Key Enablers and Barriers of Solar Paver Technologies for the Advancement of Environmental Sustainability

Abstract

Global initiatives to improve environmental sustainability have centered on reducing energy consumption and developing technological solutions for greener power generation. Current insights on innovations for environmental sustainability are primarily from developed countries, with limited studies originating from developing countries. This study focuses on solar paver technology, a potential innovation for sustainable generation of power. The interest in this technology lies in its dual-purpose ability to enable both functional road surfaces and the use of solar roadways that can generate electricity to power other road infrastructure such as electric lights. To maximize the potential of success of deployment of solar pavers, it is important to investigate the practicalities of solar pavers and understand the perceptions of stakeholders that will be responsible for the implementation of solar pavers. This research addresses this gap in knowledge. Thirty construction industry stakeholders in Malaysia were interviewed through focus group discussions and interviews. This study applied the diffusion of innovation theory to develop an understanding of the nuances of solar pavers. The findings identified three superordinate categories (motivation, opportunity, and ability) and nine categories (compliance with green initiatives, promote corporate social responsibility, dual functionality, financial incentives, sunny climate, increased environmental awareness, green experience, experts network and familiarity with solar technology) as the key enablers. Key barriers constitute two superordinate categories (challenges and weaknesses) and ten categories (reluctant authority, vandalism, complexity of installation and maintenance, high humidity and rainfall, negative environmental impact, high cost, design flaws, low efficiency, questionable practicality, and better comparative opportunities). There is an acceptance of solar pavers by the stakeholders and cost and ownership structures are the key to the deployment. The findings provide fresh insights into a new form of sustainable solar paver engendering new streams of research in construction engineering and technology management. Implications for management and organizational research are discussed.

Keywords

Sustainable technology, solar paver, qualitative study

1. Introduction

Environmental sustainability is an imperative consideration in contemporary society. Commercial organizations, governments and individuals are continually encouraged to seek ways to reduce the negative impacts that their activities have on the environment [1, 2]. The focus on environmental sustainability has manifested in various ways, such as reducing energy consumption, recycling and/or reducing waste, reusing materials, adopting more sustainable building design and personal lifestyles [3-7]. An important dimension of the global drive to be environmentally sustainable is developing technological solutions, particularly solutions that enable greener power generation (e.g., waste-to-power generation, solar technology, wind turbines) [8-13]. This research focuses on the potential of a new technology – Solar Paver – to be successfully implemented to enable the sustainable generation of power.

Solar paver is a renewable energy source to mitigate climate change. The diffusion of renewable energy in Malaysia has been very slow during the last 20 years, despite the fact that renewable energy was introduced under the Five-Fuel Diversification Policy in 2000 [14]. The Malaysian government has also promoted several other renewable energy programs such as

Net Energy Metering (NEM), the Feed-in Tariff (FIT), Large Scale Solar (LSS) and Self-Consumption (SELCO) [14, 15]. Previous literature (e.g., [15-18]) has identified a number of key factors leading to the low uptake of renewable energy development in Malaysia. Examples of factors include (1) high capital cost with long payback period that halt funding agencies and investors to support renewable energy projects [16]; (2) lengthy negotiations in signing the Renewable Energy Power Purchase Agreement (REPPA) between the developers and national power utility company [15]; (3) over-reliance on foreign technology that increase the cost of deployment [18]; and (4) lack of local technical expertise on the implementation of renewable energy [17]. Although it is important to develop technological solutions to enable greener power solutions, it is equally important that such solutions receive stakeholder approval and buy-in. This is because, without the acceptance of new technological solutions by the key stakeholders, it is unlikely that the technological solutions, no matter how promising, would be successfully deployed, adopted and managed. Therefore, the research presented in this paper focuses on stakeholder acceptance of Solar Paver technology.

This study, carried out in Malaysia, investigates the challenges and potential of implementing Solar Paver technology. The study is based on the perceptions of stakeholders from the Malaysian construction industry. Broadly defined, solar paver technology is a panel of photovoltaic cells built to be installed as concrete pavers on existing road infrastructure to utilize exposed sunlit surfaces to generate renewable energy. Successful solar paver technology will power road systems such as street lights and traffic lights without recourse to centralized national power generation systems. In addition, the solar pavers could be implementable on roads with both vehicular and foot traffic. This type of technology is relatively novel in the construction industry.

This study was carried out using focus group discussions and in-depth interviews to explore the potential for commercial adoption of solar paver technology and to understand the required customizations for industry and user applications. Therefore, the research investigates the key enablers and barriers for pursuing solar paver technology and understanding potential design configurations of solar paver technology that underpin successful implementation. The research questions that underpin this research are as follows: What are the key stakeholders' perceptions of the potential to implement Solar Paver technology in Malaysia? What factors will enable or hinder the deployment of this technology, particularly regarding the design configuration of both the technology and existing road infrastructure?

The key contributions of the study are the provision of clarity about the perceptions of stakeholders from the Malaysian private sector construction. They indicate an acceptance of the potential benefits of solar paver technology and specify that there are significant concerns about the practical aspects of its deployment with respect to cost, efficiency, maintenance, installation complexity, vandalism and government acceptance. Policy implications for private sector contractors and government administrators are the determination of where and how solar pavers may be efficiently deployed and the specification of cost models and ownership structure that will underpin the long-term success of the adoption of this technology.

The rest of the paper is organized as follows. In Section 2, a review of literature on environmental sustainability in the context of pavements, solar power generation, and solar pavers will be provided. In Section 3, the research methodology is elaborated. Section 4 are devoted to discussing results from the presented case in a Malaysian context. Finally, Section 5 concludes by providing a summary and avenues for future research.

2. Literature Review

2.1. Environmental Sustainability in Pavement Construction

Pavements are critical infrastructure in the provision of roads or pedestrian pathways. There are various categories of pavements based on materials and construction methods. For example, asphalt pavements are divided into hot-mix, stone-mastic, and cold-mix. Other mainstream types of pavements are concrete-based (with or without steel-reinforcement) or composite-based. Estimates show that 10% of the transport sector's carbon emissions can be attributed to pavements' construction and maintenance [19]. This highlights the importance of pavements in advancing environmentally sustainable solutions in the construction and transportation sectors. Environmental impacts and emissions associated with pavements' service life resulting from extraction and processing of materials, construction, maintenance, and end-of-life disposal of pavements.

The extraction of materials, processing, and transportation is the first phase in the service life of pavements. Due to the variability of materials used in pavements, the environmental impacts, and thus, potential and pathways to mitigate them are highly varied [20]. Pavements based on asphalt mixtures are estimated to be 70% less energy and emission-intensive than concrete-based pavements based on a life cycle analysis [21]. However, if the calculation of the energy and carbon inventory is done per value of generated products (output), asphalt production becomes the second most energy and carbon-intensive production process [22]. There are several opportunities to reduce the energy and carbon intensity of asphalt pavements by using warmly-mixed instead of hot-mixed materials, mixing the asphalt with recycled materials such as rubber, plastics, or used asphalt, and reducing the moisture content of asphalt [21]. This emanates from the understanding that, in the case of asphalt, 88% of energy consumption is related to the preparation of gravels, bitumen, and mixing of asphalt [22]. The construction and use phases of pavements are associated with environmental sustainability concerns related to energy and carbon emissions during materials transportation and handling, road and pathway preparation, excavation, and finishing, as well as ground-level air pollution (release of bitumen particles and particulate matters into the air in case of asphalt), traffic congestion (more frequent in case of asphalt due to faster degradation) [22-23].

A recent California highways study shows the continued release of over 300% of semi-volatile compounds from asphalt on hot summer days [24]. This study found an annual release of between 1,000 to 2,500 tons of particulate air pollution from asphalt road networks in California compared to 900 to 1,400 tons from automobiles commuting in these networks. The albedo effect is also an important aspect of pavements in relation to the urban heat island effect and global warming. A percentage of short-wave radiation from the sun is reflected by the pavement back to the atmosphere as a long wave (called the albedo effect) and the pavement absorbs the rest. The lighter the surface color of the pavement, the higher is the reflection of solar radiation. For asphalt, this percentage (albedo effect) is between 5% and 20%, and for concrete, it is from 25% to 80% for newer light-colored concrete. The high absorbance of sun waves by asphalt increases ground-level temperature and aggravates the heat island effect in urban areas [25]. The albedo effect is also an important factor in global warming. Studies show that for each square meter of the earth’s surface, with a 1% increase in albedo effect, 2.55 kg of emitted carbon dioxide can be offset [26]. Estimates show that if all urban areas make feasible choices in increasing the albedo of pavement surfaces, 22 billion tonnes of carbon emissions can be offset annually; equivalent to a 70% reduction in greenhouse gas emissions resulting from the combustion of fossil fuels [27]. In addition, the amount of lighting needed for roads and pedestrian pathways at night time depends on the types of pavement, with asphalt pavements typically needing 50% more lighting than concrete pavements [25].

The maintenance phase of pavements is also subject to environmental pollution and energy intensity. Fixing and rehabilitation of cracks and potholes are a growing issue in cold regions with occasional freeze and thaw effects in winter [23]. In hot regions, the pavements are subject to increased deformation [24]. Climate change is expected to worsen the pavements' degradation, and enforce ever increasing rehabilitation activities all year around [28]. A proper periodical scheduling of rehabilitation activities to prevent major works and prioritize critical maintenance is a strategy to reduce the cost and distribute the effort of replacements [29]. In addition, transportation planning using traffic controls to distribute heavy vehicles' journeys could extend the life expectancy of road pavements. Finally, recycled materials (such as metals and plastics) can be used to reinforce and revitalize degraded asphalt pavements [30].

There are also challenges and considerations for the end-of-life of pavements. Due to the high value of pavement materials at their end-of-life, there has been a recycling rate of over 75% [31] within the scope of widely established guidelines [32]. However, the recycling practice could remain energy and carbon-intensive depending on the recycling and reuse approach [25]. In addition, the use of recycled asphalt as part of new pavements is shown to increase the leachate of vehicle exhaust, lubricating oils, gasoline, etc. to water and aqueous ecosystems [33].

In recognition of growing urbanization, and thus, increasing extension of pavement networks, and considering the growing environmental sustainability challenges and issues related to the whole service life of pavements, particularly albedo effect and energy-carbon intensity of construction and lighting of pavements, integration of sustainable technologies such as solar paver could contribute to offsetting energy and carbon intensity. A brief overview of solar power generation technologies will be provided below, followed by an overview of solar paver technologies.

2.2. Solar Power Generation and Environmental Sustainability

Solar energy is measurably the most abundant form of energy [34]. Research on harvesting energy from the physical environment has resulted in several options, including piezoelectric, electrostatics, thermoelectric and photovoltaics (see: [35]). Of these alternatives, solar photovoltaic (PV) with a high-power density, around 1000 kW/m^2, is recognized as one of the most desirable technologies in support of renewable energy [35]. Unfortunately, legacy PV-based renewable energy systems require large expanses of land for infrastructure installation [35]. However, land clearing can severely affect the natural habitat of plants, trees, animals, and the local human community. This problem can be potentially addressed by using roads and pavements for harvesting solar energy [36, 37]. Examples of solar-power roads experimental projects include the Solar Roadways Modules (Idaho, United States of America), Wattway Solar Road (Tourouvre-au-Perche, France), SolaRoad Bike Path (Krommenie, The Netherlands), and Solar Expressway (Jinan, China).

Solar Roadways initiated the first implementation of PV cells in pavements [38]. In 2014, the world's first bike path with integrated solar panels was opened for the public near Amsterdam [39]. The power generation of the solar bike path exceeded expectations, generating 3000kWh of electricity within the first six months [40]. In 2016, the world's first solar road, comprising a one-kilometer road covered with resin-coated solar panels, was opened in the French town of Tourouvre to generate power for streetlights [40]. China has emerged as the first developing country to adopt this technology, pioneering a one-kilometer stretch of a solar expressway in Jinan in 2017 [41]. These projects have resulted in the need for academic research and literature on the implementation of solar roads.

The 2030 Agenda for Sustainable Development published by the United Nations [42] has 17 Sustainable Development Goals (SDGs), which can be viewed as different thematic issues, including energy, urbanization and transport. Some SDGs tend to be contexts for interdisciplinary research. In particular, SGD 7 – “Affordable and Clean Energy” aims to ensure access to affordable, reliable, sustainable, and clean energy for all, which could be achieved through applied research on developing solar power technology. In contrast, management research provides insights for businesses to transform and work towards set targets. It is evident that solar power provides prospective socio-economic and practical solutions to environmental sustainability in developing countries [34]. Malaysia is of particular interest in this study because the country has seen rapid urban development and solar radiation is widely available in the country. Against this backdrop, this study investigates the perceptions of industry stakeholders to solar paver technology adoption.

2.3. Solar Paver Technology

Solar Paver technology is a panel of photovoltaic cells built to be installed as concrete pavers on existing road systems to utilize exposed sunlit surfaces to generate renewable energy (see: Figure 1). Solar pavers can function on roads with both vehicular and foot traffic. While this technology is new, there have been some pioneering research into its suitability and adaptability. Research carried out in France, the Netherlands, and the United States of America, identified some of the advantages and disadvantages of solar pavers [43]. The study opined that solar pavers provided alternative usage for available landscape - producing off-grid power for road infrastructures such as streetlamps while reducing carbon emissions from fossil fuel-powered generators. On the other hand, solar pavers had low power output and efficiency due to shading, weatherproofing, and as a consequence, did not provide as much value as rooftop solar panels. Thus, while this initial research provides important insights, the potential of the technology makes it imperative to expand the knowledge base related to the design and adoption of this emerging technology. Several issues include industry structure, business models, road design factors, and stakeholder operational strategies that need a better understanding of the construction industry to successfully evaluate and deploy solar paver technology.

(Insert Figure 1 Here)

2.4. The Application of the Diffusion of Innovation Theory

The Diffusion of Innovation (DoI) theory has been widely studied in the multidisciplinary literature after Everett Rogers mapped out the process of a new idea, product or innovation becoming diffused among the people until reaching a saturation point [44]. Innovation is regarded as an idea or product viewed as new by an individual or other adopters [45]. Rogers classified five types of adopters of an innovation: innovators, early adopters, early majority, late majority, and laggards [45]. The DoI theory is broadly applied as a change model for driving innovation where the innovation itself is introduced in ways that meet the needs of all five types of adopters [44].

There are several studies (e.g., [46-48]) that built on the DoI theory to study technology adoption of solar energy. Essentially, DoI theory posits that *relative advantage*, *complexity, trialability*, *compatibility* and *observability* are all the characteristics of innovation that explain the rate of adoption [45]. DoI theory is suitable to evaluate the adoption of the solar paver technology in the context of Malaysia because these five characteristics of innovation (i.e., *relative advantage, complexity, trialability*, *compatibility* and *observability*) provide a valuable evaluation list for stakeholders from the Malaysian private sector construction to apply when first considering innovative solar paver technology for sustainable power generation. Specifically, solar paver technology has various *relative advantages* over fossil fuel-powered generators. The concept of solar paver technology is also simple to understand and use (less *complexity*) and is *compatible* with the environment of high solar radiation in Malaysia which is located in the equatorial region. Furthermore, the solar paver technology is *trialable* as it can be experimented on a partial basis on the roadway. Such visibility on the roadway provides *observable* effects which generate more discussions of solar paver technology among the stakeholders from the construction industry. For these reasons, DoI theory is ideal to develop an understanding of the perception of stakeholders towards the adoption of the solar paver technology due to its multidisciplinary nature.

2.5. The Malaysia Context

The study context of Malaysia is essential. As a developing economy country, Malaysia has rapidly rising energy demands to service increasing industrialization and domestic consumption. Data shows that Malaysia's electricity consumption per capita has grown from 3900 kWh per capita in 2010 to 4750 kWh per capita in 2019 [49]. Malaysia's electricity generation and energy mix are drawn from thermal and hydro generation [50]. The raw materials for electricity generation are oil, coal, gas and hydropower with CO_2, SO_2 and NO_x as by-products [51]. Malaysia is highly dependent on fossil fuels such as natural gas, resulting in higher CO_2 emissions [50]. The increasing concentration of these pollutants in the environment contributes to global warming and climate changes [50-51].

In 1981, the Four-fuel Diversification Strategy was launched as an extension of the Malaysian National Energy Policy. The Four-Fuel Diversification Strategy is the Malaysian energy policy that provides guidelines to reduce Malaysia's over-dependency on burning fossil fuels such as gas, oil and coal. To ensure the sustainability of energy resources, renewable energy was added to the Five-Fuel Diversification Strategy, which was introduced from 1999 until 2020 [14]. However, the transition to renewable energy in Malaysia has been difficult due to a lack of awareness and initiatives among key stakeholders to promote renewable energy [14]. Within the context of a global focus on sustainability, it is important that Malaysia explores every opportunity for green energy generation to reduce or avoid the cost, replaceability, and pollution challenges associated with fossil fuel generation. There is some evidence that the Government of Malaysia is adopting policies that underpin sustainable power generation. For example, the Net Energy Metering (NEM) policy promotes solar energy utilization by the public in Malaysia [52]. This buyback program allows Malaysians to sell back any solar-power generated energy to the national energy supplier, Tenaga Nasional Berhad (TNB), thereby recovering some initial investment costs.

However, the effects of the incentive program are limited, considering the overall energy consumption in Malaysia. The output from renewable energy sources in Malaysia in 2020 was only 102 Megawatts (MW), whereas the daily demand for power from Malaysian consumers was approximately 18 Gigawatts (GW). Consequently, there is still significant potential for renewable energy sources to contribute to national energy consumption. YB Yeo Bee Yin, the former Malaysian Minister of Energy, Science, Technology, Environment and Climate Change (MESTECC) noted that additional efforts were necessary to boost Malaysia's renewable energy generation [53-55]. Consequently, it is important to investigate the potential of new technologies such as solar pavers, which can benefit Malaysia and other countries, particularly those that will be installing new energy generation capacities to service increasing industrial and consumer demands.

There are, however, mixed reviews [56] on the institutional commitment to renewable energy generation from a legislative [57] and transfer of knowledge perspective. While there is interest in implementation, the acceptance is not industry-wide. Short-term governmental incentives and rebates can stimulate and/or enforce change, but this is not sustainable and may not be sufficient to drive the industry commitment further. Additionally, Wong et al. [58] reported that the lack of awareness of the existing incentives further impedes industry acceptance. From a knowledge perspective, most of the research in green technology is academic-oriented and has not been implemented in the industry. Thus, the barrier lies in transforming the theoretical knowledge into practical actions (such as technical guidelines and information) useful for industry practitioners [59]. In addition, there is a high dependency on imported technology, which inflates the cost of implementation [18]. The lack of technical knowledge is a significant implementation problem [60] and a high dependency on imported products. Furthermore, these technologies are developed for overseas markets or climate, which may differ from Malaysia's climate. Therefore, some adjustments to suit the local climate will be required, which may further escalate costs.

3. Research Methodology

3.1. Method of Data Collection

The research is exploratory in nature due to the emerging nature of the technology in focus. As the technology had not been deployed in Malaysia, it was impossible to evaluate how much knowledge stakeholders in the Malaysian technology sector had of Solar Paver technology. Hence it was important to adopt a research methodology that ensured that there was uniform knowledge of Solar Paver technology amongst industry participants while also collecting detailed data about their perceptions of the suitability of the technology.

This study adopted a qualitative research method based on data collection using focus group discussions and in-depth interviews. This combination of research methods is widely used in qualitative studies [61] and is particularly effective for understanding stakeholder perspectives. Focus groups provide the advantage of actualizing group interviews that encourage self-disclosure among participants by building group dynamics with the ultimate outcome of investigating a topic in greater depth. Thus, it was a suitable method for this study where detailed information about stakeholder perception of emerging technology was the key focus. One-to-one in-depth interviews were conducted to augment the qualitative data from focus groups. These interviews enabled participants to discuss sensitive issues such as financial implications and personal reservations regarding solar paver that they were reticent to share in a group setting.

3.2. Data Collection Procedure

The study was conducted between October 2019 and December 2019. All the focus group sessions and in-depth interviews were conducted in the university except for one in-depth interview session conducted on-site at the participant's request. The focus group sessions and in-depth interviews were carried out in two stages as follows.

3.2.1. Stage 1 – Technology Familiarisation

To ensure uniformity and clarity in understanding of Solar Paver technology and its potential applications, the focus group/interview participants were first introduced to the technology. A completed prototype of a concrete solar paver was shown to participants to ensure familiarity with the physical attributes of the technology. In addition, a two-minute video clip about solar paver technology was played before the focus group discussions/in-depth interviews. Finally, a Powerpoint presentation was used to highlight ten potential applications for solar paver implementation. These potential applications were road divider, Bus Rapid Transit (BRT) roadways, exposed car park top decks, shopping malls' outdoor landscape, outdoor swimming pool areas, roundabouts, petrol stations, playground/parks, restaurants and restrooms rooftops, T-junction/signaling areas.

3.2.2. Stage 2 – Focus group discussions and Interviews

A total of seven focus group discussions and six in-depth interview sessions were carried out with 30 participants. Each focus group session was guided by a moderator and lasted between 30 and 90 minutes. Each interview session was led by an interviewer and took between 30 and 60 minutes to complete. A set of starter questions was developed for use with focus group discussions and in-depth interviews to ensure that the aims of the study were achieved and to enable focus in the discussions. The questions explored different aspects of solar paver technology adoption, including the potential motivational factors as well as anticipated challenges in using solar paver technology. The questions also focused on the potential and likelihood of success of the suggested applications proposed in stage 1. All focus group discussions and in-depth interviews were audio-recorded with participants' permission and transcribed verbatim for analysis.

Participants in focus group discussions and in-depth interviews were drawn from Malaysian construction service providers, including property developers, builders, engineers, consultants, contractors and manufacturers. These participants are the key informants and are further categorized to focus groups through purposive sampling. The respondents were employees working in the companies listed in the 2019 Edition of Directory of Malaysian Construction Related Exporters; Goods and Services, published by the Construction Industry Development Board (CIDB) [62]. The focus on the private sector was for two reasons. Firstly , the primary responsibility for deploying works lies with private sector industries that the government contracts. They play a key role in developing technical specifications of such infrastructure. Secondly, it was not possible to secure the availability of public sector executives for this study. Therefore, selected companies from the CIDB directory were initially contacted by email and telephone to solicit participation. The research was approved by the Monash University Human Research Ethics Committee (project ID 20314) and was conducted in accordance with the National Statement guidelines (Australia). Potential participants that indicated a willingness to be involved in the study were subsequently contacted to make an appointment for a focus group discussion/in-depth interview. Informed consent was obtained from all participants before the interview session. A total of 30 participants were recruited. The sample comprised 73.3% of males and 26.7% of females. In terms of age, 30% were between 21 to 29 years, 53.3% were between 30 and 39 years, and 16.7% were between 40 and 49 years. All respondents were executives with job titles such as chief executive officer, architect, civil engineer, construction manager, electrical engineer, and mechanical engineer. Table 1 presents the profiles of participants.

(Insert Table 1 Here)

3.3. Qualitative Method of Analysis

This study applied grounded theory approach [63], a mode of inductive analysis which constructs codes and categories from data [64]. Grounded theory is a well-established methodology used in several qualitative studies [65]. The aim of a grounded theory study is to explore the meaning from the participants' perspective and subsequently develop an integrated set of variables about the topic researched. Grounded theory fits well with our inductive investigation in which the researcher poses questions about the information provided by participants to derive deeper explanations. This process of thematic analysis involves researchers reading and analyzing the transcripts repeatedly until data saturation occurs. The transcripts were coded by one researcher to identify key issues related to the practicalities and implementation of solar pavers. The frequently mentioned words were extracted and labeled with codes. Codes were systematically documented in a codebook, which was examined throughout the coding process by two other researchers. Data was coded in a Microsoft Word document. Subsequently, the researchers conducted discussions to assess and refine codes to develop categories, and consensus on categories was achieved after numerous iterations.

3.4. Data Processing

We adopted the active categorization approach [66] as a data analysis process to derive categories from the data through three stages namely generating initial categories, refining tentative categories, and stabilizing categories. Figure 2 shows the data processing stages. We deciphered our data and iteratively constructed categories at the three general stages of the analytical process through three moves (1) asking questions; (2) merging categories; and (3) relating categories. Grodal et al. (2021) [66] defined these three moves as the micro-processes that researchers embark on when they categorize data. At the first stage of generating initial categories, we approached the data with specific questions – What are the key enablers and barriers for pursuing solar paver technology? Asking questions is the key to early discovery process because it was through these questions that we created initial categories using the 234 pages of transcripts. These initial categories are formed using open coding [63]. Examples of categories include "green experiences," "familiarity with solar technology", "high cost," "reluctant authority" and many more.

Deeper into our analysis, we began to refine tentative categories through merging categories. We united two or more existing categories to create superordinate categories. For example, we merged three categories of "compliance with green initiatives," "promote corporate social responsibility" and "dual functionality" into a superordinate category named "motivation." This analytical process involved both axial coding and selective coding [63]. In axial coding, we focused on relating the codes to categories and on identifying relationships between categories. Selective coding is the process by which all categories are integrated into a "core" category. During this step, the data, codes and categories were re-examined. For example, quotes of "*So I think if this is successful, so this could be one point that we can gain for this GBI (Green Building Index) point.*" and "*We use this solar because of this GBI. Otherwise we won't.*" were grouped into the code of "Compliance with Green Initiatives.", which in turn, belongs to the category of "Motivation".

In the final stage of stabilizing categories, we compared different categories with one another to identify relationships between them. For example, we compared "challenges" with "weaknesses" to identify their differences. We also developed a theoretical scaffold to provide explanations for our initial questions asked at the first stage. For instance, as we re-analyzed the categories, we identified the categories of “motivation”, “opportunity” and “ability” emerged as the key enablers. We returned to the literature to make sense of our data and began to understand the categories in light of the Motivation, Opportunity and Ability (MOA) theory [67]. MOA has been largely studied in the marketing literature after MacInnis et al. [67] first advocated that the degree to which an individual processes information is based on three attributes namely, motivation, opportunity and ability. This stage informed our decisions in stabilizing the codes and concluding the findings. The data structure is shown in Figure 3.

(Insert Figure 2 Here)

(Insert Figure 3 Here)

3.5. Findings

3.5.1. Category 1 - Key Enablers of Solar Paver Technology

Key enablers refer to the categories of organizational and environmental factors that should be in place prior to developing plans to deploy solar pavers. The study identified three categories of key enablers – motivation, opportunity and ability. The analysis is depicted in Table 2.

(Insert Table 2 Here)

3.5.1.1. Motivation - motivational factors are internal and external factors that are important in ‘steering’ the organization to consider adopting Solar Paver technology. The first motivation factor identified was ‘Compliance with Green Initiatives’. The requirement for stakeholders in the construction industry to meet statutory environmental targets and objectives can be a key driver of a decision to deploy solar pavers. Malaysia has been promoting green initiatives extensively in various industries (i.e., construction, property development, and architecture) through sustainability requirements such as targets on Green Building Index (GBI) and

Leadership in Energy and Environmental Design (LEED). More than half of the participants (53.3%) mentioned that they completed development projects which required GBI or LEED certification. Three participants opined that installing the solar pavers would be a good alternative to satisfy the sustainability requirements from GBI or LEED. According to one of the participants, “It’s basically in LEED they will just say renewable energy……So this (solar paver) would probably make … let’s say another option for them to get the compliance.” (Focus group session 1)

The second motivation factor identified was ‘Corporate Social Responsibility’. In 2018, Malaysia launched a Kind Malaysia 2018 with the aims to raise social conscience and encourage company leaders to address social issues [68]. In accordance with this program, Bursa Malaysia (Malaysia’s stock market) made it mandatory for all listed companies to report their CSR program and demonstrate market leadership [68]. In this study, 13 out of 30 participants (43.3%) were willing to implement solar pavers technology to reduce carbon emissions, improve the organizational image and contribute to environmental sustainability. However, some responses also indicate that some stakeholders see CSR-led sustainability initiatives as primarily an image and compliance chore. For example, according to one of the participants, “But to me, green projects are all meaningless [laughs]. Branding, I would say. Branding and then reputation. That’s all only.” (Focus group session 3)

The third motivation factor was ‘Dual Functionality’. Solar Paver technology provides an excellent avenue for dual usage of infrastructure and the focus group/interview participants noticed this potential. From the focus groups/interviews, 11 participants (36.7%) were curious and intrigued by solar pavers. Five out of 30 participants mentioned that solar paver technology would be a great way to take advantage of the exposed sunlit surfaces in underutilized areas. Furthermore, another participant posited that the solar paver system's dual functionality would be useful in their development project. Another participant noted, “This kind of product for building industry is a new innovation. It will help to generate and use up the expose surface." (Focus group session 4)

3.5.1.2. Opportunity – Opportunity factors are factors already in existence that will make the acceptance and successful deployment of solar pavers easier.

The first opportunity factor identified was 'Financial Incentives'. Twelve (40%) of the focus group/interview participants indicated awareness of Malaysian government incentives such as Net Energy Metering (NEM), Green Investment Tax Allowance (GITA), Green Income Tax Exemption (GITE) and Feed-in Tariffs (FIT) [52]. Furthermore, the U-Solar program was introduced by United Overseas Bank (UOB) in 2019 to ease the transition for both businesses and individuals from conventional fossil fuel-generated energy to solar power [69]. These programs provide financial incentives for individuals and organizations to adopt renewable energy sources. The following was indicated during the focus groups, "The reason why I was agreed on solar power generation because I came across the previous incentive program by the government, which is what they call FIT." (Focus group session 4)

The second opportunity factor was the 'Sunny climate'. Depending on regional, seasonal, and daily fluctuations, solar radiation is limited and available during the daytime only [70]. Malaysia has one of the highest potentials for a year-round solar generation due to its location near the equator [71]. Malaysia's monthly solar irradiation is estimated at 400 – 600 Megajoule per meter square (MJ/m2) and the estimated potential for solar generation can reach up to 6500 Megawatts [71]. During the focus groups/interviews, it was suggested that this solar potential was a more viable option for Malaysia in generating renewable energy compared with geothermal, hydro, and wind energy.

The final opportunity factor was 'Increased Environmental Awareness'. A survey conducted by Mei et al. [72], showed that Malaysians had relatively high environmental awareness. The focus group discussions/interviews indicated that 14 participants (46.7%) believed that Malaysians were gradually more aware of environmental issues. For example, one participant indicated that Malaysians had higher awareness of the environmental benefits of using solar technology but were still unwilling to invest their money. Another respondent stated, “So in terms of marketability, it is ok [laughs]. People now are aware of these sustainability items and everything.” (Focus group session 2). The importance of this awareness is to enable acceptance by society in general if there will be significant changes to public infrastructure, particularly if the government will incur extra costs in deploying solar pavers.

3.5.1.3. Ability – Ability refers to the inherent capability of stakeholders in the construction industry to understand, deploy and managing solar paver technology.

The first ability factor was ‘Green Experience’. Green experience indicates historical involvement in sustainable building projects of any type. Focus group/interview participants stated that they had been involved in green projects such as the GBI Gold certified project in Putrajaya, large-scale solar systems, and the solar carpark project in KLIA 2. Past experience in sustainable projects provides the advantages of gaining easier buy-in from industry stakeholders, thereby overcoming cultural resistance to adopting new technology such as solar pavers.

The second ability factor was ‘Experts Network’. The deployment of new technology particularly in the construction industry, will require the combined expertise of different professionals to ensure that challenges applicable to understanding and integrating new technology can be adequately addressed. Fourteen (46.6%) focus group/interview participants indicated that they had a good network of professional contacts to participate in solar paver deployment. It was mentioned in the focus groups/interviews that green projects involved multiple areas of expertise such as procurement, architecture, mechanical engineering, and civil engineering. For solar paver technology to be successfully deployed, experts in these traditional construction disciplines will need to work together with solar paver technology experts to ensure effective project teams.

The third factor was 'Familiarity with Solar Technology'. While solar paver technology is new, solar technology for power generation is already well established in Malaysia. Half of the focus group/interview participants clarified that they had knowledge or familiarity with solar products and projects. Specific knowledge of solar technology would play a critical role in determining feasible designs for Malaysia. Perhaps more importantly, solar technology expertise would enable anticipation of problems relating to maintenance, installation and performance issues that characterize solar power infrastructure and the development of mitigating actions.

3.5.2. Category 2 - Key Barriers to Solar Paver Technology

Key barriers refer to the categories of organizational and environmental factors that could negatively impact the deployment or successful operation of solar pavers. The study identified two categories of key barriers – challenges and weaknesses. The analysis is listed in Table 3.

(Insert Table 3 Here)

3.5.2.1. Challenges **–** The study identified five factors that pose significant challenges to the successful installation and operation of solar pavers. Some of these factors relate to acceptance by external stakeholders, while others relate to environmental impacts and outcomes of solar pavers.

The first challenge is 'Reluctant Authority'. Focus group interview participants, especially property developers, indicated that they usually were required to transfer the road infrastructure ownership after construction. Post transfer, the local authority would assume responsibility for maintenance. However, there had been instances where local authorities would not approve projects due to complicated and expensive maintenance. For example, one participant was planning to implement new ideas regarding street lighting infrastructure. However, the project was rejected because the local authority lacked the capacity to maintain the innovative lighting. One of the participants noted, “Even if it’s on a Starta, like 10 years of development, then after 10 years who’s going to maintain it. They don’t have the fundamental capital to sustain it.” (Focus group session 2)

The second challenge identified was ‘Vandalism’. Vandalism is a recognized problem in Malaysia [73]. Focus group participants were concerned that post-installation, vandals may damage solar pavers in an attempt to steal its Photo Voltaic cells. A participant recalled the need to fit steel bars onto road infrastructures to prevent vandalism. Another participant commented, “I think in Malaysia, the problem is I think [laughs] vandalism is number one.” (Focus group session 5)

The third challenge identified was, “Complexity of installation and maintenance”. Some participants voiced their concerns on the extra installation difficulties inherent in integrating solar cells into the concrete pavers. A participant believed installing interlocking solar pavers blocks would be difficult unless a LEGO-style installation (modular) method was used. There was also concern that the requirement for a photovoltaic inverter to convert direct current (DC) from the solar pavers to alternating current (AC) further complicates the implementation process. Concerns were also raised regarding the maintenance of complicated integrated solar cells and potential difficulties if one solar paver malfunctions in an interconnected system. One of the participants commented, “Looking at the design of all these things, for me to install all these interlocking block (solar paver) at the current practice is already difficult.” (Focus group session 3)

The fourth challenge was the effect of 'High Humidity and Rainfall'. The focus group/interview participants commented that heavy rainfall, especially during the rainy seasons, could cause water seepage problems, while floods on roads could damage solar pavers and/or their wiring. Furthermore, high humidity could cause condensation to form on the polycarbonate surface, affecting the diffusion of sunlight.

The final challenge identified was 'Negative Environmental Impact'. During the focus group/interview, concern was raised about the overall carbon footprint of solar pavers taking into consideration any emissions from manufacturing, installing, maintaining and end-of-life disposal of the solar paver system. One participant also indicated that the environmental benefits of utilizing solar pavers might not be significant unless it was installed on a large scale. Furthermore, there was concern that solar pavers might replace existing greenery resulting in unattractive 'heat islands'. It was commented, "Solar panel is clean energy. However, doing the process for the solar panel, basically, it will be generating the environmental issues also, like the water the chemical to fabricate the panel itself." (Focus group session 1)

3.5.2.2. Weaknesses – The study identified five weaknesses that could act as barriers to effective solar paver deployment. These weaknesses are primarily issues that relate to the characteristics of solar pavers.

The first weakness was 'High cost'. Based on previous experience with solar-power projects, 21 (70%) focus group/interview participants believed solar pavers would have prohibitive investment costs. In addition, the nature of solar pavers implies constant contact with vehicles and pedestrians, thereby leading to rapid wear and tear and consequently increasing the cost of maintenance. Conversely, designing and producing solar pavers resistant to such constant load would imply a higher product cost. It was suggested that the profit margin for installing solar pavers might be unattractive for installers. According to one of the participants, "If we are going to self-sustain, it's going to cost a lot……. But the margin is so low at this moment." (Focus group session 2)

The second weakness identified was 'Design flaws'. These flaws could be with respect to material, shape or technical design. Participants were concerned that the polycarbonate material had a slippery surface which could be potentially dangerous for vehicles while also being susceptible to discoloration and damage from weather elements and traffic. It was noted, "The only thing is polycarbonate when it last about 5-7 years and crack after about 3-4 years. So that would be about the life span of the pavers." (Focus group session 1). Some participants believed that the solar paver's shape was too mundane and that square pavers were getting unpopular. However, other participants argued that the shape was less important than acceptance by the public. One participant commented, "My point of view is aesthetic view. It doesn't look really appealing." (Focus group session 12). Regarding technical design, a participant was concerned that solar pavers did not seem disability-friendly. At the same time, another suggested that the surface area of the polycarbonate material was too small, leading to a reduction in sunlight captured by the solar cell. One participant commented, "I have my scepticism of this……. It doesn't seem OKU (disability) friendly. You probably have a lot of regulatory hurdles to go through." (Interview session 5).

The third weakness identified was 'Low efficiency'. Low generation of power has been identified as a drawback of utilizing adopting solar technologies. Eleven (36.7%) focus group participants were concerned about this drawback. They noted that to effectively generate sufficient power, a large amount of solar pavers was needed, leading to an increase in cost. Furthermore, one participant mentioned that solar cells would decrease in efficiency over time. A participant commented as follows, "Efficiency. Efficiencies are far too low to make it worthwhile." (Interview session 4)

The fourth weakness identified was ‘Questionable practicality’. Although the concept of solar paver technology, in theory, enables dual functionality, participants were unsure about its practicality. Of concern was the situation that roads with heavy traffic would suffer shading effects that would impede the efficiency of solar pavers. Furthermore, the natural environment in the form of leaves, tree branches and dirt would also contribute to the shading effect. In addition, it was commented that the heat absorbed by the concrete pavers would reduce the efficiency of the solar pavers and shorten the lifespan of the product. The following was suggested, “Throughout the years, there will be dirt, dust. Ah, paver got dislocated position….. That will cost not just one paver, but it will cost the entire system.” (Focus group session 7)

The final weakness identified was ‘Better comparative opportunities’. Rooftop solar power generation is already well established in Malaysia and has been recognized as providing good input to the national energy mix [55]. The participants believed that rooftop panels had distinct advantages over solar pavers and, as such, were preferred by some focus group participants. The key advantages indicated included higher efficiency, lower maintenance cost, lower susceptibility to shading effects and vandalism. For example, the rooftop panels that are slanting can tilt towards the sun, have higher efficiency than photovoltaic panels installed on roads in a flat position [39]. In addition, participants noted that rooftop panels also had less wear and tear while also providing shaded areas for the benefit of pedestrians – an important consideration in a tropical clime. One participant commented, “But if it’s on the rooftop of the building, I mean it’s all guarded by security. You cannot just go in.” (Focus group session 3)

4. Discussion

The potential of solar pavers lies in their dual-purpose ability to enable the use of road infrastructure for the simultaneous generation of electric power that can then be used to run other road infrastructure such as electric lights. To maximize the potential of success of deployment of solar pavers, it is important to not only investigate the practicalities of solar pavers but to equally understand the perceptions of stakeholders that will be charged with installing and maintaining solar pavers. The focus groups and interviews held with construction industry stakeholders in Malaysia has identified important insights that need to be taken into consideration as discussed below:

4.1. Environment as both an enabler and a hindrance

The attractiveness of proposing the use of solar paver technology in a country such as Malaysia lies in its tropical weather and the inherent prodigious amount of sunshine generated. This potential is evident in the successful and widespread use of rooftop solar panels in the country and its encouragement by the government and industry. Furthermore, meeting set environmental protection targets and maintaining a favourable corporate image has also been extra motivators for adopting solar power generation. This, in combination with the technical expertise available from rooftop solar panels installation, would be expected to bode well for the success of solar paver technology.

Renewal energy technologies such as solar photovoltaic and wind power face various barriers to widespread deployment [74]. While the stakeholders involved in this research acknowledged the positives listed above, there was a clear and strong opinion that the interaction between solar pavers and the environment differed from the interaction between rooftop panels and the environment. The differences were, tellingly, not in favor of solar pavers. In particular, solar pavers are more vulnerable to shading from vehicular movement when compared to rooftop panels. Solar pavers are also more vulnerable to vandalism when compared to rooftop panels. Solar pavers are also susceptible to road floods and humidity damage. This finding is consistent with [36], which postulated that the solar cells are not suitable for roadway application because of corrosion and wear due to vehicle load and environmental challenges. These are important factors beyond the control of the stakeholders and will be ongoing concerns, thereby making solar pavers a less attractive proposition compared to alternatives. There were also concerns about heat damage to solar pavers. In effect, the tropical clime that should be a positive for the installation of solar pavers could potentially be their greatest hindrance.

4.2. Cost Implications and ‘Belling the Cat’

Solar power generation has been widely adopted because of its favorable cost attributes of converting abundant and free sunshine into electric power. A vast network of roads and pedestrian walkways would provide a very significant open area to enable the conversion of this free energy source. However, the focus groups and interviews' findings indicate significant cost concerns regarding solar paver technology and an apparent reluctance to the acceptability from this perspective. The financial concerns fall into three main categories.

The first is the cost of building road pavers that would be strong enough to withstand the load implications of constant vehicular traffic. Although solar cell materials are currently costly, it is projected that widespread deployment may reduce capital installation costs considerably [70]. Nevertheless, the industry stakeholders believed that there would be a significant manufacturing cost in this current study.

The second category of financial concerns is the ongoing maintenance of the solar pavers, particularly regarding their relatively short lifespan and replacement of faulty or vandalized pavers. These two categories of concerns can be addressed with adequate cost ownership by stakeholders. For example, the use of a solar controller, powered by Mc9S08QG8 can help address the short lifespan of storage batteries in solar technology [75]. However, the clear message from the focus groups and interviews is that the construction companies would be unwilling to accept these cost implications and that local authorities would also be reluctant to accept liability. The findings from the focus groups and interviews are consistent with the solar energy literature (e.g., [76, 77]) deducing that high financial cost is the most significant barrier to adoption because the high capital cost of solar systems is projected as outweighing the financial benefits of solar system installation. Therefore, findings from the focus group and interviews raise an important question – who will 'bell the cat' and accept the extra financial implications of the installation of solar pavers. Although there have been economic incentives from the government and private organizations, it is unclear if these incentives will be available for solar pavers or if they will be significant enough to compensate for the concerns raised. Past studies in developed countries (e.g., [74, 78]) have found that solar incentive strategies such as high state income tax credit and tax exemption remain vital to the deployment of solar photovoltaic system. Consequently, it is essential to develop innovative financing schemes for solar photovoltaics deployment in developing countries [79]. Education is needed to help users [80] and institutional decision-makers [80] understand the costs and benefits of solar technology. Faiers and neame [77] suggested that manufacturers and suppliers should work with the early solar power adopters to develop the technology's operational, economic and aesthetic aspects of the technology; in this case, for solar paver technology.

The third category of cost concerns relates to the financial output from power generation. Studies have shown that most roads are utilized by cars 20 percent of the time, enabling a high-level solar power generation in sunny climates [39]. Malaysia is a country with a vibrant tropical climate with average daily solar radiation of 4500 kWh/m2 and abundant sunshine for about 10 hours per day [81]. However, there was a concern that the effects of shading and the efficiency of power conversion may mean that the financial savings from solar paver power generation may not be as attractive in practice as it appears in principle.

4.3. Design is an Important Consideration for Solar Paver Success

A key outcome from the focus groups and interviews in the clarification of the potentially important role that the physical design of solar pavers can play in its successful adoption. Design features were also the key factors in the success of Feed-in Tariffs (FITs) [82]. The innovative design could play a significant role in allaying many of the concerns identified previously. Such design could result in robust pavers that can accommodate road traffic load while simultaneously being resistant to floods, heat damage, humidity and vandalism. Innovative paver design could also enhance power conversion efficiency and incorporate excellent 'grip' characteristics that reduce or eliminate the potential for pedestrians to slip and fall. The modular design will also improve the cost and efficiency of maintenance and repairs. From the technical aspect, modular design can detach parts and reduce their interdependency at the physical and design levels [82].

The novel nature of solar pavers may imply that the design attributes may need to be customized for different environments. There is some clarity that the physical samples shown to the focus group participants were considered to lack the physical characteristics to enable stakeholder support in Malaysia.

5. Conclusion

The study set out to investigate the potential to deploy solar paver technology in Malaysia by seeking and analyzing the perceptions of stakeholders in the Malaysian construction sector. It was imperative to understand their views on the potential benefits and perceived obstacles that will characterize the use of existing solar paver technology. The study involved 30 industry stakeholders in a series of focus groups and individual interviews. The findings clearly show that, in principle, there is significant acceptance of the technology by the industry stakeholders. This acceptance is founded on several considerations, including the need to satisfy statutory sustainability obligations, the potential to use previous experience and expertise in solar energy installation and the possibility to access financial incentives that support sustainability initiatives.

However, the study also found that there are significant challenges perceived by the stakeholders that would make the deployment of solar paver technology in Malaysia impractical and unviable at present. These challenges relate to the pavers' physical attributes and the environment, uncertainty about a viable long-term cost model and acceptance by society. These findings point to the potential of solar paver technology to play a significant role in society's energy mix if solutions can be found to the challenges perceived by the industry stakeholders.

6.1 Study Implications

The findings from this study have significant implications for research and practice. Concerning research, the results suggest that research on solar pavers will need to be multidisciplinary in nature to adequately and seamlessly address the issue of concern. Disciplines that are indicated include construction, manufacturing, business, and environmental sustainability. In addition, there is a need to consider the potential of solar pavers in different regions of the world. Key obstacles identified in this study include the impact of vegetation and rainfall, but these may not be particularly important or relevant in non-tropical climes.

For industry, the study highlights the importance of being open to considering new technological solutions and perhaps, more importantly, the imperative of engaging and contributing to the development process of such technologies. Furthermore, the study suggests that sustainability in construction has become widely accepted. As a result, industry stakeholders will need to be creative in developing business models that will make such emerging technologies financially viable during installation, operation, maintenance and disposal. This will mean engaging with both legacy and new partners to ensure novel solutions for novel technologies.

6.2 Research Limitations and Future Research

The findings of this study should be interpreted with its limitation borne in mind. First, the findings and implications of this study are drawn from qualitative data collected at a snapshot in time. A promising future line of research would be to study the evolution of solar paver design and implementation through longitudinal data and case studies. As the field moves forward, other mechanisms for solar paver technology using different theoretical intersections and methodological approaches should be explored. This is both a grand challenge and an opportunity of our time for scholars to pursue fruitful translation research on sustainable practices of businesses to protect the planet and achieve sustainable development goals [41, 83].

Second, our sample was collected in Malaysia and may not represent the construction industry in other developed and developing countries. Even within the developing countries (e.g., China, India, Thailand etc.), there are significant variations within cultures and institutional contexts. Societal norms and regulatory environment may influence how construction stakeholders think of sustainable solar paver, whether they respond to the real-world agenda and how they act. Future research may replicate this study in other countries to provide fresh insights for businesses and prepare them to adopt sustainable technology such as solar paver.

Third, our findings are based on the analyses of stakeholders from the private sector only. Although the participants represent the construction industry, we acknowledge that our work can be extended by interviewing the stakeholders from the government and public sector. Therefore, we urge future researchers to explore the sentiments and perspectives of the government and public sector on the design and implementation of solar paver technology to provide a comprehensive understanding of solar paver technology.

Despite these limitations, our findings enrich the emerging research on a solar paver that might be generalizable to stakeholders in other sectors such as manufacturing and services. For example, similar challenges are faced by professionals and consultants on Internet of Things (IoT) projects. Even within the high-technology companies in the developed countries, technological capabilities and high costs can make it difficult to implement sustainable infrastructure and systems. Our insights can be understood as broadly relevant to sustainable technology. Further research that contributes new knowledge that improves existing solutions for more sustainable consumption and production patterns would be valued.

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