current (DC) using active rectifiers.
4. Sensors: They consume the minimum possible amount of energy during sensing and data acquisition.
5. Communication protocols: They should be based on low energy wireless communication standards, such as Bluetooth low energy (BLE) or long range wide area network (LoRaWAN).

Despite significant progress in developing ultra-low power devices [18,20], challenges remain. For instance, surrounding energy sources tend to be intermittent and low-powered, necessitating ultra-low power energy storage devices. Additionally, electronic devices must be able to start up with no stored charge and with minimal energy harvested. This would maximize the overall efficiency of energy harvesting and delivery by reducing losses in power conversion and management. Continued research is also required on novel transducer materials to reduce the cost of device deployment and mass production. Other challenges include developing compact energy harvesting systems on chips (SoCs) with sensing and communication capabilities that consume low power; using advanced control systems and artificial intelligence to optimize power management and adaptive voltage scaling in energy harvesting systems; combining multiple energy harvesting sources to overcome the intermittency of a single source and ensure a more reliable power supply; and using wireless sensors to monitor machinery, detect vibrations, and track assets in industrial environments.

Accordingly, ultra-low-energy harvesters can be defined as devices that capture energy from the environment and convert it into small amounts of useful electrical energy. These devices facilitate the fabrication of self-sufficient electronic devices that require minimal maintenance, thereby establishing a sustainable alternative to conventional battery-powered systems. A comprehensive review of the existing literature reveals that the integration of these devices confers several advantages, including:

1. This technology enables the autonomous operation of electronic devices, thereby extending their functionality over extended periods, potentially indefinitely, through continuous energy

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harvesting from the environment. This eliminates the need for frequent battery replacement, which in many cases reduces operational inconvenience, safety risks, and operating costs.

2. This technology is distinguished by its low power consumption, a feature that results from its design, which is intended to operate at extremely low power levels. These levels are indicative of their compatibility with the harvesting of marginal energy from the environment.
3. This technology is an eco-friendly solution that reduces dependence on disposable batteries, which are known to contribute to environmental pollution. It also utilizes energy more efficiently, addressing a significant source of waste. This contributes to a sustainable and environmentally friendly approach.

In addition, energy harvesters can be classified according to the source of energy from which they extract energy. The most prevalent sources encompass photovoltaic, thermoelectric, piezoelectric, radio frequency (RF), and kinetic mechanisms. Photovoltaic or solar devices are engineered to transform light energy from both internal and external sources into electrical energy through the application of solar cells. These devices are utilized in a variety of applications, including calculators, clocks, and wireless sensor modules. Thermoelectric devices harness temperature gradients, facilitated by the Seebeck effect, to generate electricity. These devices are utilized in environments with heat sources, such as industrial systems, motors, or even body heat for biomedical devices. Piezoelectric devices are capable of harvesting the energy potential inherent in certain materials and thus producing electricity under mechanical stress. These devices find application in a variety of fields that demand precise monitoring of movement, including industrial machinery, aircraft wings, and human motion. RF energy harvesters are capable of converting signals from Wi-Fi, cellular networks, and dedicated transmitters into useful energy. These technologies find application in a variety of professional settings, including battery-free wireless sensors and radio frequency identification (RFID) systems. Finally, kinetic devices refer to devices that obtain energy from fluid flow, such as blood flow in pacemakers or wind flow in heating, ventilation, and air conditioning ducts.

2.3. Applications of Ultra-Low-Power Energy Harvesters

The development of ultra-low-energy technology has led to a number of innovative applications, particularly in the field of IoT and Internet of Vehicles (IoV) environments, as well as in smart homes, smart cities, industrial automation, agriculture, and personal devices such as smartwatches, fitness trackers, advanced medical sensors, human body-powered systems, and machinery-powered systems. For instance, it is utilized in wireless sensor networks for industrial monitoring, building automation, smart grids, remote monitoring, and agriculture. However, this technology is also used in biomedical implants, including pacemakers, neural implants, ingestible cameras, prostheses, and neuro-modulation devices. In addition, these technologies can power remote sensing in difficult-to-reach or hazardous environments. These technologies could be especially useful for laptops, tablets, and smartphones whose batteries are not designed to provide consistent, continuous power to support their extensive daily use. This forces users to recharge their devices once or twice a day. The widespread use of smartphones and the dependence on them have created a need for standard chargers, which can lead to practical and financial drawbacks. To improve the daily charging experience, new energy harvesting technologies are emerging that can supply electrical power to low-energy devices by obtaining useful energy from the environment [21–25].

This solution ensures a long-term reliable power supply, thus reducing the need for invasive battery replacement procedures. In the field of wearable electronics, its applicability encompasses two primary domains: extending battery life and enabling battery-free operation of fitness bands, smartwatches, and other wearable devices. This technology also finds applications in smart homes and building automation systems, particularly in wireless switches, environmental sensors, and other smart devices that require minimal maintenance. In the Industrial Internet of Things (IIoT) or Internet of Vehicles (IoV), this technology enables the use of self-powered sensors for predictive maintenance, asset tracking, and beacons powered by ambient light or motion, as well as process optimization in

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harsh or remote industrial environments. Finally, in the consumer electronics sector, this technology has been successfully implemented in remote controls, toys, and calculators.

The ultra-low-energy harvesting systems market is driven by the increasing demand for IoT devices. The need for energy-efficient and sustainable solutions, significant advancements in ultra-low-power microcontrollers and integrated circuits for energy management, the increasing adoption of this technology in sectors such as building and home automation, the growth of consumer electronics, industrial technology, and smart transportation, and the increasing development of IoV are additional factors to be considered.

Future trends for ultra-low-power energy harvesters include incorporating artificial intelligence and machine learning, developing hybrid systems that combine various energy harvesting options within a single device, and miniaturizing devices to make them biocompatible. The latter has a significant impact on biomedical applications. In addition, new materials and architectures are being developed that enable innovative energy conversion mechanisms.

Finally, it is important to note that ultra-low power harvesters are at the forefront of a paradigm shift toward sustainable, energy-autonomous electronic systems. This shift has far-reaching implications for the future of the IoT and beyond.

2.4. Decision-Making Based on Multiple Criteria

Multicriteria decision-making (MCDM) aims to determine the best alternative by considering multiple criteria in a selection process. According to Taherdoost and Madanchian [26], the process can be viewed as selecting the best or most preferred alternative from a set of alternatives. MCDM is a comprehensive framework that encompasses techniques and tools that facilitate decision-making by simultaneously assessing multidimensional criteria. The following three components are fundamental to MCDM.

- *Alternatives*. A set of alternatives should be proposed and analyzed.
- *Performance score*. A numerical scale should be used to rate the performance of each alternative.
- *Criteria*. It is used to evaluate and compare the different alternatives and choose the best one to solve the problem.

The study by Dean [27] and Taherdoost and Madanchian [26] shows that MCDM can be applied using formal or simplified methods. `Formal methods` include multi-objective programming methods such as linear programming and objective programming, which solve complex systems of equations involving an infinite or semi-infinite number of variables, constraints, and objectives. `Simplified methods` include popular techniques that consider practical reasons for solving complex systems of equations without requiring extensive knowledge. `Simplified methods` have less strict rules than `formal methods`, making them quite flexible and easy to adapt to different types of problems.

2.4.1. Competitive Profile Matrix

MCDM is a tool for creating a technological strategic plan that uses simple additive weighting methods. One of these methods is based on the competitive profile matrix (CPM), which is a graphical representation of the most important features of a product/service, providing a description of the competitive overview. The CPM was first introduced in 1986 by David [28] and is an analytical tool that provides an objective approach to evaluating and selecting alternative strategies in small and large organizations. A CPM can be defined as a strategic planning analysis instrument that assists companies in evaluating the strengths and weaknesses of their products/services or themselves in relation to those of their industry competitors. The implementation of a CPM facilitates the formulation of competitive strategies aimed at ensuring the viability, social impact, and technical feasibility of products or services. In essence, a CPM is a tool designed to facilitate the development and implementation of a strategic plan that aims to enhance a company's technological competitive factors within the market. It ensures the achievement of company objectives and allows companies to take advantage of the best practices

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identified by market leaders to surpass their competitors in specific areas. Consequently, a CPM serves as a valuable mechanism for quality management systems grounded in ISO 9001.

2.4.2. Competitive Technology Factors

In general, key competitive factors (KCF) include competitors, technological factors, environmental factors, SWOT (strengths, weaknesses, opportunities, and threats) analysis, competitive advantages, strategic analysis, and external factors. They are considered important tools for developing strategic information systems oriented toward maintaining long-term policies in an organization to differentiate itself from its competitors or to develop strategies to achieve a long-term competitive advantage over them. However, competitive technological factors (CTF) are considered relevant in the context of this work; they can be understood as product attributes that customers value and that organizations can use to compete successfully in their target markets. They are used to identify the technological superiority of a product, service, or organization over its competitors. Due to their importance, CTFs can be used in a CPM with different weights based on their importance and valuation by customers. In this way, technologies with better scores on their critical success factors could be selected. In this context, CTFs should be used to select the best electronic board on the market dedicated to ultra-low-power devices for energy harvesting, considering their physical, technical, and performance conditions when used in energy harvesting control systems to identify, design, and implement technological strategies related to energy harvesting in low power consumption systems.

3. Multicriteria Analysis Methodology

The methodology used consists of the following steps: i) Definition of the case context, ii) Identifying competing technologies, iii) Definition of CTFs, iv) Weighting CTFs, v) Scoring CTFs, vi) Building the CPM, and vii) Analyzing the scores of competing technologies. The usefulness of the methodology becomes evident when the competitive advantages are quantified based on the technological competitive factors that depend on the case study to be addressed. This methodology focuses on a soft qualitative analysis of a competitive comparison and evaluation of different ultra-low power devices for energy harvesting. The seven steps of the methodology are described below.

3.1. Defining the Case Context

The first issue is to have a common understanding of the technologies being compared. This requires defining the scope, purpose, goals, and funding of the technologies, as well as the vision and mission for their production and development. Depending on the case study, this step establishes the reference framework, defines the purpose of the technology comparison, and defines the selection strategy.

3.2. Identifying the Competing Technologies

According to Winchester and Salji [29], the literature and patent review is essential for creating a technological summary. Also, according to Hiebl [30], to select the outstanding works that should be included in the sample for analysis, the databases used and the coverage period should be specified. In addition, in this study, it is considered that technologies should be analyzed using the PEST method (political, economic, social, and technological) [31–33] and by considering Maslow's hierarchy concerning the needs and motivations of technology users [34,35].

3.3. Defining CTFs

The CTFs should describe the features of competing technologies and explain how they relate to technical features that users would appreciate. Similarly to the studies by Poston [36] and Yan *et al.* [37], a hierarchical pyramid is applied to user expectations of competing technologies in this methodology. In this case, the following five levels are considered:

- *Life cycle*. This means that users expect technology to have a long useful life and that incremental updates and improvements can be considered appropriate.

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- *Technical issues and infrastructure*. This means that users expect manufacturers to guaranty the required technological functionality of a product and the availability of the necessary infrastructure for its implementation. Satisfaction with this aspect depends on the performance and features of the technology under consideration, as well as the supplies required for its implementation.
- *Legal, political, and regulatory compliance*. In this regard, users expect the technology under consideration to comply with national or international standards and laws for operation in a particular country or region.
- *Sociocultural considerations*. This aspect relates to the actions taken by the manufacturer to increase awareness and change the user culture about the benefits that their product can bring when implemented in a specific application. This aspect is related to social impact (e.g. sustainability).
- *Environmental and ecological aspects*. These aspects are called meta-needs. It should be noted that the more users' growth needs are met, the more positive emotions they may experience. In this case, user satisfaction is a relatively non-binding process in the long term, as their growth needs change over time and with the new facilities and products. In this case, it is important to remember that it is a dynamic process with constant feedback.

3.4. Weighting CTFs

Based on the judgment of a technology expert, a hierarchy or weight should be used to prioritize the CTFs, considering their marketing and technical importance. In any case, the priority assignments should be explained, bearing in mind that each weight should be in the range (0, 1) and the sum of all CTF weights should be one.

3.5. Rating CTFs

Each CTF for each competing technology must be evaluated by assigning a specific qualification, which should be rated on a scale of 0 to 10. A CTF rating of 0 indicates that the technology does not contribute to the CTF. On the other hand, a CTF rating of 10 indicates that the technology excels in the aspect considered by the CTF.

3.6. Building CPM

A CPM must include the calculated CTF ratings for all competing technologies. This tool identifies the main strengths and weaknesses of each technology analyzed. Each CTF of each technology must be assigned a qualification, which is the result of multiplying the weight of the CTF by the value assigned to it. To obtain a score for each competing technology, the sum of the qualifications considered for all CTFs must be calculated.

3.7. Analyzing the Scores of the Competing Technologies

Competitive technologies should be analyzed according to their significance and importance in the context of the selected CTFs. The score for each technology should reflect its strengths and weaknesses. The final score is the sum of the individual scores. The technology that receives the highest total score is considered the strongest relative to its competitors.

4. Results of the Multicriteria Analysis

A case study has been prepared that focuses on the application of ultra-low power devices in an IoT context. The challenge is to select the best device for a real-world IoT application from among the various options offered by different manufacturers.

4.1. Case Study

For the purposes of this study, it is assumed that `STEP ONE` of the methodology involves a plausible and realistic use case. In the IoT context, this use case integrates ultra-low-energy harvesting principles with wireless sensor networks to facilitate the monitoring and control of seed germination processes. Furthermore, this use case proposes an innovative approach to conventional methods of

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monitoring seed germination in vertical nurseries, which currently rely on manual monitoring or wired sensor systems. Manual monitoring is laborious, vulnerable to human error, and data are provided intermittently. Wired monitoring systems, on the other hand, are costly to install and maintain, restricting flexibility in designing and implementing intelligent, autonomous germination systems. To ensure optimal germination rates, seedling health, and yield, it is essential to maintain ideal conditions for temperature, humidity, soil moisture, and light exposure at the individual seed tray level within an autonomous, intelligent germination system. In accordance with these operational requirements, the system design must be energy-efficient, even in scenarios involving the use of small, battery-powered sensors. If implemented in medium- or large-scale systems consisting of multiple trays or individual germination units, these sensors could entail significant operating costs and a serious environmental issue due to the handling and disposal of discarded batteries.

Consequently, given the focus of numerous research projects on the study or development of low-cost IoT-based seed germination systems for precision agriculture in small-scale production, the solution proposed in the use case specifies a smart, small-scale, and energy-autonomous seed germination system that must be implemented using energy harvesting systems. Therefore, it is assumed that the system incorporates ultra-low-power, self-sufficient microsensor nodes for real-time hyper-local monitoring of process conditions. It is also anticipated that the system should be conceptualized based on the principles of ultra-low-power electronics to effectively manage critical environmental factors in the process of optimal seed germination and early seedling growth. It should be emphasized that the application of ultra-low-power electronics to seed germination focuses on the following aspects of the process.

1. Precise monitoring. This is based on the use of low-power sensors that accurately and in real time measure critical process parameters, such as soil moisture, temperature, humidity, light intensity, and even pH.
2. Automated control. Ultra-low-power microcontrollers, such as the STM32L series or certain ARM Cortex-M0+ variants, are essential for activating actuators based on sensor data, ensuring that optimal germination conditions are maintained automatically.
3. Wireless connectivity. Low-power wireless protocols such as LoRaWAN, Zigbee, or Bluetooth Low Energy (BLE) are used to transmit data from sensors to a central hub or cloud platform. This feature enables remote monitoring and control through wireless connections, enhancing operational efficiency and security.
4. Energy efficiency. The design of ultra-low power electronics is typically focused on achieving minimal power consumption, a practice that can contribute to the extension of battery life. This effect is further enhanced by the incorporation of energy harvesting devices.
5. Small-scale precision agriculture. Due to its characteristics, this technology can be applied in small-scale crops, vertical farms, or research environments where precise control over the conditions of each plant is a requirement.

The conceptualized germination system offers several key benefits, including increased germination rates due to precise monitoring and dynamic adjustment of environmental parameters at the micro level. This system also reduces the waste of water and energy resources, shortens germination times, increases seedling vigor, minimizes labor costs, and enhances environmental sustainability by reducing hazardous waste and the carbon footprint associated with the manufacture and disposal of sensors and self-powered batteries. In addition, it facilitates better process understanding through sufficient data, contributing to improved agricultural and germination practices.

This case study illustrates how the integration of ultra-low energy harvesting into smart sensor networks can enhance a specific agricultural process, such as seed germination, by enabling localized, autonomous, and data-driven environmental control. This ultimately leads to significant improvements in process efficiency, yield, and sustainability.

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4.2. Competing Technologies

Considering `STEP TWO` of the methodology and to demonstrate its application, fifteen ultra-low power devices were selected from five manufacturers: Texas Instruments, Linear Technology, which has been part of Analog Devices since 2017, STMicroelectronics, Silicon Labs, and EnOcean GmbH. No energy harvesters were found from Microchip Technology Inc., e-peas, or Cymbet Corporation. Six devices were selected from Texas Instruments: BQ25505, BQ25504 (2011), TPS6273x, TPS62736, BQ25570, and BQ25504 (2023). Two devices were selected from Linear Technology: LTC3588-2 and LTC3588EMSE-1. Three devices were selected from STMicroelectronics: SPV1050 and SPV1040, and ST25DV-I2C. Two devices were selected from Silicon Labs: EFR32BG22E and EFR32BG27. Two devices were selected from EnOcean GmbH: ECO206 and ECT310.

From Texas Instruments, BQ25505 is an ultra-low-power boost converter that features an integrated charger and a maximum power point tracking (MPPT) algorithm. It is commonly used to harvest energy from various sources, including solar cells and thermoelectric or piezoelectric transducers. BQ25504 (2011) and BQ25504 (2023) refer to different revisions or release dates of the BQ25504. Similarly to BQ25505, BQ25504 is an ultra-low-power boost converter and battery charger. Although both are very similar, the 2023 version may have updated features, improved efficiency, or different packaging. Without more information, it is difficult to specify the exact differences. Nevertheless, this demonstrates that Texas Instruments has developed a commitment to continuously improving products and devices. TPS6273x is a family of ultra-low-power step-down converters. The "x" in the part number usually indicates a family of devices with different output voltages. TPS62736 is a specific member of this family. These devices are designed for applications where high efficiency and low quiescent current are critical, such as in battery-powered wireless sensors, smart meters, and other IoT devices. BQ25570 is another advanced energy harvesting solution. It combines a boost charger, a buck converter for regulated output, and an MPPT algorithm. This makes it a highly integrated solution for systems that need to charge a battery and provide a regulated voltage to a load from a low-power source. Texas Instruments offers energy harvesting solutions, such as BQ25505, BQ25504, and BQ25570, as well as high-efficiency DC-DC conversion solutions, including TPS6273x and TPS62736. These integrated circuits are essential for building low-power, long-lasting electronic systems, especially ones that operate with ambient energy or small batteries. From Analog Devices, LTC3588-2 is a nanopower energy harvesting solution designed for high-impedance energy sources, such as piezoelectric, solar, and magnetic transducers. LTC3588EMSE-1 is a nanopower energy harvesting power supply. It is a package variant of LTC3588-1 and is part of the LTC3588 family. Although LTC3588EMSE-1 shares many features with LTC3588-2, it has different output voltage options and UVLO thresholds. From STMicroelectronics, SPV1050 is an ultra-low power and high-efficiency power manager that can harvest energy from both photovoltaic (solar) cells and thermoelectric generators (TEGs). It supports various battery chemistries, including Li-ion, Li-polymer, NiMH, and NiCd batteries, as well as super capacitors, with CC-CV charge profiles. It also has dual independent low-dropout regulators that power companion integrated circuits such as microcontrollers, sensors, and RF transceivers. SPV1040 is an outdoor-optimized solar energy harvester that offers higher output power (up to 3W) with an embedded maximum power point tracking (MPPT) feature. Finally, ST25DV-I2C series are near field communication (NFC) tags that harvest energy from an external RF field to supply very low-power applications. From Silicon Labs, the EFR32xG22E family of wireless system-on-a-chip (SoC) devices—including EFR32BG22E, EFR32MG22E, and EFR32FG22E—is a key component of energy harvesting strategies due to their ultra-low power consumption design. These SoCs enable devices to operate using harvested energy and are designed for ultra-low power consumption. EFR32BG22E is optimized for Bluetooth Low Energy (BLE) applications and EFR32BG27 Series 2 BLE SoC offers an ultra-small WLCSP package and an integrated DC-DC boost converter that enables operation at voltages as low as 0.8 volts. This makes it suitable for single-cell alkaline batteries and 1.5-volt button cell batteries. From EnOcean GmbH, the ECO260 is an electromechanical energy converter that gener-

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ates power from mechanical motion. ECT310 is a DC-to-DC converter designed for thermoelectric applications. It is used with Peltier elements to harness temperature differences.

In addition, the following criteria were considered for each CTF: input current, minimum and maximum output voltage, output current, efficiency, size, market availability, customization, adaptability, wireless communication capability, versatility, technological maturity, and price. As part of the competitiveness analysis, each CTF was assigned a description and a weight between 0 and 1 based on its importance to the evaluated technology. For this reason, a CPM was constructed in which each CTF was rated from 0 to 10. Finally, all CTFs were hierarchically ranked based on their ratings. This ranking determined which devices were more technologically viable in the energy harvesting of ultra-low-power.

4.3. Competitive Technology Factors

Building on the above ideas, the `STEP THREE` of the methodology involves the consideration of the product specifications that are most valued by users or consumers. The following is an example of a set of 13 critical success factors for ultra-low-power devices for energy harvesting.

- **CTF01**. Input current, I_{in}. Determines how much energy a device can harvest. It affects the performance, autonomy, cost-effectiveness, adaptability, and potential of a device to innovate and contribute to sustainability. Devices with higher I_{in}, offering better functionality and capacity conditions, are more attractive to the market.
- **CTF02**. Minimum input voltage, V_{in}min. In an energy harvesting system, it refers to the minimum voltage required for the system to operate effectively to harvest, convert, and store energy. It can vary depending on the energy harvesting technology and the system-specific components. For example, in vibration-based energy harvesting systems, the minimum input voltage can be in the range from millivolts (mV) to several volts (V).
- **CTF03**. Maximum input voltage, V_{in}max. It refers to the maximum voltage that the system can tolerate or handle without damage or performance degradation. It is critical to ensure that the system operates safely and efficiently within its operating limits.
- **CTF04**. Output voltage, V_{out}. It refers to the electrical potential difference produced by a device, such as a battery, power supply, or circuit component, when delivering electrical energy to a load. It is measured in volts (V) and indicates how much electrical energy is available to drive current through the load. In practical terms, the output voltage determines how effectively a device can power other components. It can vary depending on the design of the device and the load connected to it.
- **CTF05**. Output current, I_{out}. It describes the current in a device when it is connected to a load. It is measured in amperes (A) and indicates how much electrical current is being delivered to that load. Determines how much power is available to operate the connected components. It can vary depending on the resistance of the load and the output voltage. In essence, it reflects the ability of the device to deliver energy to do work, such as lighting a bulb or running a motor.
- **CTF06**: Efficiency, η. It can be considered a quality feature in any energy transducer considering that energy conversion can be from kinetic or vibrational energy to electrical energy.
- **CTF07**: Size. It refers to the physical dimensions and form factor of the device, including length, width, height, and total volume. It is important to consider some constraints such as heat dissipation, electrical characteristics, mounting type, and cost.
- **CTF08**. Market availability. It concerns how easily and widely the product can be found and purchased by consumers in a given market. There are several key aspects to this CTF such as inventory levels, distribution channels, market demand, regulatory factors, and seasonal variations.
- **CTF09**. Adaptability to technology. Customizable technology includes products or systems that can be customized to meet the specific preferences or needs of users. This may involve adjusting features, settings, or components to create a more personalized experience. On the other hand,

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adaptive technology refers to systems that can adjust their performance or functionality based on user interactions or environmental conditions. Together, customizable and adaptive technologies improve the user's experience by enabling personalization and responsiveness, making it more effective and easier to use.

- **CTF10**. Wireless communication capabilities. It is determined by several factors such as bandwidth, signal strength, multiplexing, transmission speed, and interference. In general, it is essential to enable seamless connectivity and functionality in current electronic devices, affecting everything from Internet access to device interoperability.
- **CTF11**. Versatility. It refers to the ability to capture energy from various sources and convert it into usable electrical energy.
- **CTF12**. Technological maturity. The term refers to the degree of advancement, complexity, and dependability of the technology used to harvest and transform energy from diverse sources into useful electrical energy. It indicates that technology is well-developed, reliable, and ready for widespread use, which is a significant factor in its adoption of various applications.
- **CTF13**. Price. It is critical to the competitiveness of energy harvesting electronic devices, influencing consumer choice and the broader market landscape. When these devices are competitively priced, they can offer a strong value proposition, especially when used with traditional power sources. Lower costs can drive adoption in various applications, such as IoT devices, wearables, and remote sensors.

4.4. Defining CTF Weights

Before weights are assigned to the thirteen CTFs, the specifications of ultra-low-power devices for energy harvesting should be reviewed and analyzed. Table 1 shows the parameter description for each device for which the weights have been defined. Note that the description of each parameter is based on the data-sheet provided by the manufacturer, where **M** indicates the manufacturer, TI is Texas Instruments, LT is Linear Technology from the company Analog Devices, STM is STMicroelectronics, SL is Silicon Labs, EO is EnOcean GmbH, and NE is "Not reported".

Table 1. Device parameters considered, which have been related to the CTFs defined in this work.

M	Device	CTF01 mA	CTF02 V	CTF03 V	CTF04 V	CTF05 mA	CTF06 %	CTF07 mm^2	CTF13 100 pcs (USD)	CTF10	Year
TI	BQ25505	9.2000	0.30	5.50	5.10	285	90.00	3.5× 3.5	404.00	No	2019
TI	BQ25504 (2011)	0.3300	0.13	3.00	2.55	200	NR	NR	359.00	No	2011
TI	TPS6273x	0.4000	2.00	5.50	5.00	200	90.00	3.5× 3.5	85.03	No	2014
TI	TPS62736	0.0100	1.30	5.50	5.30	50	92.00	NR	84.71	No	2014
TI	BQ25570	9.2000	0.30	5.10	5.10	110	93.00	3.5× 3.5	171.16	No	2019
TI	BQ25504(2023)	0.0100	0.30	5.10	5.10	200	90.00	3.0× 3.0	540.00	No	2023
LT	LTC-3588-2	0.0015	0.30	5.00	5.00	100	89.00	3.0× 3.0	579.88	No	2010
LT	LTC3588EMSE-1	NR	4.30	18.00	5.10	100	92.00	3.0× 3.0	143.07	Yes	NR
STM	SPV1050	0.0300	0.15	18.00	5.30	70	92.00	3.0× 3.0	218.00	No	2024
STM	SPV1040	1800.0000	0.30	5.50	3.30	600	95.00	3.0× 4.4	203.00	No	2021
STM	ST25DV64KC	0.1000	NR	NR	3.35	0.5	NR	5.0× 3.0	125.00	Yes	2024
SL	EFR32BG22E	2.5000	1.80	3.80	1.80	60	91.00	4.0× 4.0	185.52	Yes	2024
SL	EFR32BG27	3.6000	0.80	3.80	1.80	60	90.00	4.0× 4.0	236.59	Yes	2021
EO	ECO260	NR	NR	NR	2.00	0.06	NR	29.3×19.5	2000.00	No	2023
EO	ECT310	NR	0.02	0.50	5.00	NR	30.00	30.0×10.0	2000.00	No	2012

The CTF09 for all devices considered corresponds to some arguments about why each device can be considered a customizable and adaptive technology to create a more personalized experience for technological users.

For `STEP FOUR`, Table 2 shows the weights assigned to each CTF (Factor A). Note that each of the weights given to the CTFs is based on the importance of the competitive factor in ultra-low power devices for energy harvesting. The weighting is subjective, according to the interests of each user. Some users will prefer to give more importance or weight to technical aspects; others will prefer to give more importance to aspects of versatility, usability, or size. For this exercise, priority has been given to the technical-electronic elements of the evaluated cards. It should be noted that the sum of

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the weight values for each CTF is equal to 1. Table 2 shows that the most important CTF is efficiency, which is assigned the highest weighted value of 0.20. In contrast, the CTF with less relevance has the lowest weighted value of 0.02. For the present case study, in order to facilitate the multiple analyzes of the performance of all devices, the Pareto principle (80/20) was applied. That is, CTFs with the highest weight, whose sum is equal to or close to 80 %, were considered the most important and defined the best performance of the devices. In this case, technical performance characteristics were given priority. The six most important technological competitive factors of the ten ultra-low power electronic cards for energy harvesting, which account for 80 % of the importance of all technological features, are efficiency (0.2), output voltage (0.15), output current (0.15), input current (0.1), minimum input voltage (0.1), and minimum output voltage (0.1). The remaining seven competitive technological factors account for 20 % of all desirable features in the ten electronic boards evaluated, namely size (0.05), versatility (0.04), technology adaptability (0.03), market availability (0.02), wireless communication capability (0.02), technology maturity (0.02), and price (0.02). The above is reflected in Table 2.

Table 2. Ordered weighting from highest to lowest of the CTFs for the devices considered.

CTF	Description	Weight (A)
CTF06	Efficiency [η]	0.20
CTF04	Output voltage [V_{out}]	0.15
CTF05	Output current [I_{out}]	0.15
CTF01	Input current [I_{in}]	0.10
CTF02	Minimum input voltage [V_{in} min]	0.10
CTF03	Maximum input voltage [V_{in} max]	0.10
		Sum 0.80 (Pareto)
CTF07	Size	0.05
CTF11	Versatility	0.04
CTF09	Technology adaptability	0.03
CTF08	Market availability	0.02
CTF10	Wireless communication capacities	0.02
CTF12	Technological maturity	0.02
CTF13	Price	0.02
		Sum 0.20 (Pareto)

4.5. Defining CTF Rates

In STEP FIVE, each CTF should be rated for each competing technology (Factor B). Consequently, it should be noted in Tables 3 and 4 that a numerical rating was assigned to each CTF for each device considered. The assigned level ranges from 0 to 10, where 0 is the lowest level, which means that the device does not meet the CTF attribute at all. A rating of 10 means that the technology is fully compliant with the CTF attribute. Intermediate ratings indicate performance, poor, fair, or good for each CTF attribute.

Table 3. Rating for each CTF for TI and LT competing technologies (Factor B).

CTF	Device rating (Rating for contribution to the CTF, 0 to 10) (B)							
	BQ25505 2019	BQ25504 2011	TPS6273x 2014	TPS62736 2014	BQ25570 2019	BQ25504 2023	LTC-3588-2 2010	LTC3588EMSE-1 NE
CTF06	7.00	0.00	7.00	9.00	10.00	7.00	6.00	8.00
CTF04	8.00	5.00	7.00	10.00	8.00	8.00	7.00	8.00
CTF05	10.00	8.00	8.00	4.00	7.00	8.00	6.00	6.00
CTF01	5.00	8.00	7.00	9.00	5.00	9.00	10.00	0.00
CTF02	8.00	10.00	5.00	6.00	8.00	10.00	8.00	3.00
CTF03	5.00	2.00	5.00	5.00	5.00	2.00	10.00	10.00
CTF07	8.00	0.00	8.00	0.00	8.00	10.00	10.00	10.00
CTF11	6.00	6.00	6.00	6.00	10.00	8.00	10.00	10.00
CTF09	7.00	6.00	6.00	6.00	9.00	9.00	10.00	10.00
CTF08	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
CTF10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.00
CTF12	4.00	9.00	7.00	7.00	5.00	2.00	10.00	0.00
CTF13	2.00	3.00	10.00	10.00	5.00	2.00	2.00	5.00

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Table 4. Rating for each CTF for STM, SL, and EO competing technologies (Factor B).

CTF	Device rating (Rating for contribution to the CTF, 0 to 10) (B)						
	SPV1050 2024	SPV1040 2021	ST25DV64KC 2024	EFR32BG22E 2024	EFR32BG27 2021	ECO206 2023	ECT310 2012
CTF06	9.00	10.00	0.00	7.00	7.00	0.00	2.00
CTF04	10.00	4.00	4.50	2.00	2.00	2.50	7.00
CTF05	5.00	10.00	1.00	4.50	4.50	1.00	0.00
CTF01	10.00	1.00	7.00	1.50	1.50	0.00	0.00
CTF02	9.00	8.00	0.00	6.00	7.00	0.00	10.00
CTF03	10.00	5.00	0.00	3.00	3.00	0.00	1.00
CTF07	10.00	9.00	7.50	8.00	8.00	2.00	3.00
CTF11	9.00	9.00	9.00	9.00	9.00	3.00	3.00
CTF09	10.00	10.00	10.00	10.00	10.00	5.00	5.00
CTF08	10.00	10.00	10.00	10.00	10.00	10.00	10.00
CTF10	5.00	5.00	10.00	10.00	10.00	0.00	0.00
CTF12	10.00	8.00	10.00	10.00	8.00	9.00	7.00
CTF13	5.00	5.00	6.00	5.00	5.00	0.00	0.00

4.6. Competitive Perfil Matrix

In order to assess the competitiveness of each of the technologies evaluated, `STEP SIX` makes it possible to develop the CPM (see Table 5). The first column lists each of the CTFs. The headings of the subsequent columns indicate the name of the technology to be evaluated. Cell values are the result of the multiplications of the weighted value (0.00 to 1.00) of the CTF (Factor A) and the score obtained for compliance with the attribute of each CTF (0 to 10, Factor B) of each evaluated device. In the end, the total sum of each of the scores obtained by each device is recorded for each of the CTFs. The devices with the highest totals are the best rated for weighting and scoring all CTFs. This quantitative approach not only highlights the relative performance of each technology, but also facilitates informed decision making by clearly illustrating which technologies excel at certain capabilities and which may fail. By analyzing these ratings, stakeholders can prioritize the technologies that best fit their strategic goals and resource allocations. Tables 5 and 6 show the CPM derived from the rating assigned to each CTF and the weight assigned to each ultra-low-power device for energy harvesting.

Table 5. Competitive Profile Matrix (CPM) for TI and LT.

CTF	Device score (A$\times$B)							
	BQ25505 2019	BQ25504 2011	TPS6273x 2014	TPS62736 2014	BQ25570 2019	BQ25504 2023	LTC-3588-2 2010	LTC3588EMSE-1 NE
CTF06	1.40	0.00	1.40	1.80	2.00	1.40	1.20	1.60
CTF04	1.20	0.75	1.05	1.50	1.20	1.20	1.05	1.20
CTF05	1.50	1.20	1.20	0.60	1.05	1.20	0.90	0.90
CTF01	0.50	0.80	0.70	0.90	0.50	0.90	1.00	0.00
CTF02	0.80	1.00	0.50	0.60	0.80	1.00	0.80	0.30
CTF03	0.50	0.20	0.50	0.50	0.50	0.20	1.00	1.00
CTF07	0.40	0.00	0.40	0.00	0.40	0.50	0.50	0.50
CTF11	0.24	0.24	0.24	0.24	0.40	0.32	0.40	0.40
CTF09	0.21	0.18	0.18	0.18	0.27	0.27	0.30	0.30
CTF08	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
CTF10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16
CTF12	0.08	0.18	0.14	0.14	0.10	0.04	0.20	0.00
CTF13	0.04	0.06	0.20	0.20	0.10	0.04	0.04	0.10
	7.07	4.81	6.71	6.86	7.52	7.27	7.59	6.66

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Table 6. Competitive Profile Matrix (CPM) for STM, SL, and EO.

CFT	Device score (A×B)						
	SPV1050 2024	SPV1040 2021	ST25DV64KC 2024	EFR32BG22E 2024	EFR32BG27 2021	ECO206 2023	ECT310 2012
CTF06	1.80	2.00	0.00	1.40	1.40	0.00	0.40
CTF04	1.50	0.60	0.68	0.30	0.30	0.38	1.05
CTF05	0.75	1.50	0.15	0.68	0.68	0.15	0.00
CTF01	1.00	0.10	0.70	0.15	0.15	0.00	0.00
CTF02	0.90	0.80	0.00	0.60	0.70	0.00	1.00
CTF03	1.00	0.50	0.00	0.30	0.30	0.00	0.10
CTF07	0.50	0.45	0.38	0.40	0.40	0.10	0.15
CTF11	0.36	0.36	0.36	0.36	0.36	0.12	0.12
CTF09	0.30	0.30	0.30	0.30	0.30	0.15	0.15
CTF08	0.20	0.20	0.20	0.20	0.20	0.20	0.20
CTF10	0.10	0.10	0.20	0.20	0.20	0.00	0.00
CTF12	0.20	0.16	0.20	0.20	0.16	0.18	0.14
CTF13	0.10	0.10	0.12	0.10	0.10	0.00	0.00
	8.71	7.17	3.28	5.19	5.25	1.28	3.31

4.7. Scores of Competing Technologies

According to the CPM obtained in Tables 5 and 6 and based on `STEP SEVEN`, the ranking reveals the following. The top five e-cards were SPV1050 (8.71), LTC3588-2 (7.59), BQ25570 (7.52), BQ25504 (7.27) and PSV1040 (7.17). However, a closer look at the weighted CTF scores reveals that while SPV1050 has the highest score (8.71), it is not necessarily the device with the best current and voltage performance. Note that the next four devices have better current and voltage performance but lower scores in the lower-weight CTFs. The specialist technician in charge must select the best device among the five best devices according to the project interests and the benefits of the CTFs that are the most important.

5. Discussion

This study provides a structured and replicable framework for selecting ultra-low-power energy harvesting devices for IoT-based applications, specifically targeting autonomous seed germination systems. The findings underscore several key insights:

- Effectiveness of MCA. The proposed methodology, based on a competitive profile matrix (CPM) and weighted critical technological factors (CTFs), proved effective in comparing fifteen devices from five leading manufacturers. By prioritizing efficiency, output voltage/current, and input parameters, the analysis identified STMicroelectronics' SPV1050 as the top-performing device (score: 8.71), followed by LTC3588-2 and BQ25570. This shows that MCA can provide transparent and quantitative decision-making in contexts where technical, economic, and environmental priorities conflict.
- Practical Implications for IoT and Smart Agriculture. The case study illustrates the feasibility of integrating energy harvesting into small-scale autonomous germination systems. Such systems reduce the need for disposable batteries, minimize maintenance costs, and improve sustainability. The approach aligns with global trends toward energy-autonomous IoT devices, offering benefits such as improved resource efficiency, reduced carbon footprint, and improved operational reliability.
- Trade-offs and Context Sensitivity. Although SPV1050 achieved the highest overall score, the analysis revealed that other devices excel in specific technical attributes (e.g., current and voltage performance). This highlights the importance of context-specific weighting of CTFs. For projects focusing on cost, size, or wireless communication, the rankings could shift significantly. Thus, the adaptability of the framework is a major strength, allowing recalibration of priorities for different applications.
- Limitations and Future Directions. The study focused on a single use case under controlled assumptions. Industrial-scale deployment would require additional considerations, including

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real-world energy variability, integration with hybrid harvesting systems, and long-term reliability testing. Future research should explore dynamic weighting strategies, incorporate lifecycle assessments, and evaluate emerging technologies such as AI-driven energy management and multi-source harvesters.

- Contribution to Sustainable Electronics. By demonstrating a systematic approach to technology selection, this work supports strategic planning for sustainable IoT solutions. The methodology can be extended to other domains—such as biomedical devices, smart homes, and industrial IoT—where energy autonomy is critical.

This study demonstrates the efficacy of a structured MCA framework for selecting ultra-low energy harvesting devices tailored to IoT-based applications, specifically autonomous seed germination systems. In this study, a CPM and weighted critical technological factors (CTFs) were utilized to evaluate fifteen devices from five leading manufacturers. The analysis placed significant emphasis on efficiency, output voltage/current, and input parameters, identifying SPV1050 (STMicroelectronics) as the best performing device (score: 8.71), followed by LTC3588-2 and BQ25570. These results indicate that MCA provides a transparent and replicable approach to decision-making in contexts where technical, economic, and environmental priorities conflict.

The findings of this study carry substantial implications for the design and deployment of sustainable IoT systems. Integrating energy harvesting into small-scale germination systems has been demonstrated to reduce the reliance on disposable batteries, minimize maintenance costs, and enhance environmental sustainability. This approach is consistent with global trends toward energy-autonomous IoT devices, offering benefits such as improved resource efficiency, reduced carbon footprint, and improved operational reliability. Additionally, the methodology's adaptability facilitates recalibration of priorities across diverse applications, thereby ensuring flexibility in strategic technology planning.

From an industry perspective, the proposed framework enables manufacturers and system integrators to make informed decisions when selecting energy harvesting solutions. By prioritizing ultra-low-power devices with high efficiency and adaptability, companies can achieve operational cost reductions, minimize hazardous waste, and adhere to sustainability regulations. The ability to ensure long-term maintenance-free operation of IoT nodes is particularly valuable for remote or inaccessible environments, such as precision agriculture, industrial automation, and smart cities. Furthermore, the methodology fosters scalability and strategic planning by providing a replicable and auditable decision-making instrument that can be adapted to evolving project objectives.

Despite its strengths, this study has limitations. The analysis was conducted under a series of controlled assumptions for a single use case. However, industrial-scale implementation would require additional considerations, including the variability of real-world energy sources, integration with hybrid harvesting systems, and long-term reliability testing. Future research efforts should explore dynamic weighting strategies, life cycle assessments, and integration with AI-driven energy management for predictive optimization. Furthermore, the integration of multiple energy sources within a unified device has the potential to address concerns about intermittent energy supply and ensure a more reliable power supply.

In summary, this work contributes to sustainable electronics by offering a systematic approach to technology selection that can be extended to other domains, such as biomedical devices, smart homes, and industrial IoT. The proposed framework integrates technical evaluation with practical implications, thereby establishing a foundation for the advancement of energy-autonomous systems and the acceleration of the adoption of eco-friendly technologies in diverse industrial contexts.

6. Conclusions

This study focused on five of the eight companies that specialize in the production of energy harvesting electronic devices. The companies examined were Texas Instruments, Analog Devices, STMicroelectronics, Silicon Labs, and EnOcean GmbH, which offer comparable products that should be

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integrated into an autonomous, intelligent, and small-scale seed germination system in the IoT context. During the preliminary selection process, electronic devices produced by Microchip Technology Inc., e-peas, and Cymbet Corporation were identified as devices particularly well-suited for projects that require the production of demonstration boards, evaluation kits, specialized sensors, or devices designed for the integration of energy harvesters. Consequently, their products were excluded from the evaluation. For the purposes of this study, representative ultra-low-power energy harvesters from each of the five selected companies were chosen. The selection of devices was made independently of their power source, and their evaluation has yielded a definitive conclusion about the technological capabilities that can be used in the IoT context. However, the decision was tailored to the specific case study. It is essential to emphasize that when the project focus changes, it is necessary to develop another set of evaluation criteria tailored to the new project. It is also important to note that various formal multicriteria analysis methodologies have been reported. However, they require in-depth knowledge of multivariate analysis and an extensive set of capabilities that facilitate the resolution of complex systems of equations. This becomes particularly relevant when the number of variables to be analyzed is very large. It is also crucial to highlight the methodological framework used in this study, which exhibited several key characteristics. Firstly, it was characterized by its flexibility, logical structure, and accessibility. These characteristics facilitate decision-making with a high degree of certainty. Secondly, it allowed for simple adjustments to the selection criteria, taking into account the restrictions imposed by the case study. The methodology used in this study offered a valuable analytical approach for the scenario considered, demanding agile decision-making and including various alternatives. It should also be noted that this study evaluated the technological advantages of fifteen ultra-low-power energy harvesting devices. The study also reviewed the offerings on the market of five out of eight leading manufacturers of energy harvesting electronics. This evaluation was based on a thorough analysis of competitive technological factors, as well as the constraints imposed by the case study pertaining to a small-scale, autonomous, intelligent seed germination system operating in the IoT context. Note that a key element in the selection of energy harvesting devices was the competitive profile matrix, a tool that provided a clear and comparative analysis of the devices under consideration. In addition, this structured evaluation enabled the classification and distinction of energy harvesting devices according to the weighted sum of the scores assigned to each device, as outlined by the established criteria for the case study in question. Finally, it should be noted that this technological assessment approach can support decision-making processes and foster technological innovation and strategic planning.

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