

Energy generation in public buildings using piezoelectric flooring tiles; A case study of a metro station

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ABSTRACT

The building sector is benefitting from the significant advancements in clean energy harvesting technologies. The function of building products is witnessing a huge leap to extend beyond mere functional requirements to account for the environmental benefit as well. Piezoelectric flooring tiles are amongst the most promising for indoor energy generation especially in public buildings with great occupancy patterns and intensity. Hence, this study presents a comprehensive review of literature for the use of piezoelectric. The next step deduced parameter integration for the proper selection of piezoelectric tiles. This determined its successful application in the building industry-especially the transportation section which has a notable contribution to energy consumption and emission release. These were divided into factors related to the project type and location, as well as proper selection of the piezoelectric tile product. This hypothesis was tested in the case study. Hence, the application of piezoelectricity was investigated in a Metro station in a core urban area in Egypt, with an estimate of almost 57,000 daily passengers. The selection of the metro line and station as well as the location of installing the tiles was based on the highest passenger density class which provided the greatest step-footage. Furthermore, the selection of the number and type of piezoelectric tiles was determined based on the current project's energy consumption. The study compared the two shortlisted types of tiles in terms of their power generation capacity, initial capital cost, lifespan and expected savings. The results showed that twelve tiles were needed to generate the station's needs for electric energy using Sustainable Energy Floor tiles while only eight tiles were needed using Waynergy piezoelectric tiles. The results also showed a decrease in energy consumption and carbon emissions.

1. Introduction

Worldwide energy consumption is increasing daily, according to the [International Energy Outlook 2017](#), the energy consumption will increase from 575 quadrillions Btu in 2015 to 736 quadrillion Btu by 2040 which is equivalent to a 28 percent increase ([Moussa et al., 2019](#); [Shreeshayana, Raghavendra, & Manjunath, 2017](#)). Fossil fuels used to generate electricity have a negative impact on the environment at every stage of production till it is consumed, and relying solely on these energy resources to meet this new massive demand will result in more CO₂ gas emissions into the atmosphere, causing a significant increase in global temperatures ([Azizalrahman & Hasyimi, 2019](#); [Dawood, Crosbie, Dawood, & Lord, 2013](#)). However, the electricity produced from clean and renewable sources has lesser greenhouse gas emissions produced. The potential of buildings to generate energy is considered a substantial

change in the vision of resilient cities ([Lu, Fu, Osman, & Konbr, 2021](#)).

Egypt suffers from energy-related problems e.g. shortage in the power supply and high carbon emission. Buildings devour approximately 39% of the energy and 74% of the electricity produced annually ([Ahmad, Zhang, & Yan, 2020](#)). Also, the transportation segment is responsible for around 28% of the energy use and around 25% of CO₂ release. Total greenhouse gas emissions (GHG) from the transportation segment in Egypt are evaluated at 29 million tons of CO₂ ([Elkadeem et al., 2020](#)). Moreover, Metro Stations are an example of project types with high energy consumption and use density. The first metro line consumes about 12.5 Million kW per month while, the second 19 million kilowatts per month. Moreover, the third line consumes about 5 million kilowatts per month ([Elkadeem et al., 2020](#)). Hence, there is an urgent need to apply energy harvesting technologies to reduce energy consumption and emission reduction ([Moussa et al., 2020a](#); [Moussa,](#)

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Mahmoud, & Hatem, 2020b).

Piezoelectricity has several applications in architecture noteworthy the use of flooring tiles. Nevertheless, its use is currently limited due to factors including economic efficiency and service life to overcome its high capital cost (Anton & Sodano, 2007; Mak, McWilliam, Popov, & Fox, 2011).

This research intend to bridge the gaps between theoretical research and the implementation of energy harvesting tiles in developing countries, by overcoming the shortage of knowledge of the interior designers toward the specifications and configurations of piezoelectric tiles.

This study intends to present the properties of piezoelectric tiles through designing tool that overcome the basic knowledge of interior designers toward the properties of energy harvesting tiles. Moreover, the presented designing tool will guide the interior designers toward using energy harvesting tiles instead of regular ceramic and granite tiles, which will create a self-sustaining project by redesigning the interior floors of public facilities. Designing energy harvesting tiles using piezoelectric material will help in harvesting the waste energy produced from human movements and use the high population density in public buildings to generate non-stop energy which can be used in electrifying the public facilities. This research intends to increase the use of energy harvesting tiles in public buildings with high population density and to encourage the use of renewable energy in building for energy generation purposes.

This study presents a pilot attempt for energy-efficient buildings through the use of piezoelectric cells. Reviewing previous attempts for

the use of piezoelectric in public buildings paves the way for defining parameter integration for proper selection of piezoelectric cells in the interior design such that it carries both functional and aesthetical benefits. Hence, their application as flooring tiles was a manifestation for applying the laws of conservation of energy; transferring mechanical energy into electric power. A public metro station located in a highly-populated core urban area was selected as a case study due to its great use pattern and density. This enables energy generation from flooring tiles installed at defined locations in the metro station where the greatest numbers of passengers pass by. Accordingly, this contributes to the advancements of energy generation in green building design, construction and operation.

The study followed the sequence of steps shown in Fig. (1); the data collection and review phase provided a background for the use of piezoelectricity, latest advancements in technology according to uses and features- particularly for Sustainable Energy Floor (SEF) and Waynergy. This helped determine parameter integration for the proper selection of piezoelectric tiles. It was later applied to a case study project-metro station in a core urban area, collecting; electricity consumption, number of passengers as well as occupation density and patterns. Then, based on the previous literature review, the type of piezoelectric tiles was determined. Accordingly, the energy generation capacity was estimated and compared for SEF and Waynergy and finally, carbon dioxide emission reduction was calculated.

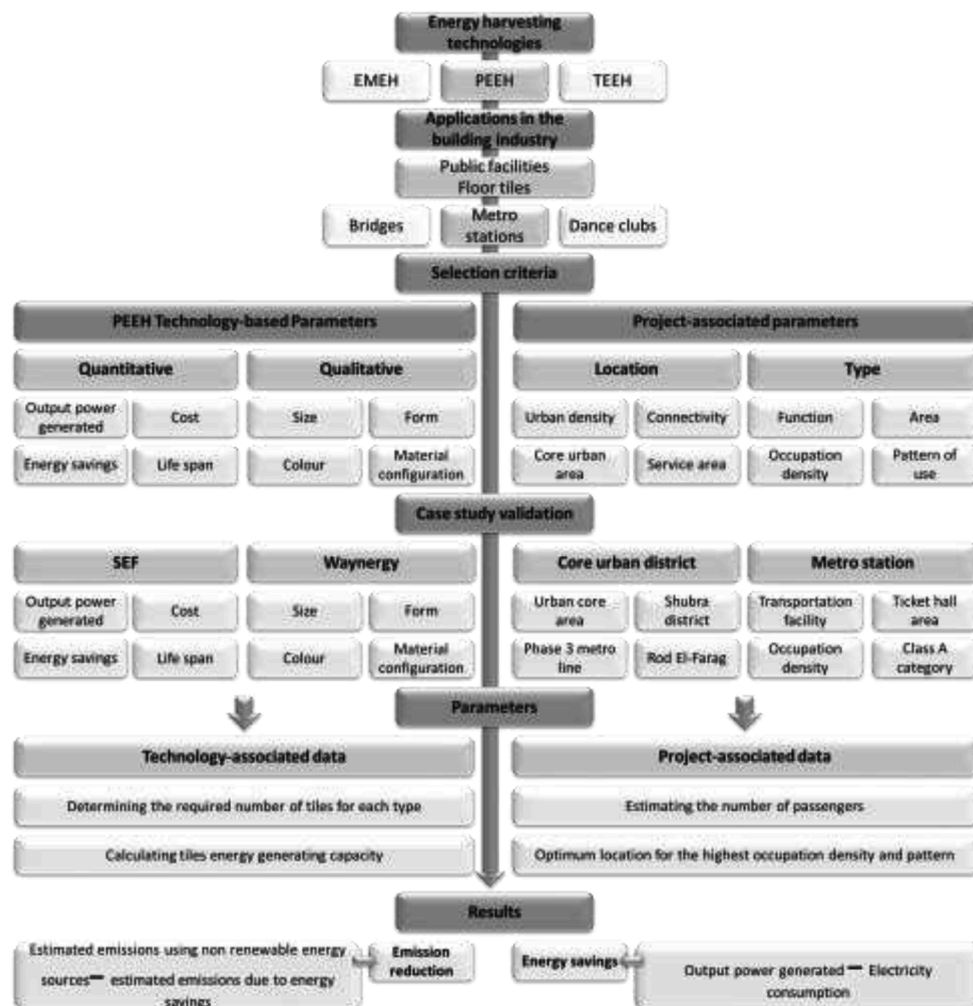


Fig 1. Research methodology.

Table 1

A comparison between the three types of Energy harvesting technologies.

Type of energy harvesting	Advantages	Disadvantages	Challenges	Ideal body parts and movements for energy harvesting
PEEH	• High energy density, high voltage output, no need for the mechanical stopper and no voltage source (Roundy et al., 2003). • High capacitance (Boisseau, Despesse, & Seddik, 2012) • Small mechanical damping (Khalid et al., 2019).	• Difficult integration, poor coupling (Roundy et al., 2003) • High impedance and low current (Khan, Sassani, & Stoeber, 2014). • Need of piezoelectric material, self-discharge at low frequency (Miao et al., 2006)	• Ultralow frequency of humans (Pillatsch et al., 2012) • Brittleness and rigidity of Piezo materials (Luo, Zhu, & Beeby, 2015) • Complex human motion (Fan, Cai, Liu, & Zhang, 2019) • Toxicity of piezo materials (Kim et al., 2015) • Designing a flexible system and difficulties in miniaturizing (Zhang, Wang, & Kim, 2015) • Difficulties in integration (Ylli et al., 2015)	• Feet motion (Cha & Seo, 2018) • Leg and arm motion (Izadgoshasb et al., 2019) • Palm and finger motion (Zhang, Chen, & Guo, 2019)
EMEH	• No voltage source, small mechanical damping, no need for contacts (Roundy et al., 2003) • High output current, robust and durable (Boisseau et al., 2012) • Low output impedance (Khan et al., 2014)	• Low efficiency at low frequency (Boisseau et al., 2012) • Coil losses and complicated to miniaturize (Miao et al., 2006) • Difficult integration and low voltage (Roundy et al., 2003)	• The inflexibility of electrodes (Lim et al., 2017) • Humidity (Yan, Lu, Song, & Xiao, 2018) • Washability (Yu et al., 2017) • Biocompatibility (Invernizzi et al., 2016)	• Wrist motion (Halim, Cho, Salaududin, & Park, 2016) • Feet motion (Wu et al., 2017) • Arm and leg (Fan et al., 2019) • Knee motion (Luciano, Sardini, Serpelloni, & Baronio, 2014) • Upper body centre of gravity (Zhang et al., 2014) • Human Skin (Wang & Daoud, 2018) • Hand tapping (Shen et al., 2017) • Cardiac and lung contraction and relaxation (Ding, Cao, Zhang, Li, & Liu, 2018) • Cloth (Ning et al., 2018)
TEEH	• Low operation frequency and device flexibility (Invernizzi et al., 2016) • High power density and high conversion efficiency (Wang et al., 2018)	• Mechanism not fully understood and difficult to integrate (Wang et al., 2018) • Low current at high voltage (Invernizzi et al., 2016) • Durability (Xu, Wong, & Hao, 2019)	• The inflexibility of electrodes (Lim et al., 2017) • Humidity (Yan, Lu, Song, & Xiao, 2018) • Washability (Yu et al., 2017) • Biocompatibility (Invernizzi et al., 2016)	

2. Literature review

In this research, the literature review section is divided into three sections. The first section presents the different technologies of energy harvesting tiles and the properties of each type and previous applications. The second section presents the environmental perspective of energy harvesting technology, especially piezoelectric cells, which is the main scope of this research. Finally, the third section presents detailed information on piezoelectric cells: types, properties, previous applications, cost, and life time, as well as a framework that helps in choosing the best type of piezoelectric cell for interior spaces.

2.1. Types and applications of energy harvesting technologies

Researchers have focused their attention on developing means of harvesting energy from the human body and motions (Dagdeviren, Li, & Wang, 2017). This includes converting mechanical energy to electricity following the first law of conversion of energy through Piezoelectric, Electromagnetic and Triboelectric applications (Mitcheson, Green, Yeatman, & Holmes, 2007).

Piezoelectricity was first identified in 1880 by The Curie brothers, and it is known as the property of materials that generate electricity from mechanical deformation. Piezoelectric technologies are generally classified into two categories: piezopolymer and piezoceramic. The former type is flexible, but they show many drawbacks e.g. low energy conversion rates and low electromechanical coefficients. The latter is usually brittle but they have high energy conversion rates and large electromechanical coupling constants (Khalid, Raouf, Khan, Kim, & Kim, 2019). Over the past decade, piezoelectric devices were the most widely discussed technology (Elahi, Eugeni, & Gaudenzi, 2018). Hence, Piezoelectric Energy Harvesting (PEEH) gained more attention in the field of energy harvesting technologies owing to its ease of use and simple structure (Priya et al., 2017). Different types of piezoelectric transducers can be used to harvest mechanical energy, including monomorph, bimorph, stack or membrane (Wang & Song, 2006; Feenstra et al., 2008). Each configuration has its own advantages and limitations, and in general, an energy harvester can't perform well in all applications. For this reason, energy harvesters are normally designed for a specific application and a particular frequency range of operation

(Mak et al., 2011). For example, Piezoelectric gadgets inserted in roadways may recover energy in the form of mechanical energy and pressure beneath the vehicle tires (Moussa, 2019).

Electromagnetism was discovered by Faraday in 1831 when a coil moves through the magnetic field causing a potential difference at both ends of the coil. The voltage induced in the coil is proportional to the time rate of change of magnetic flux (Invernizzi, Dulio, Patrini, Guizzetti, & Mustarelli, 2016). Hence, this attracted the attention of researchers as an efficient way for energy harvesting and electromagnetic energy harvesters (EMEHs) were developed (Anjum, Fida, Ahmad, & Iftikhar, 2018).

The Triboelectric effect results from a charge transfer which occurs when two materials with dissimilar polarities make contact with each other. After connecting these two materials with metal, electrodes are found at the two non-contacting ends, detachment of surfaces leads to charge accumulation due to the electrostatic induction effect. By repeating the contact between these two surfaces results in charge flow in opposite ends (Fan, Tian, & Wang, 2012). Compared to piezoelectric and electromagnetic energy harvesting, Triboelectric energy harvesting (TEEH) is considered an advanced technique, it is easily fabricated at the nano-scale size and has low operation frequency (Lai, 2018). In recent years, it has gained much attention because it produces high power density, high conversion efficiency, and low operating frequency (Invernizzi et al., 2016).

Table (1) compares the three aforementioned types showing that although electromagnetic tiles generate energy more than piezoelectric tiles, piezoelectric tiles are easier in the manufacturing and installing process.

2.2. Environmental perspective

From an environmental perspective, energy harvesting technologies such as piezoelectric tiles represent a promising innovation system. It does not require additional land space (Walubita et al., 2018) and is free of noise emissions with zero GHG emissions (Woodcock et al., 2009). Hence, it appears as a solution to the depleting trend of natural resources and the global energy problems (Andriopoulou, 2012). It is in phase with the actual adaptation strategies for global climate change (Berang-Ford, Ford, & Paterson, 2011; IPCC, 2014). Considering the

information provided by the EPA, in combination with the aforementioned Innowattech's, estimates, 1 km of pavement length with piezoelectric sensors may contribute to the reduction of an equivalent of 53 kg of CO₂ per hour. The use of energy with zero atmospheric emissions may thus aid in minimizing global warming and contribute to stabilizing the climate (Walubita et al., 2018). However, there are some limitations to their implementation compared to conventional energy sources. This includes the lack of detailed information on its economic merits and the storage problem of this system. Moreover, it is important to mention that piezoelectric tiles most widely use toxic materials such as lead zirconate titanate (Maeder, Damjanovic, & Setter, 2004). Although this material is highly valued for its high cost-effectiveness, it is also considered a health risk material due to the use of lead toxicity (Zhang, Wang, & Kim, 2014). Some studies have suggested the use of lead-free or mixed which are likely biocompatible (Maeder et al., 2004). However, the environmentally friendly properties of these alternative materials are not sufficiently established, and more research is needed to outline the cost benefits (Ibn-Mohammed et al., 2017).

2.3. Applications of piezoelectric tiles in the building industry

Previous studies implemented piezoelectric tiles for different projects in Portugal, Japan and England as shown in Table (2) (Solban & Moussa, 2019). These projects had different applications for piezoelectric tiles in different space functions, areas and installation methods; nevertheless, they all shared a large occupation density which allowed for sufficient energy generation. The examples presented the strength and weaknesses of each type, the efficiency of piezoelectric tiles as well as the properties of each tile. This showed that piezoelectric materials produced very small quantities of electricity, however, artificial piezoelectric materials such as PZT generated more electricity (Moussa, 2019; Moussa, 2020). Based on its application in East Japan Railway, 0.1 W were produced in a single second by an average person weighing 60 kg for two steps taken across the tile, but when it was used for larger areas with greater step-footage, then a significant amount of power could be generated leading to greater efficiency (Shreeshayana et al., 2017).

This section summarized the uses and features, form and implemented projects of different types of piezoelectric tiles.

- Waynery tiles were used for the 'Ponte 25 de Abril' project. The output power was either consumed or stored for indoor or outdoor uses. This included lighting, traffic control gadgets supply, large pedestrian areas, security systems supply, crosswalks, walkways, and public transport stations (Rodrigues, 2011).
- SEF tiles were used for the "Club Watt" project dance floor to power road lights and signage. The tiles could be fully customized. Other projects used it in pavements and large pedestrian regions e.g.

aeroplane terminals, sports fields, shopping centres, railroad stations, offices and condo squares (Solban & Moussa, 2019).

- Pavegen tiles were used for the Mercury mall project in London, also in various sectors including train stations, shopping centres, airports and public spaces. Each tile was equipped with a wireless that transmitted real-time movement data analytics whilst directly producing power when and where it was needed i.e. it could be used to power interactive messages, billboards and signage. This could improve data-driven smart cities by connecting to a range of mobile devices and building management systems (Pavegen, 2021).
- Electro-Active Polymers (EAPs) tiles were used for pressure mapping to trigger a control, warning or alarm signal. This could be useful for high voltage sensor Network Technology and sensor matrix (Balouchi, 2013).
- Sound Power tiles were used as power sources for many applications e.g. for emergency stairs, 0.1 W of electricity could be generated by a person steps (Hassan, Hassan, & Rahim, 2014).
- Parquet polyvinylidene fluoride layers (PVDF) tiles were characterized by a simple manufacturing process & a comparably inexpensive price. It could be produced in a large-sized foil material. It was very suitable for the application of mass-production technologies. Modules were characterized by great flexibility, robustness, resistance and could be created in almost any geometrical size and shape. The energy yield increased by the multiplication of the layers, at higher loading forces and with more thicknesses of the modules. The lengthwise arrangement was more efficient and they could be used to power small electrical loads or wireless sensor systems (Elhalwagy, Ghoneem, & Elhadidi, 2017).
- PZT ceramic (lead zirconate titanate) tiles were used in Tokyo Station. It was an example of ultra-efficient piezoelectric material that could convert up to 80% of mechanical energy to electricity. It was characterized to be extremely brittle & could be manufactured in small sizes. It was more expensive than PVDF, with higher and constant piezoelectric voltage conversion and 100 times more efficient than quartz (Elhalwagy et al., 2017).
- Drum Harvesters - Piezo buzzer tiles were used to generate low power electrical energy required to power microelectronic devices like Bluetooth, GPS modules, microcontrollers and low power sensors using ambient vibrations from various sources. The fabrication process of these drum harvesters was cheap, easy and fast. Quite robust and as such may be embedded in a variety of structures, under floors, roads, etc. (Mishra, Jain, Durgaprasad, & Sahu, 2015).
- POWERleap PZT tiles used 2-inch by 1-inch PZT plates with a brass reinforcement shim covered in nickel electrodes for low current leakage. Hence, the power was induced and stimulated momentary electrical energy impulses used to light the LED's inside each tile. The generated power could be stored in a battery in the form of direct current power (Balouchi, 2013).

Table 2

Summarizing the efficiency of piezoelectric tiles in previous case studies (Solban & Moussa, 2019).

Case Study	Ponte 25 De Abril	Tokyo Station	Club Watt
Project Type	Transportation Bridge	Metro public Station	Dancing floor inside Dance Club
Location	Lisboa, Portugal	Tokyo, Japan	Rotterdam
Cost	\$67,200	\$27,090	\$257,000
Area	Total length 2.277 km	25 m ²	38 m ²
Amount of energy	240 W per Vehicle	500 kW-seconds daily power	25 W/ square module
Energy saved	65 percent of the bridge power	1400 kw/day, more than enough to power their systems	Reduces the electricity consumption of the club by 30 percent
Tile Shape	Rectangle	Square	Square
Tile Size	25×300 cm	90 cm ² , 2.5 cm thick	75×75×20 cm
Colour	Black	Black	Transparent with LED multicolour lights
Operation frequency	155,000 vehicle users/day	400,000 users/day	1400 users/day
Type of Piezoelectric tiles	Waynery	Sound Power Tile	SEF
Location of tiles	All along the bridge	Passengers steps in front of the tickets area.	Dancing floor

- Hybrid energy floor (HEF) tiles were used to convert solar power and kinetic energy to electrical energy. It was designed for installation in commercial streets, public squares, parks and pavements. It used photovoltaic panels with Copper Indium Selenide solar technology. This included main benefits e.g. its excellent performance in shady areas and its maximum energy production with minimum power use (Solban & Moussa 2019).

According to previous research and case study projects, the properties of different types of piezoelectric tiles can be summarized in Table (3). This can be categorized based on their technical specifications; the size of each tile, energy produced from one tile, the initial cost of the tile and its average lifespan. This shows that the “PZT ceramic” type is the cheapest type of piezoelectric tiles which produces an average of 8.4 MW per tile. On the other hand, the Sound Power type produces only 0.1 W per 2 steps and its initial cost is almost 5 times more than the “PZT Ceramic”. Each type of piezoelectric tile has a specific feature and form, some of them has already been used in existing interior projects while others are still under testing.

Table (4) compares different types of piezoelectric tiles according to the cost, energy production, size, colour, material, arrangement, configuration and form as well as their functional applications.

After this thorough review of existing literature about the application of piezoelectric tiles as a means for clean energy harvesting, it can be noted it has great potentials use in public facilities and there are a variety of existing product types but there is no guide for the design and selection process. Hence, this research presents a pilot study for a self-sustained building operation to provide sufficient electric energy using

piezoelectric flooring tiles.

3. Case study

The underground station is located in Rod El-Farag neighbourhood shown in Fig. (2), located on 30°08'05.95"N and 31°24'54" E which is a part of Shoubra Masr district- a highly-populated area and home to around 33% of all population in the main capital Cairo. Its average population capacity is estimated at 170,000 occupants for every square kilometre. The newest phase of the third line (phase 3) is almost 17.7 km in length serving 15 stations. These are divided into eight underground stations, two ground and five elevated stations. A typical metro station consists of three floors, the 1st floor includes the railway, the 2nd floor includes daily passengers, the tickets office, the entrances and station exists, police station, security and supervisors' offices, toilets and services whilst the 3rd-floor consist of admission and mechanical rooms as shown in Fig (2). This shows the location of Rod El-Farag metro station, Source (google maps, 2021).

4. Method

Parameter integration for the proper selection of piezoelectric tiles was deduced from the previous literature review. This determines its successful application in the building industry. They can be divided into factors related to the project type and location, as well as the proper selection of the piezoelectric tile. The former requires prior investigation for the pattern of use, occupation density and area dedicated for installing piezoelectric tiles. Project location requires investigating the

Table 3

Comparing Piezoelectric technology types for one flooring tile.

Product type	Tiles Size	Energy produced	Price in US \$	Estimated lifespan	Source
1 Waynergy Floor	Tiles 40×40 cm	10 W per step	451.5	20 years	(Rodrigues, 2011)
2 SEF	Tiles 75×75 cm or 50×50 cm	Up to 30 W of continuous output. Typical power output for continuous stepping by a person lies between 1 and 10 W nominal output per module (average 7 W)	1693	15 years	(Solban & Moussa 2019).
3 Pavegen tiles	Tiles 50×50 cm	5 W	395	20 years	(Pavegen, 2021).
4 EAPs	Sheets	1 W	Not available	20 years	(Balouchi, 2013)
5 Sound Power	Tiles 50×50 cm	0.1 W per 2 steps	270.9	20 years	(Hassan et al., 2014).
6 PZT ceramic	Manufactured in a small size in diameter range of 10–250 µm	8,400,000 W	36.1	20 years	(Elhalwagy, 2017)
7 Parquet PVDF layers	Layers with thickness of 10µm	2,100,000 W per pulse with loads of about 70 kg	Not available	20 years	(Elhalwagy, 2017).
8 Drum Harvesters - Piezo buzzer, Piezoelectric Ceramics	Varies between 40 mm and 25 mm For better performance (35.6 mW for 70 kg)	Around 2,463,000 W	56.4	20 years	(Mishra et al., 2015).
9 Power Leap (PZT)	Tiles 60×60 cm	500,000 W per step	Not available	20 years	(Balouchi, 2013).
10 HEF	75×75 cm OR 100×200 cm	Up to 250 kWh per year, per tile	1693	20 years	(Solban & Moussa 2019).
11 • PZT Nanofibre -Nanogenerator • PZT Textile	Sheets of 0.2 cm ³ vol	6 mW/cm ³ , 0.03 µW power density up to 2.4 µW/cm ³	Not available	20 years	(Wang et al., 2018)
12 PvdF nanofibre	Thickness ~48µm thick, 200 mm x 200mm	Electricity conductivity 200 Ω	400.00	20 years	(Mishra et al., 2015).
13 ZnO nanowire WINGS	5 pW, 11 mW/cm ² , 2.7 mW/cm ³	very economically	Not available	20 years	(Elhalwagy, 2017)
14 BaTiO3	~7 mW/cm ³	Available commercially at low cost and in a variety of designs	Not available	20 years	(Elhalwagy, 2017)

W: Watts

PW: Picowatt

MW: Megawatt

Table 4

A framework of Piezoelectric tiles for designing interior spaces.

Criteria	Properties	Types of Piezoelectric tiles
1-Energy Production	0.0021 W to 0.0084 W	1. Parquet PVDF, Drum Harvester and PZT Ceramic
	0.1 W to 5 W	1. Sound Power and Pavegen Tiles
	7 W to 10 W	1. SEF and Waynergy Floor
2-Cost	Up to 60 kWh to 250 kWh per year, per tile	1. HEF
	225.7 \$ to 451.5 \$	1. Waynergy Floor, Pavegen Tiles and Sound Power
	1128.7 \$ to 1693 \$	1. SEF and HEF
	33.9 \$ to 56.4 \$ per cell	1. PZT Ceramic and Drum Harvester
3-Size	Tiles 40×40 cm	1. Waynergy Floor
	Tiles 50×50 cm	1. SEF and Sound Power
	Tiles 60×60 cm	1. Power Leap (PZT)
	Tiles 75×75 cm	1. SEF and HEF
	Tiles 1×2 m	1. HEF
	Tiles 50 cm x 50	1. Pavegen Tiles
	Sheets	EAPs, PZT Nano-fiber-nanogenerator and PZT textile nanogenerator
4-Form	Varies dimensions	1. Parquet PVDF
	Square	1. Drum Harvesters- Piezo Buzzers and Piezoelectric ceramics
	Rectangular	1. Waynergy Floor, SEF, Sound power
	Triangle	2. Power Leap (PZT), HEF, Pavegon tiles and PZT Ceramics
	Circular	1. Parquet PVDF, Drum Harvesters, HEF and Pavegon tiles
5-Colour	Comes in any colour according to the design	1. Pavegon tiles
		1. Drum Harvester and PZT ceramics
7-Configuration	Over Tile	1. Waynergy Floor, SEF, Pavegen tiles, EAPs, Sound Power, PZT ceramic, Parquet PVDF, Drum Harvesters - Piezo buzzer, Power Leap (PZT), HEF, PZT Nanofibre- nanogenerator &PZT textile nanogenerator
	Within Tile	1. Pavegon Tiles and Sound Power
	Replacing Tile	1. PZT Ceramic and Drum Harvester
8-Materials	The tiles can be all kinds of material, which makes it possible to implement them both inside and outside.	1. Waynergy, Pavegon Tiles, Sound Power and Parquet PVDF
	Covered with rubber to increase durability	1. Waynergy Floor, SEF, Pavegen tiles, Sound Power, PZT ceramic, Drum Harvesters - Piezo buzzer, Power Leap (PZT) and HEF
	Parquet PVDF	Sound Power
		Parquet PVDF

density of the surrounding urban area. Proper selection of piezoelectric tiles includes investigating their economic concerns (capital cost and as well as the running cost required for the operation and maintenance requirements), efficiency (in terms of energy generation and savings), form (shape, size, colour and configuration) and their type. It also shows its contribution to reducing energy consumption and carbon emissions. This hypothesis was tested on the case study project as shown in Fig. (3).

The newest metro line (Phase 3) was selected for the study because it was designed based on the latest planning guidelines. Three stations were selected for the study as shown in Table (5) based on the following parameters:

- A) Passenger density: transit stations in Cairo were generally classified into three classes (A, B & C) with the former having the greatest passengers' density. Class A was the most congested class that included more than 30,000 passengers/hr, whereas class C included the least number of passengers, less than 15,000 passengers/hr. Phase 3 included five stations of class A, nine stations of class B, and three stations of class C. Thus, one station of each class was selected.
- B) Type of the station: based on the alignment of the route, transit stations were classified into three types: underground station, elevated station and ground stations. Hence, one station of each type was selected noting that the ground floor level had the highest density due to the ease of access.
- C) Location of the station on the line: this was generally classified into intermediate station, intermodal station or terminal. The selected stations were two intermediate stations and one terminal station to indicate better connectivity and serviceability.
- D) Architectural design: all metro stations in Cairo followed the same prototype except for some minor modifications. Thus, the floor plans of the three selected stations were similar.

Hence, the Rod El-Farag metro station was selected. The data

collection phase included the electricity consumption of the metro station as well as the number of daily passengers, use pattern, density and distribution. This was needed to determine the number of piezoelectric tiles required to generate enough energy to power the station.

4.1. Project-associated parameters

The amount of electricity generated from piezoelectric tiles depended on the occupation pattern and density. Knowing that the metro station operated almost 16 hours/ day, hence, the numbers of daily passengers were collected from the station ticket office from January–December 2019. Then, their distribution was determined based on site visits and daily-based observations from the period January to July 2020. This showed an average of 57,000 passengers crossing the station per day with notable differences between working days and weekends. This was estimated to result in 57,000 steps per day. Table (6) showed the distribution of transient and final destination passengers for the metro station. The high-density areas were shown in Fig. (4) i.e. in front of ticket offices, entrance and exit stairs, and security gates. This determined optimum locations for installing piezoelectric tiles.

4.1.1. Calculating electricity consumption

The research identified the average daily electricity consumption of Rod El-Farag metro station which is approximately 4500 kW daily as shown in Table (7) (Cairo Metro Egypt, 2021).

4.2. Piezoelectric-technology associated parameters

According to previous research by Solban and Moussa (2019), SEF and Waynergy were the best two types of piezoelectric tiles that could be used in public facilities. Table (8) compared the properties of both types to be applied to the case study.

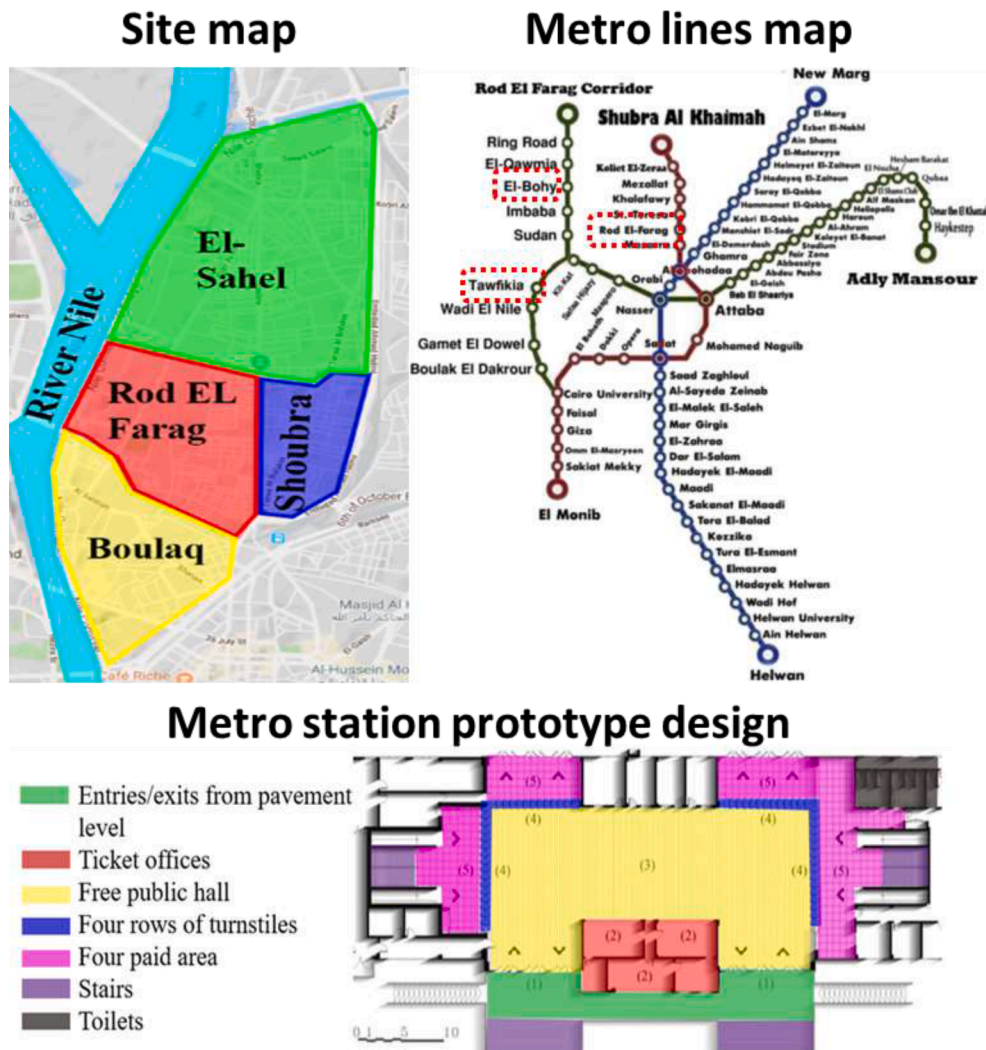


Fig 2. The location of Rod El-Farag metro station, Source (google maps, 2021)

5. Results

This investigates the efficiency of using piezoelectric tiles to generate enough electricity to supply public facilities such as the metro station in Rod El-Farag which is a core urban area in Cairo. The results help determine the most suitable type of piezoelectric tiles with enough generation capacity to balance the station's demand for electricity with a clean source of energy which shall reduce carbon emissions as well.

5.1. Determining the optimum type and number of piezoelectric tiles

The average energy daily consumption of the station is 4500 kW/day. The initial cost for buying 1 kW from the government is 0.054 US \$/kW. Hence, twelve tiles are needed to generate the station's needs for electric energy using SEF piezoelectric tiles while only eight tiles are needed using Waynergy piezoelectric tiles. Their power generation capacity, initial capital cost, lifespan and expected savings are compared in Table (9). This shows that using 12 SEF tiles will generate 4788 kW/day while installing 8 Waynergy tiles will generate 4560 kW/day. The amount of energy-saving using 12 SEF tiles is almost 92,552.1 US \$/year with a saving percentage of 99.3%, while the energy-saving from using 8 Waynergy tiles is almost 88,555.2 US \$/year with a saving percentage of 99.9%. This shows that using Waynergy piezoelectric tiles produce more energy than the SEF but with less payback time. Accordingly, the station will be a 100% self-sustained project.

5.2. Calculating carbon emission reduction

Rod El-Farag metro station is located in the Shoubra Masr district. This district is served by the "South Cairo" power station. Noting that natural gas was used to generate electricity which produces 116.999 pounds of CO₂ per million Btu, 10,408 heat rate (Btu PER kWh) and 1.22 pounds of CO₂ per kWh (Moussa, 2018; Moussa et al., 2017). Hence, each kWh produced from natural gas produces 1.22 pounds of CO₂

$$\therefore 1 \text{ billion (pound)} = 0.4536 \text{ Kg}$$

$\therefore$ The carbon emission produced from Natural gas= 1.22 billion kilowatt-hours

$$\therefore \text{CO}_2 = 1.22 \times 0.4536 = 0.5534 \text{ kg/kWh}$$

$\therefore$ Rod El-Farag metro station consumes 4500 kW/day, which is equal to 4500/16=281.25 kWh.

$\therefore$ Carbon emissions of the "Rod El-Farag" metro station are estimated to be 1.22×281.25=343.125 pounds per kWh.

By applying piezoelectric tiles in the station, a CO₂ reduction of 5490 pounds/day is expected.

6. Discussion

The search for clean sources of energy is a rising concern to overcome the problems associated with the use of non-renewable sources of energy. There are numerous advancements for energy-efficient building elements. The use of piezoelectric applications is a promising field of

The decision making process

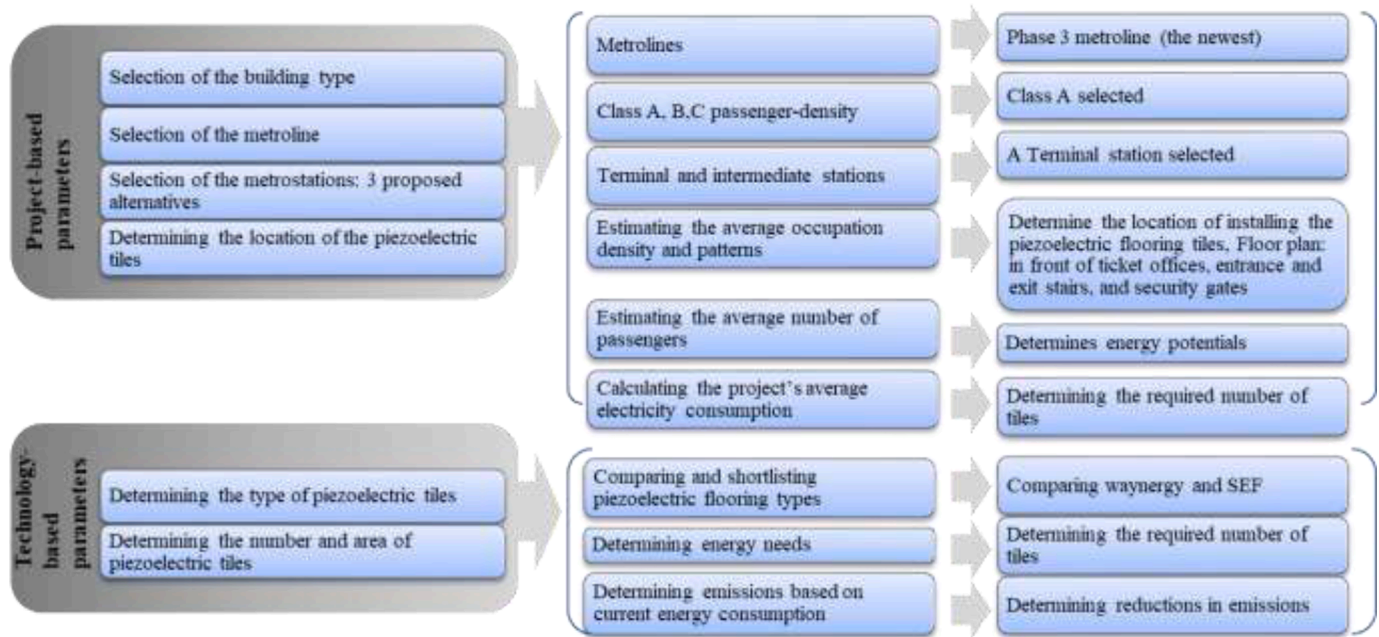


Fig 3. Drawing the decision-making process for proper selection of piezoelectric tiles in public facilities.

Table 5

Three alternative metro stations.

Station Name	No. of Levels	Passenger category	Type of the station	Location of the station	Selection
Tawfikia	3 Levels	C (less than 15,000 traveller/hr)	Underground	Intermediate	✓ Selected
El Bohy	3 Levels	B (15,000–30,000 traveller/hr)	Elevated	Intermediate	
Rod El-Farag	3 Levels	A (more than 30,000 traveller/hr)	Ground-level	Terminal	

Table 6

The number of passengers per hour using the station during the weekdays.

Passengers entering the station		Passengers exiting the station	
Days	The average number of passengers/hour	Days	The average number of passengers/hour
Friday	15,000 - 20,000	Friday	21,000 - 24,000
Saturday	22,000 - 24,000	Saturday	22,000 - 24,000
Sunday	26,000 - 29,000	Sunday	28,000 - 30,000
Monday	26,000 - 29,000	Monday	28,000 - 30,000
Tuesday	26,000 - 29,000	Tuesday	28,000 - 30,000
Wednesday	26,000 - 29,000	Wednesday	28,000 - 30,000
Thursday	27,000 - 29,000	Thursday	25,000 - 31,000

study for the conversion of energy from mechanical to electric energy. Nevertheless, its use is currently limited due to factors including economic efficiency and service life to overcome its high capital cost (Anton & Sodano, 2007; Mak et al., 2011). Moreover, previous research stated that the transportation system contributes a great deal to energy consumption and emission release (Moussa, 2021; Moussa, Mansour, & Yossif, 2021). Hence, this study shows clean methods of reducing energy consumption arising from metro stations. This can be generalized to obtain self-sufficient transportation hubs. The study bridges the gaps between theoretical research and the implementation of energy harvesting and renewable energy production using piezoelectric tiles in public buildings with high occupation density. It shows that its successful implementation depends on factors associated with the project and other with the technology itself. This indicates that an integrated approach should be adopted, looking at the contribution of individual parts in the whole process as recommended by previous researchers

(Ismaeel, 2020a, 2020b).

Few existing research about the application of piezoelectric tiles in the building industry was one of the main limitations during data gathering. It was more in the form of reports and product catalogues but fewer scientific papers were found in this regard. Also, the scope of the study did not account for the effect of the site on the successful implementation of this green solution as indicated in previous studies (Ismaeel, 2019, 2021). Furthermore, parametric design tools may be used for future research to trace the effect of changing the number of users, materials or a change in the country's energy mix. These tools were very useful to support early design decisions on the building scale (ElBatran & Ismaeel, 2021; Shams, Moftah, & Moussa, 2021) as well as on the urban scale (Ahmed & Ismaeel, 2016; Guirguis & Moussa, 2019). Hence, advanced tools and methods could be used to account for its use on the urban level e.g. using the Geographic Information System (Dabaeih, Kenawy, Ismaeel, & El-Sayed, 2017; El-Sayed, Dabaieh, Ismaeel, & Kenawy, 2018; Ismaeel, Adel, Sayed, Dabaieh, & Kenawy, 2016) and the project scale (Elsayed & Ismaeel, 2019). It may also include the use of Life Cycle Assessment to be able to compare between the aforementioned types of piezoelectric flooring tiles (Morsi, Ismaeel, El Hamed, & Othman, 2020).

7. Conclusion and recommendations

Nowadays energy is one of the most significant problems all over the world, hence, it is important to introduce clean energy harvesting technologies such as piezoelectricity in the building sector and most importantly for the transportation sector which result in major energy consumption and emission release. This is based on converting

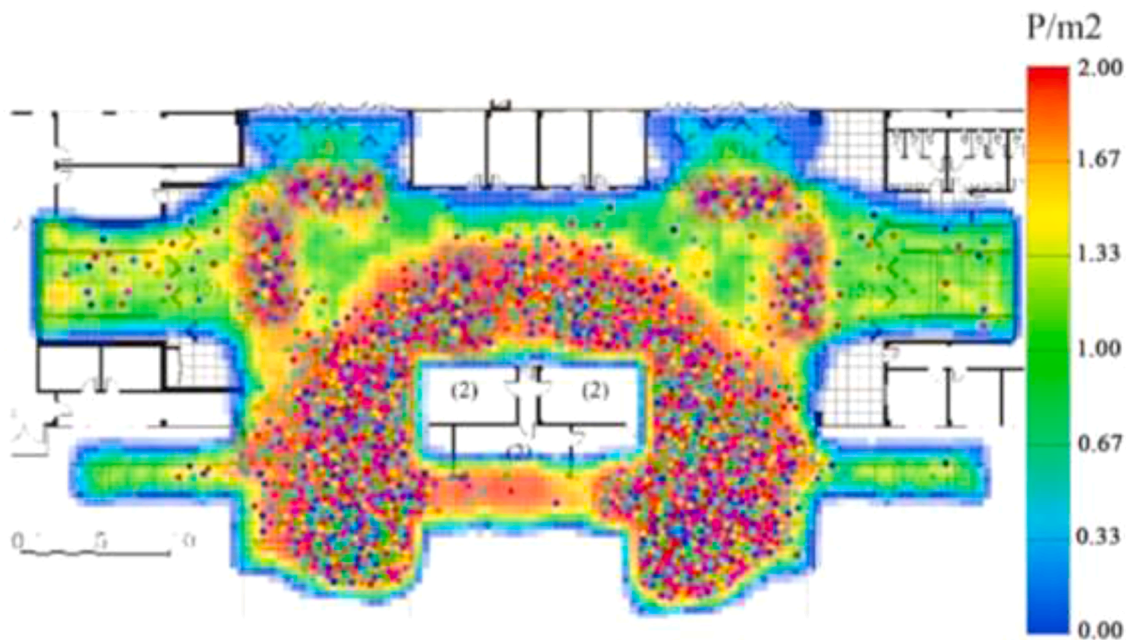


Fig 4. Determining high-density areas (People/m2) in the metro station

Table 7

The Electricity Consumption of Rod El-Farag metro station in 2020.

from	To	bill amount (EGP)	Station consumption kW/ month	Number of days	Station consumption kW/ day
12 Dec.	13 Jan	122,672	144,320	32	4510
13 Jan	29 Jan	57,800	68,000	16	4250
29 Jan	9 March	148,180.5	174,330	39	4470
9 March	1 April	80,155	94,300	23	4100
1 April	12 May	160,650	189,000	42	4500
12 May	3 June	84,150	99,000	22	4500
3 June	1 July	115,263.4	135,604	28	4843
1 July	3 Aug.	144,615.6	170,136	34	5004
3 Aug.	2 Sept.	119,850	141,000	30	4700
2 Sept.	8 Oct.	137,914.2	162,252	36	4507
8 Oct.	3 Nov.	103,275	121,500	27	4500

Table 8

Comparing the SEF and Waynergy piezoelectric tiles.

Properties	SEF	Waynergy
Power generation/ watt	7 W	10 W
Unit and its price	954.00 \$ = 15,000 EGP	254.40 \$ = 4000 EGP
Shape & Size	Tiles 75×75 cm or 50×50 cm	Tiles 40 cm x 40 cm
Materials	All types of materials can be used	
Colour	Comes in any colour according to the design	Comes in any colour according to the design
Life span by years	20	20
Number of tiles	Daily generation Capacity (kW)	
1	399	570
2	798	1140
3	1197	1710
4	1596	2280
5	1995	2850
6	2394	3420
7	2793	3990
8	3192	4560
9	3591	5130
10	3990	5700
11	4389	6270
12	4788	6840

mechanical energy to clean electricity production especially for public projects with significant occupation patterns and density. Hence, this study presents a comprehensive review of literature for the use of piezoelectric flooring tiles; citing research papers and international case study projects and as a result of the review phase two main types were shortlisted; waynergy and SEF.

Parameter integration for the proper selection of piezoelectric tiles was deduced from the literature review. This determined its successful application in the building industry. These were divided into factors related to the project type and location, as well as proper selection of the piezoelectric tile product. This hypothesis was tested in the case study. Hence, the application of piezoelectricity was investigated in a Metro station in a core urban area in Egypt, with an estimate of almost 57,000 daily passengers. The selection of the metro line and station as well as the location of installing the tiles was based on the highest passenger density class which provided the greatest step-footage. Furthermore, the selection of the number and type of piezoelectric tiles was determined based on the current project's energy consumption. The study compared the two shortlisted types of tiles in terms of their power generation capacity, initial capital cost, lifespan and expected savings. The results showed that twelve tiles were needed to generate the station's needs for electric energy using SEF piezoelectric tiles while only eight tiles were needed using Waynergy piezoelectric tiles. The results also showed a decrease in energy consumption and carbon emissions. Hence, the study encourages the use of clean energy harvesting which helps in promoting

Table 9

Comparing the efficiency of using SEF and Waynergy for the case study.

Type	SEF	Waynergy
Power generation/watt	7 W =0.007 kW	10 W =0.01 kW
Number of tiles	12	8
Initial cost for installing one tile	954.00 US \$	254.40 US \$
Initial cost for installing 12 tiles	12×954= 11,448 US \$	8×254.40 = 2035.2 US \$
Daily Generation Capacity	(57,000×0.007×12 tiles) = 4788 kW/day	(57,000×0.01×8 tiles) = 4560 kW/day
Lifespan (years)	20 years x 365 day = 7300 days	20 years x 365 day = 7300 days
Cost for generating daily energy from Piezoelectric tiles	11,448 / 7300 /4788 =0.00033 US \$/kW	2035.2 / 7300/ 4560 = 0.00006 US \$/kW
Daily saving amount/ 1 kW	0.054 - 0.00033 = 0.0537 US \$/kW	0.054 - 0.00006 = 0.0539 US \$/kW
Annual saving/ 1 kW	0.0537×360 day = 19.33 US \$/kW	0.0539×360 day =19.42 US \$/kW
Annual saving for electrifying the station using piezoelectric tiles	4788×19.33 = 92,552.1 US \$	4560×19.42 = 88,555.2 US \$
Saving Percentage %	100-((0.00033 /0.054) x100)	
= 99.3%	100-((0.00006 /0.054) x100)	
=99.9%		
Total saved amount through 20 years (lifespan of tiles)	92,552.1×20	
=1851,042 US \$		
=1771,104 US \$	88,555.2×20	

environmentally sustainable and socially resilient cities. This research is in continuous advancements, so more future research about the use of piezoelectricity in different building applications shall support the findings of this research.

Declaration of Competing Interest

The author whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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