PIEZOELECTRIC ENERGY FLOOR TILES PERFORMANCE AND EFFECTIVENESS AS BUILDING ENERGY CONSERVATION MEASURES FOR DIFFERENT TYPES OF BUILDINGS IN MALAYSIA

By

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DEDICATION

With the hopes that this imperfect thesis project will help to give some ideas for future development/research studies/projects specially to registered electrical energy manager, certified energy manager, facility manager, universities professors and researches, or any interested students out there, or anyone who is searching and investigating for the best solutions for energy efficiency, sustainability, and conservation and the betterment of the world we currently live in.

ABSTRACT

PIEZOELECTRIC ENERGY FLOOR TILES PERFORMANCE AND EFFECTIVENESS AS BUILDING ENERGY CONSERVATION MEASURES FOR DIFFERENT TYPES OF BUILDINGS IN MALAYSIA

Puteri Aisyah Bt Megat Shariffudin

In the era of urbanization, energy or mainly electrical energy is one of the main drivers of the economic, social, and environmental sustainability development. Buildings have been considered as one of the biggest contributors in the greenhouse gas (GHG) effect and other negative impacts on the environmental worldwide. Due to the high number of the CO_2 emission recorded, many initiatives or strategies have been introduced to address the issues and further helping to reduce carbon emissions mainly through the buildings decarbonizations as well as finding new reliable and cleaner ways of energy production essentially. Such initiatives include the implementation of sustainable and renewable energy technologies as building energy conservation measures to achieve low emission and optimize energy consumption in a building. Many of the technologies present today are based on the concept of energy harvesting along with the electromechanical, electromagnetism and piezoelectric mechanism integrated into the system. This study concentrates on the hybrid properties of energy harvesting which involved the mechanism of electromechanical and piezoelectric in one energy harvesting system. Several piezoelectric energy harvesting floor tiles technology have promising potential in helping the development of low energy building. Specifically in Malaysia, this kind of mechanism could outperform the solar energy harvesting system since the piezoelectric energy harvesting technology could help both in the sense that it takes

less place compared to solar energy harvesting system and the main source for this particular technology is in the form of human movement which certainly will never deplete in time. From the study, it was noted that as long as the cash flow for such technology can be manage properly, the system mechanism could help in the reduction of more than 90% of total building energy consumption and also carbon emission with payback period of less than a year from its baseline year.

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Through the process of completing this paper, I have learnt a lot. Not to mention that somehow it makes me realize that I actually have a lot more to learn. Just by finishing this paper, I try not to regret on things which I have let go especially during the process of learning and understanding newer thing related to study. Because truly, there are still a lot more to learn, a lot more to understand and a lot more to compromise.

So, thank you all including this paper who had taken half of my time this year alone.

FACULTY OF ENGINEERING AND SCIENCE

UNIVERSITI TUNKU ABDUL RAHMAN

Date: 23rd December 2021

PERMISSION SHEET

It is hereby certified that **Puteri Aisyah Binti Megat Shariffudin** (ID No: ***20UEM000717***) has completed this final year project entitled **"Piezoelectric Energy Floor Tiles Performance And Effectiveness As Building Energy Conservation Measures For Different Types Of Buildings In Malaysia"** under the supervision of Ts Dr Jun Hieng Kiat (Supervisor) from the Department of Mechanical and Material Engineering, Faculty of Lee Kong Chian Faculty Faculty of Engineering and Science .

I understand that University will upload softcopy of my final year project in pdf format into UTAR Institutional Repository, which may be made accessible to UTAR community and public.

Yours truly,

____

(*Puteri Aisyah Binti Megat Shariffudin*)

APPROVAL SHEET

This thesis entitled **"PIEZOELECTRIC ENERGY FLOOR TILES PERFORMANCE AND EFFECTIVENESS AS BUILDING ENERGY CONSERVATION MEASURES FOR DIFFERENT TYPES OF BUILDINGS IN MALAYSIA"** was prepared by PUTERI AISYAH BINTI MEGAT SHARIFFUDIN and submitted as partial fulfilment of the requirements for the degree of Master of Engineering (Mechanical) at Universiti Tunku Abdul Rahman.

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LIST OF ABBREVIATIONS / NOTATIONS

AP	Average Building Population
BEEI	Building Energy Intensity Index
BEIT	Building Energy Intensity Tool
CO_2	Carbon Dioxide
DOSH	Department of Occupational Safety and Health
ECM	Energy Conservation Measure
EHF	Energy Harvesting Floor-tiles
ESM	Energy Saving Measure
GFA	Gross Floor Area
GHG	Green House Gas
IRENA	International Renewable Energy Agency
J	Joule
KLIA	Kuala Lumpur International Airport
kWh	Kilowatt-hour
MCO	Movement Control Order
MyCREST	Malaysian Carbon Reduction and Environmental Sustainable Tool
NDC	Nationally Determined Contribution
NLA	Net Lettable Area
PZT	Lead Zirconate Titanate
RE	Renewable Energy
RM	Ringgit Malaysia
ROI	Return of Investment

SDF	Sustainable Dance Floor
SEC	Specific Energy Consumption
SEDA	Sustainable Energy Development Authority
SEF	Sustainable Energy Floor
TNB	Tenaga Nasional Berhad
TRL	Technology Readiness Level
UN	United Nation
W	Watt
H_{op}	Building Operating Hours

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CHAPTER 1

INTRODUCTION

1.1. Global Energy Issues & Scenarios: Malaysia Perspectives

For the past few decades, the only uncertainty in energy was the price of fossil fuels. However, as the year progresses, the world is heading toward the peak of the era of urbanizations and industrialization which is subsequently affecting the prospect of energy consumption globally. Based on the United Nation (UN) world population prospects data report review, there is a 5.3% jump from the final recorded numbers of world population in June 2019. Despites the current endemic situation, world population is still increasing at an alarming net increase of 1 person in every 0.39 seconds (2021 World Population by Country, 2021). Several research studies had explored the relationship between the population growth and energy consumption. While many agree that more people do not necessarily mean more energy is consumed, but many reviews had suggested that the increment of population also has a significant effect on the growing demand for energy worldwide especially in the current years of 20th century where almost everything requires energy for the mere economic and social development (Sheng, He and Guo, 2017; Vo and Vo, 2021).

In Malaysia alone, the nation population grew at a rate of 1.27% in 2019 and 1.30% as of 2020. This trend in population combined with the nation economic and industrialization growth are projected to keep on increasing at least by 2040 as revealed in the 6th ASEAN Energy Outlook Report and is supported from data evidence presented in the Malaysia Energy Statistics Handbook 2020 where the total final energy consumption had been steadily increasing with the increment of energy demand every year as early as 1990. By 2050, Malaysia would see doubling of energy demand with a share of electricity increasing faster than primary energy supply.

Presently, there are more known resources in the world than ever before besides the fossil fuels namely natural gas, crude oil, and coal. In Malaysia however, the primary energy supplies are still coming from the above-mentioned conventional energy sources with currently natural gas acting as the domain national resource. Although in the very early state of energy consumption, the biggest concern would be the price of the fossil fuels and the respectively limited quantity available to meet the ever-increasing demand, the true concern has now shifted on how these primary conventional energy supplies are the main contributors towards the rising of greenhouse gas (GHG) emissions worldwide.

One of the main GHG emissions is the carbon emission or carbon dioxide (CO_2) emissions. CO_2 makes up almost more than 70% of the whole GHG emissions and is largely responsible for the current environmental problems especially climate change and air pollution. Due to this very reason, an international agreement named the Paris Agreement has been made in 2015. Malaysia, as one the members under this agreement, has pledged to adopt a series of resolutions to address the issues and one of the issues is to reduce the GHG emissions through decarbonization by 45% by the year of 2030.

Renewable energy (RE) is noted to be one of the main key components of the Nationally Determined Contributions (NDCs) which is the central implementation tool to enhance the implementation of climate change action plan through energy transition for several member countries under the Paris Agreement (IRENA, 2021). Although Malaysia is not included in the NDCs partnership created by the International Renewable Energy Agency (IRENA), Malaysia has taken its own initiative to follow through with climate change plan which is through the implementation of the RE technologies. RE combined with the energy efficiency measure plans are as one of the high action priorites in combating climate change and increasing energy resilience with both methods combined could provide almost 90% of CO_2 emissions reductions required by 2050 (IEA,2021; IRENA, 2021). With this intention, therefore, Malaysia has committed to increase the energy production through renewable resources by increasing its capacity of energy mix to 20% by 2050 from the 2% recorded in 2018 (EC, 2020).

Following Malaysia as the case study in this paper, the RE technology is gradually taking place as the most promising ways for energy resources to fight the GHG problems. Nonetheless, the choice of particularly suitable energy resources is determined entirely by the operational environment, landscape geographical features of the area, weather and the climate of the area, available energy density and demand in the area. For example, due to Malaysia's location in the equatorial zone, Malaysia is certainly blessed with abundant sunrays for at least 12 hours and for that, many are ought to investigate more into the applications of solar energy mechanism as it could be the best solutions for energy saving mechanism. However, in many applications, solar energy mechanism may not be practical due to the many long rainy season in most of the states in Malaysia and there are only several small amounts of lands or open surfaces that are available to install large solar farm for the energy access. So, at the very first glance, it seems impossible to adopt the solutions to achieve such goals of decarbonization within the next 15 years especially through the implementation of RE technologies only, since it requires a longer-term approach and undoubtedly high investment in many aspects as many has argued.

Regardless of the many challenges, RE as a whole energy transition system still could offer a wide range of benefits including releases lesser amount of CO_2 compared to the carbon emissions from fossil and nuclear energy and as its name suggests, it is derived from natural resources that are not finite or exhaustible (Gielen et al., 2019; Vo and Vo, 2021). Thus, to integrate RE technology system with energy efficiency measure plans towards mitigating climate change, it should be able to allow high energy accessibility and affordability, additional demand side innovation and incentives, as well as stronger technical standards to provide energy sustainability while could still maintaining the goal for decarbonization. So, instead of building a whole RE harvesting plantation, one may look into a smaller scale of RE harvesting system where it could be integrated directly into a building as one of the sustainable energy solutions.

1.2. Sustainability Through Building Energy Conservation Measures (ECMs)

Buildings have been considered as one of the biggest contributors in the GHG effect and other negative impacts on the environmental worldwide. Based on United Nation (UN) 2020 Global Status Report, approximately 55% of global total energy consumption is due to the energy used in buildings and is responsible for almost more than one-third of the total CO2 emissions which is at 38% (UN, 2020). Due to the high number of the CO2 emission recorded only from the consumption in a building, many initiatives or strategies have been introduced to address the issues and further helping to reduce carbon emissions mainly through buildings decarbonizations called building energy-saving solutions. These solutions are also known as building energy saving measures (ESMs) or energy conservation measures (ECMs).

There are three types of ECMs or ESMs which are usually introduced in many energy efficiency measure implementation plans and in Malaysia, they are usually categorized based on the investment cost for each energy saving solutions or energy efficiency projects as shown in the Table 1.1 below (SEDA Malaysia, 2021).

Table 1.1: ESMs categories

No	ESMs Type	Minimum building energy saving to achieve in percentage (%)	
		Commercial	**Industry**
1	No Cost ESMs	5%	3%
2	Low-Cost ESMs	7%	3%
3	Medium/High-Cost ESMs	8%	4%

Source: SEDA Malaysia, 2021

In addition to the minimum percentage of energy savings need to be achieved, there are two other criterions used to justify the ECMs implementation namely: the payback period and the return of investments (ROI). Usually, the acceptable number of years for the payback period for the high-cost ESM for example, is 15 years. More than that, it is considered not profitable. And a good ratio value for ROI is normally considered to be more than 7% per year. Higher than that, it is considered an outstanding investment.

In the context of RE technologies implementation, it is usually categorized in the high-cost ESM category due to its typically high investment cost which normally cost more than RM 500,000.00 for at least one small system installation. However, despite the very high investment cost which also usually associated with high risk, RE technologies could outperform conventional and contemporaries energies in terms of cost when one considers the entire energy supply or electricity generation chain and it is also has been reported through the Stern Review on the Economics of Climate Change that the RE emits about 40 grammes of CO_2 per kilowatt-hour of electricity (kWh); conversely, a coal based power plant emits about 800 to 1400g of CO_2 per kWh of consumption (Pelosse, 2021). Furthermore, RE reduces pollutions in the environment, saves resources and requires less land and hence, decreasing the cost to mitigate climate change while at the same time providing a full solution for energy sustainability. So, the payback period for a certain RE technology system implementation would be acceptable considering the add-on cost for remedying environmental damage and impacts on the climate change would be lower compared to the conventional energies and its return ratio value could sometimes double than ratio value of the conventional energies (Pelosse, 2021).

Generally speaking, the ECMs can be viewed as an investment in combating climate change, despites the apparent degree of financial risk involved, considering they result in both measurable energy financial savings as a result of overall energy reduction and improved efficiency which also could help in reducing the operational and maintenance costs especially in a building. So, the key to minimize any financial and technical risks with high-cost ECM projects is by maximizing the energy savings through its implementation.

1.3. Energy Harvesting Approaches

Many of the sustainable or renewable energy technologies present today are based on the concept of energy harvesting where the generation of electrical energy is from a process of energy-to-energy conversion which includes the conversion from the solar energy, mechanical energy, chemical energy, thermal energy, and radio frequency energy (Dhar, Wijewarnasuriya and Dutta, 2012). Among the mentioned categorized energy harvesting processes, mechanical energy (ME) type has becoming one of the most promising technique to be applied in the sustainable and renewable energy technologies and one example is ME based on the combination of energy harvesting from human motion and piezoelectric effect. Considering the big human density population especially in the current year, the ideal candidate behind this idea is through the conversion of kinetic energy or mechanical stress from human footsteps into electrical energy on a surface.

In regards of building ECMs, buildings are permanently exposed to wasted potential energy especially from human activities mainly footsteps. Hence, there is a potential for energy harvesting technology to be applied in the building industry as to convert the wasted potential energy which then can be delivered back into the building as usable electrical energy.

Kinetic energy or namely energy harvesting floor tiles system that is introduced in this study is basically a coupling method of hybrid applications of the concept of piezoelectric effect as well as vibration and induction where the system can capture the energy generated via energy transformation in a way that when human walk on the tiles, the tiles could transform the energy stored in the footsteps into electricity which then can power everything from street lighting to charging electronic devices (Liang, Hao and Olszewski, 2021; Mahajan, Goel and Verma, 2021). So, with the above-mentioned idea, this study concentrates on the performance of piezoelectric floor tiles as an energy harvesting system and its applications as a ECMs for buildings in Malaysia through both enumerative and analytical study. Going forward, the term piezoelectric floor tiles is replaced by the term of piezoelectric energy harvesting floor (EHF) throughout this report.

1.4. Research Aim and Objectives

This research is intended to investigate the performance of the piezoelectric EHF as a system and analyze how the performance of the mentioned system affect the overall performance of energy consumption in different types of buildings in Malaysia. Technical analysis is conducted in order to examine the most efficient and optimized type of piezoelectric tiles technology that can be implemented as ECMs and what need to be fulfilled to improve the efficiency of the piezoelectric elements performance as an energy harvesting mechanism.

The essence of this approach is to study the significance of implementing the piezoelectric EHF mechanism on different scenarios as to help in the reduction of the building energy consumption from the local conventional electrical energy provider. So, the overall objectives of this project are as the following:

1. To investigate and conduct technical analysis on the performance of various types of piezoelectric EHF technologies as energy harvesting mechanism for several parameters and important factors in energy output generation and consumption.
2. To model the selected best piezoelectric-based mechanism and demonstrate its application in different types of buildings in Malaysia which consist of mainly big energy consumer buildings with the average monthly electrical energy consumption of more than 500,000 kWh.
3. To study and analyze the significance, compatibility, and sustainability of the implementation of the mechanism to reach an amount of at least 5% of energy savings from the total yearly energy consumption in a building.
4. To further analyze the elements to be utilized in the piezoelectric EHF mechanism to yield maximum output energy generation in a building.

1.5. Research Contexts, Limitation and Challenges

There are several important aspects that are concentrated and continually addressed in this study in order to meet the acceptable desired final outcomes as outlined in the objectives. It can be considered that there are three interconnected main groups representing this study which are the piezoelectric technology, building energy consumption and building energy saving measures. As suggested, the main key aspects in this paper would be the employment of piezoelectric EHF into floor tiles system as a solution for energy cost reduction and how it can be integrated as an energy harvesting facility in a building.

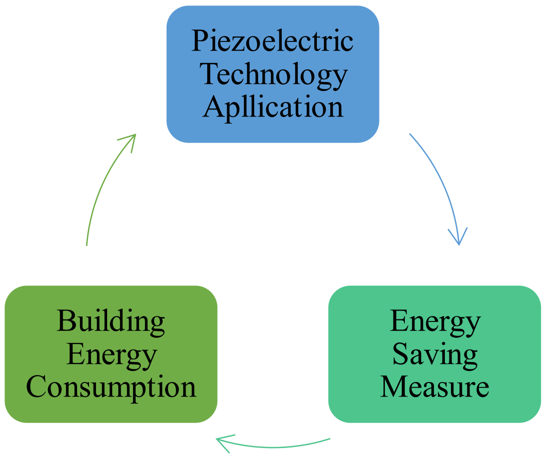

Figure 1.1: Research contexts

All three of the research contexts as introduced in Figure 1.1 are the main subjects of considerations in helping with where the projectile of this study is heading. Basically, the entire project is co-dependent on the three main subjects. All activities, points, and discussions especially within the literature review and data collection in this study, are established based on the three context subjects mentioned. Any related case studies in the literatures will be used as the baseline for the analytical brief in correlation between the piezoelectric technology and building energy consumption.

Firstly, for the subject of piezoelectric technology, this study is solely looking into the prebuilt piezoelectric-based energy harvesting devices, be it the device that has been commercialized or is still in the experimental stage. The decision to focus on the model selection among the existing devices or technologies is mainly due to the time restriction to build up a different prototype for experiment testing and analysis. Also, taking a broader view, the most significant issue before starting to build a complete device system such as a piezoelectric-based mechanism is, it requires a total financial support. So, this study opt for those original system prototypes or patents of commercialized devices that are prebuilt and are simply to be studied again as to understand their mechanisms for more potential applications.

In regards of energy saving measures and building energy consumption, the final findings or intended outcomes are derived through enumerative and analytic studies for different case studies which are also based on different type of piezoelectric technology as well as different building typology. In addition, to further investigate the overall performance and potential of piezoelectric technology as building ECMs, a computational simulation would be the best approach since it could give the validation needed specially to show the significant comparison between the commercialized and the self-built experimental prototype technology. However, should there is already a full conduct of performance test through computational simulation in any of the literatures, only performance technical analysis would be sufficient to be carried out to proceed with the energy simulation.

So, by the end of this study, a suggestion on the best piezoelectric technologies with comparison on the energy conservations potentials by the intended use and theirs impact on the overall building energy consumption are presented. This decision is considered since there is a very high probability that most of piezoelectric existing technology especially the existing innovation device patent and commercialized technology would have already had full field or experimental lab testing and computational simulation for validation ran by their own respective companies.

As for the data of the building models, they are based entirely on the estimation and projected data of pre-audited buildings and real-time case scenarios. However, it is best to note that the building models used in this study are the imitations of actual buildings which are based on the typological comparison of most average-looking building such as the shapes, area intensity and types. This is due to most of the buildings in Malaysia which are intended to be used as the models are not having a standard area intensity or baseload for the same type of buildings.

Apart from that, the decision to have the imitation of the actual building models and having estimation data are also due to the Malaysian movement restriction order which started back in the early year of 2020. Supposedly, an in-site survey evaluation is to be conducted to review and inspect the potential location with real-time building occupancy for the highest footfall density area. However, with the lack of human movement in the public spaces which is one of the most important factors in building energy consumption context, the data taken during the movement restriction order period would not be reflecting to the actual scenarios of when the building or public space is operating 100%. Since the outcomes would be unreliable and require additional measurement and verification for validity, the data collection for building parameters are estimated and projected from the previous 3 years data as of the date of the start of Malaysia movement control order (MCO).

All things considered, in realizing a comprehensive study for this paper to determine the potential of the piezoelectric EHF as a building ECM, there are several limitations and challenges that are addressed:

1. Selection of building model,
2. Selection of pre-built piezoelectric EHF technology,
3. Modeling and integration of piezoelectric EHF technology system into the building,
4. Simulation approaches for energy and performance modeling, and
5. Energy saving potential measurement and verification.

1.6. Research General Framework and Methodology

In order to ensure an effective study can be carried out, activities in main general order involve the following procedures are followed:

- Stage 1: Data information and evidence collection through preliminary building energy audit, analysis, and literature review.
- Stage 2: Construction of building model and selection of piezoelectric-based tiles model.
- Stage 3: Modeling energy simulation, qualitative and quantitative measurement through technical analysis on overall energy performance and potential.

- Stage 4: Final data analysis and energy saving calculation.
- Stage 5: Results discussion and preparation of final project report.

In Stage 1, data and information collection is carried out through preliminary building energy audit and literature review. Both approaches are conducted concurrently and respectively for the selection of suitable building models and the piezoelectric EHF technology. By conducting both activities concurrently, it will help in facilitating the study for a more comprehensive analysis study especially in finding the correlation between various factors on both contexts for example, the required electrical energy of a building with the output electrical energy produced by the piezoelectric EHF system, or the distribution of high-density footfalls with the out power per step per piezoelectric tiles. Apart from that, the literature review would help in determining the important parameters such as the technical characteristics and specifications of the different types of piezoelectric technology data.

As for the preliminary building energy audit activity, it is a process to investigate and establish the overall picture of how energy is currently consumed in a building. Table 1.2 shows the list of data information required for the data collection through desktop data collection in the preliminary building energy audit as to apportion the total energy consumption in a building.

Table 1.2: Building primary data & general information

No	Data information required	Descriptions
1	Building Typology & Operation Manual	Building architectural design shape, type, layout, and function
2	Total Gross Floor Area (GFA)	Total area of all spaces in building as measured to the outside of exterior walls of the building
3	Total Net Lettable Area (NLA)	Total occupied or usable area in a building
4	Maximum Demand (MD)	The highest point of electrical energy demand monitored in a period of month
5	Total Yearly Energy Consumption (TEC)	Total net energy of electrical energy or electricity
6	Tenaga Nasional Berhad (TNB) Electricity Tariff Classification	Consumer tariff category
6	Building Operating Hours (H_{op})	Standard hours of daily operation and building
7	Building Average Population (AP)	The number of persons legitimately working or occupying the building

In Stage 2, after gathering all the primary data and information for the selected types of buildings, preliminary building energy audit is carried out to create a baseline data that is used for the construction of the building models. All data collected are from actual case studies and building scenarios. Next step would be the construction of building models for different type of buildings and the collection of the potential piezoelectric technologies for the selection of building ECMs implementation, respectively.

For the construction of the building models, the models are developed based on the two big main consumers type defined as the commercial and industrial consumer. All building models are having a baseline of TEC at the minimum of 500,000 kWh per month consumption. From these two categories, only a few numbers of building candidates with different typology are selected and the list of the building model types is shown in the Table 1.3 below.

Table 1.3: Building model type

Consumer Type	Building Model Type
Commercial	Higher education institution
Commercial	Skyscraper: Office building
Industrial	Manufacturing factory

Furthermore, through analysis findings in the literature review, a list of potential piezoelectric technology is acquired with a full comparison of the scope of technical specification and characteristics, system mechanism, performance test performed and results achieved, installation or application method and other related factors. A performance technical analysis is used to investigate the potential of the piezoelectric technology as a building ECMs by comparing suggestion or ideas of scopes gathered from literatures and its ability to correlate and compromise between mentioned factors and other important factors that are further analyzed through suggestions and ideas in the literature review. In this stage also, the performance of the piezoelectric technology is divided into two different categories which are the commercial piezoelectric EHF technologies or patents, and the self-built prototypes

The third stage consists of simulation activities. The simulation suggested in this study is a static energy simulation on the electrical energy consumption model. The energy simulation study is conducted based on the Building Energy Intensity Tool (BEIT), a software tool meant to assess energy use in buildings, and the energy model template from the Malaysian Carbon Reduction and Environmental Sustainability Tool (MyCREST). It is used to identify the most efficient solution with the implementation of piezoelectric EHF technology. Correspondingly, the following energy performance parameters are to be set, simulated, and evaluated:

1. Overall building energy, operation, and occupancy mapping with footfall density concentrated area location
2. 5% electrical energy savings from the total yearly building electrical energy consumption goal

In addition of the energy simulation to demonstrate the energy saving, a performance test and technical analysis are carried out through modeling simulation of the selected piezoelectric technologies. A full comparison will be made upon the findings.

The fourth stage is the final evaluation on the developed building model and the selected piezoelectric technology models to determine the potential and effectiveness of the selected piezoelectric technology as building ECM by identifying the impacts of several variables as a system in a real case scenario within a building. Some of the variables may include:

1. Location of the system technology installation within the building.
2. Size and unit quantity required to be implemented in a building.
3. Number of footsteps required.
4. Cost rate of electricity with payback period.
5. Total achievable saving amount in relations to the above-mentioned variables.

Additional factors of carbon emission impact factor and incremental ESM cost effectiveness are calculated and analyzed as well to fully evaluate the overall potential of the piezoelectric EHF technology as a building ECM. Figure 1.2 illustrates the flow of the whole framework for this study.

By the end of this study, the results from all the findings should provide useful information and some insights specially to building owners or energy managers regarding the different types of the piezoelectric EHF technology available and the effectiveness of such technology to be implemented as an ECM in a building.

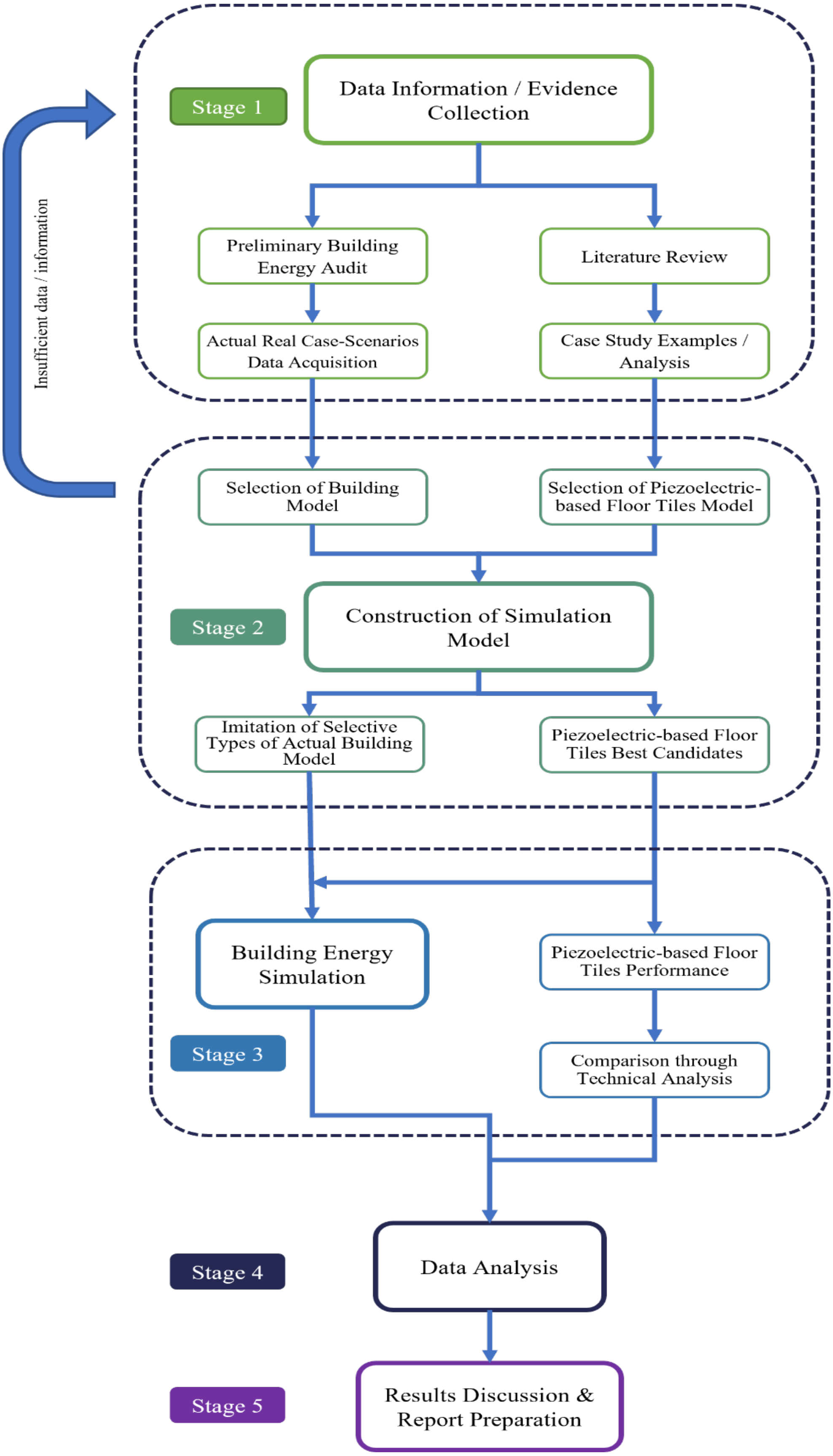

Figure 1.2: Research framework

CHAPTER 2

LITERATURE REVIEW

2.1. Piezoelectric Energy Harvesting System Mechanism

Principally, energy harvesting is the process of capturing and converting energy from the external surrounding sources into electrical energy. So, basically, piezoelectric energy harvesting is the physical process of capturing and converting energy into electrical energy through the concept and phenomenon of piezoelectric effect.

In theory, piezoelectric refers to the term of "piezoelectricity" which is a phenomenon discovered back in the year of 1880 by the Curie brothers, Pierre Curie and Jacques Curie. A good portion of the history is that it was first discovered by the Curie brothers under the phenomenon of imposition of mechanical stresses on the surfaces of crystals and the aftereffect from this activity is the production of electrical charges which is then named pyroelectricity and later changed into the term piezoelectricity or piezoelectric effect by W.G. Hankel (Ballato, 1996). The appearance of the crystals was highlighted, and it was established that the crystal used as the variables in the experiments are categorized as the piezoelectric materials which also include nonconductive materials such as the natural quartz crystals, polymers, ceramic, an even wood (Fukada, 1955; Qin, 2013; de

Jong et al., 2015). Due to this introduction of the piezoelectricity, many have interpreted that the piezoelectric effect as a phenomenon where the process of energy conversion occurs with the present of external forces acted upon the piezoelectric materials. Figure 2.1 and Figure 2.2 below illustrate the essence of the piezoelectric effect as described.

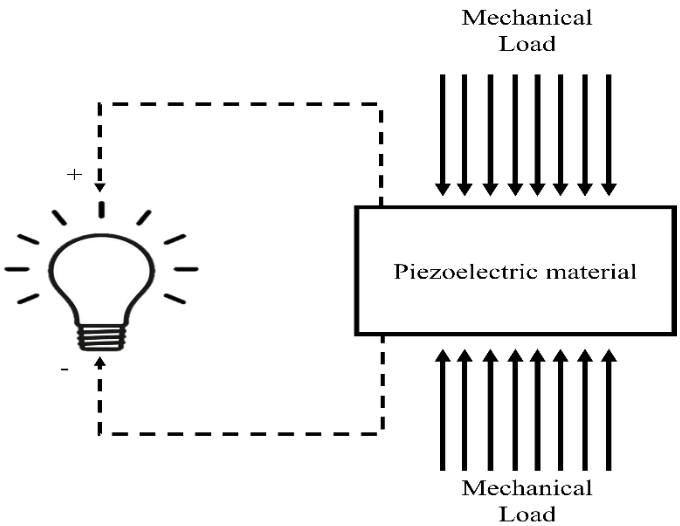

Figure 2.1: Illustration of piezoelectric effect

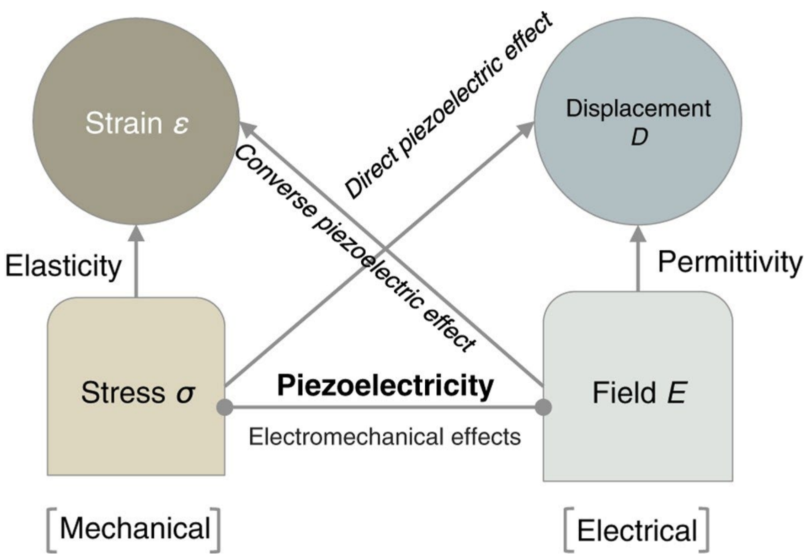

Figure 2.2: Part of Heckmann diagram of the electromechanical relationship in piezoelectric effect mechanism (Paufler, cited in de Jong et al., 2015)

Figure 2.2 above also illustrates a version of Heckmann diagram. The diagram describes the linear relationship and the coupling between the mechanical and electrical variables in piezoelectricity. Therefore, one can say that piezoelectric effect is also an electromechanical effect, and it supports the concept which is being used in this study.

So, while it is true that the piezoelectric material is the main element in the mechanism of the piezoelectric phenomenon, but many also agree that the very concept of a piezoelectric effect is the phenomenon when mechanical forces acted upon the system by kinetic energy or vibration through a coupling method or piezoelectric transduction which then create a deflection or displacement in the system atmosphere instead of the material itself to generate electrical charges. So, as a system, this concept has been adapted as one of the definition or approach in the piezoelectric energy harvesting system mechanism (Maiwa, 2016; Nia, Zawawi and Singh, 2017; Liang, Hao and Olszewski, 2021; Sezer and Koç, 2021).

According to several research studies, most of the applications of piezoelectric EHF technologies demonstrated their limitations in generating adequate high output energy power. Liang, Hao and Olszewski (2021) and Sezer and Koç (2021) specifically, in their studies had collected and listed out several different piezoelectric-based energy harvesting technologies with their respective output energy power. Some of several noteworthy technologies with high energy generation are one with different additional energy harvesting approaches such as electromechanical vibration and electromagnetism induction and with the range of 7 W to 20 W (Elhalwagy, Ghoneem and Elhadidi, 2017; Liang, Hao and Olszewski, 2021). Li and Strezov (2021) and Yingyong et al. (2021), in their respective studies, they had established that an enhanced piezoelectric energy harvesting can be developed to increase the energy production performance of energy harvesting technology by combining different mechanisms of different energy harvesting approaches such as the spring mass system for mechanical energy harvesting as shown in Figure 2.3 below but with piezoelectric effect as the main element in the harvesting technology.

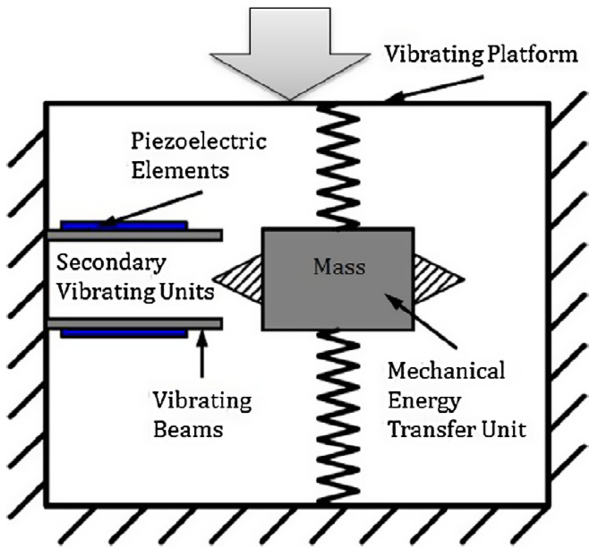

Figure 2.3: Spring mass system in piezoelectric energy generator (Rastegar, Pereira and Nguyen, cited in Li and Strezov, 2021)

In regards of piezoelectric EHF, it takes the combination of concept piezoelectric effect with different mechanisms via electromagnetic transducer or vibration spring mass mechanism in a system to convert the mechanical load exerted from human movement onto the surface of a tile into electrical charges.

2.2. Piezoelectric Energy Harvesting Technology Application

Presently, there are several types of piezoelectric energy harvesting technology available and, in this section, classification of those available types which include commercialized energy harvesting device technology and self-built prototypes as EHF are introduced and tabulated according to their features as presented in Table 2.1 and Table 2.2 respectively.

Table 2.1: Patented piezoelectric EHF technologies

Energy harvesting technology	Features description	Source reference
Pavegen tile	Triangular composite tile surface with electromagnetic generators	Pavegen, (2021)
Innowattech	Multi-layer piezoelectric generator pedestrian and road tiles	Henderson and Henderson, (2021)
Sustainable Energy Floor (SEF)	Kinetic energy tiles with electromagnetic generator	Energy Floor, (2021), Solban and Moussa, (2019), & Elhalwagy, Ghoneem and Elhadidi, (2017)
Veranu kinetic floor	Energy harvesting tiles with spring system with piezoelectric material enclosed in eco-friendly plastic materials	Startup Europe Awards, (2021)
Waynergy	Indoor & outdoor pavement tiles with electromagnetic technology	Solban and Moussa, (2019) & Elhalwagy, Ghoneem and Elhadidi, (2017)
Sound Power	Power generating floors through floor vibration of pedestrian traffics	Elhalwagy, Ghoneem and Elhadidi, (2017) & Narumi (2021)
Kinergypower	Highway road traffic pavement tiles with actuated electromechanical generator	Kinergypower (2021)

Table 2.2: Self-built piezoelectric EHF technology prototypes

Energy harvesting technology	Features description	Source reference
PZT floor tile carpet	Piezoelectric tile box consists of four piezo disc element of Lead Zirconate Titanate (PZT) and a capacitor	Chew et al. (2017)
Wood layers PZT floor tile	35 units of PZT cell disc element sandwiched between wooden layers with springs attached in between the top and bottom wooden layers	Dalabeih, Haws and Muhtaseb (2018)
Wireless occupancy sensor floor tile	An enclosed floor tile consists of cymbal transducer with PZT layers. Real function is to submit a wireless transmission as a self-powered sensor	Sharpes, Vučković and Priya (2015)
Pedestrian piezo floor tile	A tile consists of 44 units of piezoelectric cantilevers connected to a rectifier	Yingyong et al. (2021)

As tabulated, each type of piezoelectric EHF technology has their own specific features and some of them have been implemented in real time as energy harvesting devices especially the patented technologies. Some of the technologies are designed using the direct piezoelectric effect mechanism and some others especially the patented system, are designed by combining the different approach in energy harvesting which include the electromagnetism induction and electromechanical vibration mechanism. From the findings also, it was reported that the most commonly used for piezoelectric material in the mechanism of the piezoelectric EHF technology is the PZT type. However, as discussed in the previous section, EHF technology with the use of PZT material as the main element can only generate low amount of electrical energy which allow to be used in low power applications only. So, to further discern the real potential of the power generation for every different type of piezoelectric EHF technology tabulated in the previous Table 2.1 and 2.2, a comparison on their respective parameter of electrical energy generation is listed in the Table 2.3.

Table 2.3: EHF technology electrical energy production

Energy harvesting technology	Electrical energy generation per tile or per step	Source reference
Pavegen tile	7 W per step	Elhalwagy, Ghoneem and Elhadidi, (2017)
Innowattech	400 kWh with 600 vehicles on 1 km stretched of generator. Unspecified value for one step generation.	Henderson and Henderson, (2021)
Sustainable Energy Floor (SEF)	1. Nominal output: 1~10 W 2. Continuous output: Max 30 W 3. Average output: 7 W	Energy Floor, (2021), Solban and Moussa, (2019), & Elhalwagy, Ghoneem and Elhadidi, (2017)
Veranu kinetic floor	2 J per step	Startup Europe Awards, (2021)
Waynergy	10 W per step	Solban and Moussa, (2019) & Elhalwagy, Ghoneem and Elhadidi, (2017)
Sound Power	0.1 watt per 2 steps	Elhalwagy, Ghoneem and Elhadidi, (2017) & Narumi (2021)
Kinergypower	16.5 GWh a year on 200 meters of pavement with generators. Unspecified exact value for one step generation.	Kinergypower (2021)
PZT floor tile carpet	3.80 J/step or 0.000019kWh/person	Chew et al. (2017)
Wood layers PZT floor tile	215 W per 75 steps	Dalabeih, Haws and Muhtaseb (2018)
Wireless occupancy sensor floor tile	~100 mW to several watt depending on the device range and coverage area. Unspecified exact value for one step generation.	Sharpes, Vučković and Priya (2015)
Pedestrian piezo floor tile	$35mW_{rms}$	Yingyong et al. (2021)

For the self-built piezoelectric EHF system prototypes, the selected four prototypes are noticeably highlighted due to their distinct and unique features and characteristics, with the addition that they are from the most recent studies and specifically noted to be implemented as a floor tiles system in a building. Although there are several other different approaches and designs of the self-built piezoelectric EHF prototypes, most of the outcomes, though having high potential for future improvement, had showed that they are lacking in the properties of high electrical energy production making those prototypes to be insignificant to be implemented in a bigger scale. The average of maximum range of power output reported is as low as 3.5 µW to the highest at 675 mW (Nia, Zawawi and Singh, 2017; Wang, Zhao, Li and Li, 2018).

Basically, from the tabulated findings in Table 2.3, the piezoelectric EHF technologies could be arranged according to the amount of their electrical energy output generation for the framework on selecting the ideal piezoelectric EHF candidates for the implementation as ECM in this study and the three best top candidates according to their respective average electrical energy output, would be: (1) Waynergy, (2) SEF, and (3) Pavegen tiles. Best to note also that the wireless occupancy sensor floor tile self-built prototype would have been a great potential as ECM since it uses a different approach from the conventional energy harvesting mechanism whereby it uses its mechanism to self-powered and becoming a sensor to control other electrical or electronic devices in a building (Sharpes, Vučković and Priya, 2015).

2.3. Case Studies of Piezoelectric EHF Technology Application in Building

This section will present some of the case studies examples which have implemented and integrated the piezoelectric EHF technology system in a building. All case studies presented in this section are based on the selected piezoelectric EHF system technology tabulated in the previous section.

2.3.1 Case Study 1: Pavegen energy harvesting walkaway

The Pavegen walkaway tile system's key components are basically an equilateral triangular composite tile surface with a dimension of 500 mm x 500 mm x 500 mm. Attached at the bottom to it are three units of electromagnetic generators with a total height at rest of 89.50 mm. It was reported that the technology can be used either as indoor or outdoor applications. Figure 2.4 below shows the exact form of Pavegen tile module. The tile module is an innovation where it takes significant downward forces from the human footfalls which then cause the plunger equipped in the system to displaced at most 10 mm and spinning the internal flywheel of the electromagnetic generator to generate electrical energy (Pavegen, 2021).

Figure 2.4: Pavegen tile

As of current year of 2021, the technology has reached at least in 45 locations of buildings and areas around the world. It was installed and implemented as a sustainable solution in the respective location. Some of the locations include some educational center buildings, retail complex buildings, transport hub buildings and many more. However, there are no available report or literature on the system applications and implementation to report on how much it had harvested from the implementation and how much it had impacted the overall building energy consumption performance for each case location acclaimed. One can only assume that the 5W noted in the official site and some of the review studies show the exact amount contributed from the EHF technology. Nevertheless, the general main data still stands which is the kinetic energy captured from the human footfall activities will be either stored or converted into electrical energy which can at least light up a bulb for a period of time (Pavegen, 2021; EL-Eshy, El-Maadawy and Mohamed Abdalla, 2018).

Figure 2.5 below shows some of the case studies which have implemented the permanent Pavegen walkaway tile as one of their sustainable building solutions.

(a) (b) (c)

Figure 2.5: Pavegen energy harvesting walkaway at (a) Bedford Modern School, UK, (b) Barcelona Supermarket, Spain, (c) The Mercury Mall, Romford (Pavegen, 2021)

Despite no available data report on the actual Pavegen EHF system application, there are some studies which had conducted a simulation on how much it would impact the overall building energy consumption. Elhalwagy, Ghoneem and Elhadidi (2017) had conducted a feasibility study on two case studies through energy simulation. In the literature, Elhalwagy, Ghoneem and Elhadidi (2017) managed to demonstrate a 98.72% of saving percentage with only 14 units of Pavegen tiles applied at the entrance and exits platform of a metro station that is visited daily by 150 thousand persons. The second case study was conducted at a private residential apartment with 5-persons lived in family members. It was estimated that there would be an average of 150 footsteps for every tile daily with 16 units of Pavegen tiles installed in the location and with that parameter considered, the outcome of saving percentage was recorded to be in negative value of 1,434.25% (Elhalwagy, Ghoneem and Elhadidi, 2017). The only difference in the parameters is the number of steps applied onto the tile module which had significantly impacting the final results.

Similarly, a study by Li and Strezov (2021) was conducted in a library area of an educational building through energy modeling and qualitative measurement analysis. In the literature, it was noted the number of pedestrians and the number of tiles are the main parameters that affect the potential and integration of 1820 tiles Pavegen tile modules in the library building (Li and Strezov, 2021). It was concluded that with the application of 1820 Pavegen tile modules which occupy only 3.1% of the total floor areas of the library building, they managed to project the electrical energy generation to be 9.9 MWh in a year which was also approximately 0.5% of the total energy consumption in the case study building (Li and Strezov, 2021).

From both literature studies, it can be concluded that the important parameters that should be considered in determining the potential of piezoelectric EHF system technology as an ECM are the number of steps or the concentration of footfall density in a location of a building as well as the number of tiles employed in the overall system. In addition, different types of buildings with different functions may also impact the overall performance of the piezoelectric EHF as proven in the case studies conducted by Elhalwagy, Ghoneem and Elhadidi (2017)

2.3.2 Case Study 2: Sustainable Energy Floor (SEF)

The SEF is designed by using the primary concept of electromagnetic mechanism in the module with the dimension of 500 mm x 500 mm x 100 mm. The center of the tile module is made of different types of material such as recycled ceramics, recycled rubber, glass or bamboo, while the top that seal the module is made of flexible rubber seal and the housing for the entire module is made of stainless steel. Since the main mechanism of this EHF technology is the electromagnetism, a generator with a feature like a dynamo system is placed within the center of the module with springs attached in between the top seal and the inside bottom of the module. The working principle is basically when there is a vibration energy presents on the system, the generator will transform the small vertical movement into a rotating movement which then drives the generator to generate electrical energy (Energy Floor, 2021). It is also mentioned in the official specifications publication that if maintained regularly, the lifetime of the module could reach minimum of 15 years. Figure 2.6 below illustrates the actual SEF tile module.

Figure 2.6: SEF tile

SEF technology is also presently known as one of the EHF solution providers and it also has reached many locations globally. Some of locations include a retail complex and a business center as shown in Figure 2.7 below.

(a) (b)

Figure 2.7: SEF tile modules at (a) Green Pea Shopping Mall, Italy and (b) AFAS Experience Center, the Netherlands (Energy Floor, 2021)

However, similar like Pavegen technology, there are no available of actual data report on the application of SEF in real buildings. One literature did a review on one application of an EHF from the same provider as SEF in a building (Solban and Moussa, 2019). The technology mentioned is a Sustainable Dance Floor (SDF) which uses the exact same mechanism as SEF's mechanism where the module of SDF will flex when vibration energy is present on the floor tiles. The only differences are the size of the module as well as electrical energy output generation per step of per module. Solban and Moussa (2019) noticed that the SDF tile modules installed at the Club Watt located in Rotterdam could generate electrical energy which then result in the savings of 30% of the overall building energy consumption.

Accordingly, there are some studies which had conducted qualitative simulation on the application of SEF in actual buildings. From the same authors who had conducted a simulation on Pavegen tile for two different case studies, the same energy simulation was also conducted on the application of SEF at the same two locations. In the first case study of SEF application, the study showed a promising saving percentage of 99.48% with only 10 units of SEF modules at the entrance and exit of the metro station (Elhalwagy, Ghoneem and Elhadidi, (2017). Conversely to the first case study's result, the result for the second case study with 12 units of SEF modules showed a negative value of 526.22% of the saving percentage which also quite similar like the result exhibited from the application of SEF showing the significant impact of the parameters of footfall density and type of building on the EHF technology application (Elhalwagy, Ghoneem and Elhadidi, (2017).

In a different literature study, Solban and Moussa (2019) had conducted a qualitative energy simulation on SEF tile module application at a different metro station with the highest average number of visitors to be around 57,000 persons in one day. The results showed a saving percentage of 99.3% with only 12 units of SEF tile modules integrated into the building (Solban and Moussa, 2019).

Moussa (2020) in his study, had conducted a similar qualitative energy simulation but with a different parameter for the application of SEF tile module in a building. The difference was the type of the building which in this context, Moussa (2020) used a children outdoor play area at a sporting club located in Cairo, Egypt as his case study location. The floor area of the location was actually bigger than expected which was 594 m^2. Hence, the author had decided to employ 260 units of SEF tile modules in the area (Moussa, 2020). So, with an average number of visitors of at maximum 1060 persons to the area in a day, it was calculated that the total electrical energy generated would be 1820 kW per day (Moussa, 2020). This amount was reported to be approximately 83% of the total sporting club building energy consumption.

2.3.3 Case Study 3: Waynergy kinetic energy floor

The only specifications available for Waynergy technology are that it uses the concept of electromagnetic technology, and the dimension of the module is 400 mm x 400 mm. It is reported to have two types of modules: (1) Waynergy module for pedestrians with 10 W of output generation per step, and (2) Waynergy module for vehicles with 240 W of output generation for every vehicle crossing. Figure 2.8 below shows the image of the tile module for the Waynergy people version.

Figure 2.8: Waynergy people module

Similar like the other two Pavegen and SEF tile technologies, there are no available actual data report that can be accessed to know the real implications of the application of Waynergy people module in a building. Solban and Moussa (2019) however, did a case study review on Waynergy technology but with the different type of tile module used in the application. It was mentioned that Waynergy tile modules for vehicle were installed on a bridge of Ponte 25 De Abril located in Lisboa, Portugal. With the implementation of the Waynergy technology on the bridge, the bridge could save the energy and the energy cost for the bridge illumination for about 65% savings with the payback period only within 5 years (Solban and Moussa, 2019).

Elhalwagy, Ghoneem and Elhadidi (2017) also had conducted similar qualitative energy simulation like the one for Pavegen and SEF tile modules for the pedestrian's version of Waynergy tile module technology. Similar in the case of saving percentage achieved, Waynergy technology managed to save close to 99.93% with only 7 units of pedestrian Waynergy tile module installed at the entrance and the exit of the metro station. Surprisingly for the second case study in the literature, Waynergy outperform Pavegen and SEF tile modules' performance with an exceptional result of saving percentage at 12.33% with only 8 units of Waynergy tile module technology in the apartment (Elhalwagy, Ghoneem and Elhadidi, (2017). This might be due to the amount of electrical energy output generation is higher compared to Pavegen and SEF's output generation.

2.3.4 Case Study 4: Self-built piezoelectric EHF system prototypes

In section 2.2, the first highlighted type of self-built prototype is the piezoelectric tile that is built in a box with the dimension of 457.20 mm x 457.20 mm with PZT materials as the main piezoelectric material element in the prototype system (Chew et al., 2017). So, the first part of this sub-section is based on the literature study by Chew et al., (2017). The case study location for the tile implementation was at Kuala Lumpur International Airport (KLIA) Malaysia. The tile module used in the literature study was estimated to have an efficiency of 50% of energy production, making the energy that could be harvested from the tile would be 50% from the actual energy generated. It was calculated that the average electrical energy output generation that could be harvested from the prototype was 3.8 J per step which is equivalent to 0.000019 kWh per person for every 12 feet-units of tile module. So, with an approximately 31000 passengers present in an area of one focus spot in throughout the whole KLIA building, the energy that could be harvested would be 0.589 kWh in a day. It was calculated that this amount could at least illuminate 84 units of LED type of light bulb. By the end of the study, Chew et al., (2017) noted that although the initial cost for the piezoelectric tile module is very expensive that the price itself could cover almost double the price of the LED lightbulb installation, but since the principal mechanism of the piezoelectric tile module is self-generate electrical energy, hence the payment of the electrical energy for the LED light bulb's illumination had been covered. The total payback period for this tile module installation is basically 0.5 years.

The second part of this sub-section is based on the literature study by Dalabeih, Haws and Muhtaseb (2018) for the case study of specially designed floor tiles with wooden layers. The mechanism used for the piezoelectric tile module was direct piezoelectric effect. The initial result was found to be 27.988 mW. However, the author had decided to use the commercialized output power established by the manufacturer which is 2 mW per tile for every two steps. The author had tabulated the final results with the dependent of footfall traffic at different operation hours. Based on this study, one more important factor which could be considered as the parameter of piezoelectric EHF technology is the footfall density in respect with operation time.

The third part of this sub-section is based on the literature study by Yingyong et al. (2021). The piezoelectric tile module used in the literature is basically an advanced version module of the one in their previous studies. It was noted that the electrical energy generation is higher compared to the previous module with it being larger in size. 44 units of piezoelectric cantilevers were installed and connected parallelly within the module as the main element of the piezoelectric tile module mechanism. The tile module was not tested or integrated into a building. However, the significant of this literature study is that, from the test performed on the piezoelectric tile module, it showed that the voltage and energy value increase with the number of footsteps exerted on the tile module.

The fourth part of this sub-section is based on the literature study by Sharpes, Vučković and Priya (2015). In the literature, the main feature of the piezoelectric tile module was indeed energy harvesting but instead of harvesting the wasted energy from the human footfall activity to generate electrical energy which that can be used to power different type of electrical or electronic devices, it used the principle only to self-power the very piezoelectric tile module. By powering the piezoelectric tile module, the module itself will act as a sensor whereby it will indirectly control other electrical or electronic devices or appliances in the building, for example, if the room is empty then the light will automatically off. Basically, this is quite a unique approach for a piezoelectric to be act as an EHF technology and at the same time, it gives an idea of a different approach for building ECM solution.

2.4. Conclusion of the Literature Review

The overall literature review section began with an overview of the basis mechanism of the piezoelectric direct effect phenomenon in the piezoelectric EHF technology as an energy harvesting system. Following this was a detailed review of the various piezoelectric EHF technologies available. The piezoelectric EHF technologies covered include the technologies that are currently in the market, patented technology, and the prototype models which are still in the experimental stage. The literature review is then continued with several case studies of the piezoelectric EHF technologies in actual building application, paying particular attention to actual use and real implementation and integration of the piezoelectric technologies in buildings as their sustainable EHF technology mechanism as well as the models which are still in the experimental prototyping stages.

From the tables detailing the various application of piezoelectric EHF technologies: Table 2.1 through Table 2.3, a wide variety of methods, mechanism features and their respective potential electrical energy generation have been listed and presented accordingly. In addition, the variety of the piezoelectric EHF technologies are divided into two categories which are the patented piezoelectric EHF technologies and self-built piezoelectric EHF technology prototypes. The two sets of data are then compared based on their potential electrical energy generation which can be harvested on a tile for every one step occurrence. It was found that the electrical energy levels that can be generated through human footsteps are distinctly different for each technology. Specifically, there is a large gap between the amount of potential electrical energy generation for the patented technology and experimental prototypes. While the patented technologies demonstrate promising amount in macro level which are also proven to result in higher power outputs, the experimental prototypes conversely show results in micro watt level. Since the fundamental parameter that dictates a piezoelectric EHF technology feasibility is the amount of the electrical energy generation, significantly, the appropriate amount which can be considered useful for powering an appliance would be the one that could generate high watt value. In this context, the piezoelectric EHF technology itself is categorized as a micro level energy harvesting system and to create a big scale of piezoelectric energy harvesting system especially for the implementation of such technology as a building ECM, it would require a large number of the EHF modules. Hence, the best technology features would be from the technology which could harvest and generate the acceptable amount from one module of piezoelectric floor tile and able to be integrated into a larger scale of energy harvesting system in a building. These features are considered as the basis models for further analysis under the research problem in this paper and the top three piezoelectric EHF technologies chosen as are tabulated as in Table 2.4 below.

Table 2.4: Selected piezoelectric EHF technology models

No	**Energy harvesting technology**	**Electrical energy generation per tile or per step**	**Features description**
1	Waynergy	10 W per step	Indoor & outdoor pavement tiles with electromagnetic generator
2	Sustainable Energy Floor (SEF)	1. Nominal output: 1~10 W 2. Continuous output: Max 30 W 3. Average output: 7 W	Kinetic energy tiles with electromagnetic generator
3	Pavegen tile	7 W per step	Triangular composite tile surface with electromagnetic generators

Following this decision, literatures on several case studies based on actual projects or researches on the implementation of the listed piezoelectric EHF technology in a building are searched and reviewed. Given the justification for focusing on the top three chosen piezoelectric EHF technology, the review analysis necessitated the application of the mentioned three piezoelectric EHF technology in actual implementations and its potential and substantial contribution as ECM in a building. For comparative purposes, reviews on the case studies for the self-built piezoelectric EHF system prototypes are given and highlighted as to encompass both technical mechanism and potential savings context of the experimental prototypes as building ECM.

Table 2.5: Summary of the selected piezoelectric EHF technology energy saving potential

No	Energy harvesting technology	Potential electrical energy saving in percentage	Numbers of tiles installed/simulated	Building operation condition
1	Waynergy	99.93%	7 Units	Entrance & exit of metro station (150k persons)
		12.33%	8 Units	Residential house (5 persons)
2	Sustainable Energy Floor (SEF)	99.3% ~ 99.48%	10 ~ 12 Units	Entrance & exit of metro station (57k ~ 150k persons)
		83%	260 Units	Recreational area (1060 persons)
		-526.22%	12 Units	Residential house (5 persons)
3	Pavegen tile	98.72%	4 Units	Entrance & exit of metro station (150k persons)
		0.5%	1820 Units	Library hall in educational building premise
		-1,434.225%	16 Units	Residential house (5 persons)

Table 2.5 summarizes the potential ECM candidates with their respective technical implementation features. With all the information stated in the previous sections, it can be seen that all three patented piezoelectric technology chosen as the basis models are potential candidates for building ECM with most of them having great capability in generating high amount of electrical energy with acceptable amount of piezoelectric EHF modules to be installed in a building. Contrary to the conventional application of piezoelectric as listed in Table 2.5, most of the experimental prototype models are lack in the sense of higher electrical energy output generation. However, there is one noteworthy application feature which can be considered as a potential of energy harvesting technology in future application and implementation for building ECM which is the self-powered wireless sensor.

CHAPTER 3

DATA COLLECTION

3.1. Building Preliminary Energy Audit

This section presents all the findings from the data collection activity for the selection of building model for this study. All data presented in this section are estimation and some are imitation of average values for several actual buildings. In this context, the building preliminary energy audit focuses on the preliminary data gathering and simple analysis of the data collection. All necessary building primary data & general information have been listed in Table 1.2. Thus, from the list, a simple estimation of all value acquired from the data collection is calculated to result in one definite imitation value for each parameter. In general, several actual building models are audited, and the most realistic average values of the selected parameters are taken into consideration to represent one type of building. Although in actual auditing, it would be difficult to finalize the final value of each parameter for each types buildings

By the end of this section, scatter diagram based on the TEC, NLA and AP of the actual buildings as tabulated in this section are used to determine the relation of the TEC, total NLA and AP in which then can be used as the baseline model of electrical energy consumption for each building model types. The decision to choose NLA and AP as the variables for the scatter regression diagram is due to the approach taken in most literatures in determining the best parameters in optimizing the application of piezoelectric EHF technology in a building. The conclusion for the parameter selection from the TEC versus NLA and AP diagram is taken by determining the R-squared value of the relation. R-squared value is the coefficient of determinations of relationship model between several variables in a group of statistical data derived from a regression analysis. As mentioned earlier, the variables selected in this context are the TEC, NLA and AP accordingly.

3.1.1. Building model for higher educational building

For higher educational building, there are four actual buildings which are taken into consideration in the first preliminary energy audit. To be precise, four premises of different local universities and polytechnics are selected. The building typology for each premises are considerably similar to each other despites most of the buildings' shape are in irregular block shapes. In addition, that the NFA for each building block in every premises are also noticeably comparable. The summary description of the building typology of the four premises are as follows:

1. Four parallel units of three-level administration and lecture halls blocks
2. At least five units with average height of five stories of grouped hostel blocks
3. One open-spaced canteen/dining hall block
4. One activities-centered hall (Mosque/main hall/student center)

In addition, the premises' schedule operations for each premise are also similar where they operate from 8:00 am until 5:00 pm for the administration blocks and as for the lecture hall blocks, they run from 8:00 am until 5:00 pm on normal days but during special occasions or additional classes demand, they operate at least until 10:00 pm. As for the hostels block, they operate almost 24 hours considerably that the students are not entitled to empty the blocks during daytime. Basically, from this information, we can assume that the premises operate for at least 24 hours.

The only significant difference is the number of premise occupations. Thus, as mentioned earlier, all data and information are only estimation and the final average value are estimated, calculated and tabulated as in Table 3.1 below.

Table 3.1: Higher educational building data descriptions

	Details
Building Type	Higher education institution
Parameters	
General Structure Overview	- Building premise which includes scattered irregular sized of building - Hostels are more than 3 floor levels
Total Gross Floor Area (GFA)	74,327.33 m^2
Total Net Lettable Area (NLA)	74,035.49 m^2
Maximum Demand (MD)	1,542.00 kW
Total Yearly Energy Consumption (TEC)	8,425,574.00 kWh
Tenaga Nasional Berhad (TNB) Electricity Tariff Classification	C2 (Commercial with Peak and Off Peak)
Building Operating Hours (H_{op})	Monday – Friday (Administration) 8:00 am – 5:00 pm Monday – Sunday (Hostels) 24 hours
Building Average Population (AP)	4,890 persons

3.1.2. Building model for skyscraper of office building

For skyscraper of office building, there is only one sole candidate for the building model in the first preliminary energy audit. Due to the MCO situation however, the building was operating on 50% from the total load operation and thus, the actual data for several parameters might not be relevant. Hence, the projection data from the previous year is used instead. The final average values are estimated, calculated and tabulated as in Table 3.2 below.

Table 3.2: Skyscraper - Office building data descriptions

	Details
Building Type	Skyscraper – Office building
Parameters	
General Structure Overview	- 36 stories purpose-built office with several floor as common areas and lobbies - Geometrical block shape
Total Gross Floor Area (GFA)	120,666.02 m^2
Total Net Lettable Area (NLA)	100,852.34 m^2
Maximum Demand (MD)	3,598.58 kW
Total Yearly Energy Consumption (TEC)	1,736,735.83 kWh
Tenaga Nasional Berhad (TNB) Electricity Tariff Classification	C1 (Commercial)
Building Operating Hours (H_{op})	Monday – Friday 6:00 am – 6:00 pm Saturday 8:00 am – 12 pm Sunday Off
Building Average Population (AP)	2,339 office workers + ~ 1,500 visitors

3.1.3. Building model for manufacturing factory

Similarly for manufacturing factory building, there is only one sole candidate for the building model in the first preliminary energy audit. Also, due to the MCO situation, the building was not fully operating and thus, the actual data for several parameters might not be relevant. Hence, the projection data from the previous year is used instead. The final average values are estimated, calculated and tabulated as in Table 3.3 below.

Table 3.3: Manufacturing factory data descriptions

	Details
Building Type	Manufacturing factory
	Parameters
General Structure Overview	- 1 building with 3 floors above ground, 3 buildings with 1 floor and 1 tower building - Geometrical block shape
Total Gross Floor Area (GFA)	80,000 m^2
Total Net Lettable Area (NLA)	48,706 m^2
Maximum Demand (MD)	1,840.00 kW
Total Yearly Energy Consumption (TEC)	9,669,818 kWh
Tenaga Nasional Berhad (TNB) Electricity Tariff Classification	E2 (Medium Voltage with Peak/Off peak Industrial))
Building Operating Hours (H_{op})	Monday – Sunday 24 hours
Building Average Population (AP)	1,314 persons

3.1.4. TEC – AP and TEC – NLA scattered diagram with R square value

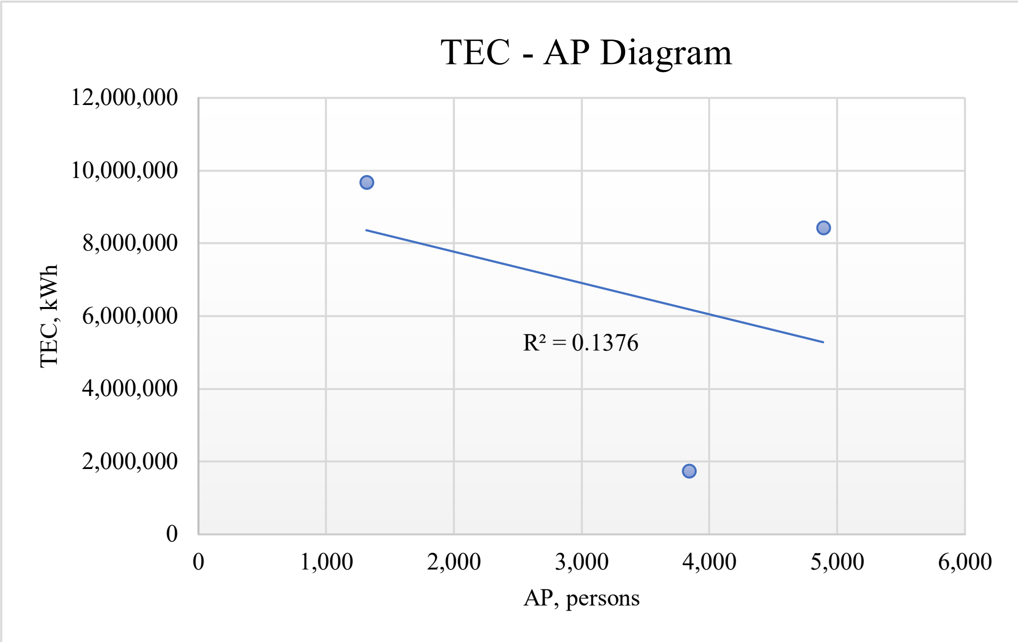

Figure 3.1: TEC-AP Diagram

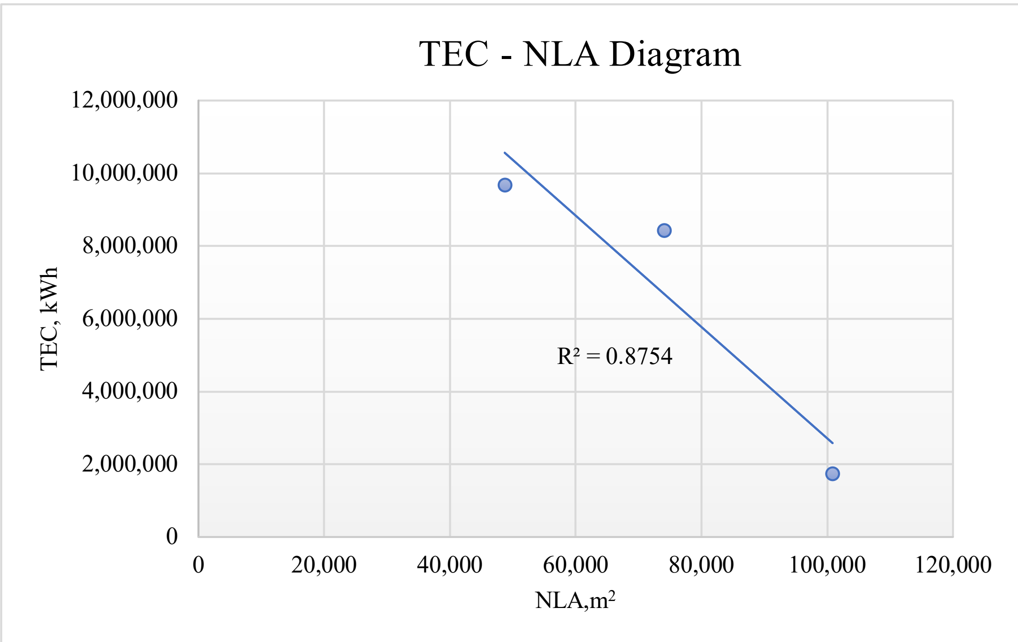

Figure 3.2: TEC - NLA diagram

As shown in the Figure 3.1 and 3.2, R^2 value for TEC – AP is 0.1376 and R^2 value for TEC – NLA is 0.8754. R^2 value for TEC – NLA is relatively higher compared to the R^2 value for TEC – AP which also relatively means that the usable space area is affecting more on the total energy consumption of a building rather than the numbers of population in the building. It is also correlated with the fact that most of the factory buildings evaluate their building energy efficiency and sustainability by using the numerical indicator of specific energy consumption (SEC) calculation rather than using the building energy intensity index (BEEI) calculation.

Thus, following these findings, the main parameter that is considered to model the energy simulation would be the space area dimension for the installation of the piezoelectric EHF technology. However, this is only an idea which is based on the relation and correlation between the three main variables. Thus, the idea is to locate the available hot spot within the building and to measure the space area that is suitable to install the piezoelectric EHF technology. By measuring and determining the space area for the installation, it would also help in determining the allowable numbers of the piezoelectric EHF which can be applied and installed at the designated area.

3.2. Piezoelectric EHF technology technical properties and specifications

This section presents all findings from the data collection activity for the selection of piezoelectric EHF technology for this study. All data presented in this section are based on the findings and information gained mostly from the literature review and in addition, the data parameter integration for the selected best piezoelectric EHF technology is deducted from the literature review.

Aforementioned, the prerequisites for a piezoelectric EHF technology system to be implemented as building ECM can be best explained in terms of its overall energy harvesting ability, technical integration, product or device life cycle and most importantly, the overall investment expenditure required to implement the technology as a system in a building. Although it is important to also investigate the mechanical properties of the piezoelectric EHF mechanism but the most crucial aspects of an ECM implementation are the electrical energy properties of the tools or appliances equipment associated to the ECM and their counterparts which could affect the overall performance of the electrical energy properties, i.e., the system conversion efficiency.

Hence, apart from the implied parameters from the previous literature reviews, there are several other parameters or properties that should also need to be considered as they could also affect the overall selection process of the piezoelectric and some of them are:

1. The conversion efficiency which is the ratio between the usable output of energy of energy harvesting or conversion device with the energy input.
2. Installation method or configuration which is the different techniques or methods to install the device.
3. Technology readiness levels (TRL) in which is a type of measurement rating or scaling system to evaluate the maturity level of a technology

during its developmental stages. The rating scale numbers of TRL are as in the Table 3.4.

Table 3.4: TRL scaling system descriptions

TRL Scale	Description
TRL 1	Basic principle observed and reported.
TRL 2	Technology concept and/or application formulated.
TRL 3	Analytical and experimental critical function and/or characteristic proof of concept.
TRL 4	Component and/or breadboard validation in laboratory environment.
TRL 5	Component and/or breadboard validation in relevant environment.
TRL 6	System/subsystem model or prototype demonstration in a relevant environment.
TRL 7	System prototype demonstration in a operational environment
TRL 8	Actual system completed and qualified through tests and demonstration.
TRL 9	Actual system proven in operational environment.

Source: Twi-global.com

The accomplishment of having high performance for the respective piezoelectric EHF technology as building ECM is an obvious target of this paper. So, to evaluate more on which technology features is the best candidate for building ECM, a comparison on each different decisive parameters as shown in Table 3.5 on the following page.

Table 3.5: Comparisons of the top performers of piezoelectric EHF technology

Properties	**Waynergy**	**SEF**	**Pavegen**
Power generation	10 W	Average of 7 W	7 W
Unit dimension	400 mm x 400 mm	500 mm x 500 mm x 100 mm	500 mm x 500 mm x 500 mm x 89.50 mm (height)
Shape form	Square box	Square box	Triangle
Materials	Unspecified	Top seal: Rubber Module center: Recycled materials such as; recycled rubber, recycled ceramics, glass or wood Module casing: Stainless steel	Top sheet: Altor stronghold 30 Toe caps: Stainless steel Surface tile: Glass reinforced plastic (GRP) Generator housing: Aluminum alloy
Price per unit tile	RM 1,910.07[1]	RM 4,037.51[2]	RM 1,671.91[3]
Conversion efficiency	50%	Unspecified	Unspecified
Lifetime	20	15	20
Installation configuration	Tile replacement	Tile replacement	Tile replacement or on-top-surface mounting
TRL	TRL 7	TRL 7	TRL 9

[1] 400 EUR, 1 EUR = 4.77252 MYR, 1 MYR = 0.209533 USD
[2] 954 USD, 1 USD = 4.23010 MYR, 1 MYR = 0.236401 USD
[3] 395 USD, 1 USD = 4.23010 MYR, 1 MYR = 0.236401 USD

CHAPTER 4

ENERGY MODELLING & TECHNICAL ANALYSIS

4.1. Building Energy Consumption Modeling

To compromise between the different parameters presented and tabulated in the previous chapters, this study suggests building an energy consumption model baseline for the selected building. It is just a simple analytical brief which uses the preliminary data obtained in Table 3.1 to 3.3 to determine the baseline consumption and space area needed for the application of the piezoelectric EHF technology in each of the building.

Table 4.1: Building models description

Parameters	**Higher education institution**	**Skyscraper – Office building**	**Manufacturing factory**
NLA	74,035.49 m^2	100,852.34 m^2	48,706 m^2
MD	1,542.00 kW	3,598.58 kW	1,840.00 kW
TEC	8,425,574.00 kWh	1,736,735.83 kWh	9,669,818 kWh
H_{op}	24 hours	12 hours	24 hours
AP	4,890 persons	3,489 persons	1,314 persons

As tabulated in Table 4.1, the TEC value is the baseline of the consumption for a year and so, to find a baseline consumption in a day is just by dividing the TEC with the numbers of operation hours as noted in $H_{op.}$ Moreover, since it has been established that the TEC is dependent on the value of NLA more than it to the number of populations. So, by using the NLA as the principal design of the size of the allowable application numbers of the piezoelectric EHF technology, the exact feasibility of power could be obtained. However, should be noted that although NLA is defined as the occupied space area, but not all usually fully occupied and having high footfalls. Hence, the estimation of 60% from the total NLA would be sufficient to be used in the calculation of feasibility of power. To justify this approach, a closed 1-door room concept can be used. A room with one exit and one way of movement, so imagine within the room, there is a table in the middle, the portion of the walkable in the area is only through the sides of the table which is also alongside the wall of room. Hence, the walkable area is the usually occupied area.

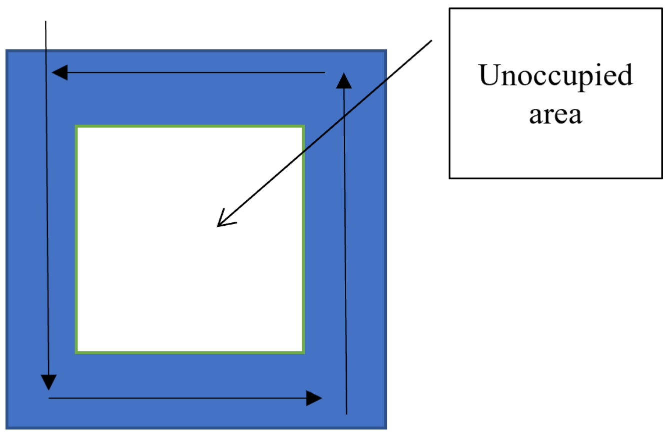

Figure 4.1: One door room concept

However, in different area of functions within the building, not all the estimated occupied area will be occupied thoroughly, so, one can deduce that within the 60% suggested occupied area, the only area that will be fully occupied with is another half of the 60% suggested occupied area.

This number also somehow had been supported in one study by Li and Strezov (2021). This practice is actually based on most countries' code of practices whereby under the occupational or workplace health, safety and welfare for the of office space per person in a standard office measurement (Bretteville, T., 2021). In Malaysia, the Department of Occupational Safety and Health (DOSH), Ministry of Human Resources had not set any exact figures on how big of an open walkable area in a room should be. The only reference given is that the personal space of per individual workstation should be 6.25 square meter and that figure is one rule of thumb given by the DOSH (Guidelines On Occupational Safety And Health In The Office, 2021).

Therefore, by exercising the rule of thumb and 1-door room concept as the main guide and reference for the assessment of the required or allowable unit quantity of piezoelectric EHF module unit which could be installed in a building accordingly. Table 4.2 on the following page summarizes the overall baseline of the allowable quantity for the installation and integration of the piezoelectric EHF modules respectively to each type of piezoelectric technology and buildings.

Table 4.2: Baseline data for building model

Parameters	Higher education institution	Skyscraper – Office building	Manufacturing factory
Average baseline daily consumption	1,393.12 kWh/d	804.04 kWh/d	1,598.85 kWh/d
Estimation of 60% of NLA	44,421.20 m^2	60,511.404 m^2	29,223.60 m^2
Estimation of 30% of NLA	22,210.65 m^2	30,255.70 m^2	14,611.8 m^2
H_{op}	24 hours	12 hours	24 hours
AP	4,890 persons	3,489 persons	1,314 persons
Allowable quantity of piezoelectric EHF module unit (= 30% NLA / AP / EHF Dimension)			
Pavegen	36 units	69 units	89 units
SEF	18 units	35 units	45 units
Waynergy	28 units	54 units	70 units

4.2. Selection of Piezoelectric EHF Technology through Technical Analysis

To perform technical analysis for the selected piezoelectric EHF technology, the parameters highlighted in Table 3.5 are fully considered and evaluated. From Table 3.5, it may be seen that most of the parameters are all filled except for the Waynergy's materials and Pavegen and SEF's conversion efficiency. On top of that, out of all the three-technology listed, Pavegen tile is having the highest rating in TRL. The value given is not referring to any literature and is totally from a personal observation as the technology brand of Pavegen has been recognized as one of the

EHF providers and the technology itself has been patented with many applications that has been implemented.

Other most important parameters that would be considered the eye-catching factor is the price of the tile technology. This price will be considered as the investment or incremental cost. From the Table 3.5, Pavegen EHF technology is the cheapest out of the three. Even at the price of RM 1,671.91 per tile module system, if applied properly could amount to a lesser payback period.

On top of that, in the case of floor tile implementation, the material itself need to be sturdy, has high durability and life cycle time. Although there are not yet any studies that have simulated the durability and the sensitivity performance of these piezoelectrical EHF technology, it can be concluded with the how long theirs life cycle.

All things considered, out of the selected three EHF technology introduced in the previous chapters, Pavegen has taken the top spot as the most preferable EHF technology that can be implemented as an ECM in a building with its being a device from an established technology, having high output generation at a considerably cheap price, high durability material components, long lifetime, and easy installation method.

CHAPTER 5

RESULTS & CONCLUSION

5.1. Energy Output Generation and Cost Analysis

The daily energy production daily which could be generated by the selected Pavegen tile for each type of building is tabulated in the following Table 5.1. As for the cost analysis, the values are tabulated in the Table 5.2. All measurement and calculation are based on the energy use in buildings assessment tool whichc is the Building Energy Intensity Tool (BEIT). BEIT is based on the Building Energy Estimation Tool (BEET) which is also used to perform easy and quick predictions of energy savings that can be achieved for various new design and retrofit measures.

Since Pavegen is selected as the basis model of piezoelectric EHF technology in this paper, the following measurements on the energy and cost savings are also based on the potential power generated by the Pavegen tiles. Respectively, for each building, the number of tiles employed are also different and thus, the probability to have different value of energy savings is also high. However, upon the first measurement, the overall energy savings for every building regardless of the different numbers of piezoelectric EHF modules employed, all three buildings show compelling results as tabulated in Table 5.1 whereby the results calculated are more than 90% energy savings for all three types of buildings.

Table 5.1: Comparison of energy generation output per tiles and operation of each building type

Parameters	**Higher education institution**	**Skyscraper – Office building**	**Manufacturing factory**
Average baseline daily consumption	1,393.12 kWh/d	804.04 kWh/d	1,598.85 kWh/d
Estimation of 30% of NLA	22,210.65 m^2	30,255.70 m^2	14,611.8 m^2
H_{op}	24 hours	12 hours	24 hours
AP	4,890 persons	3,489 persons	1,314 persons
Pavegen units (1)	36 units	69 units	89 units
Pavegen unit power generation (2)	7 W	7 W	7 W
Daily generation capacity (AP*1*2)	29,574.72 kWh/day	20,222.24 kWh/d	19,646.93 kWh/d
Daily energy difference percentage	95.29%	96.02%	91.86%

Table 5.2: Comparison of energy cost analysis of each building type

Parameters	Higher education institution	Skyscraper – Office building	Manufacturing factory
Average baseline daily consumption	1,393.12 kWh/d	804.04 kWh/d	1,598.85 kWh/d
Pavegen units (1)	36 units	69 units	89 units
Pavegen unit power generation (2)	7 W	7 W	7 W
Generation capacity (1*2)	252 kW	483 kW	623 kW
TNB tariff	C2	C1	E2
Electricity cost during peak hour	RM 0.365	RM 0.365	RM 0.355
Electricity cost during off peak hour	RM 0.224	Not available	RM 0.219
H_{op}	24 hours	12 hours	24 hours
Daily energy piezo EHF generation cost	RM 1,852.20	RM 2,115.54	RM4,460.68
Yearly energy cost	RM 666,792.00	RM 571,195.80	RM 1,605,844.80
Pavegen unit price	RM 1,671.91	RM 1,671.91	RM 1,671.91
Total Pavegen EHF system cost (A)	RM 60,188.76	RM 115,361.79	RM 146,799.99
Additional operational, maintenance, etc cost	RM 15,000.00	RM 15,000.00	RM 15,000.00
Total investment cost (B)	RM 75,188.76	RM 130,361.79	RM 161,799.99
Simple payback period (B/A)	0.11 years	0.23 years	0.1 years

5.3. Carbon Emission Impact Factor

The following values illustrate the combined margin emission factor for CO_2 in Peninsular Malaysia, Sabah and Sarawak respectively.

Table 5.3: Combined margin emission CO_2 factor

Regions	Combined Margin (tCO_2/MWh)
Peninsular Malaysia	0.585
Sabah	0.525
Sarawak	0.330

Source: Malaysian Greentech, 2017

So, by applying and implementing the piezoelectric EHF technology into a building and in this study, certain amount of CO_2 could be reduced since the energy generated is from system are circulated into the system meaning that there is no wasted energy and more importantly, the source of energy in this kind of system is from a renewable energy which is from human footsteps. The values are tabulated as in the Table 5.4 below.

Table 5.4: Carbon emission reduction

Parameters	Higher education institution	Skyscraper – Office building	Manufacturing factory
Daily generation potential savings	29,574.72 kWh/day	20,222.24 kWh/d	19,646.93 kWh/d
Carbon emission reduction	17.30 tCO_2	11.83 tCO_2	11.49 tCO_2

5.4. Discussion & Research Realization

The aim of this paper is to study the significance of implementing the piezoelectric EHF mechanism on different scenarios and the results obtained are profoundly illustrated together with the relationship between the primary variables of a building performance which in this case is the overall building energy consumption as well as the net lettable area and the numbers of people accommodating a building.

Going forward, this paper managed to investigate and conduct technical analysis on the performance of variety types of piezoelectric EHF technologies as energy harvesting mechanism for several parameters and important factors in energy output generation and consumption as stated in the very first main objectives of this paper. Certainly, there are several other input parameters which are not introduced in this study, and they should have been considered as the main factors in determining the approach for a proper performance study on either for the harvesting technology performance analysis or the building performance.

The second objective is to model the selected the best piezoelectric-based EHF technology mechanism and demonstrating its application in different types of buildings in Malaysia. The selection of proper piezoelectric EHF technology that could be implemented in a building as an ECM are conducted. For this part however, the final outcomes show no indication how the selection would have affected the ECM mechanism. However, with the lack of real time engagement with the actual building operation and real time scenarios, it somehow had slowed down the process of the selection of either the building model or also the piezoelectric EHF technology. Should there were any opportunities to conduct real time preliminary energy audit at the several selected buildings, the data would partially be accurate and realistic outcomes would be realized. Unfortunately, due to the MCO restriction, many buildings especially the big consumers are not allowing any outside visitors even for a period of time without prior appointment and valid reason.

The third objective of this paper is to study and analyze the significance, compatibility, and sustainability of the implementation off the mechanism to reach an amount of at least 5% of energy savings from the TEC. As shown in the results, the overall calculation show an impressive amount of energy savings at more than 90% for each buildings. Although, the numbers shown are relatively high but several literatures did come out with similar result confirming the validity of this results also. Perhaps, the only difference is that, the results shown are based fundamentally for the big electrical energy consumer buildings in Malaysia. Thus, this objective is seemingly achieved.

As for the final objective brought upon for this project, all things considered however, all the data presented in this study do reflect the actual data since they were based on the actual building operations and information. The only setback is that there is high probability that the results do not reflect the actual real time conditions. Similar when doing the modeling, the ecstatic of doing a modelling is so that we could get a full view on what is really happening while not really depending on the one parameter at a time and that is when the simulation takes into action where it provides a full projection and illustration ideas of what could happen and whatnot. However, again with the lack of engagement and this time is with the simulators –

simulators specifically with the performance-based simulation software. With the absence of this approach, it counters one of the approaches in this paper in which is to further analyze the elements to be utilized in the piezoelectric EHF mechanism to yield maximum output energy generation in a building. Unfortunately, the last objective is not achieved.

However, there is noteworthy items discussed within the literature review which should be taken into consideration for a betterment of piezoelectric EHF technology application. It was the wireless sensor based piezoelectric tiles. As the name itself described, it is actually a unique approach that can be further investigate and study to determine its full potential as a ECM in a building. The very main principle of the mechanism is to control other electronic devices in which when human steps on the tiles, it will send a signal into the wireless system let say a building automation system, to automatically control the usage of energy of the other equipment. So, instead of free and sustainable energy into the building, this technology would help to control the energy wastage from the study of operations within the building.

Lastly, this paper has significantly shown great results despite the shortfall of certain approaches to have a better measurement and verification.

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