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Analyzing Human-Centric Wireless Energy Harvesting for Sustainable and Resilient Energy Systems

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Abstract

Discussions around wireless communications and energy harvesting in the literature are elitist and techno-centric. There is a need for more studies on a human-centric approach that simplifies the concept and links energy harvesting with human empowerment and well-being. Also, studies so far on the implementation of wireless energy harvesting in rural settlements have been scanty despite the important role wireless communication plays in social interactions and financial transactions within rural communities. The challenge of little awareness of the human sustainability impact of WEH is impeding stakeholders' advocacy and advancement of wireless energy harvesting (WEH) despite its real and perceived benefits. So far, research efforts as reported in the literature are less than proportionate to the potential of WEH. Apart from providing sustainable energy for wireless devices and networks, its generation of non-electric renewable energy is a huge plus for ensuring access to affordable, reliable, sustainable, and modern energy for all as contained in the United Nations Sustainable Development Goal 7 (SDG 7). Given the astronomical growth in the use of wireless devices globally, more research studies are needed to create more awareness for massive WEH advocacy. This study uses a model-driven approach to simplify and highlight critical aspects of WEH such as wireless body area network, sources of non-electric renewable energy sources, green energy (environmental protection), intermittent nature of renewable wireless energy sources, and research directions. Also, the application of WEH for the sustenance of lives and livelihood in rural economies is examined using the rural community of Adum-Aiona in Nigeria as a case study. It is expected that the information provided will create more awareness and foster further discussions around the human-centric angle of WEH even as advances in technology continue to be made.

Keywords

Human Centric, Wireless Energy, Energy System

Introduction

Energy harvesting (EH) has evolved though wireless energy harvesting (WEH) is still in its infancy (Akhtar, F., & Rehmani, M. H. 2017). Research studies have shown that conversations on WEH have largely been techno-centric, with a focus mainly on advancements in technology (Zhao, N., et.al., 2017) (Ku, M. L., et.al., 2017) . However, there is a need for more research investigations on the human-centric angle of WEH as a tool for providing sustainable electrical

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energy for ubiquitous communication. In both developed and developing economies, wireless communication is pervasive, enhancing human capability and well-being. Wireless devices like mobile phones and point of sale (POS) terminals now play a crucial role in social interactions and financial transactions in developing economies whose major populace resides in rural communities. These communities have challenges of infrastructural deficit, power inclusive. Besides the perennial problem of power deficit in developing countries and their rural communities, wireless devices like mobile phones and POS have low power storage capacity. Hence, they frequently run out of power when being used for socio-economic activities.

Studies on WEH have shown that many sources of energy harvesting have great potential for generating sustainable electrical energy for wireless communication and networks (Akhtar, F., & Rehmani, M. H. 2017). WEH supports green communication and green energy. Among the sources of renewable energy for WEH, solar energy is in abundant supply in rural communities. This ambient energy can be harnessed to generate a sustainable and resilient energy system that powers mobile phones and POS with sustained power. This intends to sustainably empower the rural dwellers for improved social interactions and financial transactions driven respectively by mobile phones and POS as the cardinal wireless devices predominant in their settlements.

To this end, this present research study investigates the impact of wireless communication on the sustenance of lives and livelihoods in rural economies using the Adum-Aiona community of Nigeria as a case study. Studies by (Okewu, E., et.al, 2020) (Okewu, E.et.al., 2017) classified Adum-Aiona as a rural community, with observable infrastructural deficits, and power infrastructure inclusive. The provision of sustainable electrical energy using wireless battery charging for mobile phones and POS in a bid to enhance social interactions and financial transactions is given prime attention. We also investigate the possibility of battery-less wireless device operations using photovoltaic (solar) cells owing to the abundance of sunlight in the community. The essence is to improve the existing ubiquitous communication infrastructure to further empower the rural dwellers economically and socially.

Before now, the techno-centric approach adopted by several research studies in the field of WEH has resulted in many conversations around themes like advancement in fundamental limits of energy harvesting channel capacity, energy harvesting at the receiver side, energy harvesting models, and combination of heterogeneous energy sources, robust designs with imperfect knowledge, multiple antennas techniques, security in RF energy harvesting, energy harvesting networks with multiple nodes, and energy harvesting for activity recognition (Ku, M. L., et.al., 2017). There have also been research proposals for the use of electroactive polymers (EAPs), nanogenerators, noise, and combinations of different types of energy harvesters to further mitigate dependence on batteries, especially in environments where there are periodic changes in the available ambient energy types (Kang, X., et.al., 2014).

The paper aims to show that wireless energy harvesting is a tool for sustainable and resilient energy systems just as it enhances human capability and wellbeing. The specific objectives are to:

i. use existing literature to underscore various aspects of wireless energy harvesting
ii. ease understanding of wireless energy harvesting for improved advocacy using unified modeling language
iii. show that wireless energy harvesting offers energy for ubiquitous communication
iv. prove that ubiquitous communication impacts on human empowerment and wellbeing

Key aspects critical to generating sustainable and resilient energy for autonomous wireless devices as considered in this work are the techno-centric and human-centric dimensions of WEH.

Techno-centric Dimension of WEH

Advances in WEH technologies have received much attention in the literature. Energy harvesting (EH) devices have the potential to avail a complementary or alternative source of power for applications that need low power consumption. Examples of such applications are condition monitoring, wireless sensor networks, wearable electronics, and remote sensing. The role of the device or sub-system is to capture the energy and present the same to an energy-converting transducer such as a thermoelectric stack, photovoltaic (PV) cell, piezoelectric element, etc. In systems like most PV systems, both the transducer and capture device constitute an element. The role of the transducer is to output an electrical current. Besides offering alternative/complimentary power sources, EH devices can extend battery life as well as ensure battery-less operations. To achieve this goal, EH devices capture wasted energy and convert same into electricity for operations. The frequently used devices depend on RF, thermal, solar, and piezoelectric energy sources. For example, photovoltaic (or solar) cells convert light energy into electricity. Of the several EH devices, solar (PV) cells have the highest density and power output.

Energy harvesting focuses on small-scale energy sources that typically cannot be scaled up to large sizes such as industrial-size wind power, wave power, and solar power. Such sources include kinetic (human-body/user actions) energy, photovoltaics, thermoelectric, micro wind turbines, piezoelectric, special antennas, vibration energy based on electromagnetic induction, electrically charged humidity, user action energy, and motion energy. Small-scale energy sources (kinetic (human-body) energy, photovoltaics, thermoelectric, micro wind turbines, piezoelectric, special antennas, vibration energy based on electromagnetic induction, electrically-charged humidity, power from pressed keys (which showcase the potential of devices powered by the energy generated from user actions, such as pressing buttons or turning knobs), motion (such as that of ocean waves, into electricity to be used by oceanographic monitoring sensors for autonomous operation. Advanced EH research investigations have shown that ambient energy can result from kinetic energy such as vibration or motion of the device, stray electric or magnetic fields, or radio waves from nearby electrical equipment, light, or thermal energy (heat).

Though EH technology is in its infancy, the motivational factors for its sustenance and improvement through research are huge. A key motivational force is the need to eliminate batteries that depend on external charging since device-incorporated batteries can be charged wirelessly. Also, EH has the potential to solve the problem of climate change by reducing greenhouse gas emissions and fossil fuel consumption in line with the United Nations Sustainable Development Goal (SDG) 13 which advocates taking urgent action to tackle climate change and its impacts and SDG 7 that focuses on ensuring access to affordable, sustainable, reliable, and modern energy for all [7].

Another motivation is that EH devices can reduce the need for power transmission and distribution systems which cause loses and impacts on the environment, contributing to the development of a more sustainable and resilient energy systems.

Human-Centric Dimension of WEH

The role of energy in sustainable development cannot be overemphasized. The human-centric dimension of WEH can be evaluated by examining the impact of wireless communication on sustainable development. Socio-economic and socio-cultural activities in both urban and rural settlements are impacted by wireless communication and networks which are sustained by energy. With EH, power can be stored and converted. Power storage devices like capacitors, supercapacitors, and batteries can be used for this purpose. The efficiency of conversion is normally low and the power gathered is often tiny (in microwatts or milliwatts) but this can be sufficient for running or recharging micropower wireless devices like remote sensors which are used in several fields. Despite being a traditional storage house for energy, batteries have the drawbacks of cost, weight, size, environmental impact (disposal of used batteries), and limited lifespan.

To underscore the significance of energy harvesting in human empowerment and well-being, the growth in the EH market is an indicator. Despite being at its developing stage, the EH market is growing steadily. The market refers to the industry and technology sector focused on capturing and converting ambient energy from the environment into usable electrical power. In 2023, the EH market was valued at USD 614.9 million, and it is expected to experience a compound annual growth rate (CAGR) of more than 8.5% between 2024 and 2032. CAGR refers to the annualized average rate of growth in revenue within two years, on the assumption that growth occurs at an exponentially compounded rate.

The trend in ubiquitous communication suggests more patronage for energy harvesting. EH is used by wireless autonomous devices like sensor networks, wearable electronics, condition mentoring, wireless sensors, monitoring cameras, Internet of Things (IoT) devices, remote sensing, and wireless sensor networks. These applications have low power consumption compared with industrial power consumption. The essence of advancing wireless EH technology is to avoid the need for battery replacement or charging of wireless devices. This would allow the wireless electronics to operate as autonomous entities, further strengthening the sense of a sustainable and resilient energy system.

Review of Related Works

The study in (Zhao, N., et.al., 2017) focused on harnessing interference for wireless energy harvesting (EH). In an apparent effort to convert waste to wealth, the authors stressed that interference is a phenomenon that poses a challenge to wireless communication, but research efforts are now focused on harnessing the same for generating energy for wireless devices. To this end, interference management techniques have been developed to utilize interference as a source of power to sustain wireless node operations. This is on the basis that since wireless signal carries information and energy, interference can be harnessed through energy harvesting to generate power. The paper outlined extensive research works on the exploitation of interference for wireless energy harvesting. First, basic aspects of interference-for-wireless EH such as antenna dimension, interference management techniques, network topology, and receiver architecture were reviewed. The study also discussed in detail the two interference management techniques for wireless EH: interference alignment and beamforming optimization. In addition, research issues like jamming signals and artificial noise for EH as well as research challenges of utilizing interference for wireless EH were discussed. However, the article did not discuss the impact of WEH on human empowerment and wellbeing, the cardinal focus of this current study.

In (Akhtar, F., & Rehmani, M. H. 2017), it was emphasized that energy harvesting for powering wireless body area networks (WBAN) is in its infancy. Power from non-electric renewable energy sources can be exploited using appropriate hardware and converted into electrical form to address the energy requirement of WBAN, a concept referred to as energy harvesting. The authors stressed that such a self-reliant solution offers a green energy supply through the reduction of system costs and electrical waste in the form of depleted (dead) batteries. In addition, energy harvesting makes WBAN usage more practical as it reduces its energy constraints. To fully exploit the potential of WBAN, the authors advocated the proposal of solutions to tackle current challenges as well as channelling research efforts of future applications. The study complemented recent advancements in technology that have resulted in significant techniques for addressing energy hiccups in pervasive sensor networks by reviewing potential energy-harvesting sources for WBAN. Such advances have led to scavenging energy from several sources in the human body which previously was impossible. These potential WBAN sources are biochemical, biomechanical, and ambient. In any case, the study is largely techno-centric. The concern of this present study is to shift conversations to the human-centric side of the divide where the import of WEH on sustainable development is prioritized.

Ku et al. (Ku, M. L., et.al., 2017) acknowledged that several research efforts have been expended on developing energy-harvesting communications and networks. This is as a of growing interest in green communications. Dependence on the supply of battery energy can be reduced by leveraging energy harvesting from ambient sources, resulting in benefits to the environment and deployment. In any case, the random and intermittent nature of renewable energy unlike the traditional stable energy, is a hindrance in realizing energy harvesting transmission schemes. Though comprehensive research studies have been carried out to solve this problem, there is no detailed list of recent advances and future research directions. In response, the authors gave a detailed overview of the energy harvesting problems as well as outlined cutting-edge proposals made by several researchers. Also, to design more advanced and dependable energy-harvesting communication systems in the future, the study suggested the following research directions for the research community to pay attention to: *Fundamental Limits of Energy Harvesting Channel Capacity, Energy Harvesting at Receiver Side, Energy Harvesting Models and Combination of Heterogeneous Energy Sources, Robust Designs with Imperfect Knowledge, Multiple Antennas Techniques, Security in RF Energy Harvesting, Energy Harvesting Networks with Multiple Nodes, and Energy Harvesting for Activity Recognition.* Unlike the focus of this present research, the study did state how wireless communication and networks can be used to sustain livelihoods in rural economies.

Of the aforementioned reviewed related works, none has focused on creating awareness about the use of WEH in rural communities and economies where wireless communication makes a huge impact on the socioeconomic and social-cultural lives of the people. This gap is being filled with this current research effort.

Methodology

Research studies on wireless energy harvesting were reviewed and based on findings, critical aspects of WEH were identified. The various aspects seem highly technical for non-technical stakeholders whose role in advancing the course WEH cannot be undermined. They include development partners, government officials, public-spirited individuals, etc. who may not be technical but are interested in providing support for the advancement of WEH owing to its perceived and real benefits as a tool for sustainable and resilient energy and by extension, sustainable development.

Also, we examined the impact of ubiquitous communication in rural economies, using the Adum-Aiona community in Nigeria as a case study. The impact potential impact of WEH on rural lives is contextualized within the United Nations global framework for sustainable development – SDGs. To ease the understanding of WEH among the target audience and make it less elitist, a unified modeling language (UML) is used. We also show that WEH can be used as a tool for sustainable and resilient energy systems that support the attainment of sustainable development, especially in rural settings where little attention has been given to the body of knowledge.

Designing Wireless Energy Harvesting Frameworks

Based on the research studies reviewed, the functional requirements of wireless energy harvesting for sustainable and resilient systems are specified in Figure 1 using the Use Case diagram.

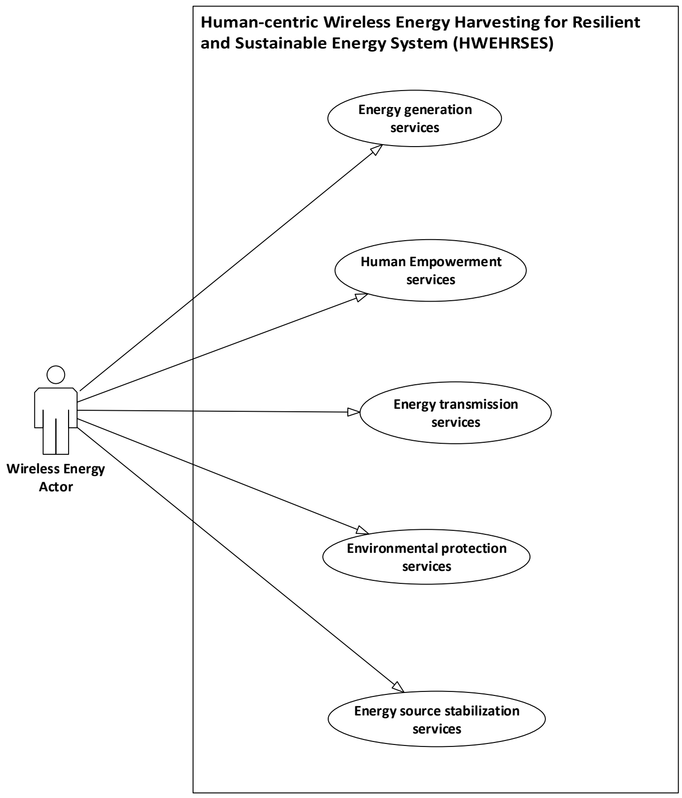

Figure 1. Use Case diagram showing functional requirements of a Wireless Energy Harvesting System (WEHS)

The study envisions that a wireless energy harvesting system will support sustainable and resilient energy for wireless devices by harnessing ambient energy sources in the environment of the application. The specific services to be rendered as indicated in Figure 1 are energy generation services, energy conversion services, energy storage services and energy source stabilization service. Further explanation and research studies that support each of these functionalities are specified in Table 1.

Table 1. Functional requirements and related research studies

Requirement	Explanation
Energy generation services	Energy to be generated from ambient sources like solar, kinetic, thermal, temperature differential, salinity differential, radio frequency, electromagnetic induction, etc.
Human Empowerment Services	The applications of wireless energy harvesting are meant for strengthening human capability and wellbeing for sustained livelihood through ubiquitous communication and transactions.
Energy conversion services	Micro energy harvested from the environment to be converted to electric energy using transducers like photovoltaic (solar) cells, thermoelectric stark, piezoelectric elements
Environmental protection/climate change services	Promoting environmental sustainability and mitigating climate change adverse effects through the use of ambient renewable energy sources and reduction/elimination of the use of batteries whose waste impacts adversely on the ecosystem
Energy storage/source stabilization services	Energy scavenging entails that the energy harvested can be stored for later use, thus stabilizing the system

Meeting the afore-mentioned functional requirements translate into a sustainable and resilient energy system. This is because ambient sources of energy are always available and clean in nature compared to non-renewable sources. Also, the fact that users of wireless devices will not need to recharge batteries from stationary electric sources is an added advantage. Mostly importantly, harnessing energy from the environment enhances resilient communities and settlements in terms of socio-economic activities, contributing to the attainment of SDG 11, whose focus is to make human settlements and cities resilient, sustainable, inclusive and safe. This is particularly true in communities in developing economies where epileptic power supply persist yet users of wireless devices such as mobile phones and point of sale (POS) have to use the devices on regular basis for communication and financial transactions.

In Figure 2, an n-tier layered architecture of a wireless energy harvesting initiatives that supports sustainable and resilient system is proposed.

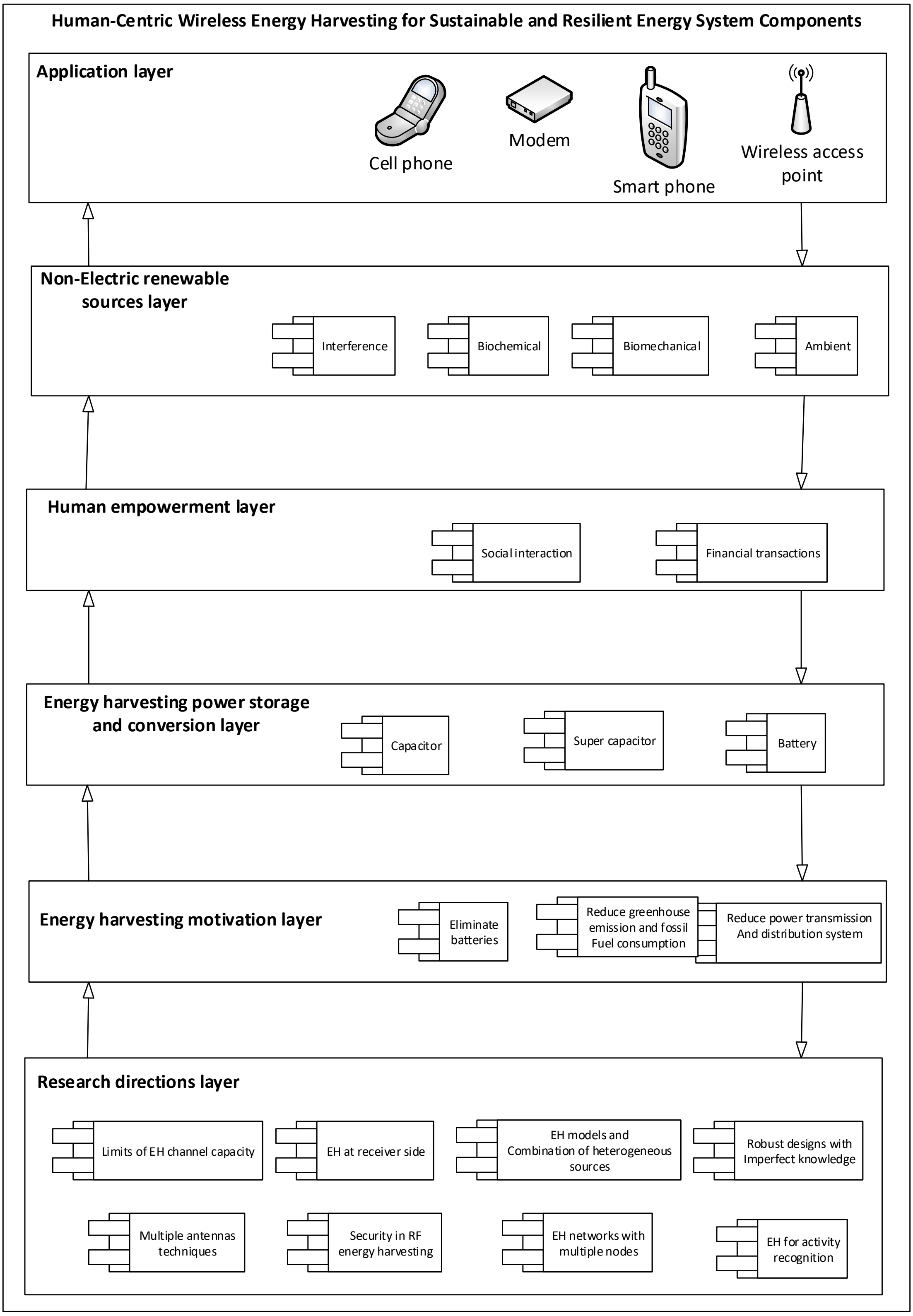

Figure 2. An n-tier layered architecture of wireless energy harvesting for sustainable and resilient energy system

The multi-tier layered wireless energy harvesting system architecture shows interactions among various components of a typical energy harvesting initiative. The model indicates that any wireless energy harvesting aimed at sustainable and resilient energy program would comprise critical layers like application layer, non-electric renewable energy sources layer, human empowerment layer, energy harvesting power storage and conversion layer, energy harvesting motivation layer, and research direction layer. The application layer comprises wireless devices that are supported sustainably by energy harvesting. Such low-power consuming devices include mobile phones, point of sate (POS) terminals, wearable electronics, wireless remote sensors, and Internet of Things (IoT) devices. The non-electric renewable energy sources layer articulates all ambient energy sources within surroundings of an application that the energy harvesting system will explore. Typical ambient sources include kinetic energy, solar energy, wind energy, thermal energy, radio frequency, and electromagnetic induction.

The human empowerment layer addresses issues of enhancing the socio-economic potentials of people through wireless communication as well as ensure environmental friendliness for safe human activities. For example, the disposal of batteries that are charged by EH devices should be done in a manner that the environment is not degraded by its waste content and hence, human lives secured. The function of the energy harvesting power storage and conversion layer is to stabilise energy supply to the applications even when there is intermittent fluctuation in energy sources. This is to give effect to the provision of sustainable and resilient energy. The energy harvesting motivation layer coordinates and reviews motivations for choosing energy harvesting options. The n-tier layered model acknowledges the importance of continuous research for advancements in wireless energy harvesting. Hence, the research directions layer articulates areas of research where sustainable commitments have to be made for the sustenance of wireless energy harvesting.

To further make it easy for actors and stakeholders to understand wireless energy harvesting and promote advocacy for this developing initiative, Figure 3 uses a Structured Chart to show the modules.

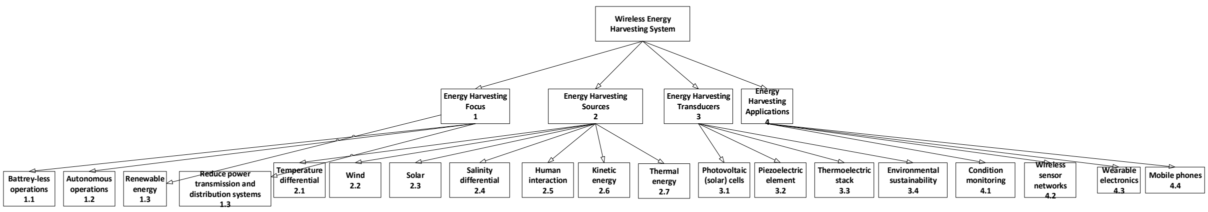

Figure 3. Structured Chart showing the modules of wireless energy harvesting for sustainable and resilient energy system

The energy harvesting focus module (Figure 3) encompasses battery-less operations, autonomous operations, and renewable energy. The energy harvesting sources module comprises temperature differential, wind, solar, salinity differential, human interactions, kinetic energy, thermal energy while the energy harvesting transducers module has photovoltaic (solar) cells, piezoelectric element and thermoelectric stack as sub-modules. The energy harvesting application modules has applications like condition monitoring, wireless sensor networks, wearable electronics and mobile phones.

Implications of Wireless Energy Harvesting for Sustainable Development

The ability of WEH to provide sustainable and resilient energy implies it is a very useful tool for sustainable development. This is because it aspires to meet the need of the present generation while not compromising on the needs of future generations [7]. The energy generated from renewable sources ensure that wireless devices are autonomous in their operations while simultaneously eradicating adverse environmental impact that are associated with non-renewable sources. The WEH initiative therefore impacts positively on the attainment of the United Nations SDG 7 in particular and the achievement of the other SDGs by the target year of 2030 given that energy and wireless communications have become a critical component of any socio-economic drive in the present fourth industrial revolution (Industry 4.0) [8].

In Table 3, the practical impact of wireless energy harvesting for sustainable and resilient energy on human capability and welfare in a rural setting is explained. We used the sustenance of lives and livelihoods in Adum-Aiona community of Nigeria as a case study, contextualizing rural sustainable development within the United Nations SDGs as a global framework for human welfare and wellbeing.

Table 3. Analysis of the expected impact of WEH on Adum-Aiona community of Nigeria

SDG	Description	Explanation	Socio-economic implications
8	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	The use of wireless devices like mobile phones and point of sale (POS) terminal in Adum-Aiona community has significantly enhance lives and livelihoods through enhanced social-economic interactions and financial transactions	Communications in all small-scale industries with the rural community such as farming, petty-trading, and food processing. The use of POS for money transfer
9	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	Wireless communication fosters new innovation in activities of cottage industries in Adum-Aiona community with regard to social interactions and financial transactions.	Enhanced human capability and wellbeing for engagement in cottage industry activities.
11	Make cities and human settlements inclusive, safe, resilient and sustainable	Power deficit in rural communities means locals in Adum-Aiona struggle with powering the wireless devices. Harvesting energy from solar as proposed in this work will provide sustainable and resilient energy for charging the batteries of the wireless devices	Batteries frequency run out of power supply since the energy storage capacity of batteries of wireless devices is low. This impedes livelihoods.
13	Take urgent action to combat climate change and its impacts	The use non-electric renewable energy sources in WEH is a tool for combatting climate change and its impact on sustenance of lives and livelihoods.	Reduction in the adverse impact of climate change on the welfare and wellbeing of the people.
14	Conserve and sustainably use the oceans, seas and marine resources for	One of sources of energy for WEH is salinity gradient (energy from ocean movement)	Better utilization of aquatic resources for the sustenance of lives and livelihoods.

	sustainable development		
15	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	The use of ambient energy sources such as solar, wind, etc. means WEH is helping in harnessing the terrestrial ecosystems for human empowerment and wellbeing	Better management of ecosystems for providing goods and services for human consumption.
17	Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development	SDG 17 lists technology, finance, trade, etc. as means of actualizing sustainable development. WEH is a technology that drives ubiquitous communication for trade, social interactions, financial transaction and global partnership which critical ingredients in sustainable development.	Achieving the SDGs means better standard of living.

Future Research Directions

Harnessing wireless energy harvesting for enhancing social interactions and financial transactions through ubiquitous communication is the key concern of this work. Energy sources that could be harvested for human empowerment and well-being in rural and urban settings include light which is captured by photovoltaic cells, pressure or vibration captured using a piezoelectric element, temperature differentials captured using a thermos-electric generator, radio energy which is captured by an antenna, and biochemically produced energy captured by cells with the capability of extracting energy from human body. Studies have shown that energy harvested from human interactions can power wireless devices as well as enhance their operational autonomy. By implication, such energy promotes the use of renewable energy and reduces reliance on traditional batteries. While energy sources for energy harvesters are mainly from ambient background (renewable), energy sources for large-scale generation (industrial generation) include non-renewable sources like oil, coal, etc. For future research directions, studies should focus on both the technological and human empowerment angles. New ways of energy harvesting using electroactive polymers, nanogenerators, noise, and mixed-mode (combination of any of these sources) should be considered.

Conclusion

It is clear from the foregoing discussion that the aim and specific objectives of this work have been achieved: Research studies were cited to underscore the relevance of every aspect of wireless energy harvesting. The use of UML to model WEH demystifies the concept for a greater understanding of the concept. Finally, we explained how WEH is emerging as a veritable tool for sustainable development. Based on these facts, it is expedient that research efforts continue to be intensified for the further advancement of WEH. Also, various approaches should be developed to enhance further simplification of the concept of WEH for greater advocacy by stakeholders. Advances in technical research and advocacy will facilitate the development of WEH which presently is still at infancy. This is in spite of its huge potentials for sustainable and resilient energy, which in turn has important implications for sustainable development. WEH can leverage on typical ambient energy sources such as solar power, wind energy, thermal energy, salinity gradient, kinetic energy, electromagnetic induction, and temperature gradient.

Conflict of Interest

There is no conflict of interest between the authors in the execution of this study.

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