HOLY CROSS COLLEGE OF CALINAN
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PAHINGA: POWERING AHEAD WITH HYBRIDIZED INTEGRATED NANOGENERATOR ARRAYS

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By

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APPROVAL SHEET

In partial fulfillment of the requirements in Practical Research 2, this study entitled **PAHINGA: POWERING AHEAD WITH HYBRIDIZED INTEGRATED NANOGENERATOR ARRAYS**, prepared and submitted by **Rhea Mae Soledad, Julia Therese Rabang, and Ajon Richard Sombon** is hereby recommended for oral examination, approval and acceptance.

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PANEL OF EXAMINERS

Approved by the panel of examiners, after the presentation of the study with the grade of - .

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Accepted in partial fulfillment of the requirement in ____________________.

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The Researchers

ABSTRACT

The study experimentally investigated the use of Hybridized Nanogenerators as an alternative-sustainable energy source. This study addresses the increasing requirement for energy sources, thus, surging the use of non-renewable energy worldwide. The innovation aims to alleviate the heavy use of fossil fuels and non-renewable energy sources by providing an affordable, reliable, clean, and sustainable energy system. Using piezoelectric nanogenerators and electromagnetic nanogenerators through an experimental research design, an output of 0.08V-0.35 V and 0.96W-2.45 W.

The study primarily addresses the hurdles of SDG-7 or affordable and clean energy and contributes to the improvement of the field of science and innovation. Furthermore, the study creates various opportunities for researchers to develop nanotechnology.

Keywords: hybridized nanogenerator, electromagnetic-piezoelectric, nanogenerator, sustainable energy source,

Chapter 1

INTRODUCTION

Background of the Study

Energy is becoming more viewed as a basic right in any growing economy than as a necessity for society (Oh et al., 2018). The increasing daily requirements of energy across the globe to satisfy social and economic development, welfare, and health causes the world to become a global village (Owusu & Sardokie, 2016). Therefore, one of the United Nations (UN) Sustainable Development Goal (SDG)-7 aims to provide affordable, reliable, clean, renewable, and sustainable energy worldwide (Trinh & Chung, 2023).

In the Philippines, the main source of natural gases since 1990 has been the Malampaya gas reserve (Ravago et al., 2021). However, the reserve is expected to run dry in 2027, forcing the nation to choose between renewable energy and exploring new gas reserves in the disputed land of the West Philippine Sea (Bozkus, 2024). Hence, meeting energy demands starting from 2022 proved to be a challenge as the Malampaya Gas Field had substantially declined in its natural gas production levels. Adding to the pressing issue is the forecast that the peak demand for electricity in the Philippines may reach up to 54,655 MW (megawatt) in 2040. This is an impending concern as this is four times the electricity demand in 2018 (Ravago, 2022). Thus, the gas field used for fuel in electric power generation has become an irreplaceable energy source and is now in crisis. This has led the Philippines to resort to importing liquified natural gasses (LNG), which is seen as costly and impractical (Ravago et al., 2021).

Locally, Davao City has been experiencing rapid urbanization and population growth throughout the past five years. This rising concern has created problems for the city, such as the accumulation of waste and energy crises affecting the lower boundaries of people (Cortez, 2023). Similarly, in the Island Garden City of Samal, power crises and outages have become rampant, affecting a majority of the city's population, causing dispute among locals (Recuenco, 2023).

On the other hand, nanogenerators (NG) are utilized in modern ways to harness renewable energy. Its transformative potential serves as a stepping stone in revolutionizing energy production and the innovation of current technological models. Also, it serves as a modern tool to enhance the capacities of batteries, photovoltaic cells, and capacitors (Mose, 2024). Nanogenerators are based on the current standards of IoT, emphasizing self-powered systems, sensors, and flexible and portable electronics.

Although nanogenerator technology integration contributes to modern innovative technology in terms of self-powering sensors in preparation for a more sustainable environment, studies related to its capacity to generate from human energy are limited. As a matter of fact, information made from several studies related to this topic fail to break down the significant types of motion that greatly alter the generated power stored. Also, prototypes which align themselves in the area of specific human motions are yet to be studied and engineered. The lack of data regarding the correlation of these subjects limits the engineering capacity of the researchers in developing nanogenerators in use for specific areas such as classroom settings, workplaces, and even transportation vehicles.

Statement of the Problem

This study aims to assess the capacity of the hybridized integrated nanogenerator to produce energy enough to power portable devices. Specifically, this study seeks to answer the following questions:

1. Is there a significant change in the energy output produced by the nanogenerator prototype throughout the trials under Set-Up A Weight-Based?
2. What is the average energy output of the hybridized nanogenerator throughout the trials in Set-up B, based on the following outputs:

    2.1 current; and

    2.2 voltage?
3. Is there a significant difference between the average energy output (in watts) of Set-Up A and the sub-sets of Set-Up B compared to the standard criteria?

Hypothesis

The alternative hypothesis of this study suggests that the proposed hybrid nanogenerator prototype will generate sufficient energy output comparable to the standard criteria.

Review of Related Literature

In this section, the researchers gathered different information from different sources that are related to nanogenerators and power-generating capacity to further understand the concept in order to support this study. For years, the state of electricity and energy production has continued to decrease. Along with this are the issues involving our climate and the environment. It is now more than ever that actions must be taken in order to avoid unlikeable circumstances in the future. Technology has been integrated to find solutions to these problems, focusing on sustainability and efficacy as a means to mitigate harmful consequences.

The proponents reviewed literature on nanogenerator technology, its role in creating sustainable energy prototypes, and their performance in energy generation sufficiency, including commercial standards.

Nanogenerator Technology Today

In response to the world's growing need for sustainable energy sources, researchers from across the globe have explored the viability of nanotechnology to replace non-renewable energy sources. Nanogenerator technology has evolved alongside the rise of cloud computing and artificial intelligence; this nanotechnology is closely working with various innovations for the acceleration of technology (Liu et al., 2022). Further, nanogenerators are highlighted in the current Internet of Things (IoT) for its effective implementation of prototype enhancement (Croitoru et al., 2024). IoT is a pioneering technology which enables the connection of technology through interaction and development. It brings upon opportunities to use solutions in encountering problems (Li et al., 2020). In a study by Jin et al., (2019) that explored and reviewed the capability of nanogenerators to power an intelligent transport system, it was mentioned that nanogenerators are capable of wireless monitoring and harvesting ambient environment technology.

Moreover, nanogenerators possess a distinct characteristic which makes them suitable for even small scale power generation, and that is its meek size. According to Indira et al. (2019), the invention of nanogenerators is a breakthrough in the field as they are small, lightweight, easily fabricated, and sustainable. Ambient mechanical energy has always been abundant in our environment, may it come from the waters flowing off a river to the simple movement of human feets walking– mechanical energy sources are everywhere, and it is most importantly sustainable. There are different types of nanogenerators, namely; Triboelectric Nanogenerator (TENG), Electromagnetic Generators (EMG), Piezoelectric Nanogenerator (PENG), Electrochemical Cell, Solar Cell, and Pyroelectric Nanogenerator (Zhang et al., 2020).

Among the types of nanogenerators, Alam et al., (2023) stated that the three main types of nanogenerators are piezoelectric, triboelectric, and pyroelectric nanogenerators. These nanogenerators have very high versatility and potential for changing the world we know today. For one, these can be used for biomechanical purposes, such as stimulating the repair process of the human body, as a substitute for battery-powered medical electronic devices (Dong et al., 2023).

The piezoelectric nanogenerator (PENG) is the most often researched type of nanogenerator, alongside the Triboelectric Nanogenerator (TENG). Piezoelectric Nanogenerators (PENGs) use piezoelectric materials that generate electric charge when experiencing mechanical stress or pressure. Electromagnetic Generator (EMG) is another type of nanogenerator. It operates on the principle of electromagnetic induction, where a microcoil and a micromagnet engage in a relative motion due to external mechanical motions that leads to an electric charge (Vidal et al., 2021). Pyroelectric Generators (PyENGs) on the other hand, generate an electric charge when certain materials respond to a sudden change in temperature in a process called the pyroelectric effect. The heating and cooling of materials leads to the reformation of the molecular structure, creating an imbalance of electrons that leads to the generation of electric current. The last type of nanogenerator is called the Tribo-Thermoelectric Nanogenerator (TTENGs), which allows the generation of electricity from both mechanical and thermal energy (Indira et al., 2019). In recent years, researchers and innovators have been merging two or more types of nanogenerators for optimal energy production; these types of generators are called hybrid nanogenerators (Wang et al., 2023).

Optimization of Energy Production Through Hybrid Nanogenerators

Hybrid generators, also known as hybrid energy harvesters, show advantages and potential in terms of high energy harvesting ability and multifunctionality. Hybrid nanogenerators are not only focused on energy harvest; they are also proven useful as multifunctional sensors (Wang et al., 2023). Hybrid nanogenerators boast practicality, flexibility, and optimization, showing significant differences in terms of performance compared to non-hybrid nanogenerators. They are practical in terms of appearance and property, as they are convenient and lightweight to carry around. Hybrid generators are also flexible in terms of each nanogenerator’s compatibility to work with one another. Most importantly, hybrid nanogenerators take advantage of each nanogenerator's ability to produce energy and power using mechanical motion, stress, and forces. Thus, combining two or more nanogenerators ensures higher energy output production while at the same time optimizing the time and effort taken to generate energy (Wang et al., 2016).

In a study conducted by Wang & Yang (2017), the use of electromagnetic and triboelectric nanogenerators in creating a hybrid nanogenerator was observed. The study assesses the effectiveness of the hybridized electromagnetic-triboelectric nanogenerator in storing energy from wind. Both the TENG and EMG were able to produce a power output of 1.7 mW under a loading resistance of 10 MΩ (megaohms) and 2.5 mW under a loading resistance of 10 kΩ (kiloohms), respectively. In another study by Zhang, et al. (2015), a hybridized electromagnetic-triboelectric nanogenerator was also utilized in harnessing biomechanical energy from walking to power-up wearable electronics. The TENG was able to produce an output power of 4.9 mW under a loading resistance of 6 MΩ, whereas the EMG was able to produce an output power of 3.5 mW under a loading resistance of 2 kΩ. Further showcasing the application of a hybridized electromagnetic-triboelectric nanogenerator is a study by Liu et al. (2018). The hybridized nanogenerator, after 100 vibration cycles, was able to charge a 1,000 μF (microfarad) capacitor to 5.09 V. It was successfully tested to power up a Global Positioning System (GPS) device, charging a lithium-ion battery and a cell phone.

Utilizing both piezoelectric and triboelectric nanogenerators, He et al. (2018), created a hybridized nanogenerator from ZnO nanoflakes (NFs)/polydimethylsiloxane (PDMS) composite films. The hybridized piezoelectric-triboelectric nanogenerator (P-TENG) was able to produce an output voltage of ~470 V, a current density of ~60 μA/cm², and an average power density of ~28.2 μA/cm². Additionally, in a study conducted by Li, et al. (2019), the proponents developed a hybrid P-TENG by using nitrocellulose nanofibril paper and Barium titanate (BaTiO3) bacterial cellulose paper. The hybrid nanogenerator was able to light up three LED bulbs and charge a 1 μF capacitor to 2.5 V within 80 seconds. It was able to produce an output of 18 V and 1.6 μA/cm². Furthermore, in a study conducted by Shen, et al. (2023), which also utilized hybridized P-TENG that gathered energy through the charge pumping method was able to produce power with an average of 2.1 mW, and its maximum reached 5.9 mW at a low drive frequency of 2.5 Hz.

The development of individual nanogenerators has advanced, but in order to fulfill the needs of commercial electronic systems and expand their application range, more output energy generation is required. To harvest low-frequency ambient mechanical energy more efficiently, Khan et al. (2022) fabricated a hybridized nanogenerator utilizing triboelectric, piezoelectric, and electromagnetic nanogenerators. The hybrid nanogenerator was capable of charging the output voltage of a 22 μF capacitor to 2.7 V within only 12 seconds. Additionally, the hybrid nanogenerator can produce an electrical power of 49 mW at a low-frequency vibration of 5Hz. Recently, a study by Tian, et al. (2023) that also utilized a hybrid nanogenerator consisting of TENG, PENG, and EMG to harvest wind energy was conducted. The hybridized nanogenerator was able to produce a power density of 62.79 mW (m3 rpm)−1 at a 3 m s−1 wind speed. The hybridized nanogenerator was able to successfully and continuously light a 5 W lightbulb and supply energy for self-powered sensing.

Application of Nanogenerators

A self-powered system is one that can function sustainably for sensing, detecting, processing, and transmitting data without the need for an external power source. In order to convert minuscule mechanical energy into electricity for self-powered systems based on the piezoelectric and triboelectrification effects, nanogenerators (NGs) were initially invented. These systems have applications in the internet of things, environmental and infrastructure monitoring, medical science, and security (Wang, 2017). Numerous studies have shown that nanogenerators can function as autonomous active sensors and renewable power sources. Research on NGs over the past 15 years has shown that it can aid in the digitalization of services provided by smart cities, such as locally sourced renewable energy sources, digital healthcare applications, intelligent transportation, and intelligent vehicles (Zhao et al., 2021).

Over the past decade, advancements in NGs have made it possible for many systems to function without an external power source. NG is capable of harvesting mechanical energies in several kinds. Moreover, NG can be powered by human body motions and activities, enabling self-powered healthcare systems (Feng et al., 2018). Conventional biomedical technologies have limitations like large equipment size, short service life, and safety risks. The emergence and development of nanotechnology and nanogenerators offer a solution by extracting thermal and mechanical energy from people and transforming it into electrical energy, creating self-powered biomedical devices (Wang et al., 2021). In the future, NG has the potential to be a very promising additional or perhaps primary power source for medical equipment, replacing conventional batteries (Feng et al., 2018).

The nanogenerator converts electrical signals for physiological and pathological indicator detection, cardiac pacing, nerve stimulation, tissue repair, and weight control. It also harvests biomechanical energy from physiological activities like muscle contraction, heartbeat, breathing, and gastric peristalsis (Sun et al., 2021). In a study by Sun et al. (2019), piezoelectric and triboelectric nanogenerators were utilized as implantable electronic medical devices (IEMDs). The nanogenerators were used as biomedical sensors, cardiac sensors, respiration sensors, blood pressure sensors, gastrointestinal sensors and bladder sensors. In another study conducted by Yu et al. (2022), the usage of textile-based NGs showed usefulness as monitoring devices for post-rehabilitation, and were also applied in the diagnosis and treatment of orthopedic diseases. Another application of NGs in healthcare is shown in a study conducted by Li et al. (2021) that specializes in assessing the sleep quality of the users. The smart wearable sensors (SWS) used in the study can be worn on the wrist, ankles, shoes, or clothes. The SWS analyzes motion signals, monitors motion states, and has a fall-down alarm and sleep quality assessment systems to monitor patients' health and notify healthcare providers.

The term "smart agriculture" refers to the comprehensive, cross-border integration of contemporary information technologies with agriculture, including the Internet of Things (IoTs), intelligent machinery, and massive data. Among these technologies, the many dispersed sensors are essential for precision planting control (Wang et al., 2022). Modern agriculture is standardized, intensive, and smart because of the rapid developments in sensor, energy, and communication technologies. However, the widespread use of intelligent technologies in agriculture is limited by the energy supply issue for the numerous sensors or other microdevices (Dai et al., 2022).

With the widespread use of sensor networks, smart agriculture is quickly emerging as a trend. In a study by Li et al. (2022), a breeze-driven, triboelectric nanogenerator was proposed to harness the breeze energy in farmlands. The prototype was able to produce 330V, 7 μA, and 137 nC (nanocoulomb), at a wind speed of 4 m/s. A hybridized prototype for a wind and solar energy harvester was also created in a study by Wang et al. (2022). The hybridized prototype was composed of electromagnetic and triboelectric nanogenerators and solar cells. Aside from harvesting wind and solar energy, it is also capable of monitoring temperature and humidity, and has a security alarm system for passive remote infrared monitoring. Aside from energy harvesting and sensors, the application of NGs in agriculture is varied, as shown in the study conducted by Jian et al. (2022). The study was able to construct a growth-promoting system that generates space electric fields from a plant-protein-enabled biodegradable TENG by integrating a polylactic acid film.

The building industry is benefiting the rewards of notable progress in sustainable collecting technologies. Building materials' functions are evolving to take into account environmental benefits in addition to their basic functional needs. One of the most promising materials for indoor energy generation is flooring, particularly in public buildings with high occupancy and intensity patterns. In a metro station in Egypt, piezoelectric tiles were installed to generate energy for the train station. The results from the study indicated that, whereas Waynergy piezoelectric tiles required only eight tiles to provide the station's required amount of electric energy, sustainable energy floor tiles required twelve tiles. Significantly, the findings also indicated a drop in carbon emissions and energy use (Moussa et al., 2022). A similar study was conducted by Ma et al. (2017), wherein the study focused on creating a smart flooring, using a triboelectric nanogenerator and applied it to security surveillance, patient monitoring, indoor positioning, asset tracking, and entertainment.

Modern vehicles require sophisticated sensors for operation, safety, perception, monitoring, and control due to industry changes. As a result of recent technological developments, cars are increasingly becoming mobile computers. In a car, there are over a hundred sensors, and many of them might be replaced by self-powered sensors based on nanogenerators (Askari et al., 2019). Nanogenerators are sensitive sensors that collect vibration, rotation, and wind energy to power devices, providing efficient, portable power sources for self-powered monitoring in vehicles (Jin et al., 2019). The majority of previous research has shown that road conditions are a contributing factor in traffic accidents. For instance, severe weather, such as strong winds or rain can make driving hazardous, while high temperatures can make driving uncomfortable (Rayegani et al., 2023). Aside from sensing the environmental conditions outside, NGs can also be applied to increase the safety of cars and pedestrians, identify driver weariness, evaluate traffic, and prolong the life of roadways (Nazar et al., 2022).

Prototypes Supporting Sustainable Energy Approach Worldwide

Following the growth of nanogenerators in the technical field, the birth of nanogenerator prototype materials also took place. From generator backpack prototypes to functional power generating mats made with hybrid nanogenerators, this scientific and technological breakthrough has opened a whole new realm of possibilities (Radhakrishnan et al., 2022). The first nanogenerator was made and developed in 2006 by Wang and his team. They utilized ZnO nanowires, with a power conversion efficacy of 17-30%, based on the piezoelectric effect or the ability to generate an electric charge as a response to applied mechanical stress (Indira et al., 2019).

In 2021, researchers from China developed an energy-harvesting vibrational turbine using piezoelectric nanogenerators. This vibrational turbine prototype uses magnetic coupling to trigger a magnetic interaction that results in the continuous rotation of the turbine. Silicon rubber strips are embedded with piezoelectric films that are deflected by the tip-driven magnets in the strip-anchor system. This magnetic interaction also causes the vibrational turbine PENG (VT-PENG) to generate electricity as the materials undergo vibration and system instability (Egbe et al., 2021). Nanotechnology integration and innovation is not only limited to harnessing the energy from nature, there are also several studies harnessing the power from manual labor. In 2021, researchers based in Australia designed a simulation guided hand-driven portable generator. This model generated electricity through the use of manual actions, where the whirligig model produced energy by the help of a human hand turning the prototype in a rotational motion. Though not automatic, this model is an ingenious example of how we can harness energy from humans (Wang et al., 2021).

In 2017, He et. al, harnessed the power produced by human motion, walking. They developed a smart floor that integrates triboelectric nanogenerators as energy harvesters. Through this study, they found out that normal human footsteps on the smart floor can produce a voltage of 238±17 V and a current of 2.4 ± 0.3 μA. Furthermore, the smart floor model was built without compromising the stability and flexibility of the wood floor.

Body Weight and Movement as Contributors to Pressure Induced Activity in Nanotechnology

In recent times, nanotechnology has been utilizing the use of pressure-sensing applications to leverage the use of mechanical energy through principles like the Piezoelectric effect (Chang, et al., 2019). The fabrication of nanoscale pressure sensors through these principles have created multifunctional innovations, ranging from wearable devices to everyday electronics. Due to its dynamic range in terms of movement, the progress of pressure-induced nanogenerators have reached various fields of applications such as in medicine, engineering, and research (Hu, et al., 2023). Furthermore, the application of pressure in nanotechnology is based on optimized conditions that take advantage of affordability, versatility, and sustainability.

The weight of an individual is one of the most significant factors influencing the surface pressure exerted when sitting. Surface pressure refers to the force exerted by a body against a surface area, typically measured in pressure units (e.g., Pascals or mmHg). Studies have shown that individuals with greater body mass tend to exert higher pressure on the surface they are sitting on. This is due to the increased force (weight) being distributed over a smaller contact area, especially if the seating surface is not designed to accommodate such pressure (Hu, et al., 2019). Furthermore, how weight is distributed across the body while sitting can impact pressure levels. Body alignment (e.g., how the spine and pelvis are positioned) affects how weight is distributed across the sitting surface. A neutral pelvic position, where the hips are aligned with the spine, generally results in better pressure distribution, whereas slouching or tilting forward increases pressure in specific regions, leading to discomfort (Mehicic, et al.,2024).

Movement is another important factor that influences the surface pressure distribution during sitting. When a person shifts their position, moves their legs, or adjusts their posture, the distribution of pressure on the seating surface changes. Moreover, movement is the key driver behind the science of nanogenerator, as these materials thrive with the help of mechanical motions (Technology Networks, 2024). The integration of nanotechnology with pressure-sensing applications has opened up innovative possibilities for harnessing mechanical energy, particularly through the use of nanogenerators.

In related studies in the previous headings, there is evidence that the impact of body weight, posture, and movement on surface pressure, as well as the ability to optimize these factors is essential for both improving comfort and enhancing the efficiency of wearable devices powered by pressure-induced nanogenerators. The continuous advancements in the field promise to address issues related to ergonomics and comfort and to contribute to more sustainable and efficient solutions across diverse sectors, including healthcare, engineering, and electronics. A deep understanding of these dynamics can be proven crucial as nanotechnology continues to evolve, offering new opportunities for practical applications in everyday life.

Energy Generation Sufficiency

Piezoelectric energy harvesters have low power outputs therefore, it is necessary to increase their power density. Out of the PENGs reviewed in a research conducted by Bhadwal et al., (2023), the highest power output was 45.87μW/cm² (microwatt per centimeter squared) from a vertically aligned Zinc Oxide (ZnO) nanowire PENG under finger tapping. The piezoelectric properties of lead-free piezoelectric materials in large volumes are substantially lower compared to lead-containing piezoelectric materials. However, on the nanoscale, the piezoelectric properties of lead-free piezoelectric materials can be significantly greater than in large volumes. The use of nanowires in harvesting energy can be advantageous because such minute physical motions can trigger the nanowires and can produce frequencies ranging from 1Hz (hertz) to 1000Hz. The voltage from a single nanowire can reach 50mV (millivolt), which is sufficient to power numerous nano-scale devices (Chacko et al., 2017).

In order to address the shortcomings of either the PENG and TENG in terms of energy production, Zhao et al. (2019), conducted research to create a prototype of a hybridized nanogenerator consisting of both the PENG and TENG (H-P/TENG). The prototype produced an output voltage of 210V, an output current of 395 μA, and 10.88 mW/6.04mWcm-2 power density at a rotation speed of 100 rpm (revolutions per minute). The prototype could retain a 210V output voltage and 400 μA output current under rotation speeds of 50-250 rpm. In a research conducted by Chen et al. (2019), the researchers created a prototype of a rotating disk-based hybridized electromagnetic-triboelectric nanogenerator that can simultaneously gather rotational energy and transmit the energy wirelessly using coils. At a rotating rate of 900rpm, the hybrid electromagnetic-triboelectric nanogenerator can produce an estimated output of 137.39mW. The hybridized nanogenerator's output current is increased to 130 mA for wireless transmission, enabling real-time power transmission up to approximately 60 cm distance using helical coils.

According to Wootton (2016), average Filipino households use 211 kWh of electricity per month. If we break it down to daily consumption, that would result in 7 kWh of electricity consumed per day. Meanwhile in 2024, the Manila Electric Company (MERALCO) released an update stating that the rate for every kWh consumed is Php 11.9, a little higher from last time's Php11.3 kWh (Manila Electric Company, 2024).

Multiple studies on energy accessibility, functionality, and performance are presented with relevant and significant ideas in relation to the researchers' goal for clean and renewable energy. Studies found in documents pertaining to NGs (Nanogenerators) represent the usage of TENGs (Triboelectric Nanogenerators) and PENGs (Piezoelectric Nanogenerators) as hybrid nanogenerators for sufficient and effective use. Moreover, the studies presented above discussed factors that bridge the gap between the relevance of efficient energy sources and the consumers' insights within the field. This can be seen in studies such as by Ong et al. (2023), which determined the consumers' satisfaction with their own electricity power providers. The studies were in line with the direction of identifying similar prototypes which provided base models for innovation and enhancement.

Challenges in Maximizing the Use of Nanotechnology

The rapid development of nanomaterials presents opportunities for high-performance applications and product innovation, but concerns arise about potential environmental impacts (Hutchison, 2016). Some nanomaterials, such as triboelectric nanogenerators, might have a significant impact on the environment and can be difficult to break down and decompose. Greener materials that are more biodegradable and ecologically friendly are prioritized in order to increase sustainability (Guo et al., 2017; Macario et al., 2022). Triboelectric nanogenerators hold promise for wearables and IoT devices, but creating reliable, efficient, industrially feasible, and environmentally friendly equipment remains a major challenge in the generator industry. The widespread adoption of triboelectric nanogenerators faces significant challenges due to output characteristics and power management issues, primarily due to high open-circuit voltages and low output currents. Additionally, integrating TENGs into wearable and flexible devices presents challenges due to long-term operation and mechanical stress, and incorporating rigid nanogenerators in textiles and apparel may be challenging (Macario et al., 2022).

The use of nanostructured piezoelectrics is a relatively new field, and knowledge of the effects of nanoscale size on ferro- and piezoelectricity is still developing (Briscoe & Dunn, 2015). At present, ZnO (zinc oxide), PZT (lead zirconate titanate), BaTiO3 (barium titanate), and PVDF (polyvinylidene fluoride) are the primary piezoelectric materials employed in the research and development of piezoelectric nanogenerators (Hu et al., 2019). Piezoelectric nanomaterials, particularly lead-free materials, have been crucial for two decades in research and applications. Their unique nanometer properties set them apart from bulk materials and polycrystalline films, leading to successful applications. Despite progress, several issues remain to be addressed, including clarifying nanoscale piezoelectric mechanism physics, developing new fabrication methods, developing a characterization tool, understanding degradation and failure of lead-free nanomaterials, and designing innovative devices based on optimal input parameters (Zhang et al., 2020).

To summarize, nanogenerators are a technological breakthrough that can lead to sustainable energy production. Nanogenerators are self-powered systems that harness ambient mechanical energy from human interaction with the environment. These nanogenerators are used for various applications in different fields, including medicine, healthcare, agriculture, construction, and transportation. By combining the different kinds of nanogenerators, a hybrid nanogenerator can be made which efficiently harvests low-frequency ambient energy. With that, researchers have created prototypes of hybridized nanogenerators using manual actions, nature elements, and human motions to harness energy from renewable sources, promoting a sustainable future where mankind can harness energy from various renewable sources.

Theoretical Framework

This study employs the Net Energy Analysis (NEA) framework. NEA is a method developed to identify and quantify all energy inputs to energy supply and conversion systems, including the indirect energy that is embedded within the energy conversion process. Energy analyses have been utilized to assess the overall energy efficiencies of various systems (Rotty et al., 1975; Bullard, et al., 1978). This method helps to determine whether a system produces net energy and allows comparison of its overall energy efficiency with other energy sources, whether renewable or non-renewable (Sinclair, 1978). NEA is applied to determine the amount of "net" energy that may be provided by a particular energy source after deducting all energy inputs needed to maintain the supply chain for that energy source (Carbajales-Dale et al., 2014; Raugei, 2019).

This study, entitled “PAHINGA: Powering Ahead with Hybridized Integrated Nanogenerator Arrays,” will utilize the NEA to assess the sustainability of the proposed prototype. The NEA framework will contribute to assessing the impact of the energy input of the proposed prototype on the environment and will also be applied due to its ability to compare the energy output of the proposed prototype against other energy sources, such as fossil fuels and other renewable sources.

Conceptual Framework

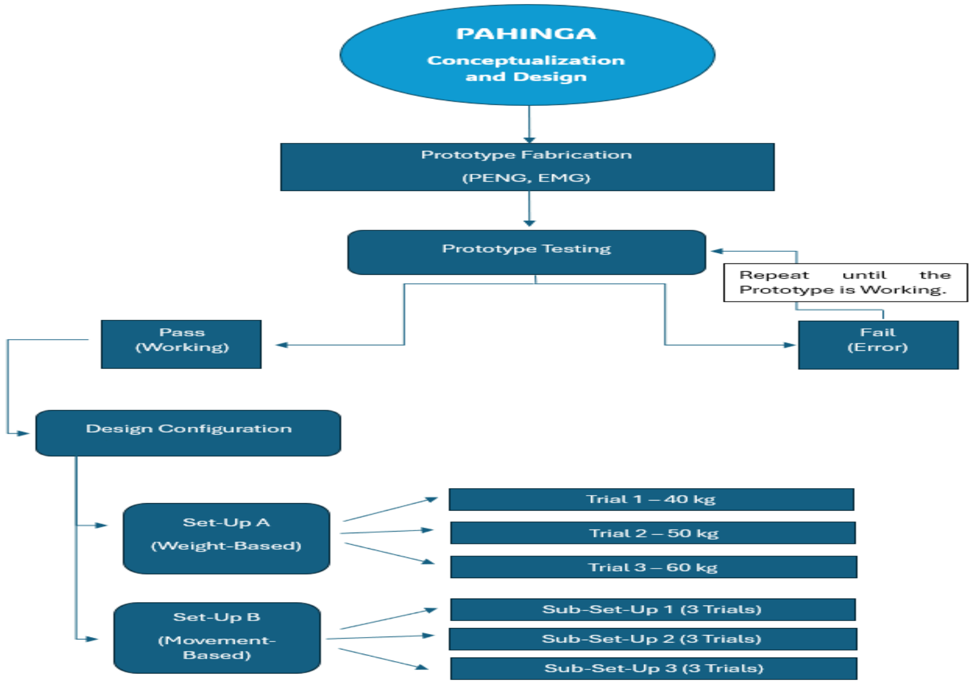


Figure 1: Conceptual Framework

This study is an experimental, descriptive-comparative study that utilized the creation and development of a prototype; therefore, the researchers focused on an original conceptualization and design which is aligned on the pursuit to create the final prototype. Based on a flow chart, this framework highlights trials, errors, and recuperations in the process of concluding the said prototype.

The creation of the prototype involves three phases namely: prototype fabrication, prototype testing, and design configuration. The prototype fabrication is the creation of the prototype as a whole, this involves the prototype testing and design configuration. The prototype testing was done with two set-ups. The first set-up is the weight-based set-up wherein user with different weights tested the prototype. For the second set-up, changes in movement were the basis for each sub-set-up with three trials each. Movements such as swaying sideways while sitting, and repeated sit-to-stand motions was recorded.

Significance of the Study

The study aims to create a device that can contribute to the production of sustainable energy and help lessen the pollution caused by non-renewable ways of energy production, this will serve as a practical solution to reduce reliance on traditional energy sources, thus mitigating environmental degradation and pollution. The research also aims to explore the importance of nanogenerators in utilizing and harnessing waste energy into sustainable energy to serve as a basis for other prototypes and contribute to the growing archive of information regarding nanogenerators.

Moreover, this research can be utilized by the public and the government as the acceptance of the alternative hypothesis can lead to the use of the prototype in both public and private establishments such as classrooms and offices to lessen reliance on commercial electricity providers. Lastly, by contributing to the body of knowledge on nanogenerators and sustainable energy technologies, this research may inspire future researchers to develop even more advanced and efficient energy solutions leading to further innovation and exploration in the field.

Scope and Limitation

This study primarily focused on developing a power-generating device using the two different types of nanogenerators, namely piezoelectric (PENG), and electromagnetic

(EMG). This study also focused on the weight and movement of the user and how it affected the energy output produced.

On the other hand, this study is limited in terms of the nanogenerators used, because it does not utilize any other type of nanogenerator except PENG, and EMG. Moreover, the user of the prototype during the second set-up of this study remained constant with a weight of 60 kg, following the average weight of Filipinos. Lastly, the composition of the prototype took into consideration the principle of weight distribution when a person is seated.

Definition of Terms

This section presents the terminology that was used in the study. The following terms are further defined conceptually and operationally by the researchers to provide comprehensible information, guiding the readers through the complexities of the study**.**

Electromagnetic nanogenerator - refers to the nanogenerator component that uses magnets and copper coils to produce electromagnetism

Energy Output- refers to the capacity of the hybridized nanogenerator in producing energy measured in terms of current and voltage

Hybridized Nanogenerator- refers to the prototype that is composed of three types of nanogenerators: piezoelectric, triboelectric, and electromagnetic.

Microampere (µA) – refers to a unit of current equal to one millionth of an ampere

Movement-based - refers to set-up B, wherein the movement of the user will be controlled and changed accordingly in the trials.

Multimeter Testing - refers to the method of testing where voltage, current and resistance is measured using a multimeter device.

Nanogenerator - refers to an energy harvesting device that generates electricity from ambient mechanical energy.

Piezoelectric Nanogenerator - refers to a nanogenerator that uses the concept of piezoelectricity to harvest ambient mechanical energy into electrical energy.

Prototype Performance - refers to the prototype's ability to generate electricity and energy output produced.

Repeated sit-to-stand motion - refers to a repetitive series of sitting and standing on the same point with constant application of pressure.

Still - refers to a sitting position where there is an absence of movement

Sufficient Energy Output - refers to the nanogenerators' overall capacity in both current and voltage to power small electronic devices such as power banks and cellphones.

Sustainable Energy - refers to the energy produced by the nanogenerator composed of both EMG and PENG that produces energy without the excessive pollution from the smoke or heat produced unlike that of unrenewable energy such as coal and fossil fuel.

Swaying sideways - refers to the constant shifting of one's weight fromleft to right while in sitting position.

Weight-based - refers to set-up A, where every trial corresponds to a particular user with a particular weight.

Chapter 2

METHODOLOGY

This chapter contains the research design and procedures used by the researchers in conducting the study. It discusses the locale of the study, research instruments and statistical treatment of the study.

Research Design

This study is quantitative in nature and employs a descriptive-comparative and experimental type of research. Quantitative research produces numerical data using information gathered about individuals or processes. The objective of quantitative research is to address concerns related to intervention, prognosis, causation, association, description, or assessment, depending on the underlying intent. In 2019, McCombes defined descriptive research as observing and measuring results without manipulating the variables. On the other hand, comparative research studies similarities and differences between two or more variables (Iranifard & Roudsari, 2022).

This study falls under the experimental category as it involves the creation of the prototype as well as the manipulation of variables to see which trial shows optimum results. In true experimental research, an intervention is made in the variables through the use of both control groups and randomization (Kotronoulas & Papadopoulou, 2023). On the other hand, this study also falls under the descriptive type research category as this study describes the characteristics of the dataset and its results. Lastly, this study falls in the category of comparative research as it compares the results to see which trial and set-up has the best energy output production.

Research Locale

This study was conducted in one of the private Catholic Schools in Davao City, Philippines administered by the Presentation of Mary Sisters. The school achieved a Level II accreditation from the Philippine Accrediting Association of Schools, Colleges, and Universities (PAASCU). On that note, the school aims to forge strong individuals with admirable characteristics, who are both intellectually capable and skillful.

Figure 2: Research Locale

Research Instrument

The researchers utilized a hybrid nanogenerator prototype in conducting the study. The prototype was tested under two different set-ups which was used to quantify if there is a significant difference among their power-generating output and performance. Set-up A (weight-based) involved having 3 different users with varying weights of 40 kg, 50 kg, and 60 kg in trials 1, 2, and 3 respectively. Meanwhile Set-up B (movement-based) involved manipulating a single user’s movement, the weight of this user is 60 kg which according to Garcia (2020), is the average weight of a Filipino adult.

Figure 3.1 Top of hybridized nanogenerator prototype illustration

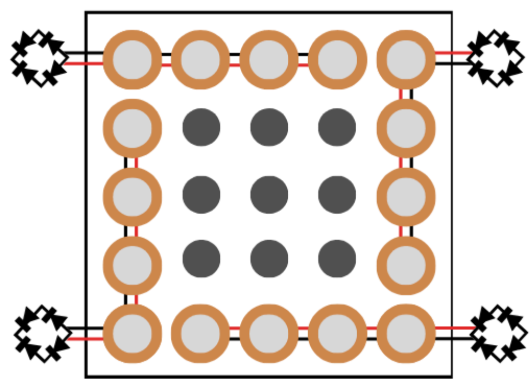


Figure 3.2. Base circuitry of the hybridized nanogenerator prototype illustration

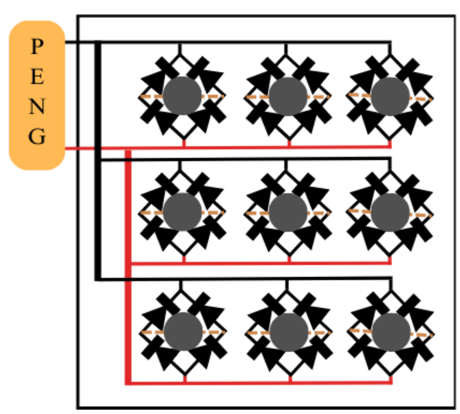
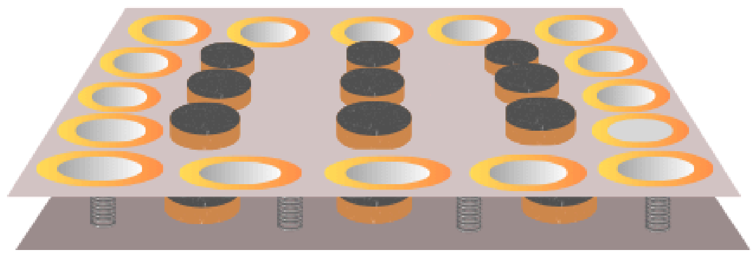


Figure 3.3. Hybridized nanogenerator prototype illustration



Data Gathering Procedure

To abide by the ethical principles in the conduct of the research, certain measures were implemented. Prior to the gathering of data, the proponents sought the approval of the Basic Education Principal and the School President to conduct the said study inside the school premises. Once approval was secured, the proponents then began with the developmental process. The developmental phase consisted of assembling the prototype and fixing any errors that occurred prior to the testing process.

The process began with the fabrication of the prototype, and afterwards led to testing. Through testing it for power generating abilities, its ability or inability to produce energy can be determined; The result of that process determined the next step for development. If the result is in favor of failure, then the testing process was repeated, along with developmental procedures. If the result is in favor of succession, then it led to the next phase of development. The design configuration process determined the most suitable and practical design for the prototype.

The following phases was divided into two set-ups, namely Set-up A and Set-up B, all trials of both set-ups underwent multimeter testing using a multimeter device. Set-up A was a series of trials where the user sitting on the prototype varied depending on their weight. For the first trial, the user weighed 40 kilograms (kg), for second, 50 kg, and for the last trial, the user weighed 60 kg; No unnecessary movements were employed. Whereas Set-up B focused on changing the movement of the user throughout the three sub-set with three trials each. For the first sub-set, the user sat still, for the second, the user moved by swaying sideways rhythmically, and for the last sub-set-up, the user repeatedly performed sit-to-stand motions. The results of this testing process were used to draw a conclusion.

Ethical Considerations

Ethics is one of the most principal aspects that researchers must abide with. According to Resnik (2020), the following should be included in order to maintain the ethical considerations throughout the conduct of a study: planning a research study, safeguarding collection of information, and lastly, following the guidelines and avoiding plagiarism. These will enable researchers to promote an effective objective of the research study.

That being said, the proponents of this research were very keen in following the ethical considerations in conducting the research to ensure validity and authenticity of the data gathered. Moreover, the proponents wi seek permission from other researchers whose original concept and design will be adopted and adapted.

Data Analysis

For the 1st research question, a bar graph was utilized as the statistical tool to display the difference between the energy output produced by the nanogenerator prototype. In 2014, Slutsky defined bar graphs as statistical tool that can present data in either horizontal or vertical orientation. The length of the bars corresponds to the magnitude of the value, with longer bars indicating higher values. In this study, bar graphs are used to display the energy output result of every trial from Set-Up A to see if there is a notable change when the weight of the user varies.

For the 2nd research question, mean was utilized as the statistical tool to know the average energy output of the prototype nanogenerators based on voltage and current. Mean summarizes a dataset with a single number representing the center point or the arithmetic average and is also one of the measures of central tendency (Frost, 2024). This statistical tool was used to know what the central value of the prototypes' energy output in Set-Up B. Moreover, mean was utilized to find the average Watts (J/s) for Set-Up A and every Sub-sets of Set-up B in order to have numerical data relevant in the next research question.

Lastly, One Sample T-Test was utilized as the statistical tool for the 3rd research question. Hayes (2023), defined T-Tests as a statistical tool used to determine if there is a significant difference between the mean of two groups and is also used to see if there is a relationship. In this study, it was used to know if the result gathered is comparable to the standard criteria in electricity production.

Table 1: Electricity Standard Criteria

Criteria	**Description**	**Measurement Tool / Method**	**Expected Outcome**	**Significance Level (P-Value)**
Energy Output	Measure total energy generated (V)	Multimeter	≥ **15 Watts (**Baseline, running watts of an LED Light Bulb**)** **For 24-hour usage:** 15 watts x 24 hours = 360 watts/hours or 0.36 kWh **When broken down from kWh to J/s:** (1000W/1kW)*(0.36kW/1h)*(1 h/60m)*(1m/60) = **0.1 J/s**	0.05

According to a wattage chart information by Claes (2023), small devices like an LED light bulb, internet router, phone charger, ceiling fan, and others, have a total wattage requirement range of 15 to 100 watts. The kWh consumption of these devices solely depends on the hours of use. According to Ullah (2024), a Watt-hour is a small unit of energy equivalent to one watt of power used for one hour. Meanwhile, Watts represent the amount of work done per second and are defined as the power needed to transfer or convert 1 joule of energy each second.

Chapter 3

RESULTS AND DISCUSSION

This chapter contains the results and discussion of the data obtained from the experimentation process. The researchers developed a working prototype containing 16 pieces of piezoelectric nanogenerators (PENG) and 9 pieces of electromagnetic nanogenerators (EMG). The experiment consisted of two set-ups, namely; Set-up A, Weight-Based and Set-up B, Movement-Based.

Statement of the Problem #1: Is there a significant change in the energy output produced

by the nanogenerator prototype throughout the trials under Set-Up A?

Figure 4.1: Set-up A – Current (µA)

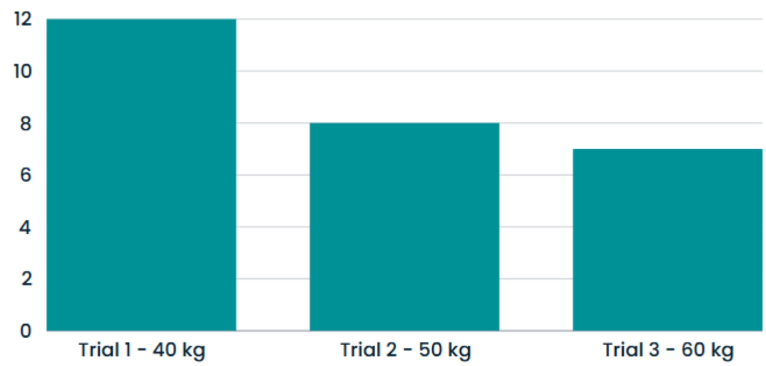


Figure 4.1 displays the current produced by the nanogenerator prototype throughout the trials under the first set-up which was weight-based. Trial 1, whose user weighed 40 kilograms showed the highest energy output produced with a result of 12 microamperes (µA). In trial 2, 8 microamperes (µA) were produced by the user who weighed 50 kg. Lastly in trial 3, the lowest energy output in terms of current was recorded in 7 microamperes (µA) by the user who weighed 60 kilograms. Based on the data shown, it is observable that the weight of the user is inversely proportional to the current produced.

Figure 4.2: Set-up A – Voltage (V)

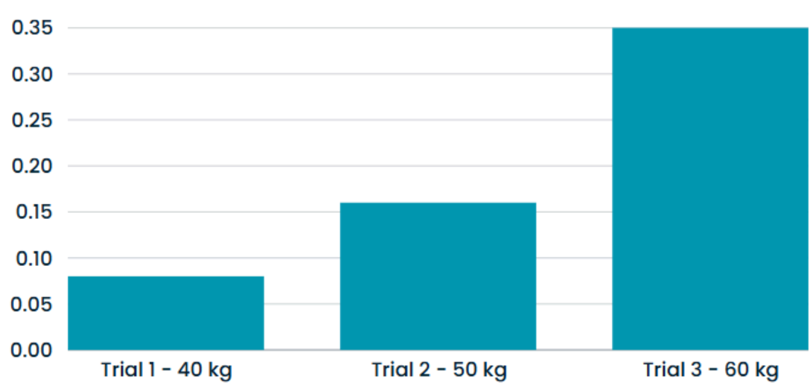


Figure 4.2 displays the voltage produced by the nanogenerator prototype throughout the trials under the first set-up. Trial 3, whose user weighed 60 kilograms showed the highest energy output produced in terms of voltage with a result of 0.35 V. This was followed by trial 2 at 0.16 V, produced by the user who weighed 50 kg. In trial 1, the lowest energy output in terms of voltage was recorded at 0.08 V by the user who weighed 40 kilograms. Based on the data shown, it can be inferred that the weight of the user is directly proportional to the voltage produced.

Figure 4.3: Set-up A – Watt (J/s)

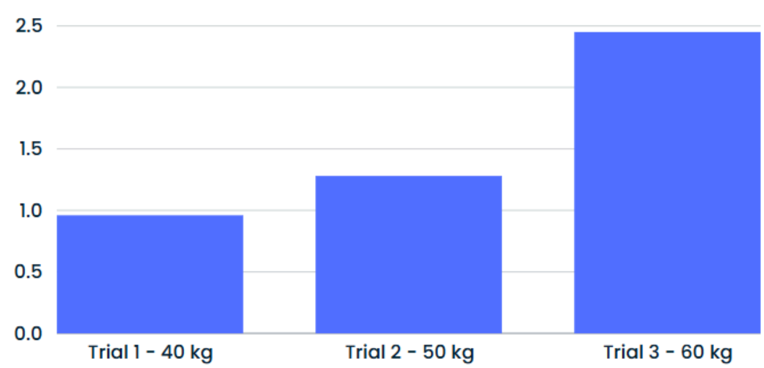


Figure 4.3 is a visual representation of the joules per second (Watt) produced by the nanogenerator prototype throughout the trials under the first set-up. Trial 3, whose user weighed 60 kilograms showed the highest output in Watts with a result of 2.45 W, followed by trial 2 at 1.28 W, produced by the user who weighed 50 kg. Lastly, trial 1 showed the lowest output in terms of Watts at 0.96 W by the user who weighed 40 kilograms. Based on the data shown, it can be inferred that the weight of the user is directly proportional to the Wattage produced.

These results, specifically the result in the voltage and wattage output produced strengthens the attribution of weight as a crucial variable that affects energy production.

This can be attributed to the study of Hu et al. in 2019, where it was inferred that individuals with greater body mass tend to exert higher pressure on the surface they are sitting on. And as Vidal et al. has stated in their research in 2021, Piezoelectric Nanogenerators (PENGs) which is the major component of this hybrid nanogenerator, uses piezoelectric materials that generate electric charge when experiencing mechanical stress or pressure.

Statement of the Problem #2: What is the average energy output of the hybridized nanogenerator in Set-Up B (Movement-based), based on the following outputs:

2.1 current; and

2.2 voltage?

Energy Output	**Sub-Set-Up**	**Trials**			**Mean**
Current	**1 (Still)**	7 µA	25 µA	31 µA	**21 µA**
	2 (Swaying Sideways)	2 µA	1 µA	9 µA	**4 µA**
	3 (Repeated Sit-to-stand Motion)	14 µA	14 µA	25 µA	**17.67 µA**
Voltage	**1 (Still)**	0.18 V	0.16 V	0.27 V	**0. 20 V**
	2 (Swaying Sideways)	0.34 V	0.45 V	0.33 V	**0.37 V**
	3 (Repeated Sit-to-stand Motion)	0.40 V	0.40 V	0.47 V	**0.42 V**

Table 2.1: Average Energy Output of the Hybridized Nanogenerator in Set-Up B Based on Current and Voltage.

Table 2.1 exhibits the average and the result of every trial from all three sub-sets of Set-Up B. Firstly, Sub-set-up 1, where the user sat still, produced a current output of 7 μA, 25 μA, and 31 μA for trials 1, 2, and 3 respectively with a mean output of 21 μA. Secondly, in Sub-set-up 2, where the user swayed sideways, an output of 2 μA, 1 μA, and 9 μA for trials 1, 2, and 3 respectively was recorded, with a mean output of 4 μA. Lastly, in Sub-set-up 3, where the user repeatedly performed sit-to-stand motions, an output of 14 μA, 14 μA, and 25 μA for trials 1, 2, and 3 respectively was recorded, with a mean output of 17.67 μA.

As for voltage, the sub-set with the highest average output is also Sub-set-up 3, with an individual result for trial 1, 2, and 3 of 0.40 V, 0.40V, and 0.75V respectively. This is followed by Sub-set-up 2 with a lesser mean of 0.37V and an individual result for trial 1, 2, and 3 of 0.34 V, 0.45V, and 0.33V respectively. The set-up with the least recorded mean of energy output in voltage in Sub-set-up 1 with a mean of 0.20V and an individual result for trial 1, 2, and 3 of 0.18 V, 0.16V, and 0.27V respectively.

Energy Output	**Sub-Set-Up**	**Trials**			**Mean**
Watts (J/s)	**1 (Still)**	1.26 W	4W	8.27W	**4.51 W (J/s)**
	2 (Swaying Sideways)	1.02W	0.45W	2.97W	**1.48W (J/s)**
	3 (Repeated Sit-to-stand Motion)	5.6W	5.6W	11.75W	**7.65 W (J/s)**

Table 2.2: Average Energy Output of the Hybridized Nanogenerator in Set-Up B in Watts (J/s).

Table 2.2 exhibits the average and the result of every trial from all three sub-sets of Set-Up B. Firstly, Sub-set-up 1, where the user sat still, produced a wattage output of 1.26W, 4W, and 8.27W for trials 1, 2, and 3 respectively with a mean output of 4.51W. Secondly, in Sub-set-up 2, where the user swayed sideways, an output of 1.02W, 0.45W, and 2.97W for trials 1, 2, and 3 respectively was recorded, with a mean output of 1.48W. Lastly, in Sub-set-up 3, where the user repeatedly performed sit-to-stand motions, an output of 5.6W, 5.6W, and 11.75W for trials 1, 2, and 3 respectively was recorded, with a mean output of 7.65W.

These results propose that constant and repetitive motions produce optimal result under the attribution of movement as a crucial variable that affects energy production. This can be attributed to the presence of electromagnetic nanogenerators that operates on the principle of electromagnetic induction, where a micro coil and a micromagnet engage in a relative motion due to external mechanical motions that leads to an electric charge as stated by Vidal et al. in their research in 2021.

Statement of the Problem #3: Is there a significant difference between of the average energy output (in watts) of Set-Up A and the sub-sets of Set-Up B compared to the standard criteria?

	A	B1	B2	B3
	0.96	1.26	1.02	5.6
	1.28	4	0.45	5.6
	2.45	8.27	2.97	11.75
Mean	1.563333	4.51	1.48	7.65
Standard Deviation (s)	0.784368	3.532718	1.321476	3.550704
Count (n)	3	3	3	3
Standard Error of Mean (SEM)	0.452855	2.039616	0.762955	2.05
Degrees of Freedom (df)	2	2	2	2
Hypothesized Mean	0.1	0.1	0.1	0.1
t-statistic	3.23135	2.162172	1.808757	3.682927
p-value (one-tailed)	**0.041947**	**0.081558**	**0.106106**	**0.03323**
p-value (two-tailed)	0.083895	0.163117	0.212213	0.066459

Ho- The proposed hybrid nanogenerator prototype will not generate sufficient energy output comparable to the standard criteria.
Ha- The proposed hybrid nanogenerator prototype will generate sufficient energy output comparable to the standard criteria.
p-value < 0.05 = reject the null hypothesis
p-value > 0.05 = accept the null hypothesis

Figure 5: T-test: One Sample

Criteria	**Description**	**Measurement Tool / Method**	**Expected Outcome**	**Significance Level (P-Value)**
Energy Output	Measure total energy generated (W)	Multimeter	**≥ 15 Watts** (Baseline, running watts of an LED Light Bulb) **For 24-hour usage:** 15 watts x 24 hours = 360 watts/hours or 0.36 kWh **When broken down from kWh to J/s:** (1000W/1kW)*(0.36kW/1h)*(1h/60m) *(1m/60) = **0.1 J/s**	0.05 **p-value < 0.05 = reject the null hypothesis** **p-value > 0.05 = accept the null hypothesis**
Criteria	**Description**	**Measurement Tool / Method**	**Outcome**	**Significance Level (P-Value)**
Actual Energy Output of the Prototype	Measured total energy generated in Voltage (W)	Multimeter	**Set-up A:** 0.96W+1.28W+2.45W = 4.69W Mean = 1.56 W	**0.041947 = reject the null hypothesis**
			Set-up B (1): Mean = 4.51W	**0.081558 = accept the null**

				hypothesis
			Set-up B (2): Mean = 1.48W	**0.106106 = accept the null hypothesis**
			Set-up B (3): Mean = 7.65W	**0.03323 = reject the null hypothesis**

Table 3: The average energy output (in watts) of Set-Up A and the sub-sets of Set-Up B compared to the standard criteria?

Table 3 shows an analysis of the average energy output of Set-Up A and the sub-sets of Set-Up B in comparison to the standard criteria with an expected outcome of 0.1 W (J/s). The data revealed that the p-value of both Set-Up A and one sub-set from Set-Up B which is Sub-Set-Up 3, falls under 0.05, which indicates that the null hypothesis is within the area of rejection. Moreover, Sub-set-up 3, showed the highest significant difference among the four. On the other hand, Sub-set-up 1 and 2 both showed a p-value higher than 0.05, with sub-set-up 2 having the highest p-value. Therefore, the null hypothesis was accepted for these set-ups.

Chapter 4

CONCLUSION AND RECOMMENDATIONS

Conclusion

The findings revealed that there is a significant difference between the set standard criteria and Set-up A, which involved the control variable weight. The Similar is observed in the last sub-set of Set-Up B, movement-based. For these two set-ups, the null hypothesis was rejected, and the alternative hypothesis was accepted. This indicated that the proposed hybrid nanogenerator prototype was able to generate sufficient energy output comparable to the standard criteria. The movement in this set-up was a series of repetitive sit-to-stand motion. As for the 1st and 2nd sub-sets of Set-up B, the recorded p-value was higher than 0.05, which lead to the acceptance of the null hypothesis. This indicated that the proposed hybrid nanogenerator prototype was not able generate sufficient energy output comparable to the standard criteria.

The findings of the research suggests that the energy output in Set-up A, in terms of current (μA), is inversely proportional to the user's weight, with the highest current produced by the lightest user (40 kg) and the lowest current by the heaviest user (60 kg). However, when examining voltage (V), a direct proportionality to the user's weight is observed, with the heaviest user (60 kg) producing the highest voltage (0.35 V) and the lightest user (40 kg) producing the lowest voltage (0.08 V). For wattage (W), a similar direct proportionality to weight is seen, with the heaviest user (60 kg) producing the highest wattage output (2.45 W) and the lightest user (40 kg) producing the lowest wattage output (0.96 W).

The results from the three sub-sets in Set-Up B highlights how different types of movements influences the energy output of the nanogenerator prototype. Sub-set-up 1 (where the user sat still) produced the highest average current (21 μA) and wattage (4.51 W), as well as a relatively moderate average voltage (0.20 V). This suggests that stationary movements might generate a consistent but not particularly high voltage output. Sub-set-up 2 (where the user swayed sideways) resulted in the lowest current (mean of 4 μA) and voltage (mean of 0.37 V), reflecting the limited energy generated by minimal movements. Sub-set-up 3 (where the user performed sit-to-stand motions) showed the highest voltage (mean of 0.40 V) and wattage (mean of 7.65 W), suggesting that dynamic, repetitive movements are more efficient in generating energy compared to stationary or minimal movements.

The findings indicate that both user weight and the type of movement significantly impact the performance of the nanogenerator prototype. The insights gathered through these data can inform future designs and optimizations for nanogenerators, particularly in wearable or motion-based applications, where specific movement patterns could be leveraged to maximize energy production.

Recommendations

Based on the results of the study and observations during the conduct of data gathering, the researchers recommend that the local government units should invest in projects such as the innovation of nanogenerators to create clean and renewable energy sources. These renewable energy sources can provide significant benefits, particularly for communities in far-flung areas with no access or inadequate energy infrastructure. By investing in nanogenerator projects, the local government unit can address energy deficits within the community and foster sustainable development as well. Moreover, such investments can increase the awareness and knowledge of local residents about renewable energy technologies, especially with nanogenerators as this is a new innovation. This may empower local residents to contribute to the development and innovation of improved models. These innovations can be promoted and utilized to build smart cities, integrating nanogenerators to the community's infrastructure and improving public services.

The researchers also recommend that private sectors, including private organizations with no affiliations with the government, delve into the innovation of nanogenerator projects to contribute significantly to sustainability, particularly in industrial sectors. Further, the researchers suggest that private organizations actively engage in research and development of nanogenerators to promote the adoption of smart technology. These compact, efficient devices hold the potential to revolutionize various industries by powering sensors, wearable devices, and IoT (Internet of Things) applications, which are integral to smart cities and industrial automation.

Lastly, the researchers recommend for the future researchers to experiment with the different types of nanogenerators in order to produce hybrid nanogenerators with higher energy output, suitable for different environments, conditions, and usage. In addition, the future researchers must experiment with the set-up arrangement as different arrangement of the components may have varying results. The future researchers are also challenged to invent and innovate other nanogenerator type to contribute to the studying of nanogenerators.

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