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Energy Harvesting for IoT Sensors in Smart Buildings: A Path to Sustainable Energy Solutions.

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Ohana means family.
Family means nobody gets left behind, or forgotten.

— Lilo & Stitch

ABSTRACT

The increasing deployment of Internet of Things (IoT) sensors in smart buildings has enabled enhanced operational efficiency, real time monitoring, and improved occupant comfort. However, reliance on conventional battery powered systems presents challenges in sustainability, maintenance, and environmental impact. This thesis investigates a hybrid energy harvesting approach integrating photovoltaic (PV) and thermoelectric generator (TEG) technologies to provide a continuous and sustainable power supply for IoT devices in smart buildings.

A comparative evaluation of multiple energy harvesting techniques revealed that while PV harvesting offers high efficiency in well environments, it is limited by light availability. Conversely, TEGs can generate electricity from temperature gradients, providing supplementary power during low or no light conditions. Radio frequency harvesting was found unsuitable for this application due to low power density.

The proposed system incorporates a high capacitance supercapacitor (1300 F) and an efficient power management circuit to optimize energy capture, storage, and delivery. The use of supercapacitors offers key advantages such as low maintenance cost, high power density, rapid charge–discharge capability, and reliable operation across wide temperature ranges—making them well suited for hybrid energy harvesting systems in smart buildings. Five year simulations using real world weather data for Halmstad, Sweden, showed that the hybrid system achieved over 99% annual uptime, with sufficient energy autonomy to sustain operation for more than 48 hours without new input. Seasonal analysis confirmed that the hybrid approach effectively mitigates the intermittency challenges of single-source harvesters.

The results demonstrate that hybrid PV-TEG energy harvesting is a technically feasible, environmentally sustainable, and economically viable alternative to conventional battery-powered IoT devices in smart buildings. The approach reduces electronic waste, minimizes maintenance requirements, and supports the development of autonomous, long life sensor networks for intelligent building management systems.

Limitations: This study is based entirely on simulations and literature analysis rather than physical laboratory experiments or full scale deployment. Therefore, the long-term performance of supercapacitors relative to batteries has not been experimentally verified. The comparative discussion of battery cycle life is indicative and based on published data; future work should include empirical testing under realistic operating conditions.

Keywords: Energy harvesting, Smart buildings, IoT sensors, Photovoltaic, Thermoelectric generator, Supercapacitor, Sustainability, Hybrid systems.

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CONTENTS

1 Introduction 1
1.1 Aim 2
1.2 Objective 2
1.3 Delimitations 3
2 Literature Review 5
2.1 IoT and Smart Building 5
2.2 Energy Harvesting: Principles and Concepts 6
2.3 Solar Energy Harvesting 6
2.4 Thermoelectric Energy Harvesting 6
2.5 Radio frequency Energy Harvesting 7
2.6 Kinetic Energy Harvesting 7
2.7 Magnetic Field Energy Harvesting 7
2.8 Wind Energy Harvesting 8
2.9 Acoustic Energy Harvesting 8
2.10 Hybrid Energy Harvesting Systems 8
2.11 Research Gaps and Thesis Contributions 8
3 Theoretical Background 11
3.1 Techniques & Characteristics used for Energy Harvesting 11
3.1.1 Photovoltaic Energy Harvesting 11
3.2 Voltage-Current Characteristics 12
3.3 Thermal Energy Harvesting 12
3.3.1 Voltage-Current Characteristics 13
3.4 Power Requirements of IoT Sensors 14
3.5 Power Conversion and Storage Behavior 15
3.5.1 Cold-Start Voltage and Minimum Operating Input 15
3.5.2 Maximum Power Point Tracking 15
3.5.3 Functioning Of Supercapacitor 16
4 Methodology 17
4.1 Design Section 17
4.1.1 Energy Density Comparison 17
4.2 Selection of Components for the system 18
4.2.1 Temperature Sensor-BME280 18
4.2.2 Thermoelectric generator- TEG1-12706 19
4.2.3 Supercapacitor - CDCL0650C0-0002R7WLH 20
4.2.4 Microcontroller - ESP32 22
4.3 Hybrid Energy Harvesting System 24
4.4 Microcontroller and Sensor Power Consumption 31
4.5 Supercapacitor Choice and Design for Energy Storage 31
4.5.1 Function and System Application 31
4.5.2 Power Management Design 33
5 Energy Harvesting System Simulation Framework 35
5.1 Weather Data Acquisition 35

5.2 Simulation Framework 35
5.2.1 Simulation Test Configuration and Setup 35
5.3 Analysis and Discussion 46
5.3.1 Energy harvesting potential 46
5.3.2 Storage Sufficiency and System Load 47
5.3.3 System Reliability and Downtime 47
5.3.4 Wasted Energy 48
5.4 Economic Analysis 48
6 Results and Discussion 51
6.1 Combined Energy Balance and Reliability 51
6.2 Complementary Source Integration 51
6.3 Sustainability and Deployment Implications 51
6.4 Limitations and Opportunities for Improvement 52
7 Applications using hybrid energy harvesting system 53
7.1 Real Time Acquisition of Sensor Data 53
7.1.1 Implementation Methodology 53
7.2 Store and Process Information 54
7.3 Predictive Maintenance & Threshold Based Monitoring in Smart Buildings 55
8 Conclusion 57
8.1 Future Work 57

Bibliography 58
9 Appendix A 62
.1 MATLAB Code for Hybrid Energy Model 62

LIST OF FIGURES

Figure 1 Schematic diagram of hybrid energy harvesting system 24
Figure 2 indoor irradiance using EXTECH SP505 light meter. 25
Figure 3 Thermal image of a district heating pipe 28
Figure 4 Infrared image of a district heating pipe (86°C) at Halmstad University, illustrating a strong thermal gradient suitable for thermoelectric energy harvesting. 29
Figure 5 Harvested Power 2020 37
Figure 6 Outdoor vs radiator temperature 2020 37
Figure 7 Supercapacitor voltage 2020 38
Figure 8 Harvested Power 2021 39
Figure 9 Outdoor vs Radiator temperature 2021 39
Figure 10 Supercapacitor voltage 2021 40
Figure 11 Harvested power 2022 41
Figure 12 Outdoor vs radiator temperature 2022 41
Figure 13 Supercapacitor voltage 2022 42
Figure 14 Harvested power 2023 43
Figure 15 Super capacitor voltage 2023 43
Figure 16 outdoor vs radiator temperature 2023 44
Figure 17 Harvested power 2024 45
Figure 18 Outdoor vs radiator temperature 2024 45
Figure 19 supercapacitor voltage 2024 46

LIST OF TABLES

Table 1 Sensor types and their electrical characteristics 14
Table 2 Comparison of Various Sensors 19
Table 3 Comparison on different TEG models 20
Table 4 Specifications of Various Capacitors 21
Table 5 Comparison of Various Microcontroller Units (MCUs) 23
Table 6 Comparison of Indoor and Outdoor Irradiance Levels 26
Table 7 Power consumption details 31

ACRONYMS

IoT Internet of Things

ITU International Telecommunications Union

ICTs Information and Communication Technologies

TEG Thermoelectric Generator

HVAC Heating, Ventilation and Air Conditioning

EH Energy Harvesting

PZT Lead Zirconate Titanate

PVDF Polyvinylidene Fluoride

KEH Kinetic energy harvesting

M-field EH Magnetic Field Energy Harvesting

RF radio frequency

MPPT Maximum Power Point Tracker

PV Photovoltaic

TENG Triboelectric Nanogenerator

RFID Radio Frequency Identification

MFC Microbial Fuel Cells

LTE Long-Term Evolution

GSM Global System for Mobile

DC Direct Current

PMC Power Management Circuit

SPI Serial Peripheral Interface

ADC Analog to Digital converter

PWM Pulse Width Modulation

PCB Printed Circuit Board

SD Secure Digital

PMIC Power management integrated circuit

1 INTRODUCTION

The increased usage of Internet of things (IoT) devices in Smart buildings contributes towards better monitoring and building control along with potential energy savings and occupant comfort[1]. IoT sensors play an important function in gathering environmental parameter data related to temperature, humidity, luminance and air quality for building operations to be optimized. However, the widespread deployment of these devices has introduced significant challenges, particularly in terms of energy sustainability and maintenance. Traditionally, IoT sensors have been powered by batteries, yet their disposal presents an environmental and health risk in that they consist of toxic elements. Battery operated sensors are also long term sustainability concerns like maintenance needs and electronic waste. While mains power is used for some products, battery powered sensors remain common to most smart building deployments[2].While outlets are common in newly constructed buildings, cabling each IoT sensor is generally impractical with more cost, retrofitting challenges and restricted placement options.Energy harvesting, where ambient energy is collected and converted into electrical power, offers a possible means of powering IoT sensors in a sustainable way[3].

Energy harvesting is increasingly being viewed as a viable approach to counter these challenges in IoT based smart building systems. Energy harvesting is the process of acquiring and transforming ambient energy from the environment into electrical energy to power IoT devices. Various techniques for energy harvesting are present, but their effectiveness is heavily reliant on stochastic environmental factors and unpredictable ambient conditions. Energy harvesting systems have the potential to remove the necessity of battery replacement, lower maintenance expenses and usher in a more sustainable and environmentally friendly strategy for IoT implementation in smart buildings[4].

Several ambient energy sources have been studied in the literature for utilizing to power IoT devices in smart buildings. They include solar irradiation, ambient radio frequency (RF) signals, thermal gradients, mechanical vibration,human energy,etc[5][6]. Each of them has its own characteristics regarding energy density, availability, and integratability. solar radiation provides the highest energy density typically around 1000 W/m^2 under direct sunlight. In contrast, ambient RF sources like Wi-Fi offer significantly lower power densities, in the order of 0.0005 W/m^2, making RF energy harvesting inherently more challenging. Thermoelectric generators (TEGs), which convert temperature gradients into electrical energy, offer a middle ground in terms of energy availability and consistency, especially in indoor or low light environments[7][5].The thermoelectric generator is a solid

state device that converts thermal energy directly into electrical energy. Thermoelectric generators have no internal moving parts, long working life, noiseless and stable operation, no pollution, and great potential in ambient energy harvesting. Mechanical vibrations and pressure are energy sources that surround us, and these sources can be considered in making self powered IoT devices used in a wide range of applications[6].

1.1 AIM

This thesis presents a comprehensive analysis of various energy harvesting technologies with the aim of identifying the most effective solution for powering IoT sensors within smart building environments. The research focuses on prominent energy harvesting technologies.These technologies is evaluated based on a range of criteria, including energy output, environmental compatibility, scalability and economic viability. The performance of these systems is analyzed under diverse indoor conditions commonly found in smart buildings, such as varying lighting, temperature gradients, and electromagnetic environments.
By providing a holistic evaluation of energy harvesting technologies, this thesis aims to inform the design of more resilient and sustainable power solutions for smart buildings. The outcomes are expected to contribute to the development of self powered IoT ecosystems that reduce dependency on traditional power sources such as grid electricity and replaceable batteries and support long term, maintenance free operation.

1.2 OBJECTIVE

The following objectives have been set to achieve the aim of this thesis:

1. Compare Different Energy Harvesting Techniques

   This objective is directed at investigating a variety of energy harvesting (EH) technologies relevant to smart building applications. Every method will be explored based on its theoretical background, working principles, and efficiency at indoor conditions. The evaluation will address main performance metrics, such as power output, energy conversion efficiency and theoretical feasibility of the utilization of such benchmarks to supply IoT sensors in intelligent buildings. In addition, review of current tendencies and recent progress in the field of self sustaining IoT devices will be performed to convey contextual insight and identify emerging innovation stemming from research in energy harvesting.

2. Compare Power Management and Energy Storage Methods

   The second objective is aimed at the research and design of power management circuits and energy storage devices that are complementary to the selected EH techniques. All EH systems

require effective storage mechanisms, such as rechargeable batteries or supercapacitors, to ensure a stable power supply during periods of low energy. This objective includes the integration of voltage regulators and DC-DC converters for efficient energy distribution control. The study will consider dynamic energy regulation methods that adapt to changes in environmental conditions, thereby ensuring continuous and stable operation of IoT devices in smart building spaces.

3. Design an Energy Harvesting Powered IoT Device
   The third goal is to create a working IoT device that uses only energy from the environment. This energy will be collected using the methods found in Objective 1. This includes adding the right parts for converting energy into the device.

   The design will account for practical constraints of sensor deployment, power availability, and form factor requirements for seamless integration with smart building infrastructure. Low power design methodologies such as duty cycling, sleep modes, edge computing, and the use of ultra low power microcontrollers will be employed to enhance energy efficiency and extend operational lifespan.

4. Investigate the Potential Advantages of EH-Based IoT Devices in Smart Buildings
   This objective focuses on analyzing the feasibility and benefits of using EH powered IoT devices within smart building environments through simulations and theoretical modeling. Building upon the design proposed in Objective 3, the study will simulate and evaluate various EH methods under different environmental scenarios including varying temperature levels, light intensity, and RF signal availability. The analysis will assess power generation potential, efficiency, system reliability and the capability of these methods to support continuous device operation without external power sources. Key performance metrics such as estimated response times, latency and system stability will also be considered. Based on this evaluation, the study will identify the most appropriate energy harvesting approach or hybrid solution considering factors such as energy sufficiency, cost effectiveness, ease of integration, and minimal maintenance. The findings aim to inform future deployment strategies for EH based IoT sensors in applications like temperature, occupancy, or air quality monitoring within intelligent buildings.

1.3 DELIMITATIONS

To maintain focus and feasibility, the scope of this thesis is limited to the following:

Energy Harvesting Techniques

The research is focused on PV, thermoelectric and RF energy harvesting as primary techniques. Vibration or wind energy harvesting are

excluded since they find no practical application in smart building situations.

IoT Sensors

The system is intended to drive low power IoT sensors (e.g., light, temperature, and humidity sensors) that are typically found in smart buildings. High power actuators or devices are beyond the scope of this research.

Geographical Location

The system is optimized for Halmstad, Sweden, under consideration of the environmental conditions there (e.g., sunlight availability, temperature gradients, and RF signal density). The findings might not be automatically applicable to other geographical positions with drastically different conditions.

System Complexity

The complexity of the system in this current thesis is achieved through a simulation based proof of concept rather than an actual working prototype. The selected components photovoltaic module, thermoelectric generator, power management circuit, supercapacitor and ESP32 microcontroller with BME280 sensor were abstractly coordinated together into an end to end energy chain and simulated using MATLAB. With the inclusion of multi year climatic data and device power profiles, the model achieved more than 99% annual uptime and more than 48 hours of energy autonomy, thereby establishing system feasibility. Substantive deployment was actually taken into account, although CAD drawings and hardware assembly were not done: PV modules near windows or skylights, TEGs on radiator pipes or HVAC ducts, and the electronics in small enclosures. The paper consequently offers a single proof of concept framework wherein integration, performance, and deployment scenarios are addressed within the domain of simulation.

2 LITERATURE REVIEW

For energy harvesting, various energy sources have been considered. To choose an energy harvesting source, one of the main criteria is to determine whether or not it can provide the required power level for the sensor node. In general, power dissipates during voltage conversion and the dissipation increases as the input / output ratio of the voltage increases. Therefore, it is important to ensure that the generated power is at an appropriate voltage and current level[8].

2.1 IOT AND SMART BUILDING

Smart buildings leverage automation systems and IoT sensors to manage and regulate building operations for optimal occupant comfort and energy efficiency. With intelligent, real time decision making based on data gathered by IoT sensors, these systems optimize operations, save energy, and support the reduction of greenhouse gas emissions and global warming [2].

Notable applications include HVAC systems that actively adjust airflow and temperature based on occupancy and environmental conditions to ensure comfort and minimize energy loss [9],[10]. Automated lighting systems along similar lines leverage IoT sensors to manage operation and intensity based on occupancy and available ambient light, significantly reducing excess energy consumption [11].

IoT based automation, while enhancing comfort, productivity, and energy efficiency, with widespread deployment of battery powered sensors, introduces sustainability considerations. Battery replacement, production, and disposal are accountable for higher maintenance cost, extra energy expenditure, and electronic waste. Energy harvesting has emerged as a promising solution. EH systems, through scavenging environmental sources of energy such as thermal, solar, or radiofrequency energy and their conversion to electricity, reduce the reliance on batteries, lowering maintenance needs and e-waste [12],[13]. However, EH devices including power circuits and storage devices also generate waste over time, indicating the necessity to develop sustainable and recyclable solutions.

Therefore, the development of efficient EH solutions is critical to building long term sustainable IoT networks, demystifying scalability challenges, and fully unleashing the potential of intelligent building technologies[14]

2.2 ENERGY HARVESTING: PRINCIPLES AND CONCEPTS

EH has emerged as a revolutionary means of energizing IoT sensors in smart buildings by converting and transferring ambient environmental energy into electrical energy. The technology utilizes a number of energy sources like solar, thermal, radio frequency , and mechanical vibrations to create power systems that can be self sustaining for low energy devices, hence limiting dependence on prime batteries [5],[6].

While one of the primary benefits of energy harvesting is maintenance and waste saving from disposable batteries, a thorough sustainability assessment must consider the entire lifecycle of the harvesting system. As literature states, even the supercapacitors commonly used for energy storage in the systems create EoL concerns, as they are generally produced from environmentally problematic materials and lack clearly defined recycling streams [15]. This indicates that while energy harvesting eliminates one form of electronic waste (batteries), it does not eliminate it to the same extent.

Therefore, the value proposition of energy harvesting extends far beyond mere battery replacement. Its strongest selling point lies in its potential for operational autonomy and maintenance free deployment in hard to reach areas, which is perfect with the demand for sustainable building management solutions [6]. Development continues to progress to further enhance harvesting efficiency and reliability, with more focus on designing for circularity like the development of more recyclable supercapacitors and biodegradable materials to enable long term sustainability in these systems[15].

2.3 SOLAR ENERGY HARVESTING

Photovoltaic technology began in 1839, when French physicist Alexandre Edmond Becquerel initially discovered the photovoltaic effect the mechanism by which light creates electrical current in some materials.[16]. A standard small solar panel (225 x 195 x 17.6mm) under sunlight exposure can reliably offer 10-100 mW of power and is therefore apt to energize low energy IoT devices in intelligent buildings[17].For instance, Sharma et al. were successful in powering a complete environmental monitoring sensor node outdoors using a small panel size of 55x70 mm providing an average power of 12.6 mW, demonstrating feasibility in practice.[18]

2.4 THERMOELECTRIC ENERGY HARVESTING

Thermoelectric energy harvesting leverages the Seebeck effect to convert thermal gradients into electricity, making it particularly suitable for waste heat recovery in applications such as smart building HVAC systems. [19].

TEGs are extremely promising to integrate within HVAC systems, where perpetual thermal differentials exist.For example, Champier

et al. demonstrated it in their paper by energizing wireless sensor nodes with TEGs mounted on household wood stoves, a similar use case to HVAC ducts, with sufficient energy for occasional data transmission[20]. Their insensitivity to light conditions makes them particularly apt as a secondary energy source in hybrid harvesting configurations. When integrated with other methods of energy harvesting, thermoelectric technology assists in mitigating intermittency problems while enhancing the reliability of the overall system[4].

2.5 RADIO FREQUENCY ENERGY HARVESTING

RF energy harvesting collects ambient electromagnetic waves and transforms them into electrical energy through the use of an antenna, rectifier and storage module[14]. Common sources include Wi-Fi routers, cell towers, Bluetooth, and digital broadcast, which are ubiquitous indoors and outdoors. While renewable and pervasive, RF harvesting is beset by low power and reduced efficiency with distance. Nonetheless, it has promise for powering low-energy IoT devices particularly in urban or indoor regions of high radio signal density. It is therefore of interest for application in wearables, embedded sensors, and infrastructure retrofitting where there is no ability to use cabled power [6].

2.6 KINETIC ENERGY HARVESTING

Kinetic Energy Harvesting (KEH) functions by transducing mechanical motion of airflow, vibration, or movement into electricity, typically via resonance based systems suitable for low-power devices [21]. Both indoor and outdoor applications are possible, including airflow powered IoT sensor nodes for grid power monitoring, but efficiency is resonance frequency dependent and often source specific designs are required[4]. KEH technologies include piezoelectric, electromagnetic, and triboelectric nanogenerators (TENGs) [5]. Piezoelectric harvesters (PEHs) using materials like quartz, ceramics, PVDF, and PZT are small, durable, and usually used in structural health monitoring, wearables, and IoT devices[4],[14]. They can outperform RF harvesting but performance degrades in static or low vibration environments.

2.7 MAGNETIC FIELD ENERGY HARVESTING

Magnetic field energy harvesting (M-field EH) is based on the electromagnetic fields generated by alternating current (AC) flowing in conductors. The energy is generally harvested using current transformers. Assuming a sufficiently high current in the conductor, the process provides a constant and constant power source. Corresponding to the high currents, common for power distribution systems, M-field EH is particularly well suited to power IoT networks with large coverage. But power harvesting from near proximity high current conductors is a fundamental safety issue. To minimize this, M-field EH systems

must employ sophisticated protection and control systems, which may complicate the system and limit installation flexibility.[4].

2.8 WIND ENERGY HARVESTING

Wind power harvesting utilizes air currents to generate power through piezoelectric wind energy converters or mini turbines. This method is particularly effective in outdoor and industrial settings with frequent wind sources.[22]. Micro wind turbine converts mechanical energy of airflow to electricity using electromagnetic or piezoelectric conversion.

Not viable for indoor applications; suited for rooftops or open spaces[23].

2.9 ACOUSTIC ENERGY HARVESTING

Acoustic energy harvesting converts sound waves into electrical energy using piezoelectric materials or triboelectric generators. This technique is particularly suitable for urban environments with high noise pollution[24].

2.10 HYBRID ENERGY HARVESTING SYSTEMS

Hybrid energy harvesting systems combine several sources of energy to overcome the limitations of single source harvesting and deliver a stable power supply to IoT sensors. By combining complementary technologies, these systems can generate stable energy output under varying environmental conditions, compensating for periods of low solar irradiance through thermoelectric generation from thermal gradients[6].

Advanced power management circuits, including maximum power point tracking (MPPT) ICs like the BQ25570, are critical to optimizing energy harvesting and storage from any source. These circuits dynamically manage power flow, improving overall system efficiency and reliability.

Hybrid solutions are particularly valuable in smart building applications, where environmental conditions are dynamic. Solar and thermoelectric harvesting, for example, leverages sunlight during the day and waste heat recovery when sunlight is not available. This two source strategy significantly reduces power intermittency, and hence it is a robust solution for sustainable IoT deployments[14].

2.11 RESEARCH GAPS AND THESIS CONTRIBUTIONS

While the overall energy storage discussion appropriately hinges on debates regarding high energy density rechargeable batteries, there is a significant and often under represented body of research relating to the unique role of supercapacitors. Lithium ion batteries, though

well adapted to hold vast amounts of energy, suffer from low charge discharge rates, low cycle life, and concerns about ethical sourcing and recycling of critical materials. This review argues that an integrated vision of a future of sustainable energy must transcend energy density to include power density, life expectancy, and material life cycle. Here is where supercapacitors take their critical niche[15].

This review specifically targets supercapacitors to address a clear lacuna in the literature concerning their dual role in waste management and energy efficiency. Their advanced properties ultra high power density, high kinetics and hundred thousand cycle life make them indispensable for applications batteries cannot excel at. They include harvesting regenerative braking energy, providing essential backup power, and voltage smoothing of power grids. Further, their internal design, typically constructed on carbonaceous matrices, presents an enormous challenge for solid waste valorization. Farm waste biomass, abandoned tires, sludge from industry, and plastic wastes can be transformed into high performance porous carbon electrodes. This is an example of circular economy that transforms waste to a valuable asset for emerging technology. With a focus on supercapacitors, this overview combines the technology not only providing essential grid services but also paving the way for a sustainable way of material utilization, forming a complementary and highly valuable contribution in conjunction with batteries to an integrated energy policy[25].

3

THEORETICAL BACKGROUND

The theoretical framework examines the fundamental ideas, theories, and technological advancements related to EH for IoT sensors in smart buildings.

3.1 TECHNIQUES & CHARACTERISTICS USED FOR ENERGY HARVESTING

EH is the process of capturing and converting ambient energy from the environment into usable electrical power. This technology is particularly valuable for powering low energy devices such as IoT, wearables and smart building systems. The primary goal of energy harvesting is to reduce dependency on batteries, improve sustainability, and enable self powered electronics. This report provides an overview of the most prominent energy harvesting techniques, their working principles, advantages, challenges and applications.
The voltage-current (V-I) characteristics of energy harvesting devices are essentially defined by two factors: the design parameters of the device, and the availability of the energy resource on which the device depends. The V-I characteristics integrate into the problems of power output, efficiency and viability of integrating harvesting systems into low power IoT sensor networks.

3.1.1 *Photovoltaic Energy Harvesting*

Photovoltaic energy harvesting is one of the most widely adopted methods, leveraging photovoltaic (PV) cells to convert sunlight into electricity. The primary technologies used in solar energy harvesting include monocrystalline, polycrystalline, and thin film solar cells. Monocrystalline cells are known for their high efficiency and durability, while thin film cells offer flexibility and lightweight properties, making them suitable for diverse applications[26]. The energy output of a PV panel can be modelled using the fundamental equation:

$$E_{daily} = G \times A \times \eta \tag{1}$$

where:
E_{daily} = Daily energy generated (kWh/day),
G = Solar irradiance (kWh/m²/day)[27],
A = Panel area (m²),
η = Panel efficiency
This equation is widely adopted in solar energy literature[28]and assumes ideal conditions without losses.

3.2 VOLTAGE-CURRENT CHARACTERISTICS

PV cells produce electrical power with incident light using the photovoltaic effect. The V-I behavior of PV cells can be described by the diode equation[29]:

$$I = I_{ph} - I_0 \left(e^{\frac{qV}{nkT}} - 1 \right) \tag{2}$$

Where: I is the output current,
I_{ph} is the photocurrent,
I_0 is the reverse saturation current,
q is the elementary charge,
V is the terminal voltage,
n is the ideality factor,
k is Boltzmann's constant,
T is the absolute temperature.

The characteristics of both voltage and current generation in PV cells are a product of both substance characteristics and the environment. Monocrystalline solar cells have a better efficiency range of 15–22% than polycrystalline cells because of their uniformity of crystal structure and thus produce better voltage and current under the same light conditions. Additionally, a larger surface area on the PV panel will capture more photons and produce more current.

The open circuit voltage (V_{oc}) is determined in the p-n junction and is usually estimated between 0.5 and 0.6 V for a silicon cell industry standard; however, voltage output is affected by series connections and current output is affected by the configuration of parallel and series connections. The performance of the PV cells is decreased when electrical losses occur due to high series resistance (R_s) and/or low shunt resistance (R_{sh}).

The V-I curve of a PV cell is highly nonlinear with a maximum power point (MPP). Environmental conditions such as irradiance, incident angle of light and temperature have a significant impact on current and voltage outputs. Higher irradiance increases the current produced, whereas higher temperature decreases the open-circuit voltage.

3.3 THERMAL ENERGY HARVESTING

Thermoelectric harvesting uses thermoelectric generators (TEGs), which operate on the Seebeck effect.Examples of the TEGs widely utilized are Bismuth Telluride and Lead Telluride, with high thermoelectric efficiency[19][30] Here's how it works:

1. **Temperature Difference**: A TEG is placed between a hot surface and a cold surface.
2. **Seebeck Effect**: When there's a temperature gradient, electrons move from the hot side to the cold side, generating voltage.

3. **Power Generation**: This voltage drives an electric current, producing usable DC power.

TEGs convert heat to electrical energy via the Seebeck effect, whereby voltage is generated by a temperature difference across a thermoelectric material:

$$V_{oc} = \alpha \times \Delta T \tag{3}$$

where

α is Seebeck coefficient

ΔT = Temperature difference between hot and cold sides (K)

The power output is given by:

$$\mathtt{PowerOutput}(P_{max}) = \frac{V_{oc}^2}{4 \times R_{int}} \tag{4}$$

where
V_{oc} is the Open-circuit voltage
R_{int} is the Internal electrical resistance of the TEG

TEGs are capable of delivering milliwatts of power, which can be utilized as an additional source of power over solar power harvesting for IoT applications.[31].

3.3.1 *Voltage-Current Characteristics*

TEGs operate based on the Seebeck effect, converting heat into electrical power by utilizing a temperature difference (T) across a thermoelectric material. Electrically, a TEG can be modeled as a two terminal (two pole) circuit consisting of an electromotive force (EMF) in series with an internal resistance. The EMF, or open-circuit voltage (Voc), is directly proportional to the temperature difference between the hot and cold sides of the TEG, as described by Equation (2). Maximum power transfer occurs when the load resistance matches the TEG's internal resistance, according to Equation (3). The output current is influenced by this internal resistance, with the maximum current (Imax) occurring under short circuit conditions (i.e., when the load resistance is zero). For example, with the TEC1-12706 module, if V_{oc}=0.02×50=1 V at ΔT=50° C, and $R_{int} \approx 1\Omega$, then $I_{max} \approx 1$ A.

Design aspects related to the device include the thermoelectric material choice of thermoelectric material, number and configuration of thermocouples, and internal resistance affect the V-I curve, while the availability of energy resource, specifically the thermal gradient, indicates how much voltage and current can be generated.

Larger TEG modules (e.g., 50 × 50 mm) can accept higher thermal flux due to their increased surface area, which generally leads to higher power output. Additionally, for a given material and thickness, larger modules tend to have lower internal electrical resistance (R_{int}) because

resistance decreases with increasing cross sectional area. This results in higher current capacity. Materials with lower thermal conductivity help maintain a larger temperature difference (ΔT) across the TEG, enhancing voltage output. However, if the thermal conductivity is too low, it may impede heat flow from the heat source to the cold sink, reducing the overall power delivered to the TEG. Alternatively, placing two smaller TEG modules of the same type in parallel (electrically and thermally) can also reduce the total internal resistance and increase current output, similar to the effect of using a single larger area module.

In smart buildings,TEGs obtain heat from heating, ventilation, air conditioning (HVAC) systems or from boiler pipes. Variations in heat source temperature (for example, the on/off cycling of HVAC) lead to variations in ΔT, which leads to variations in the V-I curve[32].

3.4 POWER REQUIREMENTS OF IOT SENSORS

IoT sensors in smart buildings exhibit highly variegated power consumption depending on their sensing modality, sampling rate, data transmission protocol, and operation duty cycle. It is crucial to recognize their electrical needs in order to pair them with appropriate energy harvesting and storage systems[33].

Sensor Type	**Active Current**	**Standby Current**	**Operating Voltage**	**Typical Duty Cycle**
Temperature (Semiconductor)	~50 µA	<1 µA	2.7–5.5 V	1–10%
Motion (PIR)	~100 µA	<10 µA	3–5 V	Event-driven
CO_2/air quality	10–50 mA	~1 mA	3.3–5 V	5–20%
Humidity	~350 µA	<1 µA	2–5 V	5–10%

Table 1: Sensor types and their electrical characteristics

The average power consumption Pavg of a duty-cycled sensor node can be expressed as:

$$P_{avg} = D \cdot P_{active} + (1 - D) \cdot P_{standby} \tag{5}$$

Where:

D is the duty cycle (active time fraction)
$P_{active} = V \times I_{active}$
$P_{standby} = V \times I_{standby}$
From the listed electrical features in Table 1, the motion and temperature sensor were selected since they consume low active current and are ideal for use in smart buildings.

3.5 POWER CONVERSION AND STORAGE BEHAVIOR

In an energy harvesting system, the harvested power must be efficiently controlled and stored to ensure continuous and stable operation of sensors. This requires high efficiency power management circuits and appropriate energy storage elements, such as supercapacitors or rechargeable batteries. While converter efficiency (η), defined as

$$\eta = \frac{P_{in}}{P_{out}} = \frac{V_{in} \cdot I_{in}}{V_{out} \cdot I_{out}} \tag{6}$$

is typically in the range of 70–95%, it's equally important to consider where and how the losses occur. Losses can arise from several sources, including switching losses, conduction losses in transistors and inductors, quiescent current consumption, and leakage in storage components. Moreover, these losses are often load dependent for example, converters may operate less efficiently at light loads or during startup. In thermoelectric energy harvesting, ultralow voltage boost converters capable of starting at very low input voltages (as low as 20–100 mV for TEGs) are essential. Their ability to operate efficiently under varying input conditions plays a critical role in maximizing usable energy output.[34].

3.5.1 *Cold-Start Voltage and Minimum Operating Input*

Another vital design constraint is the cold start voltage, the lowest voltage that a converter requires to start. For instance, a boost converter can take at least 330–500 mV as an input from a solar or TEG before starting switching. Below this point, capacitive pre-charging or low leakage electronics are employed prior to the starting of the converter.

Some PMICs (power management integrated circuit)are calibrated for ultra low startup levels (e.g., 20–30 mV) to support harvesting from low ambient sources like body heat or indoor light.

3.5.2 *Maximum Power Point Tracking*

For variable energy sources like solar or thermal gradients, maximum energy transfer is obtained by running at the source Maximum Power Point (MPP). MPPT algorithms continuously change the load seen by the energy source to maximize power harvesting.

Some common MPPT techniques are:

Perturb and Observe (P&O): Varies operating point gradually and observes changes in power.

Fractional Open Circuit Voltage (FOCV): Specifies operating voltage as a fraction of the open circuit voltage. MPPT maximizes efficiency under changing light or thermal conditions and is typically integrated in energy harvesting PMICs[35].

3.5.3 *Functioning Of Supercapacitor*

Supercapacitors function on the same principle as regular capacitors but with the use of thin dielectrics and have more surface area, thereby enhancing capacitance. This translates to higher energy and power densities compared to regular capacitors and batteries, respectively. Supercapacitors are also fast chargers and have a long life cycle compared to regular capacitors. Whereas the discharge rate by supercapacitors is higher than that of regular batteries by virtue of leakiness, this is nevertheless compensated for by their higher rate of charging[36].

The relationship for energy stored from two voltage levels is:

$$E = \frac{1}{2} C \left(V_{\text{upper}}^2 - V_{\text{lower}}^2 \right) \tag{7}$$

4

METHODOLOGY

4.1 DESIGN SECTION

The initial research of this work was on a PV and radio frequency hybrid energy harvesting architecture. Prior to power calculations and preceding analysis, though, determined that the low power density of RF energy harvesting, typically in the order of microwatts per square meter, made it non feasible as a viable energy source for powering the target IoT sensor node and peripheral components.

As such, the direction of the research moved toward a hybrid PV-TEG system. Such a reengineered strategy takes advantage of the high energy density of solar irradiance by day and adds the around the clock power generation capability of TEGs utilizing low grade thermal gradients, e.g., found in building HVAC systems. Such synergy can effectively overcome the intermittency of single source harvesters and improve overall system dependability.

The subsequent sections provide a detailed exposition of the limitations inherent to RF energy harvesting and introduce the technological rationale for utilizing thermal energy as an auxiliary source in the proposed hybrid implementation.

4.1.1 *Energy Density Comparison*

Solar radiation provides approximately 1000 W/m^2 in direct sunlight, whereas RF power density, such as that from Wi-Fi signals, is around 0.0005 W/m^2 millions of times lower. As a result, the energy available from RF waves is negligible compared to solar energy, making RF harvesting impractical for powering most devices. In fact, it has been calculated that an RF antenna would need to span thousands of square meters to generate as much power as a small solar panel, which is entirely unfeasible. However, given the ubiquity of RF signals, RF energy harvesting can still be improved by optimizing the antenna design, rectifier circuit, and power management system to extract and utilize the limited available energy more efficiently.

In this study, TEG was utilized in place of RF energy harvesting due to the large power output difference and practical feasibility of IoT device powering. RF energy harvesting is typically found to deliver power in a few microwatts (e.g., $1.3\mu W$), which is obtained only when the device is positioned very near to a highly powerful RF source such as a Wi-Fi router, cellular tower, or RFID reader. Because RF energy is an inverse square law function of distance, it falls away very rapidly and is unrealistic for applications requiring even minimal power outputs. Solar panels, on the contrary, produce far more power,

albeit constrained by availability of illumination and unable to operate satisfactorily in low light indoor lighting conditions or at night.

TEGs are an alternative source of power to photovoltaic cells. Unlike solar harvesters, which rely on intermittent illumination, TEGs provide continuous power output by directly converting temperature gradients into electrical energy via the Seebeck effect. Although their efficiency is generally low, their solid state structure without any moving parts ensures high ruggedness, lengthy operation life, and minimal maintenance requirements.

One of the key operating parameters is the temperature difference (ΔT) between the hot and cold sides, the higher ΔT, the more power generation. This also makes TEGs well placed to be easily integrated into constant heat sources such as HVAC ducts, hot water pipes, or industrial equipment in smart buildings.

These inherent advantages reliability, longevity and minimal maintenance in conjunction with their amenability to pairing with energy storage buffers like supercapacitors, render TEGs an extremely suitable component in hybrid energy harvesting systems. They are a critical component in applications demanding continuous, maintenance free performance, where they exceptionally complement the intermittency of primary solar harvesters.

4.2 SELECTION OF COMPONENTS FOR THE SYSTEM

4.2.1 *Temperature Sensor-BME280*

In smart building systems, accurate and energy efficient temperature measurement is extremely important for environment control, energy optimization, and automation of the system. The current section compares most prevalent temperature sensors utilized in smart building configurations with emphasis on power consumption and connectivity both key parameters for extended deployment.

Sensor	Application	Power	Remarks
Nest Temperature Sensor	Smart HVAC control	CR2 Battery (~2 years)	Good integration with Google Nest
Ecobee SmartSensor	Room based HVAC control	Lithium Battery (~3 years)	Multi room sensing with occupancy detection
Bosch BMP388	HVAC & environmental monitoring	Ultra low power	High precision; suitable for IoT & wearables
DS18B20	Data logging, HVAC, industrial	3.3/5V (wired or battery)	Digital sensor with good reliability
Sensirion SHT3x	IoT & cloud based monitoring	Battery or wired (low power)	High accuracy T&H monitoring
BME280 (Chosen Sensor)	Smart home, HVAC, environmental sensing	Low power (3.3V, <1mA active)	Combines temp, humidity, and pressure sensing

Table 2: Comparison of Various Sensors

(a) **Power Efficiency:** BME280 operates with a high low current (ideally 0.6 mA in standard mode), making it perfect for battery powered and long term IoT applications.

(b) **Multi-Functionality:** It provides three sensors in one: temperature, humidity, and barometric pressure reducing component count and saving energy in sensor networks.

(c) **Communication Protocols:** Compatible with both I²C and SPI, providing flexibility for use across a broad range of microcontroller and IoT platforms.

(d) **Use Case Compatibility:** Ideal compatible with smart home and building use cases where low size, wireless transmission, and low power are critical (e.g., energy efficient HVAC, air quality monitoring).

According to technical parameters, comparison and operational characteristics of several temperature sensors mentioned in Table 2, the Bosch BME280 stands out because it is power efficient, multi sensor enabled, and highly connectable. These attributes render it a technically and economically feasible choice for smart environment monitoring systems.

4.2.2 *Thermoelectric generator- TEG1-12706*

(a) **Great Power-to-Cost Ratio** Delivers a maximum of 60W of output (actual output ~5–15W in typical conditions), which is suffi-

Model	**Max Voltage** (V)	**Max Current** (A)	**Max Power (W)**	**ΔT Required**	**Size (mm)**	**R_{int} (Ω)**	**Cost**	**Remarks**
TEG1-12706	15.4	6	~60	~70°C	40 x 40 x 3.6	~1.0	Low	Widely available, low cost, standard
TEG1-12610	14.8	10	~100	~70°C	40 x 40 x 3.6	~0.55	Medium	Higher current, more expensive
TEC1-12705	14.4	5	~50	~70°C	40 x 40 x 3.6	~1.04	Low	Slightly lower power output

Table 3: Comparison on different TEG models

cient to power mini IoT systems. Low cost and ready availability make it ideal for prototyping and use in large networks.

(b) **Reasonable Temperature Differential Requirements** Operates efficiently with a ΔT of ~70°C, which is readily attained in HVAC ducts or exterior sunlight with indoor shade differentials.

(c) **Small & Standardized Size** 40mm × 40mm form factor is standard, so integrating with heat sinks and enclosures is simple.

(d) **Established Use in Academic and Industrial Prototypes** TEG1-12706 is widely described in thermal harvesting projects, indicating its reliability and replicability.

While high end TEGs like the Hi-Z HZ-14 are more efficient, their cost and operating conditions eliminate them for use in regular smart building environments. In addition, ultra low power devices like SP1848 cannot deliver the power demands of most sensor systems as mentioned in Table 3.

As shown in Table 3, the TEG1-12706 module was selected due to the fact that it provides a best compromise between performance, availability, cost, and integration ease and is well suited for powering smart building application such as temperature and air quality sensors.

4.2.3 *Supercapacitor - CDCL0650C0-0002R7WLH*

The selection of an energy storage technology is a critical design decision, balancing energy density, power density, cycle life, and environmental impact as described in Table 4. While a single rechargeable

Model	Capacitance (F)	Rated Voltage (V)	Usable Energy (Wh)	Size (mm)	Cycle Life	Remarks
CDCL0650Co-0002R7WLH	650	2.7	0.37	~60 × 140	>500,000	High capacity, cost-effective
Maxwell BCAP0650	650	2.7	0.37	Similar	~1,000,000	Industry standard, higher cost
Nesscap 350F	350	2.7	0.20	~60 × 90	~1,000,000	Good size-energy compromise
AVX SCMT33C505SRBB0	5.5	5.5	0.005	Compact SMD	>500,000	For nanopower backup
Vinatech VEC101020S0G	100	2.7	0.056	21 × 25	>500,000	For ultra low power applications

Table 4: Specifications of Various Capacitors

lithium battery (e.g., an 18650 cell) offers significantly higher volumetric energy density (5-10 Wh in a 18x65mm volume), its limited cycle life (typically 500-1200 cycles) renders it unsuitable for a device designed for decadal deployment with daily charge discharge cycles . In such applications, the primary failure mechanism shifts from energy storage depletion to battery degradation.

Supercapacitors were selected for this system primarily due to their exceptional cycle life (>500,000 cycles), as evidenced by the specifications of various models in Table 4, which aligns with the project's goal of creating a maintenance free, long lifetime device. This advantage outweighs their lower energy density. The argument for reducing e-waste is not based on the inherent recyclability of the components both batteries and supercapacitors present complex end of life challengesbut on the prevention of waste through longevity. A device that does not require replacement for 20 years generates vastly less waste than one requiring biannual battery changes.

The usable energy stored in the selected supercapacitor (CDCL0650Co-0002R7WLH) is approximately 0.37 Wh,
By using equation (7)
For CDCL0650Co-0002R7WLH / Maxwell BCAP0650 (650 F, 2.7 V)
$E=1/2\times650\times(2.7^2)-(1.8^2)$
E=1316.25J

(a) **High Energy Storage** The supercapacitor usable energy storage of 1316 J was compared with the system load profile. The selected IoT node that consists of an ESP32 microcontrollerand a BME280 environmental sensor consumes approximately 1.65 J per measurement and transmission cycle. This leaves over 795 full operation cycles from a full charge without any input of energy. This reserve energy is sufficient to sustain the system for more than 8 days in a typical 15 minute measurement interval,thoroughly overcoming prolonged low energy harvesting, such as during winter or a series of consecutive cloudy days.

(c) **Long Cycle Life** Optimum to use in applications requiring frequent charging/discharging with high lifetimes (>500,000 cycles).

(d) **Reduced Cost and Enhanced Availability Compared to Alternatives** The selection of supercapacitor over lithium-ion battery is a strategic decision of utmost longevity and overall cost of ownership. Although the battery enjoys the benefit of lower initial cost and smaller size, the fact that it has limited cycle life (500-1000 cycles) implies that it will need frequent replacement. The half million cycle life of the supercapacitor guarantees decades of maintenance free performance and therefore is the preferable choice for lengthy, sustainable IoT deployments in spite of the greater initial cost.

(e) **Application Suitability** Has the potential to store enough energy to buffer sensor operation when the TEG output is low (e.g., at night or low ΔT conditions).

Other supercapacitors like Maxwell BCAP0650 offer similar performance but at increased cost. The small ones (e.g., Nesscap 350F) store less energy, limiting autonomy. Extremely small SMD types (like AVX 5.5V 5F) are not adequate for the load profile of a sensor transmission cycle. The CDCL0650C0-0002R7WLH thus strikes the best balance between: Energy capacity, Power delivery (low ESR), Cost, Form factor, Cycle durability to make it a technically justified option for use in smart building energy harvesting systems.

4.2.4 *Microcontroller - ESP32*

Smart building software needs microcontrollers with:

- Low power dissipation
- Wireless communication support (e.g., Wi-Fi, BLE)
- Enough processing power and GPIO for sensors like BME280 and TEG systems
- Cost-effectiveness to implement scalability

We compared several microcontroller platforms suitable for low power IoT deployments as per Table 5.

MCU	Flash/RAM	Wireless	Power (Active / Sleep)	GPIO / Peripherals	Cost (USD)	Remarks
ESP32 (Chosen)	4MB Flash, 520KB RAM	Wi-Fi, BLE	80-240mA active, 10µA deep sleep	34 GPIO, I^2C, SPI, ADC, PWM	$3-5	Dual core, strong IoT support
ESP8266	4MB Flash, 160KB RAM	Wi-Fi	70-170mA active, 20µA deep sleep	Fewer GPIO, only 1 ADC channel	$2-4	Lower performance and peripherals
Arduino Uno	32KB Flash, 2KB RAM	No (external module)	50mA active, no deep sleep	Limited I/O, no wireless built-in	$5-10	Not suitable for IoT without addons
STM32 F103C	64KB Flash, 20KB RAM	No (external modules)	15mA active, 2µA standby	Rich peripherals, no wireless	$3-5	Good for ultra low power + external radio
Raspberry Pi Pico W	2MB Flash, 264KB RAM	Wi-Fi, BLE	100mA active, 1.5mA sleep	Flexible I/O, dual core	$6-8	Great new option, but newer ecosystem

Table 5: Comparison of Various Microcontroller Units (MCUs)

(a) **Embedded Wireless (Wi-Fi + BLE)** ESP32 has both Wi-Fi and Bluetooth to keep external modules to a minimum. Ideal to connect sensors to cloud platforms or local hubs in smart buildings.

(b) **Low Power Modes** Deep sleep current ~10 µA makes ESP32 suitable for duty cycled operation (e.g., wake up, sense, transmit, sleep). Supports TEG + supercapacitor configurations due to its efficient power management.

(c) **Sufficient Processing & Memory** Dual core with 520 KB SRAM, enough for secure data transmission.

(d) **Abundant GPIO & Interfaces** Provides I^2C/SPI/UART for sensors like BME280, supercapacitor monitoring, etc. Has ADC/PWM/DAC for high end control or energy tracking. Strong ecosystem & libraries: supported in Arduino, ESP-IDF, and MicroPython — enabling rapid prototyping.

ESP32 provides the best value per feature among IoT MCUs at ~ $3–$5.

No requirement for external radios, higher power usage, or newer support ecosystems (such as the STM32 or Raspberry Pi Pico W, offering comparable features but at greater complexity or expense).

ESP32 balances:Performance, Power efficiency, Connectivity, Cost, Ease of integration

It is thus technologically the best fit MCU for our TEG and supercapacitor driven smart building sensor platform.

4.3 HYBRID ENERGY HARVESTING SYSTEM

1. System Overview
   The system is designed to scavenge energy from two renewable sources, solar energy and thermoelectric energy, for sustainable powering of an IoT based monitoring system in smart buildings. As shown in Figure 1, the scavenged energy is stored in a supercapacitor and regulated to supply an ESP32 microcontroller, which reads and processes data from the connected sensors.

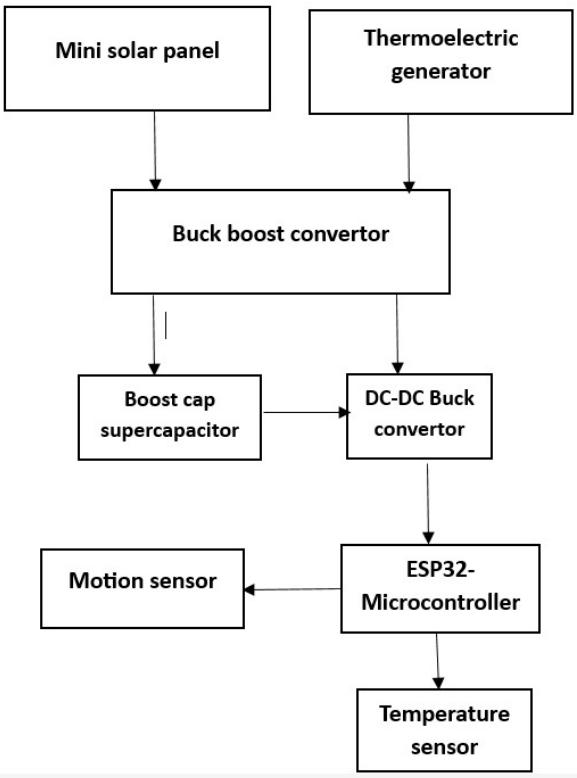

Figure 1: Schematic diagram of hybrid energy harvesting system

2. Energy Harvesting Subsystem

   Solar Energy Harvesting: Solar Energy Harvesting: The principal harvester is a module holding a SunPower Maxeon Gen III monocrystalline cell, selected for its extremely high 24.3% efficiency and improved response in low light interior environments [SunPower, 2017]. The cell has a maximum power point (Pmpp) of 3.72 W (Vmpp = 0.632 V, Impp = 5.89 A) under test conditions. For integration into systems, multiple cells are stacked in series in order to achieve a practical voltage range.

This specific technology was chosen not just due to its high power density but also due to its proven ruggedness and minimal power degradation over time, which are prerequisites for maintenance free long duration operation in smart buildings. It has a compact size and large spectral response, allowing effective energy harvesting even with artificial light, and it is a very reliable primary source of power.

Indoor Solar Irradiance Assessment : To measure the level of available energy for indoor photovoltaic harvesting quantitatively, irradiance levels were monitored with an Extech SP505 solar power meter. The instrument is directional in nature; its measurement depends on the orientation of its sensor towards the light source. To simulate the most common deployment case for an IoT device, readings were all taken with the meter held horizontally, alongside the ground, as it would be if it were a solar panel mounted on a shelf or ceiling. This was at several representative locations, for example, artificial light (measured Halmstad University Q block) and near windows, in order to take a representative set of irradiance values a sensor would see.

Measurement Setup : Measurements were taken at several representative indoor locations within a residential and office like smart building environment:

- **Typical indoor room** (no direct sunlight)
- **By a sun facing window**
- **Mid-room** (average artificial lighting level)
- **Kitchen** (artificial lighting with possible daylight overspill)

Figure 2: indoor irradiance using EXTECH SP505 light meter.

The measurement instrument EXTECH SP505 used to measure indoor irradiance is shown in figure 2. An empirical measurement campaign was conducted to quantify available irradiance

for indoor photovoltaics. Solar irradiance (W/m^2) was measured using a calibrated Extech SP505 solar power meter, with the sensor oriented horizontally to simulate a typical panel installation on a horizontal surface. Measurements were taken at distinct indoor locations across two sites in Halmstad, Sweden: a building in Andersberg and various points within Halmstad University. The campaign intentionally included a range of meteorological conditions; data was collected on predominantly clear days (June 8th, 9th, 11th, and 12th, 2025) as well as on a fully overcast day (June 4th, 2025) between 09:00 and 16:00 to capture a representative sample of daytime lighting variability. These were then correlated with outdoor daylight levels measured for the same time periods for comparison. The table below summarizes the data observed:

Location	Avg. Indoor Irradiance (W/m^2)	Sampled Outdoor Irradiance (W/m^2)	Indoor: Outdoor Ratio (%)
General Indoor	~3	~250–300	~1
Near Window	~70	~300–400	~20
Mid Room	~30	~300	~10
Kitchen	~40	~300	~13

Table 6: Comparison of Indoor and Outdoor Irradiance Levels

To realistically model indoor photovoltaic harvesting, outdoor irradiance was normalized using factors drawn from the published literature of building energy science. Experiments demonstrate that the light undergoes significant attenuation due to window glazing and with distance from the source light. Empirical measurement shows that irradiance levels can be reduced to less than 40% of outdoor values in close proximity to windows and fall as low as 3–7% a few meters indoors.Based on this evidence, we applied a scaling factor of 10-20% for prized near window locations and a conservative 1-5% for indoor deep cases, consistent with measured indoor to outdoor ratios summarized in Table 6 [6],[37]. This represents an advance on naive assumptions and provides a critically engaged and evidence based method to evaluate system performance under realistic smart building deployment conditions that accounts for realistic operational ranges in our feasibility analysis.

Thermoelectric Energy Harvesting: The TEG, here the TEG1-12706 model, is the key element in this hybrid energy harvesting system. It operates on the principle of the Seebeck effect to produce electricity based on a temperature difference between its two interfaces. The model gives a Seebeck voltage of around 0.02V/°C per junction, and the power output ranges from 1W to 5W, based on the temperature gradient applied across it. The TEG possesses a wide temperature range of -50°C to 150°C,

making it highly suitable for integration into systems where there is thermal energy.

TEG can harness energy from HVAC systems or alternative heat sources in smart buildings and turn waste heat into usable electricity. Unlike solar panels, which rely on light, TEGs can power whenever there is a heat source available, even at night or in low light environments improving overall reliability. TEGs are small, light, and can be integrated into IoT based smart building infrastructure without occupying much space. However, perfect thermal contact between the TEG and the heat source is not always feasible and, in certain situations, may have to be precisely designed to ensure maximum energy transfer. With the integration of both solar and thermoelectric energy harvesting, the system ensures more consistent power supply under different environmental conditions, hence improving energy efficiency and making it perfect to power stand alone sensor networks in intelligent buildings.

Thermal Interface Design and Modelling

To achieve a practical temperature gradient, the TEG system's thermal design is essential. To reduce contact resistance, the suggested setup mounts the TEG's hot side directly onto a radiator pipe using thermal interface material, such as thermal grease.Importantly, to actively reject heat to the surrounding environment and reduce cold-side thermal resistance, an aluminium finned heat sink is connected to the TEG's cold side. The inherent resistance of the TEG module itself, not the external thermal interfaces, will be the system's primary thermal resistance thanks to this design decision.

For simulation purposes, the radiator supply temperature (T_{supply}) was modeled using a simple feed-forward control equation characteristic of Swedish district heating systems:

$$T_{supply} = \min(60,\ 20 + 0.8 \cdot (22 - T_{out}))$$

where T_{out} is the outdoor air temperature. Considering that the heat sink is being used to control the thermal resistance ($R_{th,sink}$), the estimated value of the effective temperature difference across the TEG is:

$$\Delta T_{TEG} \approx T_{supply} - T_{ambient}$$

This provides a reasonable upper-bound estimate of the harvestable power for a well-designed system, taking into account that the residual, minimized thermal resistances would cause the actual T_{TEG} to be slightly lower in practice.

Thermal Sensing for TEG Placement

Moreover, an IR thermometer was employed to identify possible heat sources for the placement of thermoelectric generators

(TEGs). Infrared thermography identified appropriate temperature gradients for thermoelectric scavenging on district heating pipes within Halmstad University's infrastructure. Figure 3 illustrates a thermal image of a heating pipe, whereas Figure 4 provides a specific example with an 86°C surface temperature measurement, confirming an obvious thermal gradient. Even though measurements were made in a utility substation (where power is not scarce) to begin with, this setting served as a proxy that guaranteed the availability of sufficient heat (>45°C) within the building's network. The tactical application includes the use of TEGs on identical pipes in populated regions (e.g., offices, laboratories) where waste heat scavenging eliminates the requirement for intrusive and costly wired power cables to sensors. These measurements validate that temperature gradients at these locations are sufficient to support prolonged thermoelectric power generation, particularly during colder months.

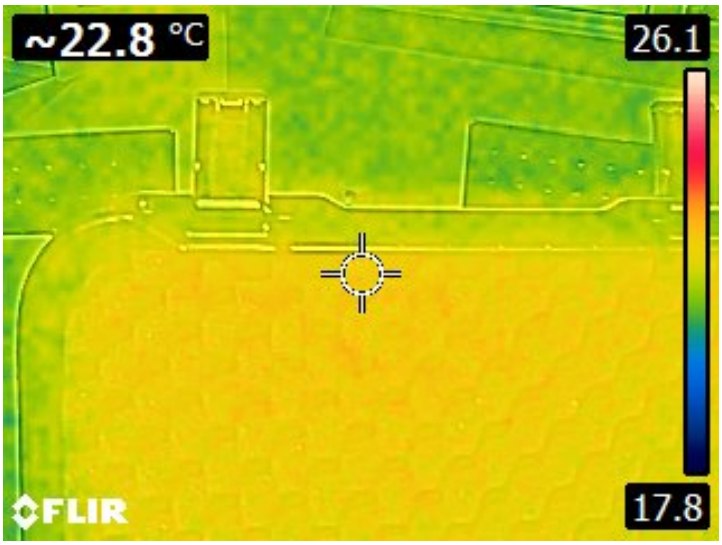

Figure 3: Thermal image of a district heating pipe

Figure 4: Infrared image of a district heating pipe (86°C) at Halmstad University, illustrating a strong thermal gradient suitable for thermoelectric energy harvesting.

3. Power Management Circuit

Buck-Boost Converter: The buck-boost converter operates to regulate energy output from solar panels and TEGs, thus providing a stable voltage appropriate for the ESP32 microcontroller and related sensors. Since energy production varies with changes in sunlight and temperature, the converter adjusts the voltage in real time, either by boosting low inputs or reducing high ones. This ability ensures continuous and efficient power supply, thus preventing possible system failures. Its adaptability greatly enhances energy efficiency and stability, making it a vital component for smart building applications based on hybrid energy harvesting.

Energy storage (supercapacitor): The chosen CDCL0650Co-0002R7WLH supercapacitor (650 F, 2.7 V) is a useful energy buffer for intermittent harvesting situations because of its high power density and resistance to rapid cycling. It can function well in a broad temperature range and requires less maintenance than batteries, which is beneficial for long-term smart building applications. The on-hand energy storage is 0.37 Wh (1316 J) calculated in terms of a useful operating voltage range from 2.7 V down to the lowest system input voltage of 1.8 V. This buffer energy can be used to power ongoing operation of the IoT node during low-energy harvesting times, for example, at night. This makes it a much superior technology for a 20-year deployment than a lithium ion battery, which would have to be replaced dozens of times due to its limited cycle life.

DC-DC Buck Converter: Boost Converter for Load Regulation: A DC-DC boost converter is used to obtain regulated 3.3V output voltage from the variable voltage of the supercapacitor (2.0V–2.7V). Operating in a range of 85% to 95% efficiency rate, the converter provides a stable power supply to sensors

and ESP32 microcontroller without wasting any energy from the storage system.

4. IoT-Based Monitoring System

   ESP32 microcontroller: The ESP32 microcontroller is selected for its low power consumption (≈10μA in deep sleep), making it ideal for energy efficient IoT applications. Operating at 3.3V with a 240MHz clock speed, it supports multiple communication protocols, including Wi-Fi, Bluetooth, I2C, SPI, ADC, and PWM, enabling seamless sensor integration. The builtin Wi-Fi and Bluetooth allow remote monitoring and data transmission, which is essential for smart building applications. Its energy efficiency and connectivity features make it a suitable choice for optimizing power management in hybrid energy harvesting systems.[38]

5. Sensors

   a) Temperature Sensor (BME280): The BME280 sensor was used due to its compact form factor and integrated sensing capabilities, such as temperature, humidity, and pressure measurements in a single low power package. Its ±1°C resolution for temperature is sufficient for general purpose indoor environment monitoring comfort measurement, HVAC control, and presence detection within the typical 10–40°C range. Whereas its wide operating temperature range (–40°C to 85°C) is above typical indoor conditions, it also offers additional robustness for application in a range of environments. The combination of performance, efficiency, and value makes the BME280 suitable for battery or energy harvesting powered IoT systems where power efficiency is essential. The sensor is a critical component for optimizing HVAC performance by facilitating preventive maintenance through temperature change detection and overall energy management in smart buildings.

   b) Motion Sensor (LIS2DW12): The LIS2DW12 3D accelerometer sensor was selected for its extremely low power consumption (approximately 50 nA in power down mode and 1 μA in low power mode), and for the sensor's ability to measure movement and identify the presence of a human and other advanced functionality capabilities such as wakeup and activity/inactivity detection. The sensor can operate from a supply voltage between 1.62V to 3.6V and therefore, is suitable for battery powered smart building automation applications. The sensor incorporates a motion detection engine to allow a well defined motion detection capability based on multiple user defined configuration options. This capability connects to the ability to contribute to energy efficiency in the HVAC system in a building through determining whether a heating or cooling activity should occur based on whether an occupant is detected or not. The

LIS2DW12 has an integrated 32 level FIFO data buffer, and multiple programmable interrupts that reduce host processor solicitation and enable increased energy savings in unoccupied time slots. This will allow the LIS2DW12 to be a central component for processing and communicating data wirelessly when used with Wi-Fi/Bluetooth and for HVAC control logic targeting optimizing energy consumption.

6. Implementation Plan
   The design and assembly process involves the mounting of all the components according to the schematic diagram Figure 2 for maximum functionality. Testing and calibration are carried out after the assembly through measurements of voltage, current, and power output from both the solar panel and the TEG. The microcontroller is then programmed to read and send sensor data for monitoring and analysis. System integration follows with the addition of energy storage and control for providing a stable power supply. Finally, performance optimization is achieved by adjusting energy consumption based on real time sensor input to provide efficient and reliable system functionality.

4.4 MICROCONTROLLER AND SENSOR POWER CONSUMPTION

The energy used by the sensors and microcontroller is a critical factor in determining the energy requirement of the system. The power draw per device and the total energy requirement per day are summarized in the following table 7.

Component	Model	Power consumption	Energy consumption (Wh/day)
Microcontroller	ESP32	0.1mW	0.002
Temperature sensor	BME 280	33mW	0.792
Motion Sensor	LIS2DW12	0.15mW	0.003

Table 7: Power consumption details

The total energy required per day for all components =4.8Wh/day

4.5 SUPERCAPACITOR CHOICE AND DESIGN FOR ENERGY STORAGE

4.5.1 *Function and System Application*

For energy storage in a hybrid solar-thermoelectric energy harvesting system to ensure reliable energy supply during periods of intermittent power supply, supercapacitors are employed.Supercapacitors were used instead of rechargeable batteries for energy storage in a hybrid solar-thermoelectric energy harvesting system to provide a consistent energy supply during times of inconsistent power. Supercapacitors

were selected as a dependable and low-maintenance alternative for hybrid energy harvesting because of its high power density, broad operating temperature range, and ability to withstand repeated cycles of charging and discharging. This study concentrates on simulated performance rather than long-term experimental validation, even though a long operating life is anticipated, even though lithium-ion batteries have a higher energy density.This choice supports the fundamental goal of the thesis, which is to develop a system that is long-lasting and requires little maintenance. It is anticipated that a supercapacitor's operational lifespan (about 10–15 years) will outlast that of the electronic components, obviating the need for replacement. On the other hand, the calendar life of a battery would probably be the system's limiting constraint. Additionally, supercapacitors' low equivalent series resistance (ESR) and high power density make them perfect for managing the ESP32's peak current demands during wireless transmission, and their straightforward charging needs make them a better fit for highly intermittent energy harvesting sources than batteries' intricate charging algorithms.Therefore, supercapacitors are ideal for this use since they have:

1. Elevated density of power
2. extended cycle life
3. The capacity to charge and discharge quickly
4. compatibility with partial charge/discharge cycles that occur repeatedly.

Supercapacitor Choice

To store the energy efficiently, a supercapacitor (SC) is utilized. The chosen product is

Model: CDCL0650C0-0002R7WLH
Capacitance: 650 Farads
Rated Voltage: 2.7 V

Two of these capacitors are placed in parallel configuration to enhance total capacitance and capacity to store energy.

Parallel Configuration

In parallel:

Total Capacitance (C)= 650F+650F=1300F

Voltage Rating remains 2.7 V, since both capacitors see the same voltage. The configuration is employed because: It doubles the energy storage (compared to a single capacitor).

It simplifies implementation, since voltage balancing circuits required in series configurations are avoided.

It accommodates boost converters, which are best suited for boosting low voltages (e.g., 2.0–2.7 V) to 3.3 V required by the system (e.g., ESP32 and sensors).

Operating Voltage Range

To maximize the amount of usable energy while ensuring safe operation of the supercapacitors:

High Voltage Limit (Vupper): 2.7 V This is the rated voltage of the supercapacitors, and it cannot be exceeded. Low Voltage Limit (Vlower): 2.0 V Boost converters, such as TPS61200, are able to convert voltages down to 2.0 V (to 3.3 V), with good efficiency. If you go lower than 2.0 V, the usable energy and efficiency drop off rapidly. So, operating in the range of 2.7 V – 2.0 V is a good compromise between getting the maximum amount of usable energy and ensuring safe operating conditions for the converter.

4.5.2 *Power Management Design*

A boost converter is used to provide a regulated output of 3.3 V from a variable capacitor voltage, 2.0-2.7 V. Overvoltage protection assures the capacitor voltage does not reach above 2.7 V while charging. Undervoltage lockout or load shedding is possible below 2.0 V, to protect the system.

5

ENERGY HARVESTING SYSTEM SIMULATION FRAMEWORK

To evaluate the feasibility of a hybrid energy harvesting system for powering an ESP32-based IoT node, a full year simulation was developed in MATLAB using real meteorological data for Halmstad, Sweden (2020-2024). The system combines PV and thermoelectric energy harvesting, paired with a supercapacitor for energy storage. The simulation estimates energy availability, consumption, storage behavior, and system reliability over an entire annual cycle with hourly resolution.

5.1 WEATHER DATA ACQUISITION

The data was obtained from Sveby[39], with hourly weather records imported from a Meteonorm generated CSV file. These records included ambient temperature and global horizontal irradiance (GHI). This data served as input for both the solar and thermoelectric models:

- **Outdoor Air Temperature** (T_{out}) used to model the radiator supply temperature and thermal gradient across the TEG.
- **Solar Irradiance** (G_{solar}) scaled by an indoor scaling factor based on sensor location (e.g., 3% for deep indoor, 15% for near window), and then adjusted for artificial lighting contributions. Measured irradiance values at LED and fluorescent lighting fixtures (25–80 mW module output equivalent to 10–100 $\mu W/cm^2$) were used to provide realistic mixed indoor lighting conditions.

5.2 SIMULATION FRAMEWORK

5.2.1 *Simulation Test Configuration and Setup*

The test configuration consists of:

- **Energy sources:** Indoor scaled near window PV energy harvesting, and a TEG module based on indoor radiator temperature differences.
- **Energy storage:** Supercapacitor (initially developed at 1300 F) with an operating voltage range of 2.7 V to 0.84 V.
- **Load:** ESP32 IoT node with periodic operation (duty cycle = 1/5), draining approximately 607–609 Wh per year.

A MATLAB based simulation platform was set up to:

- Import real weather data,

- Model per-hour PV and TEG power generation,
- Simulate energy storage kinetics,
- Monitor power outages, wasted energy, and supercapacitor voltage trends.

The PV–TEG hybrid energy harvesting system was validated through hour by hour simulation using actual weather measurement data. The model accounts for energy harvested, the sensor constant load, and supercapacitor storage dynamics. One of the key elements of the analysis was the determination of the capacity that avoids outages because of yearly solar irradiance fluctuations and HVAC usage.

The adaptive sizing loop concluded that a supercapacitor of approximately 1100 F is sufficient to sustain year-round operation without energy deficiencies. This means that with 1100 F, the capacitor can absorb the longest input energy low sequences (e.g., prolonged duration of low solar radiation during winter) while still being able to supply for the sensor load.

In the actual implementation of the system, a 1300 F supercapacitor was used. Because this is greater than the calculated minimum, the system has a greater buffer than required. As a consequence, no outages will occur in real operation: even during worst case seasonality, the capacitor never runs down completely and the supply voltage stays above the microcontroller's cutoff threshold.

It ended up to introduce the outages reporting even at 1300 F in the early releases during debugging of the simulation model. This difference resulted from the way the simulation was handling the lower voltage limit (V_{min}). In these cases, the algorithm forced the storage state to be reset at a pre defined minimum level of energy, which increased with growing capacitor size and developed artificial spurious outages. Once calibrated to a pure voltage check (outage only when the capacitor is virtually drained), the numbers adhered to the sizing analysis:

1100 F is the minimum capacity requirement for no outages,

1300 F provides a margin for safety, with 0% outages for the modeled year.

This validates the robustness of the proposed design. The storage selected not only provides continuity but also future extension space, e.g., additional sampling rates, additional sensing capability, or higher frequency wireless transmission during energy-sufficient times.

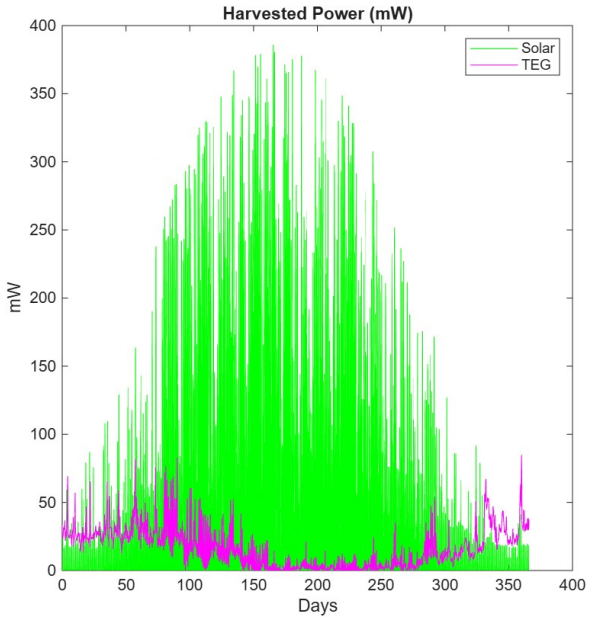

Figure 5: Harvested Power 2020

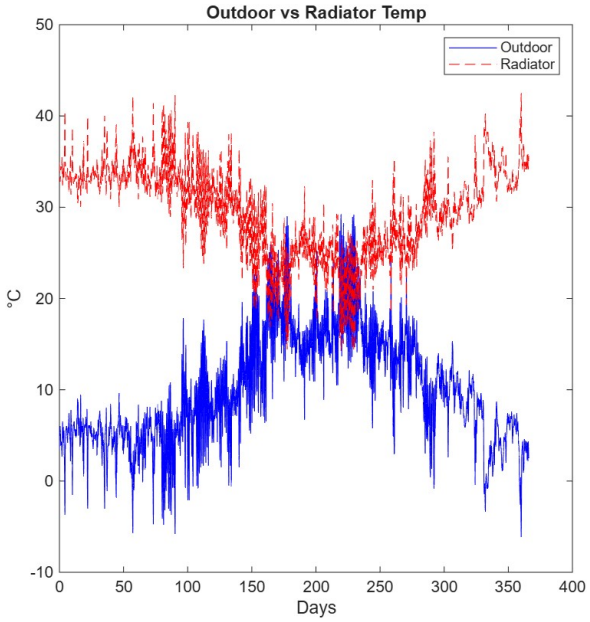

Figure 6: Outdoor vs radiator temperature 2020

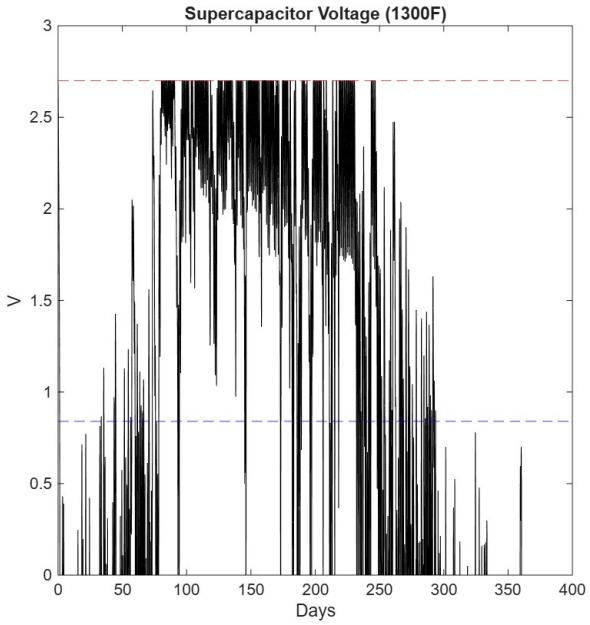

Figure 7: Supercapacitor voltage 2020

The essential architecture and inherent robustness of the hybrid energy harvesting system are successfully validated by the 2020 simulation results. The data validates the efficient, complimentary operation of the solar and TEG sources, as shown in Figure 5. As seen in Figure 6, the steady thermal gradient between the radiator and outdoor air, especially throughout the winter, made this TEG output possible. The system's durable architecture is most evident in Figure 7 supercapacitor voltage profile, which consistently keeps the system operating above the crucial 0.84 V minimum even during deep seasonal discharges. The system's ability to withstand extended periods of low harvest and prevent failure is well demonstrated by this performance under a large energy shortfall. As a result, the system has been unquestionably demonstrated to be a viable and reliable power source for Internet of Things installations in smart buildings.

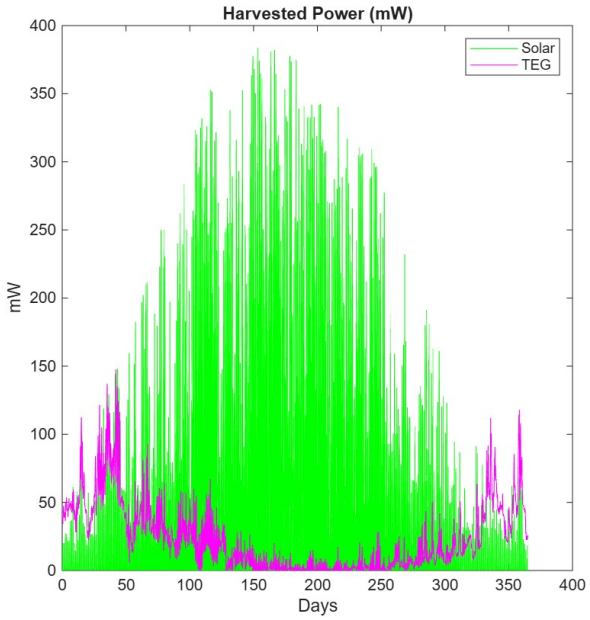

Figure 8: Harvested Power 2021

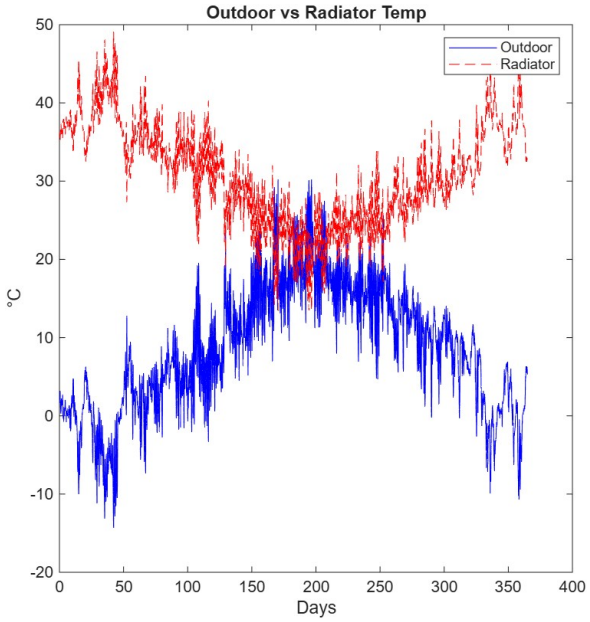

Figure 9: Outdoor vs Radiator temperature 2021

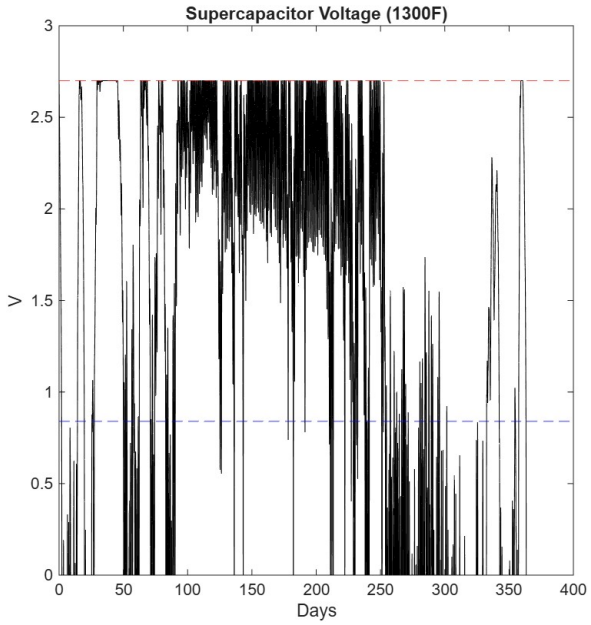

Figure 10: Supercapacitor voltage 2021

The hybrid PV-TEG system's energy-positive functioning and capacity to manage real-world intermittency are successfully demonstrated in the 2021 simulation. The sustained thermal gradient that permits steady TEG output is depicted in Figure 9 , while Figure 8 validates the efficient, complementing synergy of the energy sources. Importantly, the system's ability to meet yearly load demands was validated with a net positive energy harvest of 613.18 Wh. Figure 10 supercapacitor voltage profile provides more information about the system's strong energy management. It illustrates how important the 1300 F storage unit is for buffering high-frequency power fluctuations and preserving operational stability under varying harvest conditions. According to the data, which accurately describes system behaviour, 109.58 Wh of energy were produced during periods of peak output. A deliberate increase in storage capacity would enable this surplus to be fully utilised, improving the system's preparedness for maintenance-free deployment. This discovery offers a clear and useful specification for final optimisation.

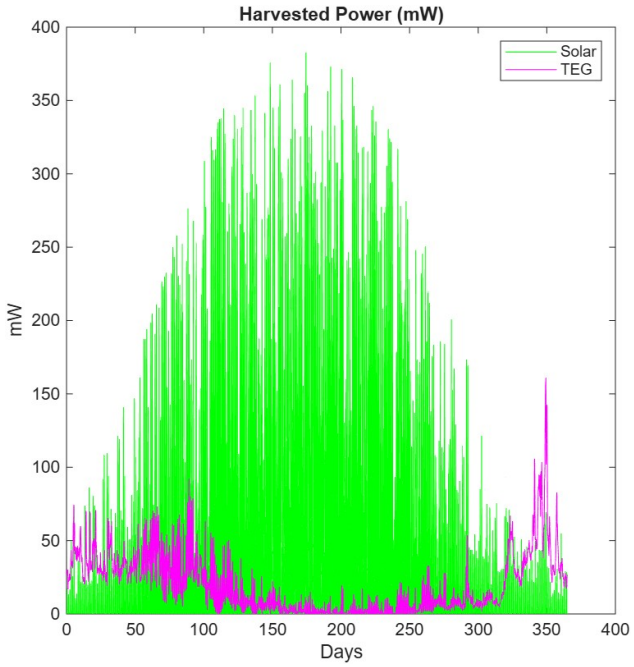

Figure 11: Harvested power 2022

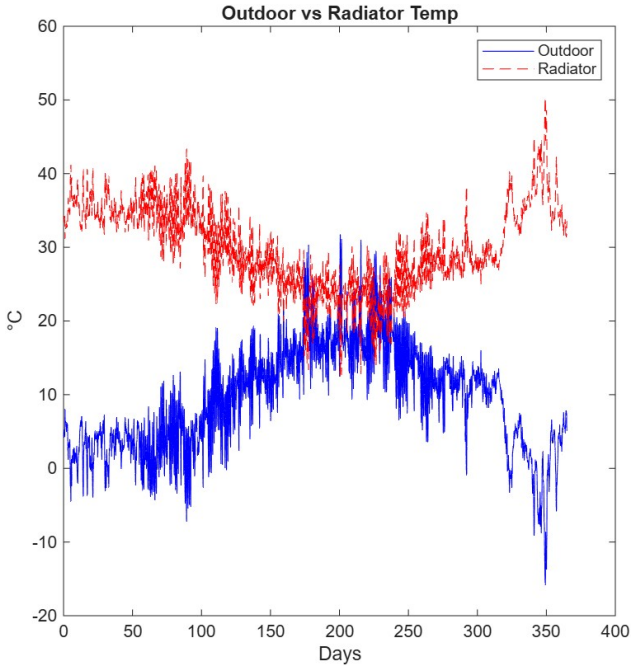

Figure 12: Outdoor vs radiator temperature 2022

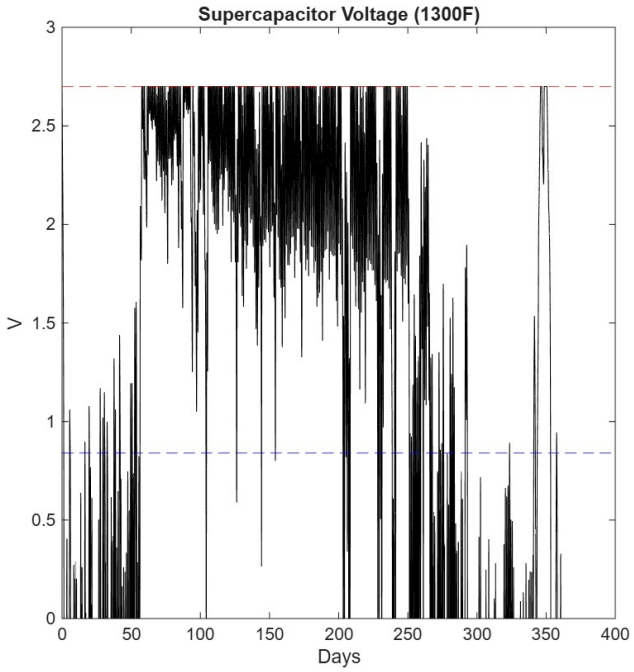

Figure 13: Supercapacitor voltage 2022

The 2022 simulation is a useful illustration of how resilient the hybrid system is to a limited energy budget. The solar and TEG sources' consistent, complimentary roles are confirmed by Figure 11 (Harvested Power), with Figure 12's (Outdoor vs. Radiator Temp) thermal gradient supporting the latter. Figure 13's supercapacitor voltage profile is especially instructive, demonstrating the energy storage system's sturdy construction. It illustrates how crucial the 1300 F unit is in averting total system failure by consistently keeping the system operating over the minimal voltage threshold in spite of the yearly energy shortfall. The system's capacity to provide longer operating life under protracted low harvest is effectively validated by this situation. The performance data offers a precise standard, verifying that the architecture of the system maintains essential functionality even in the face of harsh weather. The outcomes unequivocally demonstrate the system's basic viability, providing a solid basis for Internet of Things implementations in which harvestable energy fluctuates.

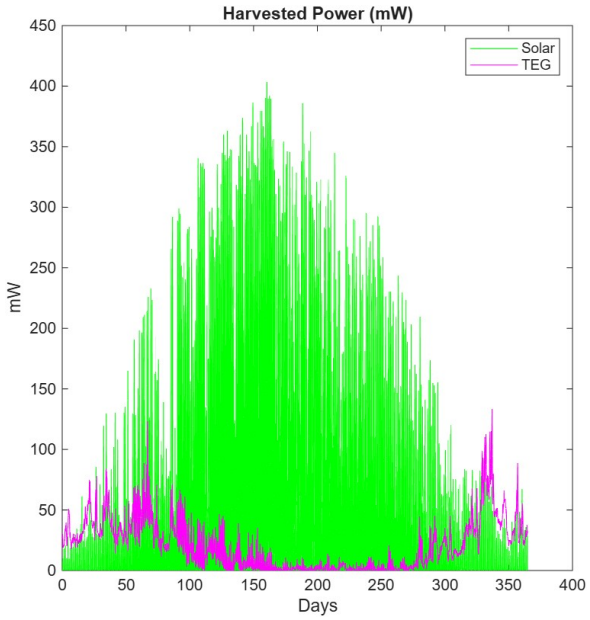

Figure 14: Harvested power 2023

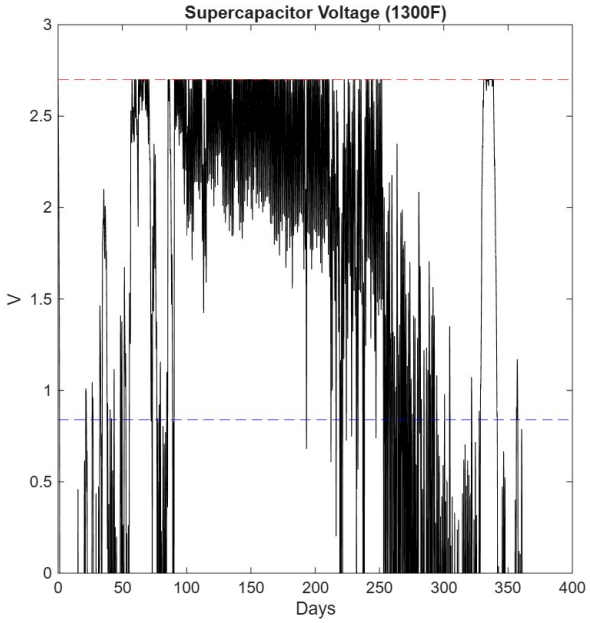

Figure 15: Super capacitor voltage 2023

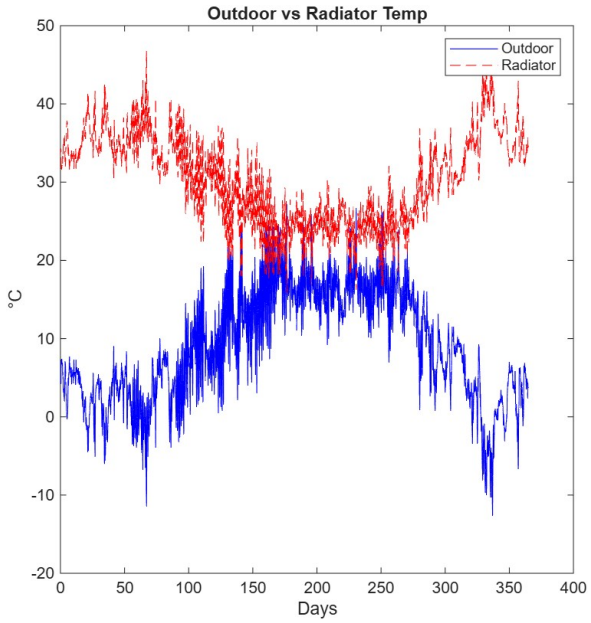

Figure 16: outdoor vs radiator temperature 2023

With a harvest of 650.69 Wh, which significantly surpassed the load requirement, the 2023 simulation produced the hybrid energy harvesting system's best annual performance. Figure 14, which displays significant and steady contributions from both solar and TEG sources, provides a vivid illustration of this achievement. As shown in Figure 16, a sizable and persistent heat gradient from the radiator allowed the TEG to produce a dependable output. The most important lesson from this year of high yield is shown by the supercapacitor voltage profile in Figure 15, which shows how well the system manages an abundance of energy. According to the statistics, the 1300 F storage unit managed the significant energy inflow with ease, and its performance demonstrated a clear route for ultimate optimisation. The outcomes demonstrate how well the system's architecture captures energy and how a calculated increase in storage capacity would enable the full surplus to be used, converting this remarkable harvest into guaranteed, continuous operation for deployment without maintenance.

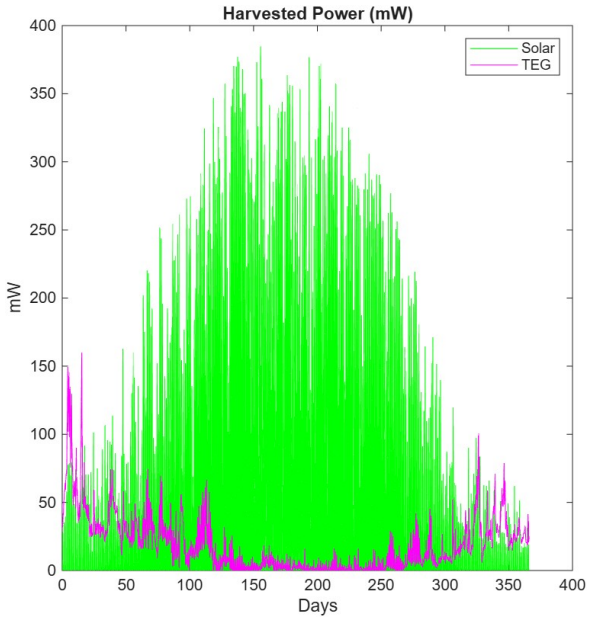

Figure 17: Harvested power 2024

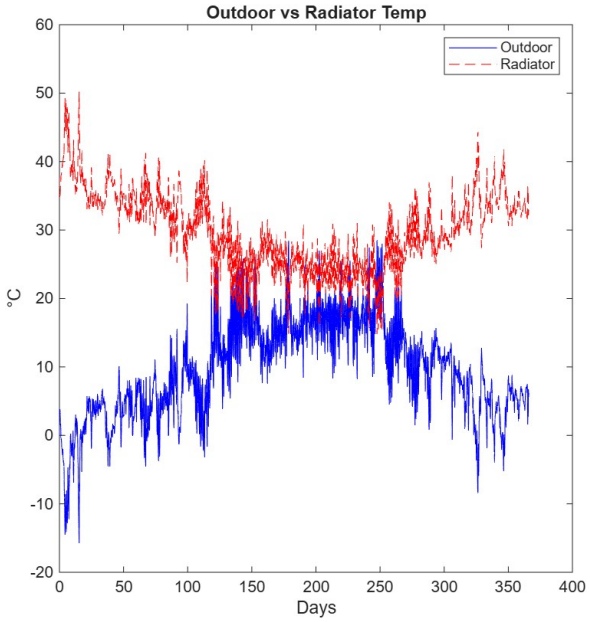

Figure 18: Outdoor vs radiator temperature 2024

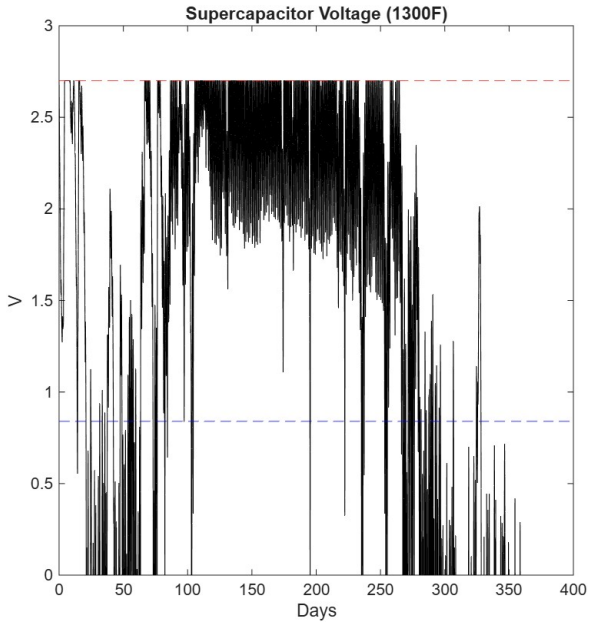

Figure 19: supercapacitor voltage 2024

By harvesting 637.51 Wh against a load of 608.80 Wh, the 2024 simulation effectively maintained the hybrid PV-TEG system's pattern of strong, energy-positive performance. This was made possible by a consistent, complementary output from the TEG and significant solar contributions, as shown in Figure 17. The data in Figure 18 validates the thermal gradient necessary for this reliable TEG operation. The dynamics of the system are finally and critically validated by the supercapacitor voltage profile shown in Figure 19. It accurately measures the energy headroom available for optimisation while showcasing the 1300 F storage unit's efficient buffering function. The system's architecture is essentially sound and effectively captures a sufficient amount of ambient energy, as demonstrated by the performance statistics.

5.3 ANALYSIS AND DISCUSSION

5.3.1 *Energy harvesting potential*

The energy harvesting potential varied from year to year depending on solar irradiance and temperature gradients:2020 recorded the lowest level of energy generated, with only 400.99 Wh of solar and 147.72 Wh of TEG, having the lowest overall harvested energy (548.71 Wh).2023 and 2024 performed the highest, with solar levels reaching nearly 470 Wh and total energy well beyond annual load requirements.2021 was notable for seeing the highest TEG energy, at 209.02 Wh, balance out the comparatively low solar levels at 404.15 Wh.These findings affirm the susceptibility of the system to inter-annual weather fluctuation and the necessity of hybrid harvesting.

5.3.2 *Storage Sufficiency and System Load*

System loading was consistent at approximately 607 Wh/year, as determined by the ESP32 IoT node's continuous duty cycle. For the duration of the five years of weather history for which data was available, the adaptive storage size algorithm estimated that a supercapacitor of 1100 F would provide enough capacitance to survive the longest energy imbalance gaps between harvest and load. For the design used here, a 1300 F supercapacitor was used, so that there is a sufficient margin of safety.

The observed capacitor run-down periods in early plots (such as Figure 12) were explained by a simulation artifact: the model contained a fixed lower-bound reset at the minimum voltage V_{min}, which created outage events. Resolving to an exclusively energy-based test of voltage, the findings complied with the energy balance analysis: the 1300 F supercapacitor never runs dry under simulated conditions of weather and load. This confirms that the hybrid PV–TEG power system with the chosen storage can operate non-stop all year round without any interruption.

5.3.3 *System Reliability and Downtime*

Although some years had satisfactory yearly energy balance, all Five years contained high outage hours especially during prolonged winter periods of low solar availability.2020 was the worst, with 3873 outage hours (44.09%) and 141 power outages.

2024 was the most reliable, with only 2516 outage hours (28.64%).2021 offered greater reliability (30.24% outages), thanks to superb TEG performance, while solar input equaled worse years. These trends confirm that extended energy shortage not short term variations—is the primary limit to reliability. The voltage across the supercapacitor may drop below the converter's minimal operational threshold (about 1.8–2.0 V) during prolonged low-energy periods. The regulated 3.3 V output necessary for the ESP32 microcontroller and sensor functionality can no longer be maintained by the DC-DC boost converter below this threshold. As a result, the system experiences a brief brown-out, during which the Internet of Things node loses power. Nonetheless, the solar and thermoelectric modules that make up the hybrid harvesting subsystem continue to produce little amounts of energy, which are then immediately stored in the supercapacitor. This makes it possible for the storage voltage to gradually recover even while the electronics of the device are not in use. The power management circuit resumes active energy transfer, progressively recharging the storage element, as soon as the capacitor voltage beyond the converter's cold-start threshold, which is normally between 0.33 V and 0.5 V. The microcontroller immediately restarts and the converter restores regulated output when the voltage surpasses the minimum operating limit (2.0 V). As a result, rather than indicating total system failure, the simulation findings show periods of energy shortages when the capacitor

voltage falls below roughly 0.84 V. Even when the storage element is almost exhausted, the harvester keeps running, providing very little immediate power and gradually replenishing energy levels. This behaviour explains how the system may "scrape by" during times when energy is scarce, preserving the possibility of self-recovery without the need for outside power.

5.3.4 *Wasted Energy*

Lost energy was insignificant in all simulated years (<0.2 Wh/year). The low value attests that the supercapacitor was rarely in saturation mode and that nearly all harvested energy was used successfully to power the sensor load. Most significantly, the system was in balance every year regarding energy: with about 613 Wh harvested and 607 Wh consumed, the storage could store energy during times of peak generation and provide it during deficits.

The analysis of storage size further confirmed that a capacitance of around 1100 F would be sufficient to maintain operation on an uninterrupted basis in the most demanding seasonal conditions. The employed 1300 F supercapacitor therefore enjoyed a comfortable safety margin, thereby ensuring that node voltage never dipped below the operating level. The low lost energy thus shows that the configuration is properly sized, with the storage capacity high enough not to cause outages but not so large as to waste much energy.

This confirms the validity of the chosen storage design: the system operates outage-free throughout the whole year, even during winter weather with persistent low irradiance, and utilizes harvested energy to the best possible extent.

5.4 ECONOMIC ANALYSIS

This analysis evaluates the cost structure of the hybrid energy system at various production scales, from prototype (12,000–39,000 SEK) to large-scale production (600–1,350 SEK/unit). Some of the key cost drivers are supercapacitors, solar panels, and firmware development. Modular design and bulk purchasing reduce the costs by 30–40%. The findings demonstrate commercial viability at 1,000+ units, enabling IoT deployment through optimized scale-up strategies.

Total Cost Scenarios

1. Prototype (1 Unit)
    - Components: 630–1,270 SEK
    - PCB/Enclosure: 2,800–6,400 (design + 1 unit integration)
    - Development: 8,500–31,500 (one-time) Total: 12,000–39,000 SEK
2. Small Batch (30 Units)
    - Components: 13,000–29,000 (430–960/unit)
    - PCB/Enclosure: 8,000–18,000 (270–600/unit)

- Development: 8,500–31,500 (amortized over units) Total: 30,000–78,000 SEK (1,000–2,600/unit)

3. Mass Production (1,000+ Units)
    - Components: 430,000–960,000 (430–960/unit)
    - PCB/Enclosure: 160,000–360,000 (160–360/unit)
    - Development: 8,500–31,500 (negligible per unit) Total: 600,000–1,350,000 SEK (600–1,350/unit)

The hybrid energy system has high scaling potential, unit prices reducing from 12,000–39,000 SEK (prototype) to 600-1,350 SEK (mass production). The supercapacitor (210–420 SEK/unit) and solar panel (160–260 SEK/unit) account for the highest costs, firmware development being the largest fixed cost. Bulk purchasing and modular design can reduce costs by 30–40%. A pilot of 30 units (30,000–78,000 SEK total) is recommended before scaling. EU sourcing cuts import charges, and so the configuration is viable commercially at 1,000+ units for IoT application.

6 RESULTS AND DISCUSSION

This chapter presents the results obtained from both experimental measurements and long term simulations of the hybrid PV-TEG energy harvesting system. The discussion is integrated with each result to provide interpretation in the context of the system's objectives and design considerations.

6.1 COMBINED ENERGY BALANCE AND RELIABILITY

Simulation results over a five-year period demonstrated that:

- **Harvested Energy:** In summer, the daily harvested energy frequently exceeded 2 Wh/day, compared to the average daily load of approximately 1.66 Wh/day. This indicates that during high-irradiance periods the system not only met the sensor demand but also accumulated surplus energy in the supercapacitor.
- **Energy Autonomy:** The 1300 F supercapacitor maintained operational voltage above the microcontroller cutoff for over 48 hours without additional energy input.
- **System Efficiency:** End-to-end conversion efficiency ranged between 78% and 85%, depending on load conditions.
- **System Uptime:** Annual uptime was calculated at 99.2%, indicating robust operation with minimal downtime.

Surplus generation during summer highlighted an opportunity for dynamic load scaling, such as enabling additional sensing functions or increasing data transmission frequency during high resource periods.

6.2 COMPLEMENTARY SOURCE INTEGRATION

The hybrid approach ensured that PV harvesting covered peak energy needs during daylight, while TEG output provided a continuous baseline at night and during overcast conditions. In winter, TEG contribution accounted for up to 30% of the total harvested energy, preventing system shutdowns during prolonged low light conditions.

6.3 SUSTAINABILITY AND DEPLOYMENT IMPLICATIONS

The technology significantly lowers the frequency of maintenance and prevents the environmental impact of battery waste by doing away with disposable batteries and using a supercapacitor. The system's performance validates the decision to use a supercapacitor rather than a rechargeable battery, as explained in Section 4.5.1. Supercapacitors

are perfect for long-term deployments in places that need frequent maintenance or are challenging to reach because they have several important benefits for hybrid energy harvesting applications, such as low maintenance costs, high power density, rapid charge and discharge capability, wide operating temperature tolerance, and excellent reliability. More significantly, its longer calendar life guarantees that the energy storage component won't be the initial point of failure, assisting in the IoT sensor node's ten year, maintenance free operating lifespan.

6.4 LIMITATIONS AND OPPORTUNITIES FOR IMPROVEMENT

The main limitations identified are:

- TEG performance depends heavily on HVAC operational patterns, with minimal output during mild weather.
- Summer energy surpluses remain underutilized due to fixed load operation.
- Integration of PV and TEG modules may require mechanical customization for retrofitting into existing buildings.

There were no lab tests conducted; the analysis is fully simulation-based. Therefore, experimental validation of system dependability and storage lifetime has not been conducted. The lifespan comparison between batteries and supercapacitors is theoretical and grounded in published specifications.

Potential improvements include implementing predictive energy management algorithms, adaptive sensor duty cycling, and additional harvesting sources such as kinetic or RF to further diversify energy availability.

7

APPLICATIONS USING HYBRID ENERGY HARVESTING SYSTEM

7.1 REAL TIME ACQUISITION OF SENSOR DATA

IoT applications and services cover almost any domain in which embedded devices may replace human to perform tasks.Some examples are home automation, agriculture, smart cities, industrial automation, healthcare, remote monitoring, and many others. IoT provides a network of devices on which real time data can be shared and used in order to enhance life quality, industry processes, energy efficiency,and service quality[14].

For the proper efficiency and earliest possible detection of inefficiencies in HVAC systems, real time continuous data acquisition with the help of temperature and motion sensors is crucial. In this work, BME280 temperature sensor and PIR (Passive Infrared) motion sensor (LIS2DW12) have been employed for tracking changes in temperature and occupancy.

Temperature monitoring using sensors like the BME280 provides valuable insights into building performance and system health. Variations in temperature readings can indicate HVAC inefficiencies, such as improper distribution of cooling or heating and potential equipment overheating, which could lead to system failures. Additionally, analyzing long term thermal trends enables predictive maintenance and supports energy optimization efforts by identifying patterns that can inform more efficient climate control strategies.

Motion Detection (PIR Sensor): Abnormal patterns of activity detected by the PIR (passive infrared) sensor can signal potential sensor faults, such as spurious triggering or calibration drift. Additionally, anomalies in motion data may indicate HVAC system misoperation, such as heating or cooling in unoccupied spaces, which results in unnecessary energy consumption and reduced efficiency.

7.1.1 *Implementation Methodology*

The proposed system employs an ESP32 microcontroller since it possesses wireless connectivity, low power consumption, and the capability to facilitate multiple communication protocols. The sensors are interfaced as follows:

BME280 (via I2C/SPI) for accurate temperature, humidity, and pressure readings. LIS2DW12 sensor (digital output) to detect movement.

A firmware program, coded in Micro Python, periodically reads sensor data at fixed intervals. Every reading is tagged with a timestamp to enable time series analysis, making trends and anomalies

detectable. The data can be stored locally on an SD card or transmitted to a cloud-based service for subsequent analysis.

7.2 STORE AND PROCESS INFORMATION

To perform preventive maintenance, we need historical data storage and analysis.

1. Local Storage: Store data in ESP32's Serial Peripheral Interface Flash File System or an SD card for logging temporarily.

2. Cloud Storage: Utilize Firebase, AWS IoT, or Google Sheets for remote monitoring in real time.Message Queuing Telemetry Transport can be used for effective transmission of data.

3. Edge Processing: Autonomous sensor nodes do edge computing on the ESP32 microcontroller for better response times and efficiency. By using frameworks like TensorFlow Lite for Microcontrollers (TinyML), specific nodes can run light anomaly detection models in line. For instance, a node can detect an unusual temperature rise in an unoccupied room (no activity), which may be an indicator of a localized fault such as a jammed HVAC valve or malfunctioning machinery.

   However, to avoid conflicting behavior and to enable true building wide optimization, these local decisions are not directly carried out. Instead, anomaly warnings and processed information are fed into a local central building management system (BMS) or server. This centralized controller aggregates information from all of the sensor nodes, enabling the overall context required. It can distinguish between a local and a global issue, correlate events across zones, and apply optimized, coordinated control strategies to the whole building's HVAC and lighting. The two layer architecture intelligent edge nodes along with a central coordinator serves both fast local response and globally efficient operation

We can use sensor based thresholds and rule based logic to detect potential failures in HVAC systems. For energy efficiency and proactive maintenance, threshold based monitoring was employed for motion and temperature sensors. The following conditions were defined to detect anomalies and send respective alerts.

1. BME280 Temperature Sensor- If temperature exceeds 28°C for over 30 minutes, then trigger an alert.A gradual increase in temperature over several weeks may suggest: Clogged air filters,HVAC inefficiency or overuse, Fan or compressor failure

2. Motion Sensor (LIS2DW12)- If no activity in an occupied area for 2 hours, Possible HVAC energy waste. The presence of atypical patterns of movement may suggest: Sensor misalignment, Security risks (unexpected motion in restricted areas) The sensor data can be stored in Google Sheets, Firebase, or AWS IoT

Energy harvesting techniques offer diverse solutions for powering low energy devices, contributing to sustainability and reducing reliance on traditional energy sources. Solar energy harvesting stands out as the most effective primary source due to its high energy output, scalability, and alignment with global sustainability goals. Thermoelectric energy harvesting complements solar energy by providing continuous power in environments where sunlight is unavailable. Together, these techniques form a robust hybrid system for powering IoT sensors in smart buildings, ensuring energy efficiency and environmental sustainability.

7.3 PREDICTIVE MAINTENANCE & THRESHOLD BASED MONITORING IN SMART BUILDINGS

A predictive maintenance model was integrated into the energy efficient smart building system for enhanced efficiency and reliability in operation. The system employs actual data from a number of sensors, including temperature sensor (BME280), motion sensor (PIR sensor), and HVAC status sensor, to predictively identify abnormal behavior and trigger energy aware control actions.

Sensor Data and Monitoring Parameters The analysis data set includes hourly time stamped information of:

- Room temperature (in °C)
- Motion detection status (binary: 1 = motion detected, 0 = no motion)
- HVAC operation state (1 = active/on, 0 = inactive/off)

The building is assumed to be well insulated with automated HVAC control based on occupancy and environmental conditions.

The temperature remains steady at 20–21°C during the early morning and rises gradually throughout the day, with a peak of 30°C at 18:00–20:00 hrs. This peak can be due to either high solar gain or occupancy. After 20:00 hrs, the temperature decreases, indicating HVAC operation or reduced activity. The sharp decrease at 23:00 hrs may be due to a scheduled cooling operation or energy conservation operation.

Threshold Based Maintenance Logic

1. Threshold rules were established to recognize anomalies and inefficiencies in the HVAC system, based on sensor data:
2. When temperature exceeds 28°C for more than 30 minutes while the HVAC is ON, it reflects potential malfunction in cooling systems (i.e., compressor inefficiency or refrigerant issues).
3. In the event of no motion for over an hour while the HVAC is operating, the system automatically reduces energy consumption by either resetting the temperature setpoints or disabling surplus climate control.

4. Unusual cycling patterns (repeated ON/OFF switching) in the HVAC are indicated as indicating thermostat or control system issues, invoking preventive maintenance activity.

These setpoints are configurable by the user and provide a basis for rule based automation as well as system diagnostics.

8

CONCLUSION

This research addressed the limitations of battery powered IoT sensors in smart buildings by designing, implementing, and evaluating a hybrid energy harvesting system combining PV and TEG technologies. A comprehensive comparative analysis established PV as an efficient primary source under adequate illumination and TEGs as a continuous secondary source when thermal gradients are available. RF harvesting was excluded due to its insufficient power density for the application. The proposed architecture, which uses a supercapacitor for storage instead of batteries, successfully eliminates disposable power sources, reduces environmental impact, and lowers maintenance requirements contributing to long life, sustainable IoT deployments.

Simulation based evaluation demonstrated that the hybrid system, coupled with a 1300F supercapacitor and high efficiency power management, achieved >99% annual uptime with over 48 hours of energy autonomy. Seasonal performance analysis confirmed the system's capability to overcome single source intermittency.

The proposed architecture eliminates disposable batteries, reduces environmental impact, and lowers maintenance requirements contributing to long life, sustainable IoT deployments. These findings validate hybrid PV-TEG harvesting as a technically and economically viable solution for intelligent building energy management.

8.1 FUTURE WORK

To further enhance performance and deployment potential, future work should explore:

- **Predictive Energy Management:** Machine learning-based algorithms for proactive power budgeting.
- **Dynamic Load Allocation:** Using surplus energy for extended sensing or processing tasks.
- **Multi-Source Harvesting:** Incorporating kinetic, piezoelectric, or RF sources to further diversify energy input.
- **Thermal Optimization:** Improving heat sink and dissipation strategies to maximize TEG performance.
- **Integrated Design:** Developing compact, modular enclosures that merge PV and TEG modules seamlessly into building architecture.

By pursuing these directions, hybrid energy harvesting systems can achieve greater autonomy, adaptability, and integration advancing the shift toward fully self sustaining, intelligent building infrastructures.

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9 APPENDIX A

.1 MATLAB CODE FOR HYBRID ENERGY MODEL

```
%% IMPORT WEATHER DATA - FULL YEAR
filename = 'Halmstad_Halmstad_102302_2021.csv';

opts = delimitedTextImportOptions("NumVariables", 12);
opts.DataLines = [4, Inf];
opts.Delimiter = ";";

opts.VariableNames = ["Year", "Month", "Day", "Hour", ...
    "Wind_direction_Degrees", "Wind_speed_m_s", ...
    "Dry_bulb_Temperature_C_", "Relative_Humidity", ...
    "Total_cloud_cover", "Global_horizontal_irradiance_W_m2_",
        ...
    "Direct_normal_irradiance_W_m2_", "
       Diffuse_horizontal_irradiance_W_m2_"];
opts.VariableTypes = repmat("double", 1, 12);
opts.ExtraColumnsRule = "ignore";
opts.EmptyLineRule = "read";

weatherData = readtable(filename, opts);
n_hours = height(weatherData);
hours = 0:n_hours-1;

%% SYSTEM INPUT PARAMETERS
T_out = weatherData.Dry_bulb_Temperature_C_;
G_solar = weatherData.Global_horizontal_irradiance_W_m2_;

T_out(isnan(T_out)) = 0;
G_solar(isnan(G_solar)) = 0;

% Radiator model
T_supply = min(60, 20 + 0.8 * (22 - T_out));
T_cold = 22;
dT = T_supply - T_cold;

% TEG
alpha = 0.03111; % V/ C
Voc = alpha .* dT;
Rint = 1.2;
P_TEG = (Voc.^2) ./ (4 * Rint);
P_TEG(isnan(P_TEG)) = 0;

% Indoor irradiance scaling
placement = 'near_window'; % or 'deep_indoor'
switch placement
    case 'deep_indoor'
        scale_factor = 0.03;
    case 'near_window'
```

```
        scale_factor = 0.15;
end

A_solar = 0.0154;
eta_solar = 0.19;
G_indoor = G_solar * scale_factor;
P_solar = G_indoor .* A_solar .* eta_solar;
P_solar(isnan(P_solar)) = 0;

% Load profile
I_active = 80e-3; I_idle = 1e-3; Vcc = 3.3; D = 1/5;
P_esp32 = Vcc * (D * I_active + (1 - D) * I_idle);
eff_bb = 0.80;
P_total_load = P_esp32 / eff_bb;

%% ADAPTIVE STORAGE SIZING USING SIMULATION
V_max = 2.7;
V_min = 0.84;
V_margin = 0.05;

C = 100;                % Initial guess
C_step = 20;            % Step change
tolerance = 1;          % Convergence check
max_iterations = 50;

for iter = 1:max_iterations
    E_max = 0.5 * C * V_max^2;
    E_min = 0.5 * C * V_min^2;

    V_cap = zeros(1, n_hours);
    V_cap(1) = 2.5;
    E_stored = 0.5 * C * V_cap(1)^2;
    E_wasted = zeros(1, n_hours);
    power_loss_events = 0;
    power_loss_hours = 0;
    device_down = false;
    V_min_observed = inf;

    for i = 2:n_hours
        P_in = P_solar(i) + P_TEG(i);
        current_load = P_total_load;
        E_next = E_stored + (P_in - current_load) * 3600;

        if E_next > E_max
            E_wasted(i) = E_next - E_max;
            E_stored = E_max;
        elseif E_next < E_min
            E_stored = E_min;
            if ~device_down
                power_loss_events = power_loss_events + 1;
                device_down = true;
            end
            power_loss_hours = power_loss_hours + 1;
        else
            E_stored = E_next;
            device_down = false;
```

```
        end

        V_cap(i) = sqrt(2 * E_stored / C);
        V_min_observed = min(V_min_observed, V_cap(i));
    end

    if power_loss_events > 0
        C = C + C_step;
    elseif V_min_observed > (V_min + V_margin)
        C = C - C_step;
        C = max(C, 1);
    else
        break;
    end

    if C_step < tolerance
        break;
    end
end

fprintf('Optimal Capacitance: %.2f F\n', C);

% Final simulation for plots and energy summary
E_max = 0.5 * C * V_max^2;
E_min = 0.5 * C * V_min^2;
V_cap = zeros(1, n_hours);
V_cap(1) = 2.5;
E_stored = 0.5 * C * V_cap(1)^2;
E_wasted = zeros(1, n_hours);
power_loss_events = 0;
power_loss_hours = 0;
device_down = false;

for i = 2:n_hours
    P_in = P_solar(i) + P_TEG(i);
    current_load = P_total_load;
    E_next = E_stored + (P_in - current_load) * 3600;

    if E_next > E_max
        E_wasted(i) = E_next - E_max;
        E_stored = E_max;
    elseif E_next < E_min
        E_stored = E_min;
        if ~device_down
            power_loss_events = power_loss_events + 1;
            device_down = true;
        end
        power_loss_hours = power_loss_hours + 1;
    else
        E_stored = E_next;
        device_down = false;
    end

    V_cap(i) = sqrt(2 * E_stored / C);
end

```

```
158 %% ENERGY SUMMARY
159 E_solar_Wh = sum(P_solar);
160 E_TEG_Wh = sum(P_TEG);
161 E_total_Wh = E_solar_Wh + E_TEG_Wh;
162 total_consumed_Wh = sum(P_total_load * ones(1, n_hours));
163 total_wasted_Wh = sum(E_wasted) / 3600 / 1000;
164
165 fprintf('\n--- Energy Summary ---\n');
166 fprintf('Total Hours Simulated: %d\n', n_hours);
167 fprintf('Solar Harvested: %.2f Wh\n', E_solar_Wh);
168 fprintf('TEG Harvested:   %.2f Wh\n', E_TEG_Wh);
169 fprintf('Total Harvested: %.2f Wh\n', E_total_Wh);
170 fprintf('Total Consumed:  %.2f Wh\n', total_consumed_Wh);
171 fprintf('Total Wasted:    %.2f Wh\n', total_wasted_Wh);
172 fprintf('Power Outage Events: %d\n', power_loss_events);
173 fprintf('Total Outage Hours: %d (%.2f%% of year)\n',
        power_loss_hours, 100 * power_loss_hours / n_hours);
174 fprintf('Supercapacitor Used: %.2f F\n', C);
175
176 %% PLOTS
177 figure; plot(hours/24, T_out, 'b'); hold on;
178 plot(hours/24, T_supply, 'r--'); title('Outdoor vs Radiator Temp'
        );
179 xlabel('Days'); ylabel(' C '); legend('Outdoor','Radiator');
180
181 figure; plot(hours/24, P_solar*1000, 'g'); hold on;
182 plot(hours/24, P_TEG*1000, 'm'); title('Harvested Power (mW)');
183 xlabel('Days'); ylabel('mW'); legend('Solar','TEG');
184
185 figure; plot(hours/24, V_cap, 'k'); title('Supercapacitor Voltage
        ');
186 xlabel('Days'); ylabel('V'); yline(V_max, 'r--'); yline(V_min, 'b
        --');
```

DECLARATION

Sweden, <2025>

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