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ENERGY HARVESTING FROM UNCONVENTIONAL SOURCES TO POWER IOT SENSOR APPLICATIONS

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ABSTRACT

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The rapid technological advancement in electronics and communication systems has boosted the interest in the Internet of Things (IoT) based system with its applications in monitoring and control of not only industrial processes, transportation, education, defense, and smart city management but also in the sports and healthcare industry. The state-of-the-art integrated systems on the chip now consume ultra-low power of micro and nano watts thus bringing the possibilities for the design and development of miniaturized and cost-effective IoT systems. Most of the IoT devices are used in remote or mobile units with wireless sensor nodes powered using batteries which adversely affect the lifespan and cost of the sensor node but also impact the reliability of the whole IoT system.

Micro energy harvesting solutions from unconventional energy sources can now address such challenges of battery charging and extend the lifespan of IoT systems but also can eliminate the use of batteries in some applications. These solutions reduce the initial and maintenance costs of IoT-based sensor systems and improve the ecology of the environment. In battery-less IoT systems, supercapacitors are used to temporarily retain the energy, and the operation time is optimized in slots especially to operate the most power-hungry blocks such as communication radios of the IOT sensor node. The energy harvesting systems deploy techniques to yield power from sources present in the ambiance of IoT sensor nodes.

In this work, the chemical energy harvesting technique from unconventional sources such as salt water is studied to run ultra-low power on-chip IoT sensor applications. The chemical energy harvesting electrodes are developed using various materials and an extensive set of experiments are performed to validate the proposed idea in a controlled lab environment. The aim is to develop flexible energy-harvesting electrodes using off-the-shelf rolled sheet materials which can later be used as printable solutions to harvest green energy from urine to power the economical and disposable wearable healthcare sensor node for smart diapers.

Keywords
Battery-less solutions, Chemical energy harvesting from saltwater, Energy harvesting, Healthcare sensor nodes, IoT applications, Printed electronics, Sensor nodes, Wearable devices

CONCEPT DEFINITIONS

HCI	Human Computer Interface
IoT	Internet of Things
IoE	Internet of Everything
LiPo	Lithium-ion Polymer
RF	Radio Frequency
MPPT	Maximum power point tracking
WSNs	Wireless sensor networks

CONTENTS

FIGURES

1 INTRODUCTION

Over the last decade, the Internet of Things (IoT) has been more widely used in all aspects of life, especially in smart cities, automation, smart homes, security systems, and health gadgets. The IoT techniques are deployed in physical devices to sense, control, and monitor for the implementation of economical solutions. Powering IoT devices extensively poses a significant challenge, particularly in scenarios where access to wall power is impractical. There has been a lot of development in this area to optimize the power consumption of IoT-based devices to eliminate bulky batteries.

The advancement in IoT technology aims to overcome the challenges of human-computer interface (HCI) by developing state-of-the-art sensors, control systems, and actuators with better communication protocols and interfaces. The researchers are focusing on designing the least power-consuming electronic hardware on one end and looking for options to power them with small batteries to achieve the low cost and size of IoT devices on the other end. Usually, IoT devices consume a small amount of power, however, in the near future the introduction of billions of IoT devices will not only bring power load challenges on the global power grid but also bring the challenge of recharging or replacing the batteries in billions of IoT sensor nodes. The cost of disposable IoT sensor nodes used in the healthcare industry is also very high because of batteries. There is a dire need to look for alternate energy harvesting options to fulfill the emerging enormous demand for power for IoT devices.

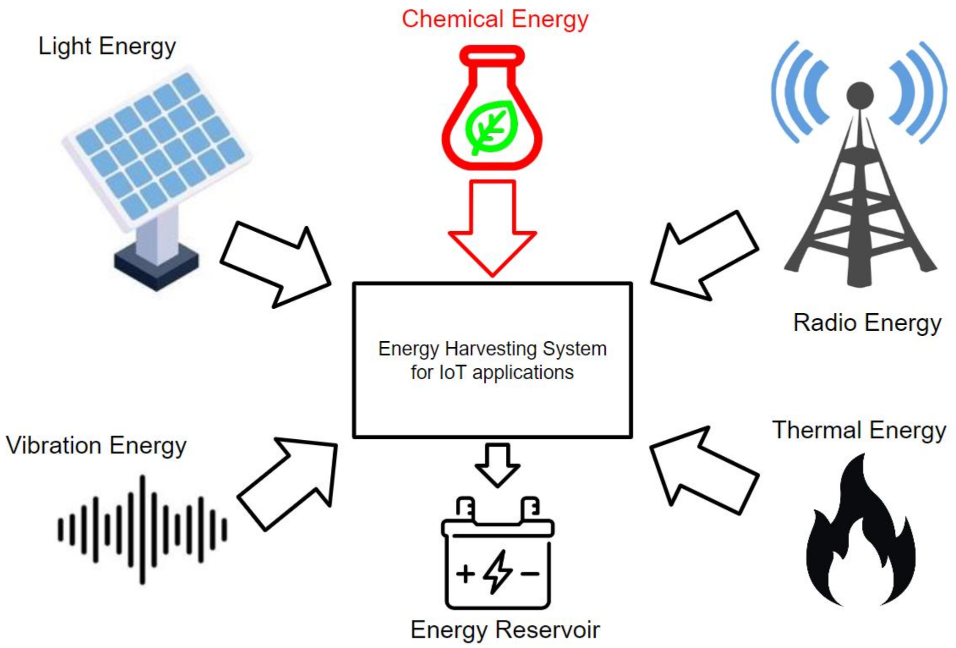

FIGURE 1. The proposed system of multi-energy harvesting for IoT applications.

This study explores and discusses possible micro energy harvesting solutions from several power sources available in the environment such as solar and ambient light, radio frequency (RF) energy, vibration power, and chemical energy as shown in FIGURE 1. This work focuses on green energy harvesting from saltwater using an electrochemical energy harvesting mechanism as red highlighted in FIGURE 1 and proposes the development of flexible energy-harvesting electrodes using various commercially available rolled sheet materials to power small, autonomous, mobile, and disposable IoT sensor nodes for healthcare applications for battery-free operations. It includes a comprehensive set of measurements conducted in a controlled laboratory environment to validate the concept of green energy harvesting for creating cost-effective disposable IoT sensor nodes. This potential is expanding the application of energy harvesting in wireless sensor networks (Zahid, Reza, Saleh & Ramiah 2014). This kind of energy harvesting is crucial to the answers to the energy shortage. All researchers participating in this sector have already completed projects and there are some advantages and disadvantages to these projects. Also, some limitations and challenges are still there which are hopefully overcome in the future.

Chapter 2 discusses the theoretical background of IoT systems, energy harvesting techniques, and challenges and introduces the concept of printed electronics for sustainable and green solutions. The materials used for the development of flexible energy harvesting electrodes and the measurement methods are discussed in Chapter 3. The results are presented and discussed in Chapter 4. Finally, the work is concluded in Chapter 5, where recommendations for future work are also provided.

2 BACKGROUND

The IoT devices and their components operate on the power of batteries. The batteries need to be charged from the grid or alternate energy harvesting sources for such applications. In energy harvesting, usually non-conventional sources are used to hunt energy and power the IoT devices. The harvested energy is stored in batteries and supercapacitors to retain the energy for short terms. The energy harvesting system consists of power management and other support circuitry to protect the energy reservoir. (Aldin, Ghods, Nayebipour & Torshiz, 2024.) In this section, the discussion is about the methods of energy harvesting for remote and portable applications and the technical challenges involved in energy harvesting system design.

2.1 Internet of Things (IoT) system

At the start of the 21st century, the IoT got the attention of the global community when a report on IoT was produced by the International Telecommunications Union (ITU) about its needs and applications and outlined the scope of the information and communication technologies (ICTs) in Geneva. IoT devices have now become the most vital technology with their vast range of applications in almost every aspect of life. These devices give freedom of connectivity around the globe regardless of time and space. It is predicted that more than 22 billion IoT devices will be in use by 2025A typical IoT system consists of a sensor element, a front-end interface of the sensor with analog electronics, a processing unit, memory, a power management block, a battery with a charging or harvesting solution, and a transmitter with an antenna or output interface. (Lueth 2020.) The block diagram of a typical IoT system using an energy harvesting option is depicted in FIGURE 2 where the red highlight block of energy harvesting is the focus of this thesis.

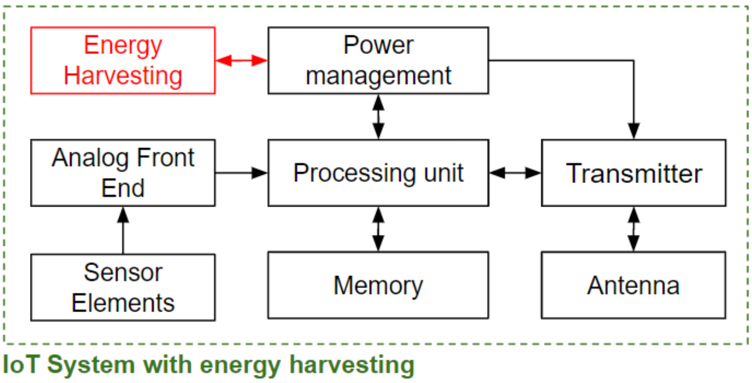

FIGURE 2. Block diagram of typical IoT system.

2.2 Energy harvesting for IoT applications

Energy harvesting (EV) is a process of scavenging power from outer sources such as light, vibrations, radio frequency (RF), or magnetic field. The energy harvesting techniques usually produce a small amount of power for storage in small batteries or supercapacitors to run low-power IoT devices. It eliminates the need to run power cables to distant places and reduces the batteries recharging, replacement, and maintenance costs. Energy harvesting enables the remote monitoring and control of processes and events without any disruptions thus increasing the scope of its applications to smart cities, remote sensing, access control, asset tracking, industrial processes, sports, and healthcare sectors. (Elahi, Munir, Eugeni, Atek & Gaudenzi 2020.)

2.3 Energy Harvesting Sources and Techniques

IoT devices can benefit from ambient energy sources like photovoltaic energy, vibration energy, heat energy, and radio frequency, often in hybrid configurations to optimize performance and efficiency. For example, kinetic energy can be converted to power IoT devices using mechanisms like MEMS that are developed for micro-scale energy harvesting. This approach to powering IoT devices is crucial for their widespread deployment in remote and inaccessible areas, and for reducing reliance on batteries that pose ecological challenges and maintenance issues due to their limited lifespan. (Famitafreshi, Afaqui & Melia-Segui 2021.)

Research in this field points out the diversity in energy densities of ambient sources and the advantages of hybrid systems that utilize multiple sources to enhance system efficiency and performance. Such innovation is not only pivotal for IoT device longevity but also for the broader objective of sustainable and environmentally friendly technology deployment. (Mishu, Rokonuzzaman, Pasupuleti, Shakeri, Rahman, Hamid, Tiong & Amin 2020.) In this thesis report, two methods are discussed. First is magnetic energy harvesting and the second is radio frequency energy harvesting. FIGURE 3 presents the block diagram of a typical energy harvesting system for IoT devices.

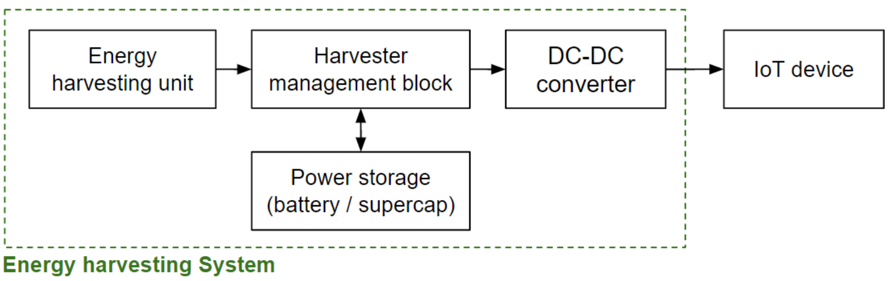

FIGURE 3. The block diagram of an energy harvesting system for IoT devices.

2.3.1 Magnetic energy harvesting

The movement of electrons or electric charges produces magnetic fields carrying magnetic energy. The most common source of magnetic energy is permanent magnetism on Earth. Magnetic energy is also observed near electric motors, speakers, and electric generators which are because of current flowing through conductors. The electric busbars, high-tension power lines, and cables also produce magnetic fields. The magnetic energy harvester uses an inductor to scavenge the energy because according to Faraday's law, the changing field induces alternating electromotive force (AC) inside the conductor nearby. (Halliday, Resnick & Walker 2010.)

FIGURE 4 presents the block diagram of a magnetic harvesting unit for IoT systems. The harvesting inductor harvests the energy from varying magnetic fields. An over-voltage protection circuitry protects the following block from damage. The harvested alternating current (AC) is rectified and filtered to be direct current (DC). The DC power is regulated and stored on a supercapacitor or battery to further power the IoT systems. This harvesting technique is deployed in applications where varying magnetic fields are present, for example near high-tension power transmission lines. (Halliday et al. 2010.)

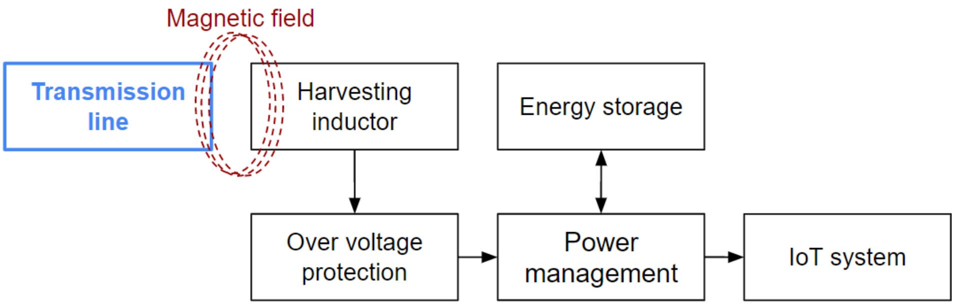

FIGURE 4. The block diagram of magnetic energy harvesting.

2.3.2 Radio frequency energy harvesting

Radiofrequency (RF) waves are transmitted from communication antennas and are present in the environment. The strength of the RF waves is defined by the power transmitted from the antenna. They are strong near the antenna and get weaker as move away from the transmitting antenna. Radio waves are also formed naturally by lightning or by astronomical bodies. The recent development of communication technology has led to an enormous presence of stronger RF energy in the global atmosphere and the race of 5G in cellular networks has brought the capability to transmit even more powerful RF signals in the environment. (Luo, Pu, Wang & Zhao 2019.)

The permanent presence of RF energy in the environment brings the feasibility to directly power the battery-free IoT systems. The complexity of the RF harvester system design is higher to enable it to harvest from even ultra-low levels of RF energy. (Luo et al. 2019.) FIGURE 5 depicts the block diagram of a typical RF energy harvester which involves an RF antenna, a matching network, a rectifier, a power converter, and a storage unit to retain energy and further power the IoT system.

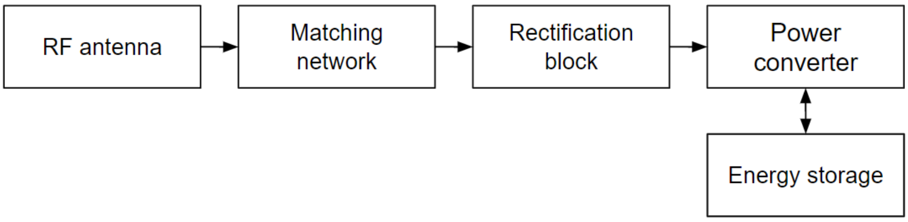

FIGURE 5. The block diagram of RF energy harvesting.

2.4 Energy Harvesting from Saltwater

A study on generating electricity through the capacitive deionization (CDI) method by utilizing the salinity gradient between fresh and salty water, often referred to as blue energy is presented by Muhthassim, Thian & Hasan (2018). The study aims to explore effective techniques for small-scale applications and evaluate various factors like electrode materials and electrolyte concentrations that affect the performance of the CDI technique.

The research begins by highlighting the vast potential of water as a renewable energy source, given that the surface of the earth is predominantly covered by water, most of which is in the oceans. The study categorizes Blue Energy as a promising yet underexplored sector, which has seen increased interest due to fluctuations in oil supply and advancements in renewable energy technologies. The Pressure Retarded Osmosis (PRO), Reverse Electrodialysis (RED), and Capacitive Deionization (CDI) techniques of chemical energy harvesting are explored. The CDI was chosen for the detailed analysis due to its potential for smaller-scale energy generation and lower operational costs. (Muhthassim et al. 2018.)

Experimental setups were conducted to test the effectiveness of various electrode combinations (carbon/aluminum, copper/aluminum, and carbon/copper) in different concentrations of salty water. Copper and aluminum electrodes showed the most promising results. A DC-DC boost converter was employed to enhance the voltage output, demonstrating an efficiency of 38.17% in converting the input power to usable electrical output. The study underscores the need for further research and development in the field of Blue Energy, particularly in capacitive deionization, to make it a viable option for renewable energy generation. It suggests that CDI, with its unique advantages over other salinity gradient technologies, could play a crucial role in sustainable energy production, especially in portable or small-scale applications. (Muhthassim et al. 2018.)

2.5 Electrochemical Cell (Galvanic Cell)

A galvanic cell, also known as a voltaic cell, is named in honor of scientists Luigi Galvani and Alessandro Volta. It is an electrochemical device that generates an electric current through spontaneous oxidation-reduction (redox) reactions. The setup typically contains two different metals, each submerged in separate beakers filled with a solution called electrolyte, each beaker is called a half-cell. These half-cells are either connected by a salt bridge or divided by a porous membrane. (Mcmurry, Fay & Robinson 2014.) The schematic of a galvanic cell of zinc in the electrolyte of zinc sulfate making a half cell and copper electrode in the electrolyte of copper sulfate making the other half cell is depicted in FIGURE 6.

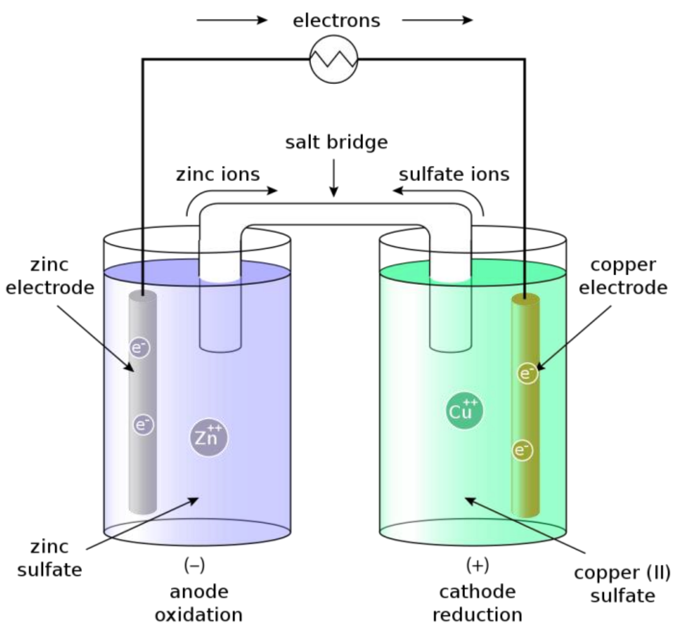

FIGURE 6. The Zinc-Copper electrochemical cell ((Mcmurry et al. 2014).

Galvanic cells utilize certain types of chemical reactions in electricity. These reactions happen naturally and involve electrode materials to gain or lose electrons. For example, when a piece of zinc metal is used as an electrode and immersed in water mixed with copper sulfate (which is blue), the zinc gets covered in a dark material and the water will lose its blue color. This dark material is copper, and the water now has zinc in it. This change happens because zinc gives away electrons to the copper, making the zinc into zinc ions and the copper into solid copper. (Mcmurry et al. 2014.)

2.5.1 Zinc Copper Galvanic Cell

When these reactions happen, they usually produce only heat. However, in galvanic cells, this energy can be captured and turned into electrical power. A simple version of this cell has a metal electrode in a water solution that has ions of the metal and other ions to keep the electric charge balanced. A complete cell has two of these setups connected by a special membrane or a salt bridge that stops the metal ions from moving over and disrupting the process. In a classical example, the redox process involves zinc and copper where electrons are transferred between substances. It is used to demonstrate how redox reactions work. In this process, zinc and copper ions participate in a reaction where zinc metal loses electrons and copper ions gain electrons. A simple breakdown of chemical reactions for the galvanic half-cell are precented in Equation 1, 2 and 3. Zinc (Zn) starts as a neutral metal and then loses two electrons to become zinc ions (Zn^{2+}) as expressed in Equation 1. This loss of electrons is called oxidation. The zinc metal is the reducing agent because it gives up electrons. At the same time, copper ions (Cu^{2+}) in solution accept two electrons to become copper metal (Cu) as depicted in Equation 2. This gain of electrons is called reduction. The copper ions are the oxidizing agent because they accept electrons. The Equation 3 shows the overall redox reaction when these two half-reactions are put together. (Mcmurry et al. 2014.)

$$Zn \rightarrow Zn^{2+} + 2e^- \tag{1}$$

$$Cu^{2+} + 2e^- \rightarrow Cu \tag{2}$$

$$Zn + Cu^{2+} \rightarrow Zn^{2+} + Cu \tag{3}$$

In the galvanic cell, this redox process is set up so that the oxidation and reduction occur in separate half-cells. They are connected by a wire and a salt bridge (or a porous membrane), allowing the electrons lost by the zinc to flow through the wire to the copper. This flow of electrons through the wire is what we use as electricity. The salt bridge prevents the solutions from mixing directly but allows ions to move to maintain a balance of charge as the reaction proceeds. This reaction is energetically favorable, meaning it releases energy. In a battery, this energy is harnessed as electrical energy that can power devices. (Mcmurry et al. 2014.)

2.5.2 Zinc Air Galvanic Cell

Zinc-air galvanic cells work by using zinc metal and oxygen from the air. Oxygen comes into the battery through a part called the air cathode. Since there is enough oxygen in the air it can be used for the zinc air galvanic cell. The air cathode is a very important part of the cell. When the zinc and the oxygen gas react together it generates electric potential as given in the chemical reactions. It works by zinc reacting with oxygen through a series of steps involving hydroxide ions to produce zinc oxide. The process involves both oxidation (zinc losing electrons) and reduction (oxygen gaining electrons), making it an effective way to generate electrical power from chemical reactions. In the first reaction at the zinc electrode the zinc (Zn) reacts with hydroxide ions (OH^-) to form zincate $Zn(OH)_4^{2-}$ and releases two electrons $(2e^-)$ as shown in Equation 4. (Dobley 2013.)

$$Zn + 4(OH)^- \rightarrow Zn(OH)_4^{2-} + 2e^- \tag{4}$$

$$Zn(OH)_4^{2-} \rightarrow ZnO + H_2O + 2(OH)^- \tag{5}$$

$$O_2 + 2H_2O + 4e^- \rightarrow 4(OH)^- \tag{6}$$

$$O_2 + 2H_2O + 4e^- \rightarrow 4(OH)^- \tag{7}$$

$$Zn + \frac{1}{2}O_2 \rightarrow ZnO \tag{8}$$

The second reaction is expressed in Equation 5 where the zincate $Zn(OH)_4^{2-}$ formed in the first step breaks down into zinc oxide ZnO, water H_2O, and hydroxide ions (OH^-) at anode. This step is crucial for the continuation of the overall reaction and prepares the by-products for further reactions. In the reaction at the cathode as shown in Equation 6, oxygen (O_2) from the air reacts with water (H_2O) and electrons $(4e^-)$ to form hydroxide ions (OH^-). Equation 7 represents the reduction reaction in which oxygen gains electrons. Combining the anode and cathode reactions gives the overall cell reaction as shown in Equation 8. Zinc reacts with oxygen to form zinc oxide (ZnO). This reaction sums up the chemical changes in a zinc-air battery, converting chemical energy into electrical energy.

The harvesting cell potential starts with a voltage of a little above 1.1 volts and decreases very slowly while discharging. After about 90% of the battery life has been used up, the voltage drops quickly to 0.9 volts, which is when the cell is considered to be fully exhausted at room temperature, and with an alkaline liquid as electrolyte to help conduct the electricity. The zinc-air battery has a theoretical energy capacity of 1353 watt-hours per kilogram (Wh/kg). However, it usually delivers around 400 Wh/kg in reality. They are especially common in hearing aids, where they have been employed for many years. Larger versions are used by the military for powering electronic gadgets. The main benefits of zinc-air batteries include their affordability, lightweight, and eco-friendliness. However, they do have some drawbacks, such as their lower voltage output and the use of a harsh, caustic liquid inside them. (Dobley 2013.)

2.6 Challenges for Energy Harvesting

Even though energy harvesting technology has made considerable strides over the past ten years, several technological hurdles need to be overcome before the production of self-sustaining IoT devices becomes commonplace. There are several challenges in energy harvesting, some of them are It is necessary to maintain a balance between the power that is generated and the power that is used. Since the technology used to store the harvested energy influences the cost, size, and working life of IoT devices, this requires the development of appropriate storage elements like rechargeable batteries and supercapacitors. In some cases, a single energy harvesting source is not sufficient to power up IoT devices. The reliability of devices can be improved by mixing energy from several sources. (Sanislav, Mois, Zeadally & Folea 2021.)

2.7 Sustainability and green electronics

Sustainability refers to the practice of utilizing natural resources responsibly to support both current and future generations. It is about creating a balance between environmental health, social equity, and economic vitality to foster thriving and resilient communities. It highlights the limitations of the natural resources. There is a need to use these resources conservatively and wisely with a long-term perspective. It's closely tied to the idea of sustainable development, which aims to meet present needs without compromising the needs of future generations. The United Nations has defined 17 sustainable development goals to follow by all the member states. (McMurry, Fay & Robinson 2015.)

2.7.1 Green electronics

Sustainability in green electronics focuses on integrating environmental considerations into the lifecycle of electronic products, from design and manufacturing to use and end-of-life management. Nature Materials highlights the importance of early design strategies, innovations in materials selection, manufacturing technologies, and recycling strategies to foster sustainability in electronics. These approaches aim to minimize environmental impacts by utilizing natural materials like cellulose or textiles that are biocompatible, low-cost, and environmentally friendly. Advanced technologies such as additive manufacturing and 3D printing support the creation of flexible devices that consume less energy and avoid harmful chemicals. (Mater 2023.)

2.7.2 Sustainability for Batteries

The recycling of conventional batteries is a growing challenge due to their hazardous nature. Batteries contain various metals and chemicals that can be toxic to the environment, and efficient recycling processes are essential to mitigate these hazards and contribute to sustainability efforts. Lithium-ion polymer (LiPo) batteries, commonly found in consumer electronics, are challenging to recycle. While recycling technologies are being developed, recovering metals like lithium in a pure enough form for reuse in batteries is not yet cost-effective. Therefore, lithium from spent batteries is often used for non-battery applications like lubricants, glass, and ceramics. (Kang, Chen & Ogunseitan 2013.)

Nickel Cadmium (Ni-Cd) batteries, which contain the toxic metal cadmium, can pose threats to human health and the environment. These batteries are labeled with the chemical symbol Ni-Cd, and there are specific recycling programs to handle them due to their hazardous nature. Zinc-Carbon batteries with NH4Cl (Ammonium Chloride) are another type of battery that has environmental implications. Like other batteries, they must be recycled properly to avoid releasing toxic substances into the environment. Overall, the battery recycling process typically starts with sorting batteries by chemistry, followed by thermal processes to remove combustible materials and recover metals. This process can be energy-intensive and may produce pollutants if not managed correctly. It is essential to cover battery terminals during recycling to prevent electrical conductivity and potential hazards. (Toro & Luigi 2023.)

2.8 Printed electronics

Printed electronics, introduced in the late 20th century, have undergone significant evolution, transforming electronic manufacturing through cost-effective printing on flexible substrates. Advances in materials, processes, and applications have been key drivers of progress. The initial focus on basic components has shifted toward developing novel materials with enhanced properties, enabling greater versatility. Printing technologies, including inkjet, gravure, and screen printing, have improved resolutions and pattern intricacies. The integration of organic and flexible semiconductors has broadened applications to flexible displays, wearables, and IoT sensors. (Caironi & Sirringhaus 2007.)

3 MATERIALS AND METHODS

This thesis proposes chemical energy harvesting to power IoT sensor nodes used in the healthcare industry, particularly those embedded in disposable diapers. It emphasizes the green energy extraction from urine in diapers for this purpose. This chapter describes the design and development of energy-harvesting electrodes by employing a variety of materials and electrolytes. The measurement setup and methodologies using different energy harvesting scenarios are explored to validate the feasibility of sustainable electrochemical energy harvesting as proposed in this study.

3.1 Harvesting mechanism design

In this development, the electrodes are meticulously crafted into a square shape, as illustrated in FIGURE 7. Each electrode boasts dimensions of 7 cm in length (L) and 7 cm in width (W), cumulatively covering an area of 98 cm² according to (Tanweer, Sepponen, Tanzer & Halonen 2024). The thickness (T) of the electrode is minimal, to the extent that it is negligible for design. The construction of the galvanic cells involves the utilization of electrodes made from a variety of materials, which will be elaborated upon in subsequent sections. To ensure effective electrical connectivity, a copper tape equipped with a conductive adhesive (manufactured by 3M, St. Paul, Minnesota, USA) is employed. Furthermore, a pliable copper wire is adeptly soldered onto this tape, facilitating the establishment of connections.

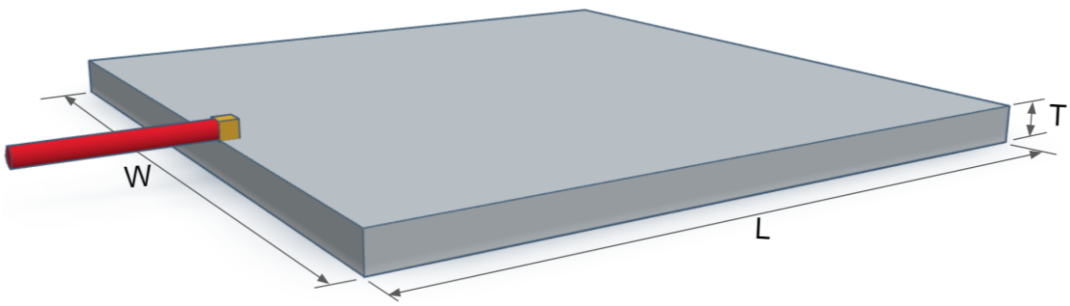

FIGURE 7. The design of harvesting electrodes

3.1.1 Material used for harvesting electrodes

In this thesis work, five different off-the-shelf rolled sheet materials were selected for the chemical energy harvesting electrode developments on the geometry described in FIGURE 7. Zinc and

Aluminum are used for the anode (-ve) electrode development. Whereas Carbon, Copper, Aluminum, and Silver are used as cathodes (+ve) electrode development. The Silver electrode was developed with L of 7 cm2 and a width of 2 cm contrary to other electrodes having the geometry of 7 cm x 7 cm. FIGURE 8 shows the developed energy-harvesting electrodes from (a) rolled carbon sheet, (b) Copper sheet on FR4 board, (c) rolled Aluminum sheet, (d) rolled Zinc sheet and (e) rolled silver sheet.

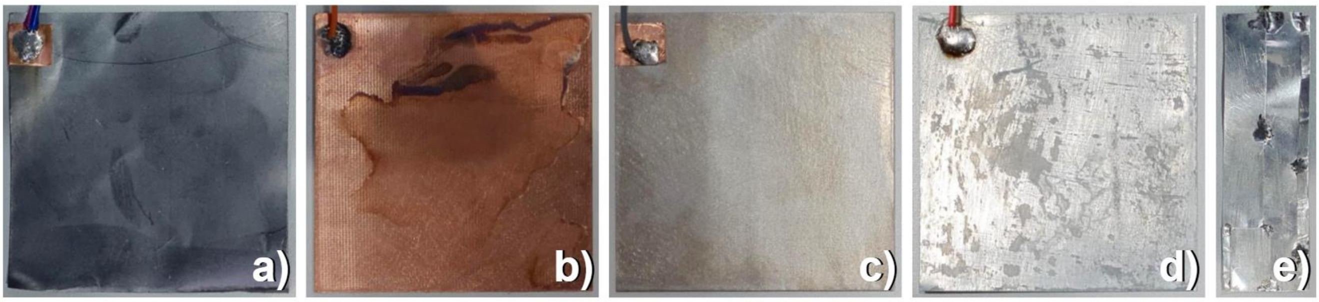

FIGURE 8. Rolled sheet base energy harvesting electrodes; a) Carbon sheet, b) Copper sheet, c) Aluminum sheet, d) Zinc sheet, e) Silver sheet.

In addition to the electrodes developed from off-the-shelf rolled sheets of various materials, the printed energy harvesting cathode, also known as the reducing electrode, on the same geometry outlined in FIGURE 7 is crafted by depositing and curing an electrically conductive carbon ink (Saral Carbon 700A, produced by Saralon GmbH). Two consecutive layers of this carbon ink, each with a sheet resistance of 30 Ω / square /25 µm, are applied one after the other. Following each application, the layers are thermally dried at 100 °C for 10 minutes in a 95 °C preheated oven (ProtoFlow E, supplied by LPKF Laser & Electronics) at the labs of Aalto University. Electrical connections are established via a small segment of copper tape with conductive adhesive (manufactured by 3M, St. Paul, Minnesota, USA) placed on the cured carbon ink layer. To safeguard against short circuits by preventing water ingress, water-resistant tape is used to secure these connections. (Tanweer et al. 2024.)

3.1.2 Electrolyte used for energy harvesting

In this thesis work, a synthetic urine solution was utilized as the electrolyte and facilitates the salt-bridge. According to data from the Laboratory of Helsinki University Hospital and FimLabs in Finland, the normal concentration range of sodium electrolytes in human urine is between 80 to 240 mM, while chloride electrolytes range from 85 to 260 mM for adults. For this experiment, the chemical makeup of the synthetic urine is specifically formularized at Aalto University labs, using sodium chloride (NaCl) to achieve an electrolyte concentration of 220 mM, aligning with the natural concentration ranges of sodium and chloride found in human urine. (Tanweer et al. 2024.) In addition, the electrolyte having a NaCl concentration of 1.15 M and 2.875 M are also formularized according to (Muhthassim et al 2018.) It is important to note that a one-mole solution of NaCl is composed of sodium with a molar mass of 23 g/mol and chloride with a molar mass of 35.5 g/mol, adhering to values reported in recognized chemical literature.

3.2 Measurement setup

The measurement setup of the electrochemical energy harvesting from developed electrodes was established to validate the idea of green energy harvesting. For this purpose, a galvanic cell is configured within a vertical container, which holds exactly one liter of NaCl solution serving as the electrolyte. The choice of NaCl solution is pivotal, not only for its role as an electrolyte but also as a salt bridge, facilitating the essential ion exchange and connecting the oxidation and reduction reactions needed for energy harvesting. The electrodes are placed on the inner sides of the container strategically and oriented in parallel in order to harvest electrochemical energy efficiently from the electrolyte. A specific model of a multimeter (73 III Fluke) is used from Aalto University labs to accurately measure the open circuit voltages (OCV) which is the potential difference between the electrodes when no external load is applied. This step is important as it provides a baseline understanding of the maximum voltage that the galvanic cell is capable of producing under ideal conditions.

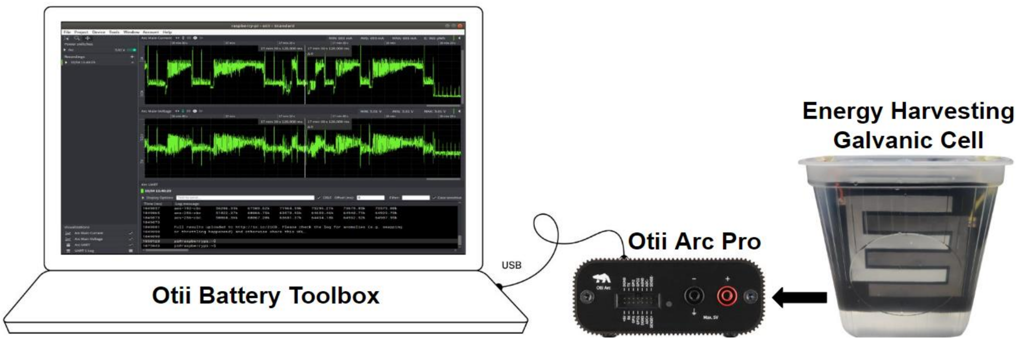

FIGURE 9. The measurement setup for energy harvesting from saltwater using various materials as harvesting electrodes.

The characterization of the developed electrodes is conducted using a direct current (DC) energy analyzer and power profiler instrument known as Otii Arc Pro, along with the Otii Battery Toolbox software. Both are provided by Qoitech AB from Sweden offering an efficient solution to analyze the performance of the electrodes in-depth regarding their efficiency, power output, and time-based durability. The measurement setup is presented in FIGURE 9 with a single energy-harvesting galvanic cell. This intensive assessment is crucial to understanding the practical implications of using NaCl solution as an electrolyte for electrochemical energy harvesting and evaluates the potential for this method to contribute towards sustainable and renewable energy solutions for disposable IoT applications.

3.3 Measurement methods

An extensive set of measurements, to validate the capability of electrodes developed using various materials for energy harvesting, is conducted through a series of carefully designed measurement scenarios inside the controlled lab environment of Aalto University labs. These scenarios aim to provide a detailed assessment of both the voltage levels and the total energy that can be extracted from the NaCl solution, employing developed electrodes in various combinations. This investigation explores the efficiency of NaCl solution as an unconventional electrolyte to generate electrical energy to particularly power self-sustaining IoT devices. The experimental scenarios explore diverse combinations of electrode materials, with Zinc and Aluminum selected for the anode (positive electrode) and Carbon, Copper, Aluminum, and Silver utilized for the cathode (negative electrode) in the construction of the galvanic cells. These meticulously planned scenarios pave the way for a deeper understanding of energy harvesting possibilities, which are elaborated upon in subsequent subsections.

3.3.1 Single-cell in-jar measurement scenarios

In the controlled environment, single-cell configurations are examined. Each scenario uses one liter of NaCl solution at a concentration of 220 mM as the electrolyte inside the jar as depicted in FIGURE 10. This approach allows for a clear comparison between the different material combinations used to form the galvanic cells. The single galvanic cells of Zinc-Silver, Zinc-Copper, and Zinc-Carbon combinations are then connected to a fixed power load of 500 μW using the Otii Arc Pro system, alongside the Otii Battery Toolbox software, providing precise data on the energy harvesting efficiency and capabilities of each setup. The variations in voltage and current are monitored over a span of 90 seconds.

3.3.2 Multi-cell in-jar measurement scenarios

The energy harvesting from the synthetic urine is further explored by establishing the multi-cell setups in series and parallel combinations, as depicted in FIGURE 10, established to observe the collective effect on energy harvesting for various materials where single-cell voltages are too low to meet the minimum voltage threshold of the measurement instrument (Otii Arc Pro system). In this measurement scenario, four galvanic cells are used, each filled with one liter of NaCl solution at a concentration of 600 mM. Aluminum-carbon and Aluminum-Copper combinations are specifically chosen to explore their electrochemical properties. The measurement setup is established to withdraw a constant power of 100 μW for the first 20 seconds, then continues to withdraw 200 μW for the until 200 seconds. Throughout this period, the Otii Arc Pro system precisely logs the variations in voltage and current, providing valuable data to validate insights into the scalability and efficiency of multi-cell configurations.

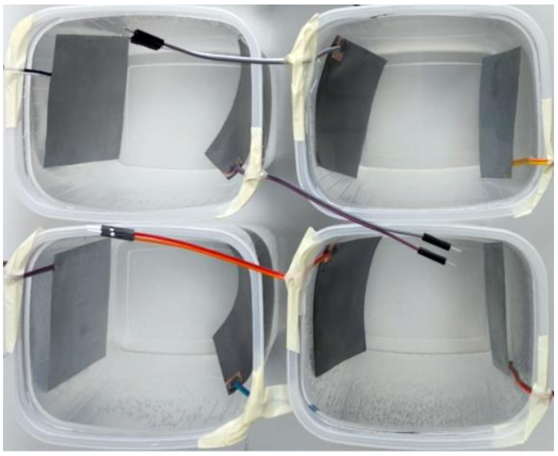

FIGURE 10. Multicell energy harvesting measurement setup using 4 in-jar galvanic cells.

3.3.3 Electrolyte concentration-based measurement scenarios

A single galvanic cell measurement scenario is established as depicted in FIGURE 10 to evaluate the performance of energy harvesting with variation in the concentration levels of the NaCl solution used as electrolyte. The electrolyte amount of one liter with varying NaCl concentrations of 220 mM, 1.15 M, and 2.875 M is used for these measurement scenarios for the zinc-carbon electrodes combination as cathode and anode respectively. The fixed power load of 500 uW is applied for 2000 seconds and the behavior of the voltages and current variations is observed using Otii Arc Pro, along with the Otii Battery Toolbox software.

3.3.4 Coplanar electrode structure-based measurement scenarios

The coplanar structure of zinc carbon anode and cathode electrodes, as depicted in FIGURE 11 (a), was deployed inside jar as shown in FIGURE 11 (b) as a galvanic cell and the electrolyte solution of 1 liter is used for the energy harvesting with fixed power with drawl of 100 uW for first 100 seconds and then 500 uW for 400 seconds using Otii Arc Pro, along with the Otii Battery Toolbox software and the behavior of voltages and current are observed. In the second measurement phase as shown in FIGURE 11 (c), the inter-digitated coplanar structure of zinc-carbon electrodes is deployed inside an adult diaper (by Tena a subsidiary of Essity) under the super-absorbing polymer (SAP) material. The electrolyte, consisting of a NaCl solution with a concentration of 220 mM as synthetic urine, is poured in a quantity of 100 ml inside the diaper. The energy harvesting in this scenario is executed with fixed power with a drawl of 100 uW for the first 100 seconds and then 500 uW for 400 seconds using Otii Arc Pro, along with the Otii Battery Toolbox software. The behavior of voltages and current is observed when the energy harvesting electrodes are deployed inside the diaper application setting.

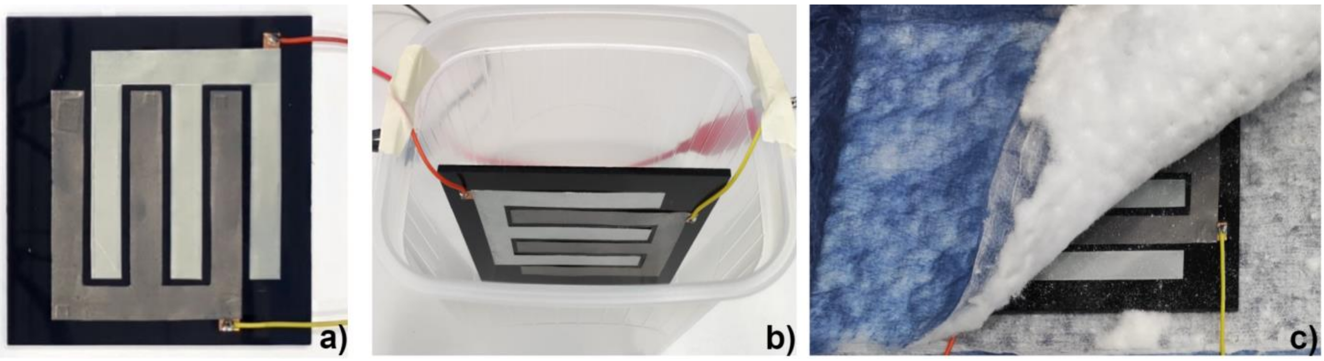

FIGURE 11. Coplanar structure of Zinc-Carbon electrodes; a) Interdigitated design of electrodes, b) Galvanic cell using in-jar measurements, c) Galvanic cell using in-diaper measurements.

Throughout these comprehensive measurement methods, the research thoroughly evaluates the potential of various electrode materials and configurations to harvest energy from NaCl solutions. The goal is to pave the way for developing efficient, sustainable energy sources for powering the next generation of self-powered IoT applications, with a keen eye on integrating biochemical processes into energy production landscapes.

4 RESULTS

The measurements were conducted utilizing electrodes specifically designed for energy harvesting, which were developed from various materials combined in multiple configurations according to the defined measurement scenarios as discussed in Section 3.3. These electrodes were used to evaluate their performance in different settings. The Otii Arc Pro battery toolbox plays a crucial role in this process, as it captures the energy harvesting measurement data. Once collected, this data was meticulously saved and organized into CSV files representing each unique measurement scenario. These files were then prepared for further processing. MATLAB software is employed to process the raw data, plot the results for visual inspection, and conduct a detailed analysis of the gathered measurements. The capabilities of MATLAB facilitate a comprehensive examination of the data, allowing for the extraction of meaningful insights regarding the performance of the various electrode combinations under study. For the graphical presentation, the blue color is employed to show the behavior of the voltages, and the red color is employed to depict the current behavior of the galvanic cells having various electrode materials in different configurations.

The results of these measurements are thoroughly discussed in different sections of the accompanying document. Section 4.1 delves into the outcomes of the ‘in-jar’ measurement scenarios. Here, the focus is on the behavior of different energy-harvesting electrode combinations when tested within a controlled jar environment. This section evaluates how effectively these combinations can harvest energy under these specific conditions. In contrast, Section 4.2 focuses on the ‘in diaper’ measurements. This part of the study explores the energy harvesting capabilities of selected electrodes configured in a coplanar interdigitated geometry. This unique setup is scrutinized to understand how well these electrodes perform when embedded in diapers, demonstrating the practical applications and effectiveness of these energy harvesting systems in real-world scenarios.

4.1 In-jar measurement results

In the first scenario of in-jar energy harvesting, the experimental setup involved a single galvanic cell configuration using zinc-carbon, zinc-silver, and zinc-copper electrode combinations arranged in a parallel orientation inside a vertical jar containing one liter of electrolyte solution as described in subsection 3.3.1. The NaCl solution with a concentration of 220 mM per liter was chosen as an electrolyte of galvanic cell to mimic synthetic urine with a similar salt concentration. This concentration was within the typical range found in adult human urine, as outlined in subsection 3.1.2. The developed galvanic cells were connected to an Otii Arc Pro System, which was programmed to draw a fixed power of 500 μW for a duration of 90 seconds. This setup allows for precise analysis of the voltage and current behaviors for each electrode combination within the single galvanic cell configuration. These measurements are crucial for assessing the performance of each material combination under identical experimental conditions.

The results of these experiments are visually represented in FIGURE 12, where different line styles are used to distinguish between the behavior electrode combinations. The blue solid line illustrates the voltage (V) behavior of the zinc-carbon electrodes, while the red solid line tracks the changes in current over the 90-second period. Dashed and dotted lines represent the voltage and current behaviors of the zinc-silver and zinc-copper combinations, respectively. Observations from the experiment indicate that the zinc-carbon electrode combination experiences a linear voltage drop from 880 mV to 780 mV under a constant power (P) load of 500 μW over the 90-second period. In contrast, the zinc-silver combination starts at a lower voltage of 600 mV, which decreases steeply during the first 20 seconds before the rate of decline slows, resulting in a total voltage drop of 100 mV by the end of the 90 seconds. The zinc-copper combination, meanwhile, shows an exponential initial drop from 800 mV to 650 mV within the first 10 seconds, then stabilizes and shows no further decrease for the remaining 80 seconds. The withdrawn current (I) flow shows the same and opposite trend to fulfill the $P = IV$ criteria when a load of fixed power is deployed.

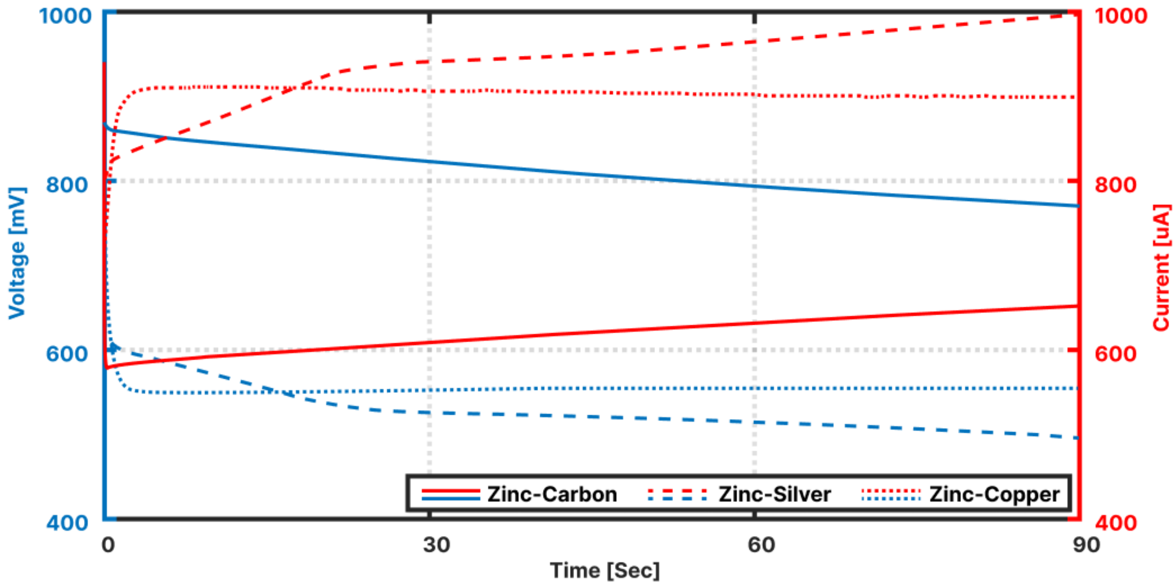

FIGURE 12. Single galvanic cell harvesting results in current and voltage.

The analysis suggests that the zinc-carbon combination is preferable for applications requiring higher initial voltage levels, while the zinc-copper combination offers greater voltage stability under constant loads, making it ideal for applications where maintaining a fixed voltage is critical. Furthermore, the performance of these single galvanic cells is promising for powering IoT sensor nodes, which consume sub-nanowatt power levels, allowing them to operate for several minutes on the energy harvested.

In the second measurement scenario of the in-jar setup, a multi-galvanic cell approach was employed, involving four identical cells connected in series to increase the overall voltage output for the electrode material combinations of copper-carbon, aluminum-copper, and aluminum-carbon. This configuration is necessary because the Otii Arc Pro system used in the study has a low voltage cutoff threshold of 500 mV, necessitating higher output voltages to meet this minimum requirement for successful measurements as outlined in subsection 3.3.2. Each of the four galvanic cell in this setup was filled with a one-liter solution of NaCl at a concentration of 600 mM, serving as the electrolyte. Initially, a constant power load of 100 μW is applied for the first 20 seconds, which is then increased to 500 μW for the subsequent 180 seconds. The voltage and current behaviors of these multi-galvanic cell configurations under energy harvesting conditions are depicted in FIGURE 13, where the plot uses solid, dashed, and dotted lines to represent the copper-carbon, aluminum-copper, and aluminum-carbon electrode combinations, respectively.

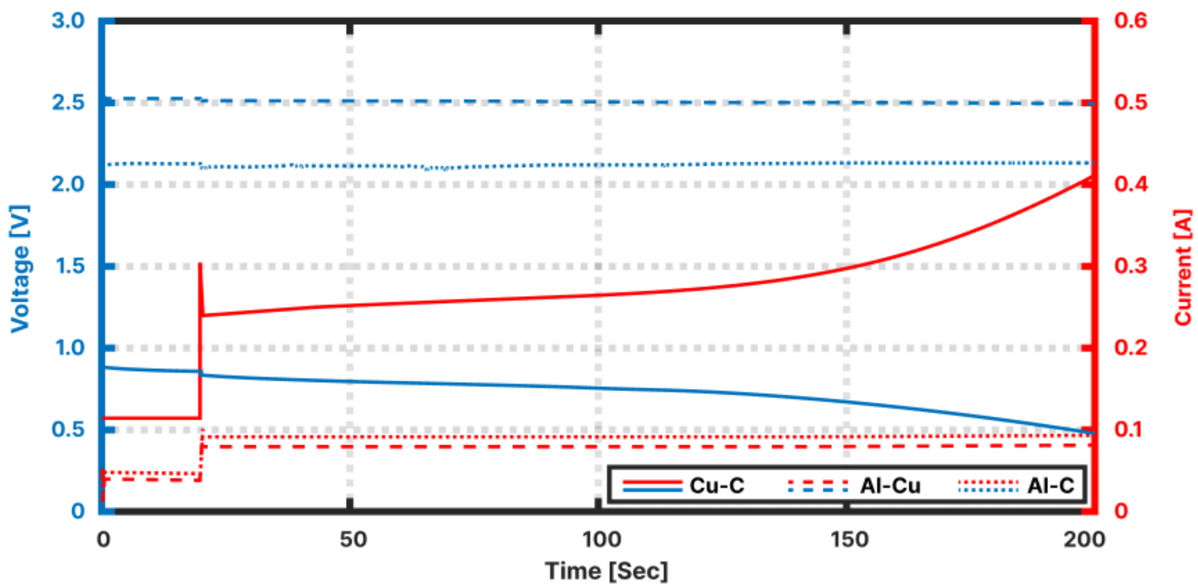

FIGURE 13. Energy harvesting from multi-galvanic cells with series combination.

Observations from the data indicate that the four-cell series configuration with copper-carbon electrodes starts with a voltage of 900 mV (225 mV per cell), which declines to 500 mV over 200 seconds. In contrast, the aluminum-copper combination in series starts at a higher voltage of 2.6 V (650 mV per cell), with only a 100 mV drop noted during the same 200-second interval under continuous power draw. Similarly, the aluminum-carbon series configuration exhibits a starting voltage of 2.2 V (550 mV per cell), which remains notably stable over the 200-second duration under a constant power withdrawal of 500 µW.

In a different experimental setup, four cells composed of aluminum-carbon electrodes were connected in parallel, with a consistent power load of 500 µW applied for an extended duration of 2000 seconds. The outcomes of this parallel cell configuration are presented in FIGURE 14. Here, it is noted that the starting voltage of 550 mV experiences a slight reduction to 510 mV across the lengthy energy harvesting period of 2000 seconds. This behavior suggests that this setup could be particularly advantageous for powering more energy-demanding electronics, such as the communication radios in IoT sensor nodes, which require a stable and sustained power supply.

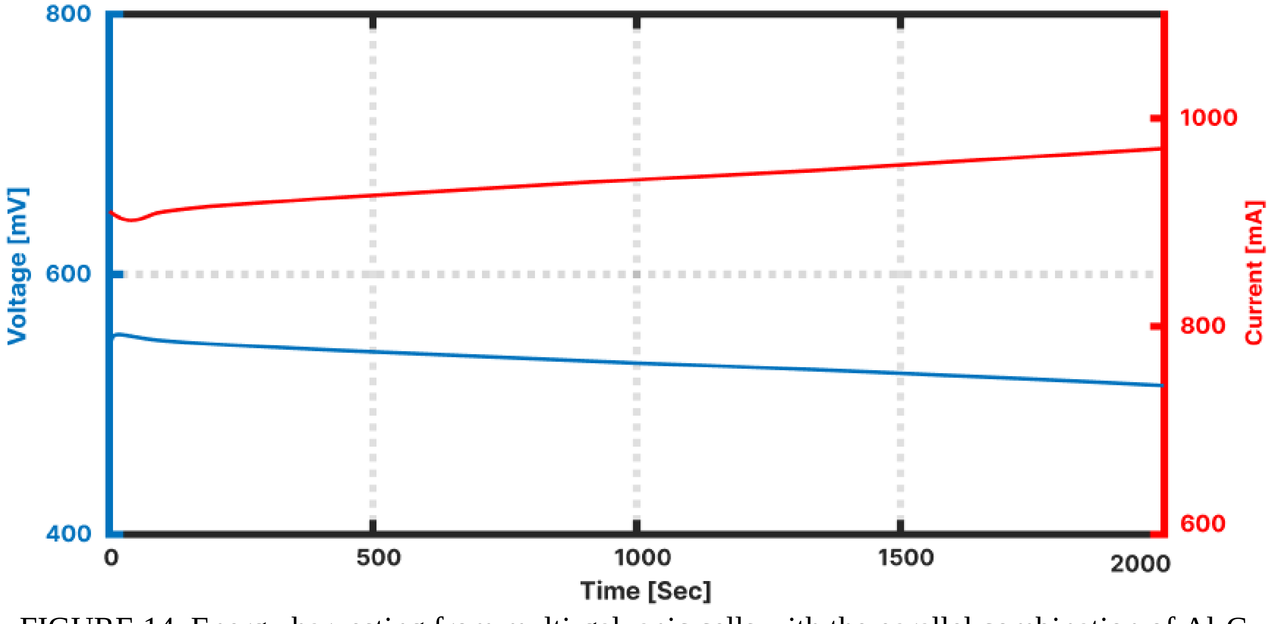

FIGURE 14. Energy harvesting from multi-galvanic cells with the parallel combination of Al-C.

In the third measurement scenario within the in-jar measurement setup, a focused study was conducted using a single galvanic cell composed of zinc-carbon harvesting electrodes. This scenario is designed to explore the effects of varying NaCl solution concentrations on the energy harvesting capabilities of the galvanic cell. Three distinct concentrations of NaCl solution (220 mM, 1.150 M, and 2.875 M) were used to prepare one-liter electrolyte solutions for the single galvanic cell setup as described in subsection 3.3.3. This variance allows for a comprehensive analysis of how different electrolyte concentrations influence the electrochemical performance of the galvanic cell consisting of zinc-carbon electrodes under consistent experimental conditions. To carry out this analysis, a constant power load is applied using the Otii Arc Pro System over a period of 30 minutes. This setup enables detailed observation of the voltage and current behaviors of the galvanic cell in response to the different electrolyte concentrations. The results of this experiment are depicted in FIGURE 15, where solid, dashed, and dotted lines respectively represent the electrolyte concentrations of 220 mM, 1.150 M, and 2.875 M.

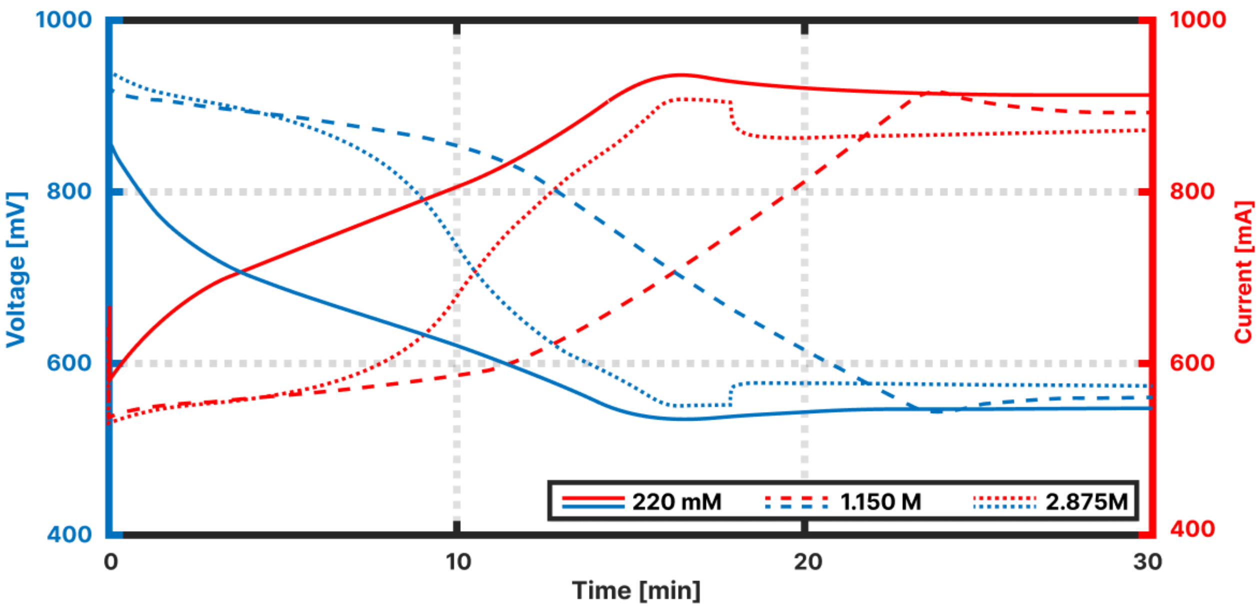

FIGURE 15. Energy harvesting from zinc-carbon electrodes in electrolytes of various concentrations.

It is observed that the voltage initially experiences a steeper drop in cells with the lowest (220 mM) and the highest (2.875 M) NaCl concentrations compared to the cell with a 1.150 M concentration. Despite these steeper initial drops, the voltage in both the 220 mM and 2.875 M cells eventually stabilizes at 550 mV after 15 minutes of continuous harvest at a power of 500 µW. In contrast, the cell with the 1.150 M concentration shows a slower voltage decline and stabilizes only after 25 minutes, also reaching 550 mV when subjected to the same constant power load. Based on these findings, it is concluded that varying the NaCl concentration affects the initial voltage stability and the time taken to stabilize. Furthermore, to accommodate sensor electronics that operate at higher voltage levels such as 1.2 V or 1.8 V (common requirements of various IoT sensor nodes) can be implemented by employing a voltage multiplier of either 2x or 3x. Such a setup would ensure that the harvested energy is sufficient to supply reliable power to IoT sensor nodes consuming sub-nanowatt power hence enhancing the feasibility of using zinc-carbon galvanic cells in practical energy harvesting applications. This approach allows for a tailored configuration that can meet the specific power requirements of various electronic devices, making the system versatile for cost-effective real-world applications such as disposable smart diapers.

4.2 In-diaper measurement results

A coplanar interdigitated energy harvesting electrode mechanism is designed for integration within diapers as detailed in subsection 3.3.4. The zinc-carbon single-cell configuration is adopted for this innovative approach to analyze in-diaper energy harvesting. Initially, the coplanar configuration of electrodes is tested in a controlled environment using a single galvanic cell setup within a jar containing one liter of a 220 mM NaCl solution. This stage is established to validate the functionality of the coplanar interdigitated orientation of the electrodes, ensuring they perform effectively for energy harvesting. In the subsequent phase, these electrodes are implemented inside an adult diaper. An amount of 100 ml of the same 220 mM NaCl solution is introduced into the diaper, simulating a real-world application as described in subsection 3.3.4. During this test, a constant power load of 500 µW is applied for 400 seconds using the Otii Arc Pro System, and the resulting voltage and current behaviors are meticulously recorded and displayed in FIGURE 16. In the diagram, the solid line represents the measurements taken in the diaper, while the dashed line corresponds to those from the in-jar setup.

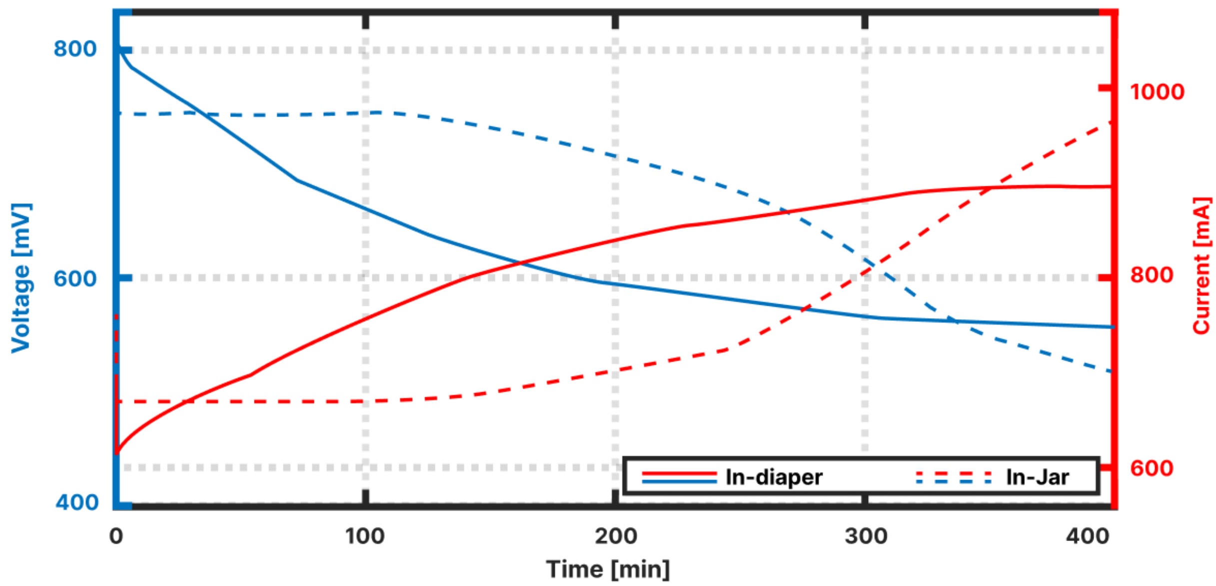

FIGURE 16. Energy harvesting using interdigitated coplanar electrodes.

It is observed that in the diaper setup, the voltage initially drops more steeply compared to the in-jar setup within the first 300 seconds. However, unlike in the jar where the voltage continues to decline, the voltage in the diaper stabilizes thereafter. This stabilization suggests that the diaper's materials may interact with the electrodes in a way that moderates the voltage drop, illustrating the complex dynamics between the electrode design, electrolyte solution, and the diaper material in this advanced energy harvesting application.

CONCLUSION

The rapid technological advancement in electronics and communication systems has boosted the interest in the Internet of Things (IoT) based system with its applications in monitoring and controlling not only industrial processes, transportation, education, defense, and smart city management but also in the sports and healthcare industry. The majority of IoT devices are utilized in remote or mobile units with wireless sensor nodes powered by batteries, which negatively impacts both the sensor node's lifespan and the overall reliability of the IoT system. In this thesis work, energy harvesting is discussed in the context of scopes, challenges, and approaches. Energy harvesting can now be used as an alternative energy source for a more dependable system that is used for remote and unreachable regions.

In this study, an extensive set of measurements was conducted on chemical energy harvesting electrodes developed from various materials combined with NaCl electrolytes to explore the feasibility of using urine to power IoT sensor electronics in smart diapers. The electrode combinations tested included zinc-carbon, zinc-silver, and zinc-copper for single galvanic cell analysis, which demonstrated that zinc-carbon notably outperformed others, particularly when a high voltage was needed. Additionally, combinations of copper-carbon, aluminum-copper, and aluminum-carbon were examined in multi-galvanic cell configurations involving both series and parallel setups. The zinc-carbon electrodes not only proved to be the most effective for high voltage applications but were also found to be the most cost-effective and environmentally friendly option, making them ideal for sustainable disposable IoT sensor node solutions that require both cost efficiency and environmental safety.

Further analysis focused on the zinc-carbon electrodes to study the effects of varying NaCl concentrations in the electrolyte, matching the range typically found in human adult urine. This helped refine the choice of electrolyte concentration for optimal energy harvesting. Additionally, a set of interdigitated zinc-carbon electrodes was developed in a coplanar orientation for integration within adult diapers, and their functionality was validated in both in-jar and in-diaper energy harvesting scenarios. Looking ahead, it is recommended to explore the use of printable inks made of conductive carbon and zinc for the electrodes. This could facilitate the integration of energy harvesting mechanisms directly onto diaper material through roll-to-roll printing, streamlining the production process and ensuring easy incorporation into the diaper manufacturing line.

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