Preliminary Study on the Potential of Harvesting Energy from Malaysian Road Pavement

By

Wan Muhammad Aiman Bin Wan Abdullah Sani

19281

Dissertation Submitted in partial fulfilment of

the requirement for the

Bachelor of Engineering (Hons)

(Civil)

SEPTEMBER 2017

Universiti Teknologi PETRONAS,

Bandar Seri Iskandar,

32610 ,Tronoh,

Perak Darul Ridzuan.

CERTIFICATION OF APPROVAL

Preliminary Study on the Potential of Harvesting Energy from Malaysian Road Pavement

By

Wan Muhammad Aiman Bin Wan Abdullah Sani

19281

A project dissertation submitted to the

Civil Engineering Programme

Universiti Teknologi PETRONAS

in partial fulfilment of the requirement for the

BACHELOR OF ENGINEERING (Hons)

(CIVIL)

Approved by,

____

(Dr Muslich Hartadi Sutanto)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

September 2017

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

____

WAN MUHAMMAD AIMAN BIN WAN ABDULLAH SANI

ABSTRACT

Unused energy occurred at the pavement in the form of solar radiation, vibration and stress have the potential to be converted into more useful energy mainly into electrical energy. It is an alternative way to produce renewable energy source for electricity generation in order to replace the depleting non-renewable energy resources. This paper is to review and evaluate different methods of harvesting energy from road pavement as well as to identify the most promising method to be used for Malaysia road. Evaluation on the efficiency and cost-analysis are done based on the information of current harvesting energy technologies which are piezoelectric and photovoltaic energy harvesters. Secondary data such as average daily traffic (ADT) in Malaysia expressways and average annual solar radiation in Malaysia are collected in order to identify the real potential of harvesting energy from Malaysia pavement. It is found that harvesting energy by photovoltaic noise barrier (PVNB) can produce the highest potential amount of energy which is about 0.614 kWh per m^2 per day compared to other embedded photovoltaic system and piezoelectric system. Levelised cost of electricity for PVNB is also much lower compare to others which is about RM2.22/kWh. This preliminary study have determine the potential of generating electricity from Malaysia pavement and further investigation as well as testing on the real application of each system should be carried out.

ACKNOWLEDGEMENT

Firstly, I am grateful to the Creator for the good health and wellbeing throughout the project to ensure that I could complete my research project. I am very glad and thankful to Universiti Teknologi PETRONAS (UTP) especially the Department of Civil and Environmental Engineering for providing me a great place to complete my degree study in civil engineering.

I would like to express my deepest appreciation to my supervisor, Dr. Muslich Hartadi Suntato for his valuable guidance, passion, full time support and continuous encouragement toward me from the beginning until the project is complete. He always provides new information as well as shares his knowledge and experience in order to improve my research project.

My thanks and appreciations to the entire department faculty members for their cooperation and assistance while doing my research project. Not to forget for my partner, Mohd Hakim who had done his project together with me and always ready to exchange information as well as data while comparing the result. I am also thankful to my family and all my friends that always give full support to me. They keep supporting me and will be there for me for any help.

Lastly, I would like to express my sense of gratitude everyone who directly or indirectly have lent their hand to help me throughout completing this research project. Thank you very much for everything.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Highway is the infrastructure that helps people and goods to move or commute from one place to another. It acts as a significant role to provide connection between the places and people as well as act as linkage of transportation for the daily activities. Highway pavements have the potential to be the alternative source for energy harvesting. The pavement is exposed to energy in the form of vehicle vibrations, traffic loading deformation, and solar or thermal gradients that could be potentially converted into some usable sorts of energy such as electric power.

Andriopoulou (2012) proposed energy harvesting procedures involve there steps which consist of capturing the energy, storage of energy and use of energy. Capturing the unused energy from the road pavement is the major and the most challenging aspect in energy harvesting process. Different methods were developed and studied by the researchers to capture each type of energies from the road pavement. The most famous technique is using piezoelectric transducer (PZT). This system generates electricity from the vibration and vertical loading stress caused by vehicles movement along the road as PZT are embedded in the road pavement. Factors such as pavement thickness, traffic speed, volume and load affect the output voltage from the system.

Besides, photovoltaic (PV) or solar cell technologies are also being applied to capture the thermal energy from the road pavement. Kang-Won et al. (2010) from Korea had investigated the feasibility photovoltaic technology as a harvesting solar energy system and claimed this technology currently is having difficulty to sustain through rough conditions in road pavement due to variation of environmental condition as well as excessive loading from the traffic. Malaysia naturally has bountiful of sunlight and solar radiation as it is located near the equator. The natural climate is a humid tropical that obtain much sunlight during day time which is suitable to be harvested.

Various studies were done related to the harvesting energy from the roadways. To identify what are the potential of harvesting energy from Malaysia road pavement, two type of energy harvesting methods are being reviewed and compared. By using these road energy harvesters to the real application on the road, the wasted energies can be fully utilized to create a better sustainable transportation system.

1.2 PROBLEM STATEMENT

Majority countries of the world currently depend on non-renewable energy sources such as coal, oil, and natural gases as an energy source. However, in order to be a developing country, we are facing problem with these non-renewable sources as the consumption is greater than production which eventually will lead to depletion of non-renewable energy. In Malaysia, demand for electricity over the past decade has increased, almost doubling alongside population growth, reaching 134billion kWh in 2012 according to data from the Malaysia Energy Information Hub (MEIH). The use of non-renewable energy sources has a variety of harmful effects to the environment while in contrast with renewable energy resources such as wind, water and solar, they have the tendency to become regenerative energy with endless supply yet have no consequence of environmental damage. Therefore, numerous researchers are working on the innovation potential in harnessing renewable resources and exploring to increase the energy harvesting efficiency to make it likely to be more competitive in the future.

Road pavement is one of the resources for renewable energy. It receives huge amount of solar or heat energy during the day time and movement of vehicle on the road surface provide mechanical stress or deformation to the pavement. These unused energies should be harvested to produce new energy or for any suitable usage.

1.3 OBJECTIVE

The objective of this paper is to review the available methods of harvesting potentials energy from road pavement which are by piezoelectric and photovoltaic technologies as well as to evaluate their reliability to harvest energy from pavement. Overview from previous studies and result from the tests as well as comparison of different energy harvesting methods are provided in the paper. The most suitable and promising method will be refined and proposed to be used for Malaysia road pavement.

1.4 SCOPE OF STUDY

The scope of this study is to review the current research literature on the methods of harvesting energy from road pavement. This paper covers how the mechanism of the system works and to what extends it helps to utilize the wasted energy for different usage. The methods that had been developed are being reviewed in this study which consists of harvesting system using piezoelectric transducer (PZT) and photovoltaic cell (embedded photovoltaic cell as well as photovoltaic noise barrier). The climate and type of road pavement in Malaysia are studied in order to evaluate and identify the suitable method of harvesting energy to be applied. The analysis of traffic data in certain part of Malaysia will help to indicate the effectiveness of harvesting methods available towards Malaysia road pavement.

CHAPTER 2

LITERATURE REVIEW

Voigt et al. (2005) studied on several energy harvesting technologies which are thermoelectric, electromagnetic, photovoltaic and piezoelectric. The results of the study in term of power density for each technology is compared and summarised as in Figure 1. They found out photovoltaic is capable to generate highest power density compare to others. However, they claimed that piezoelectric energy harvesting is also effective as energy productivity by photovoltaic will be varies and highly depended on climate of certain area.

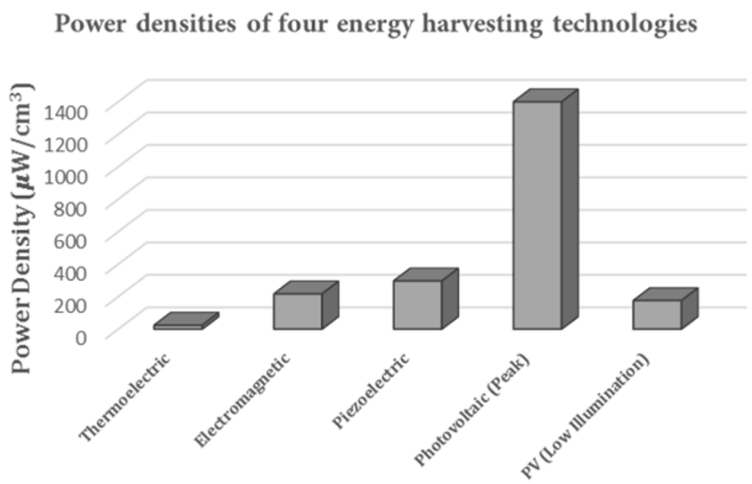


Figure 1: Comparison chart of the output power of energy harvesting technologies (Voigt et al., 2005)

2.1 PIEZOELECTRIC ENERGY HARVESTER

Most of the researchers currently are working on the piezoelectric material as a road energy harvester. It is the most popular type in the area of energy harvesting to generate electricity for low energy consuming devices. The system produces an electric voltage as there is deformation of their dimensions that is caused by the vibration and stress from the road pavement. A piezoelectric harvesting system with multiple cylindrical piezoelectric produced by Xiong (2014) cited in Papagiannakis et al. (2016) able to generate voltage of 400 to 700V and electric current ranges from 0.2 to 0.35mA with traffic volume of 4,000 vehicle per day (167 vehicles/hour).

Wang et al. (2014) claimed that advantage of piezoelectric is compactness of the design but it only can produce small amount of voltage in order of μW. However, according to Zhang (2015), an Israel company, Innowattech had developed a series of piezoelectric transducer at a depth of 5 cm beneath the road's upper asphalt layer and they claimed that with average traffic condition, it can generate about 250 kW power in 1 km road under traffic volume of 600 vehicles per hour. According to Xiong (2016), the power generation of all piezoelectric energy harvesters that he had studied at Troutville weight station reduced significantly after one year installation of the system. The degrading of energy output was identified and observed from Innowattech product as the researches from Virgina Tech conducted tests and demonstration on the system. It was found that the energy production is less than as Innowattech claimed (about 80-140kwh) after about 6 months operation.

Many piezoelectric harvesting systems had developed and tested in the roadways for the small scale application using various approach. However, Guo et al. (2017) claim that the results vary significantly due to the calculation conditions differ to each other such as the transducer material, traffic loading pattern and electric rectification design. With consistency of result from some researchers can produce 40mW of electric power, they estimated that from each single-wheel load, 0.00103 J of electricity can be generated by one PZT. They claimed that the output from the transducer is highly depending on velocity of vehicles, position of the transducer, foundation condition, and the position of the moving load. High vehicle velocity, rigid pavement with smaller rotation angles at transducer ends, moving load passes directly through the transducer will lead to high voltage and power output.

Study done by Papagiannakis et al. (2016) stated that California Energy Commission (CEC) had evaluated the piezoelectric technologies produced by different vendors and the energy output results from these vendors are considered different with respect to the assumption made for the number of sensors involved as well as the traffic level. CEC recommended a standardized way to be practiced for the report of energy output by piezoelectric unit surface that referred as energy density or power (W/unit area).

2.2 PHOTOVOLTAIC ENERGY HARVESTER

Photovoltaic (PV) or solar cell is another type of road energy harvester that draws attention of the researcher to investigate on its feasibility to generate energy from the road pavement. In general, when the sunlight hits the surface of a photovoltaic cell, the electric field that is formed by two different materials of the cell will supply the momentum as well as direction in order to stimulate electrons thus produce current flow. The energy productivity is highly depending on the surface area and period of exposure to direct sunlight which is limited under low sun radiation due to the weather condition or structure obstruction.

In 2014, the Netherlands had built the first solar road for bike path known as SolaRoad. It replaces 70 meters of the origin tarmac bike path with embedded solar panels which are covered by 1cm thick transparent coating. Rooij (2017) stated that SolaRoad is able to produce 9,800 kWh of electricity in the first year which is likely equivalent to the average annual consumption for three Dutch houses. The project was expended further together by improving the system for a better benefits return.

While in France, a road with solar panels is invented by Colas, providing enough energy to power the street lights of the small Normandy town of Tourouvre. The 1km long road covered with 2,800 sq. meters of resin-coated solar panels also called as “Wattway” applied the combination of road construction and photovoltaic techniques to generate clean, renewable energy in the form of electricity, while allowing for all types of traffic. However, Andriopoulou (2012) stated that it is difficult to install the current thin solar cells into the pavement which take extensive load cycle by the vehicles and the solar cells also will be exposed to wear and damage due to environmental condition. Therefore, to meet these requirements, researchers are developing new type of solar cell that will be suitable for road energy harvester.

The current technology had developed photovoltaic sound or noise barrier (PVNB or PVSB) as an alternative for harvesting energy from the roadways and railways. Grasseli et al. (2007) tested 6 PVNB sites with common constraints for road application to analyse energy performance, durability, maintainability and construction method. They found out that the maintenance of PVNB highly affects its reliability due to the factor of overheating as well as pollution from the vehicles during long life operation. The traffic dust and contamination also will reduce the efficiency of the photovoltaic panels to generate energy instead of the shading effect. However, Carder and Barker (2006) stated that rain actually help to clean the surface of photovoltaic panels effectively thus sustain the efficiency and reduce the maintenance activity.

Research done by Goetzberger et al., (1999) on the available PVNB technologies had identified several designs of PVNB structures as per Figure 2. They found out integrated PVNB structures (types 3, 4 and 5 of Figure 2) are more practical as well as cost-effective since they can generate electricity and also act as a noise barrier along the pavement.

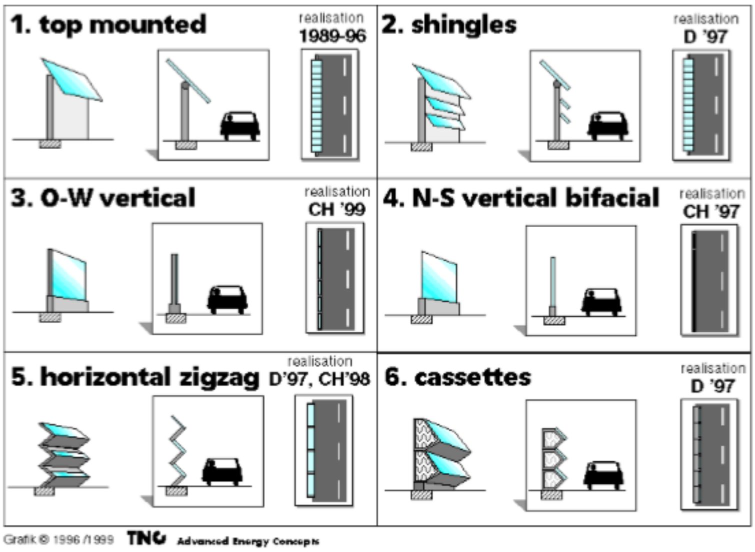


Figure 2 : Different types of PVNB structural designs. Retrieved from Goetzlerger et al. (1999)

In economic feasibility aspect, the important factor is that the efficiency of solar cells is increasing while the cost for photovoltaic systems is decreasing as the technology improved as stated by Poe et, al (2017). Therefore, it is good to make investment on this system which can have low payback period as recent studies have estimated that the installation costs of a series of PVNBs in the U.K. could possibly be offset by the electricity generation revenue almost for 20 to 25 years.

CHAPTER 3

METHODOLOGY / PROJECT WORK

3.1 RESEARCH METHODOLOGY

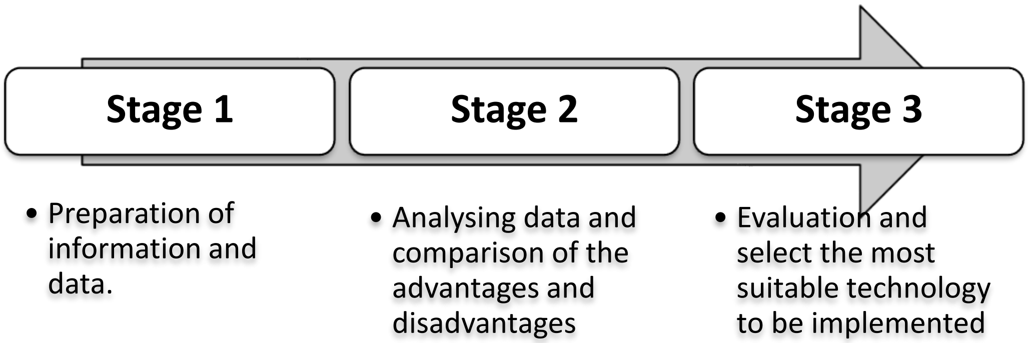


Figure 3 : Major stages of research methodology

3.1.1 Stage 1

This study is broken down into three major stages. The first stage of the project is preparation on the study which involves collection of information and understanding the main concept of the energy harvesting. During this stage, extensive literature reviews are required in order to collect enough information and understanding the matters related to the topic. The literatures are searched from online journal, books, newspaper and other internet based resources.

For piezoelectric energy harvester, there are several piezoelectric materials have been developed such as single crystalline (quartz), piezoceramics (PZT), piezoelectric semiconductor and polymer piezoelectric. Therefore, piezoceramic of lead zirconate titanate (PZT) is used in the study as its availability in many variations and is the most widely used materials for commercial products today. It is also cost effective and can be built into any shape conveniently. (Xiong, 2014)

Several secondary data are gathered in order to analyse the productivity of each energy harvester for Malaysia road pavement. Malaysia traffic data is obtained through web portal of Ministry of Transport Malaysia. Data such as the average daily traffic at 63 locations in Penisular Malaysia as well as 16 locations in Sabah and Sarawak on 2006 to 2015 is used in order to calculate the efficiency of piezoelectric energy harvester on Malaysia pavement road. Amount of electricity produce by piezoelectric is highly depends on the stress of the road pavement as the vehicles pass which is come from the load as well as the velocity of the vehicles. Hence, input data from Malaysia traffic is essential to evaluate the real potential of each energy harvester.

For photovoltaic energy harvester, two types of harvesters that are being studied on this paper which are embedded solar panel and photovoltaic noise barrier. Data of average solar radiation in Malaysia is used to calculate the efficiency of the photovoltaic system to generate energy. The data is taken study done by Mekhilefa et al, (2012) on the current state and prospects of solar energy in Malaysia. "Although solar radiation is one of the largest factors in calculating photovoltaic generation potential, other factors like technology, orientation and maintenance play important roles as well," (Carl et al, 2014). The parameters to calculate the energy generated as well as the total cost are assumed based on previous research of existing photovoltaic systems.

3.1.2 Stage 2

The second stage is to compare and analyse the gathered information in details. The scope of this paper will focus on harvesting potential energy from Malaysia road pavement and few available harvesting energy technologies are selected to be scrutinized which are piezoelectric and photovoltaic harvesters. Each harvester is able to generate energy by harvesting different type of wasted energy from road pavement and their advantages as well as disadvantages are further discuss in this paper.

For piezoelectric energy harvester, the electrical energy generated from each vehicle was calculated using $\boldsymbol{W = \int P\, dt}$. Zhang et al. (2015) estimated each PZT can generate 0.00103 J of electricity from a single wheel load and 0.0012 J from each four wheel load. Since the size of each PZT used in Zhang's study is 0.1m x 0.1m, 100 PZTs can be fit in a $1m^2$ roadway lane without stacks. With traffic volume inputs (N), total of electric energy generated can be calculated as **E = 100 x W x N**.

While for photovoltaic energy harvester, this general formula is used to calculate the potential energy generated;

$$E = A * r * H * PR$$

E = Energy output (kWh/day)
A = Solar panel area (m^2)
r = Conversion efficiency (%)
H = Solar radiation for the day ($kWh/m^2/day$)
PR = Performance ratio, coefficient for losses (range between 0.5 and 0.9, default value = 0.75)

r is the yield of the solar panel given by the ratio : electrical power (in kWp) of one solar panel divided by the area of one panel.
PR is the performance of solar installation which depends on the orientation, inclination of the panel, includes all losses and shading effect.

3.1.3 Stage 3

The last stage is evaluation part of the harvesting energy technologies and to propose the most productive harvester that is suitable to be implemented in Malaysia roadways. The criteria that been assess are previous expertise, energy efficiency, prospective cost and service life. Therefore the productivity of energy harvesters (piezoelectric, embedded photovoltaic and photovoltaic noise barrier) are evaluated based on the investment cost per unit electricity generated over their lifetime and is defined as levelized cost of electricity (LCOE). The general formula for LCOE is expressed as;

$$LCOE = \frac{sum\ of\ costs\ over\ lifetime}{sum\ of\ electrical\ energy\ produced\ over\ lifetime}$$

3.2 FYP KEY MILESTONES

Detail	Week													
	FYP 1													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Selection of FYP title	■	■												
Approval of FYP title		■												
Submission of Extended Proposal						■								
Proposal Defence								■	■					
Submission of Draft Interim Report													■	
Submission of Interim Report														■
	FYP 2													
Submission of Draft Progress Report				■										
Submission of Progress Report							■							
PreSEDEX											■			
Submission of Draft Final Report												■		
Submission of Dissertation (soft bound)												■		
Submission of Technical Paper												■		
Viva														■
Submission of Project Dissertation (hard bound)														■

3.3 GANTT CHART FOR FYP 1

Detail	**Week**													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Preliminary research on possible FYP title	■													
Selection of FYP title	■	■												
Approval title by Supervisor and Coordinator		■	■											
Collection of Information For Research				■	■	■	■	■	■	■	■	■	■	■
Preparation for Extended Proposal				■	■	*								
Discussion with Supervisor			■	■	■	■	■	■	■	■	■	■	■	■
Conduct Research						■	■	■	■	■	■	■	■	■
Preparation for Proposal Defence Presentation						■	■	■	*					
Preparation and Research for Interim Draft Report										■	■	■	*	*

3.4 GANTT CHART FOR FYP 2

Detail	**Week**														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Preparation on Progress Report							*								
Gathering and Analysis Data															
Discussion with Supervisor															
Poster Preparation for Pre-SEDEX											*				
Preparation of Final Report and Technical Paper												*			
Preparation for Viva														*	
Preparation of Project Dissertation (hard bound)															*

CHAPTER 4

RESULT AND DISCUSSION

4.1 COMPARING ENERGY HERVESTING TECHNOLOGIES

Main sources of energy at road pavement surface can be in solar radiation from the sun and stress or mechanical energy from the traffic flow. This part of study compares the advantages and disadvantages of each energy harvesters for Malaysia road pavement.

4.1.1 Advantages and Disadvantages of Piezoelectric Energy Harvester

The electricity produced by piezoelectric generator will be collected and stored in a storage system before the accumulated energy to be used to power the street lamps, traffic lights or routed into the power grid. Although one unit of piezoelectric transducer can generate small amount of electric current, it has high frequency response towards the rapid stress changes.

Roshani et al. (2015) evaluate the effects of external factors such as pavement thickness, traffic speed, volume and load on the output energy. Based on the study, piezoelectric energy harvester is best to be place on the road with high traffic speed, volume and load as these parameters will generate more electrical energy. Furthermore, the power generation can be significantly increased by arranging the piezoelectric in stacks arrangement. However, piezoelectric energy harvester require regular and constant inspections for moderate the effects of heavy traffic load. Process of installation the new system to replace the existing infrastructure requires huge cost and expertise. Therefore, large scale energy harvesting using piezoelectric is not appropriate.

4.1.2 Advantages and Disadvantages of Photovoltaic Energy Harvester

The efficiency of this system is mainly depends on the duration of the exposure towards sunlight. Malaysia can be described a country that having a typical tropical climate with 2 seasons which are dry and rainy season. Therefore, abundance sunlight exposure from the pavement can be utilised using photovoltaic technology. By using photovoltaic panels embedded on surface of the pavement, it can help to control pavement's temperature as well as protect pavement layers from deformation thus increase the pavement life. Besides, the technologies nowadays are going to develop solar road that contain LED lights that can act as road lines and warning signs which are built into the road itself. However, using normal thin film solar cells are difficult to be implemented in road surface that receives lots of mechanical load cycles and environmental condition which leads to wear as well as damaged. Therefore, repairing and maintaining the solar panel will be more expensive compare to normal asphalt pavement. In addition, the safety of solar panel as pavement surface is still not proven suitable for vehicles' tires.

Photovoltaic sound or noise barrier (PVNB or PVSB) had been developed as the alternative of embedded photovoltaic on pavement surface. This technology use photovoltaic panels as a noise barrier along the road or highways. It will help to improve the efficiency of harvesting solar energy to be much higher as it can be tilted to a certain angle in order to obtained maximum sun radiation while able to reduce the noise pollution from the road. PVNB also reduce the issue of low durability of photovoltaic cell but it is still exposed to contamination from the vehicles and weathering action after a long time operation.

The major drawback of photovoltaic is its cost. As for now, cost for manufacturing the solar panels is huge and according to the Missouri department of transport (MoDOT), the small 12ft-by-20ft (3.6m x 6.1m) patch of solar road will cost $100,000 (RM 427 00) to install. However, most solar company claims that even though the roads would be very expensive to install, the savings in the long run would be beneficial as solar roadways require less maintenance compared to normal pavement. Table 1 below summarise the advantages and disadvantages of each energy harvester.

Table 1: Summary of comparison between advantages and disadvantages of energy harvesting technologies

Energy Harvester	Advantages	Disadvantages
Piezoelectric	▪ Exploitation of waste stress energy ▪ High efficiency for busy road ▪ No significant changes on pavement surface	▪ Regular and constant inspection due to heavy traffic loads ▪ High cost and good expertise require for the installation
Embedded Solar Panel	▪ High efficiency due to Malaysia climate ▪ Lower pavement temperature and increase pavement life	▪ High manufacturing cost ▪ Low illumination during high volume traffic ▪ Fragile materials
PV-Noise Barrier	▪ Higher efficiency with maximum solar exposure ▪ Not affect the condition of pavement	▪ High manufacturing cost ▪ Exposed to contamination from vehicle

4.2 ESTIMATION OF ELECTRICAL ENERGY GENERATION FROM MALAYSIA ROAD PAVEMENT

4.2.1 Potential of Energy Generation from Piezoelectric Energy Harvester

Based on Zhang et al, (2015), he estimated that each PZT can supply around 0.0012 J ($3.3x10^{-7}$ kWh) from a vehicle with a constant speed of 30 m/s (108 km/hr) and distributed load of 0.267 MPa. The PZTs are placed at the placed under the trajectory path of wheels in order to get the maximum output which is known as four wheels load in their study. Total electrical energy generated can be calculated by multiplying electrical energy for one unit PZT with average daily traffic (ADT) of that road. The size of each PZT used in that study is 0.1m x 0.1m, and 100 PZTs can be fitted in $1m^2$ of a road area without stacking.

For an example, the highest average daily traffic (ADT) based on Malaysia Transportation Statistic 2015 is from Kuala Lumpur which is along Kuala Lumpur-Seremban Expressway with 221 066 vehicles per day. The total potential energy generated is about 0.00736 $kWh/m^2/day$.

Energy each PZT = 0.0012 J

Power $= \frac{Energy}{Time} = \frac{0.0012J}{3600s} = 3.3x10^{-10}$ kWh

Total energy output = 100 x P x ADT(max)

= 100 x $3.3x10^{-10}$ x 221 066

= 0.00736 $kWh/m^2/day$ (KL - Seremban Expressway)

Figure 4 shows the average of potential energy output generated by piezoelectric energy harvester for major roadways in Malaysia according to the regions. Kuala Lumpur, largest and busiest in city the country with high traffic volume can generate highest average potential electrical energy of 0.0066 $kWh/m^2/day$. Other fast developing regions such as Selangor and Pulau Pinang are also having great potential to generate electricity by using piezoelectric system.

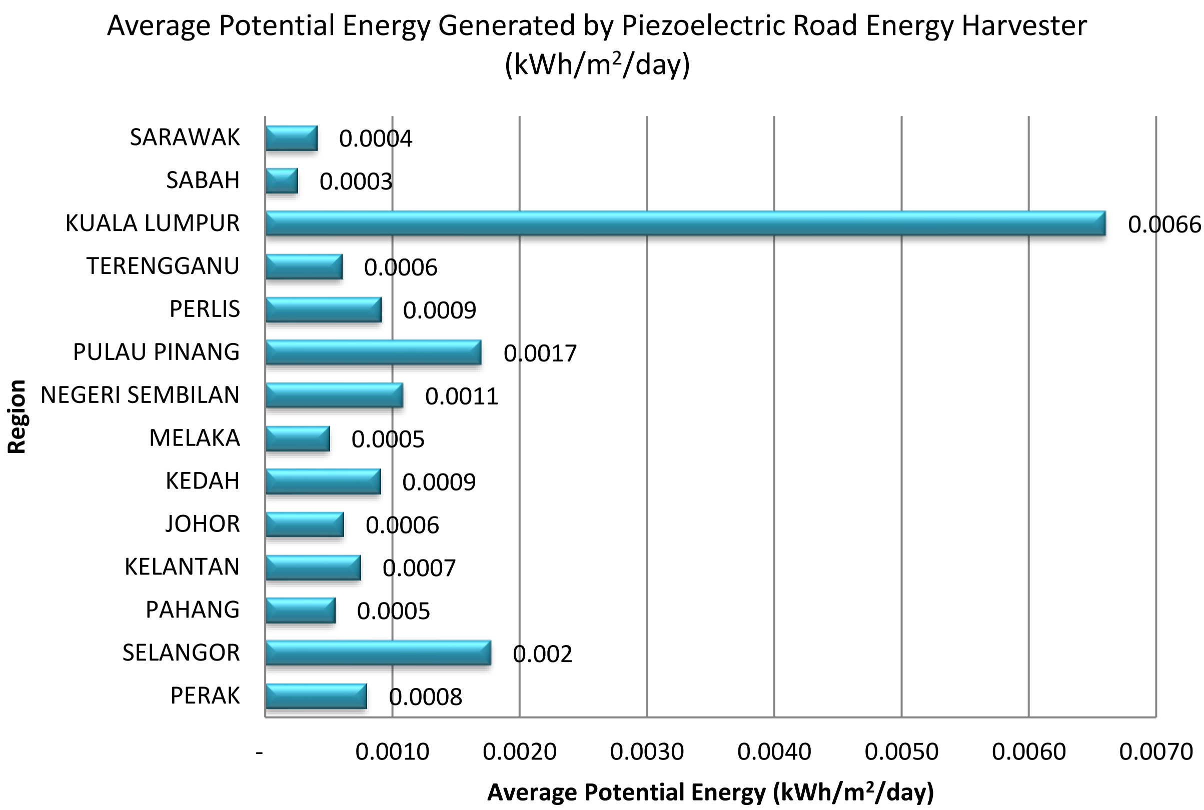


Figure 4: Average of potential energy generated by piezoelectric road energy harvester for major roadways in Malaysia

By having 0.3m width of PZT in two parallel lines under the standard trajectory path of the wheels for a stretch of 1km roadway, the area covered is 600m^2 per lane. Assuming the average Malaysia roadways are four lanes in two directions, the total area of PZT will be approximately 2400m^2 for 1km length. Thus, the piezoelectric system may generate about 15.85 kWh/day for 1km roadway with area of 2400 in Kuala Lumpur. The rest potential energy generated for other regions are shown in Figure 5 below.

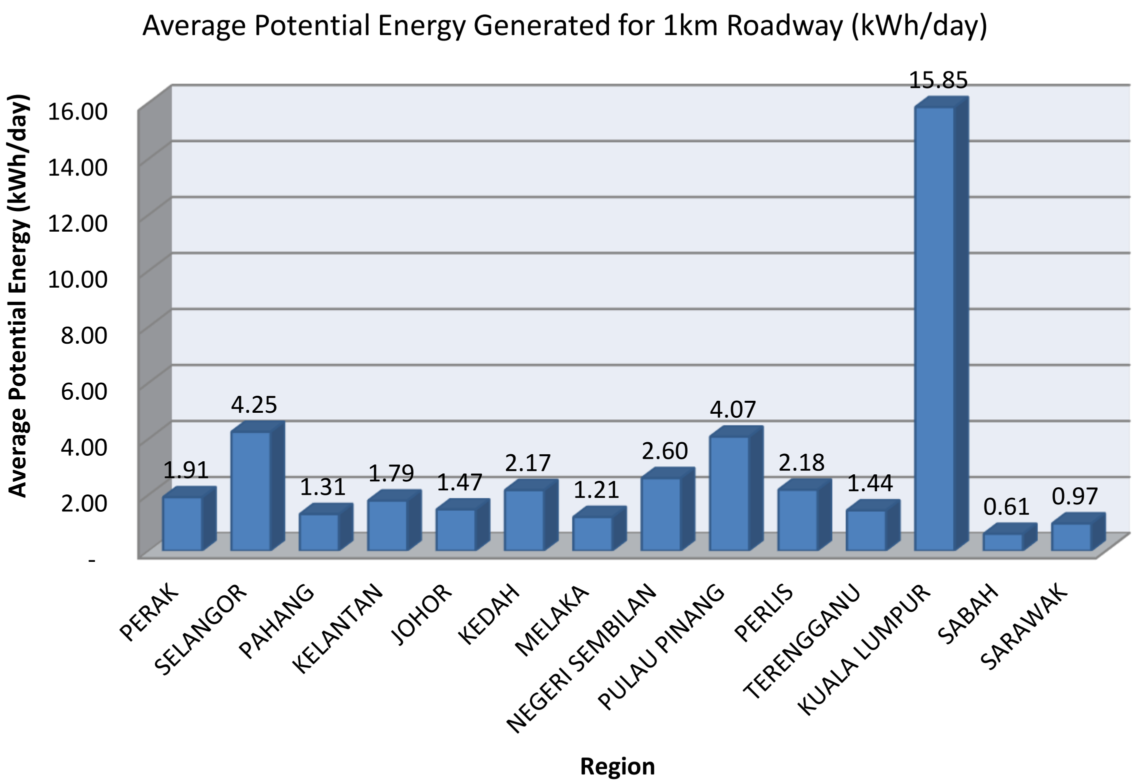


Figure 5: Average of potential energy generated by 1km of 2400m^2 area piezoelectric road energy harvester for major roadways in Malaysia

If the area of 2400m^2 PZT used in 1 km roadway in Kuala Lumpur, it can generate about 15.85 kWh/day, almost 475 kWh electricity per month. On average, Malaysia's per household electricity consumption is 251 kWh per month. Thus, the generated electricity from the piezoelectric system along this 1km pavement stretch in Kuala Lumpur may light up almost 2 homes in Malaysia.

4.2.2 Potential of Energy Generation from Photovoltaic Energy Harvester

Based on data from Mekhilefa et al., (2012), Kota Kinabalu is having the highest annual average solar radiation which is 1900 kWh/m^2 that equal to 5.2 kwh/m^2 per day. For road embedded photovoltaic, the solar conversion efficiency for Wattway pavement by Colas is 15%. However this 15% efficiency still doesn't take into account the fact that traffic, snow or standing water could block the sunlight and reduce efficiency even further. The blockage of sunlight is highly depends on traffic volume as well as the traffic speed. Generally, the higher traffic volume of a certain pavement, the lower the sunlight exposure to the embedded photovoltaic and due to this shading effect, it is assumed that the maximum conversion efficiency loss is about 4%. Thus, 11% efficiency will be used in estimating the potential energy generation by road embedded photovoltaic. It is also assumed that the performance ratio (PR) is about 75% by default due to the loss of inverter, cables and other losses.

While for PVNB, the efficiency is assumed about 18% based on realistic projects studied by Goetzberger et al., (1999). They have more solar conversion efficiency compare to road embedded photovoltaic as the tilted angle of PVNB surface will increase its efficiency to obtain optimum sun radiation depends on the type of PVNB structures and its orientation. The shading effect also is not that crucial in such the sunlight will not be blocked by the vehicles on the road but just the shadow of barrier itself and might be from the neighbouring structures. However, the performance ratio (PR) for PVNB is also assumed to be 75% due to the losses. In general, the electrical generation from photovoltaic energy harvester can be estimated using formula below;

$$\mathbf{E = A * r * H * PR}$$

E = Energy output (kWh/day)
A = Solar panel area (m^2)
r = Conversion efficiency (%)
H = Solar radiation for the day (kWh/m^2/day)
PR = Performance ratio (%)

Table 2: Total potential energy output by road embedded photovoltaic and PVNB in Malaysia based on 2012 average annual solar radiation.

Bil	Region	Average Annual Solar Radiation (kWh/m²)	Daily Solar Radiation (kWh/m²)	Embedded Photovoltaic		Photovoltaic Noise Barrier (PVNB)	
				Solar Conversion Efficiency	Potential Energy Output (kWh/m²/day)	Solar Conversion Efficiency	Potential Energy Output (kWh/m²/day)
1	Kuching	1470	4.027	0.11	0.332	0.18	0.544
2	Bangi	1487	4.074		0.336		0.550
3	Kuala Lumpur	1571	4.304		0.335		0.581
4	Petaling Jaya	1571	4.304		0.335		0.581
5	Seremban	1572	4.307		0.335		0.581
6	Kuantan	1601	4.386		0.362		0.592
7	Johor Bahru	1625	4.452		0.367		0.601
8	Senai	1629	4.463		0.382		0.603
9	Kota Bharu	1705	4.671		0.385		0.631
10	Ipoh	1739	4.764		0.393		0.643
11	Taiping	1768	4.844		0.400		0.654
12	Georgetown	1785	4.890		0.403		0.660
13	Bayan Lepas	1809	4.956		0.409		0.669
14	Kota Kinabalu	1900	5.205		0.429		0.703

Based on the data from Mekhilefa et al., (2012), the average daily solar radiation differences between the regions in Malaysia are not varies significantly as shown in Table 2. However, these differences of solar radiation will produce different amount of electrical energy harvested by piezoelectric system that have to be considered for the design optimisation especially when the cost of investment is huge. It is found that Kota Kinabalu has the highest average annual solar radiation which is about 1900 kWh/m^2. Thus, photovoltaic energy harvester system is best to be implemented in Kota Kinabalu as for every meter square of PVNB, it may approximately generate 0.703 kWh electricity per day in Kota Kinabalu with 18% efficiency of solar conversion, as compared to only 0.544 kWh per day in Kuching which is having the lowest average annual solar radiation. By having less conversion efficiency, the differences of the energy output between road embedded photovoltaic and PVNB be observed in Table 2 and Figure 5.

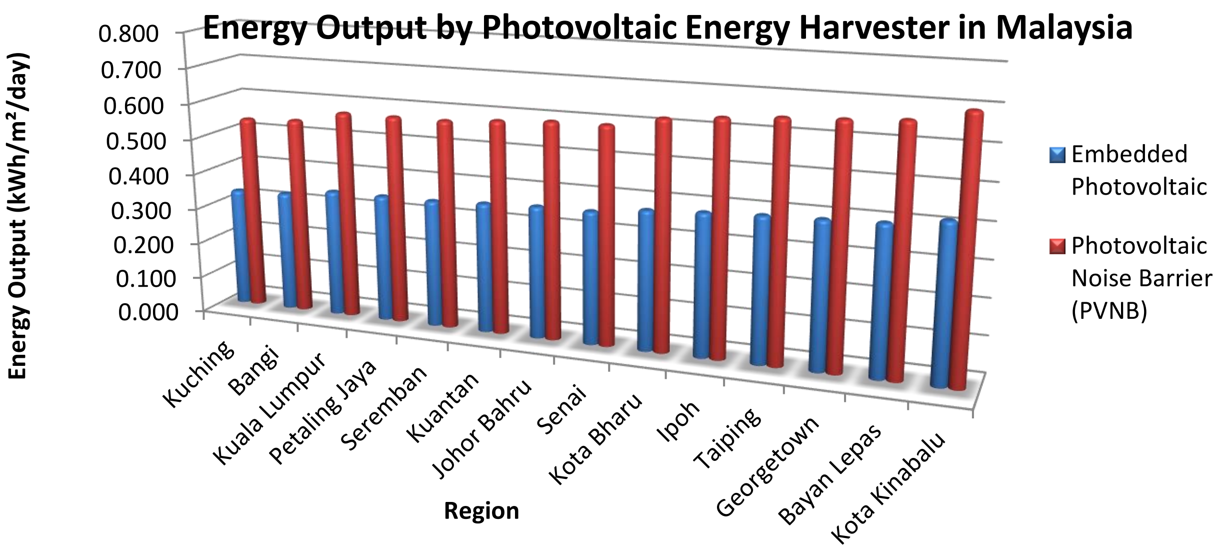


Figure 6: Average energy output of the regions generated by road embedded photovoltaic and PVNB in Malaysia

If the embedded photovoltaic panels are installed on the roadway with average width of 3.5m roadway, assuming the roadway is 4four lanes with two directions, for 1km length, the area covered is 14 000m^2. For that area in Kuala Lunpur roadway, the embedded photovoltaic system can generate about 4 970 kWh electricity per day which is almost 149 100 kWh/month or 149.1 MWh /months. The generated electricity can power up about 590 homes with average Malaysia household electricity consumption and some further electricity supply for various road-side applications, such as traffic lights, billboards, traffic cameras and road signs.

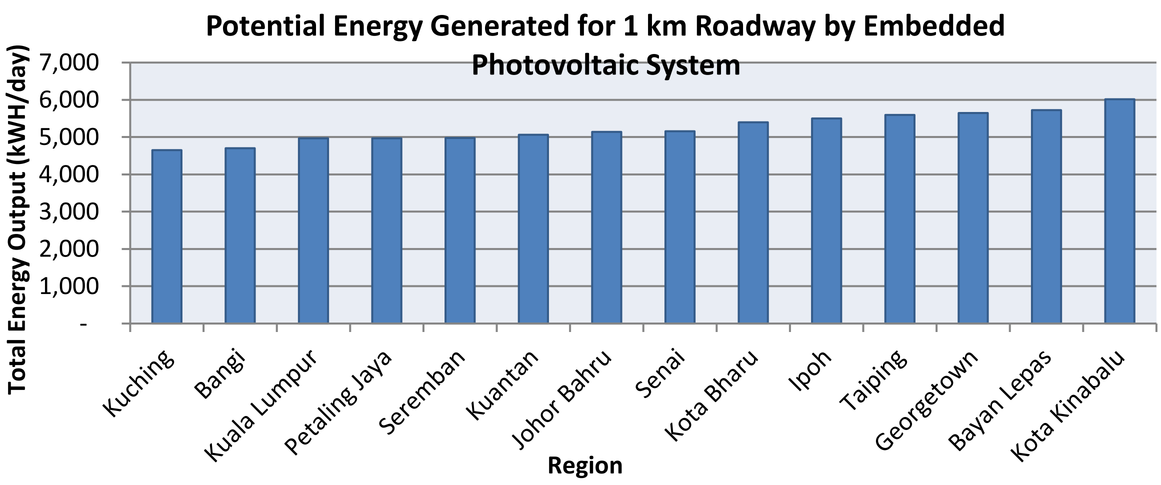


Figure 7: Potential energy generated by 1km of 14 000m^2 area embedded photovoltaic energy harvester for major roadways in Malaysia

While for PVNB, based on A27 highway project in Netherland, the height of the PVNB is about 1m which is installed on the 3 m noise barrier. If 1 m height of photovoltaic panels are installed both sides of the 1 km road in Kuala Lumpur, the potential energy generated is about 1162 kWh/day with area of 2000 m^2. Theoretically, the system can supply approximately 34 860 kWh electricity per month which cover up electricity for almost 138 homes.

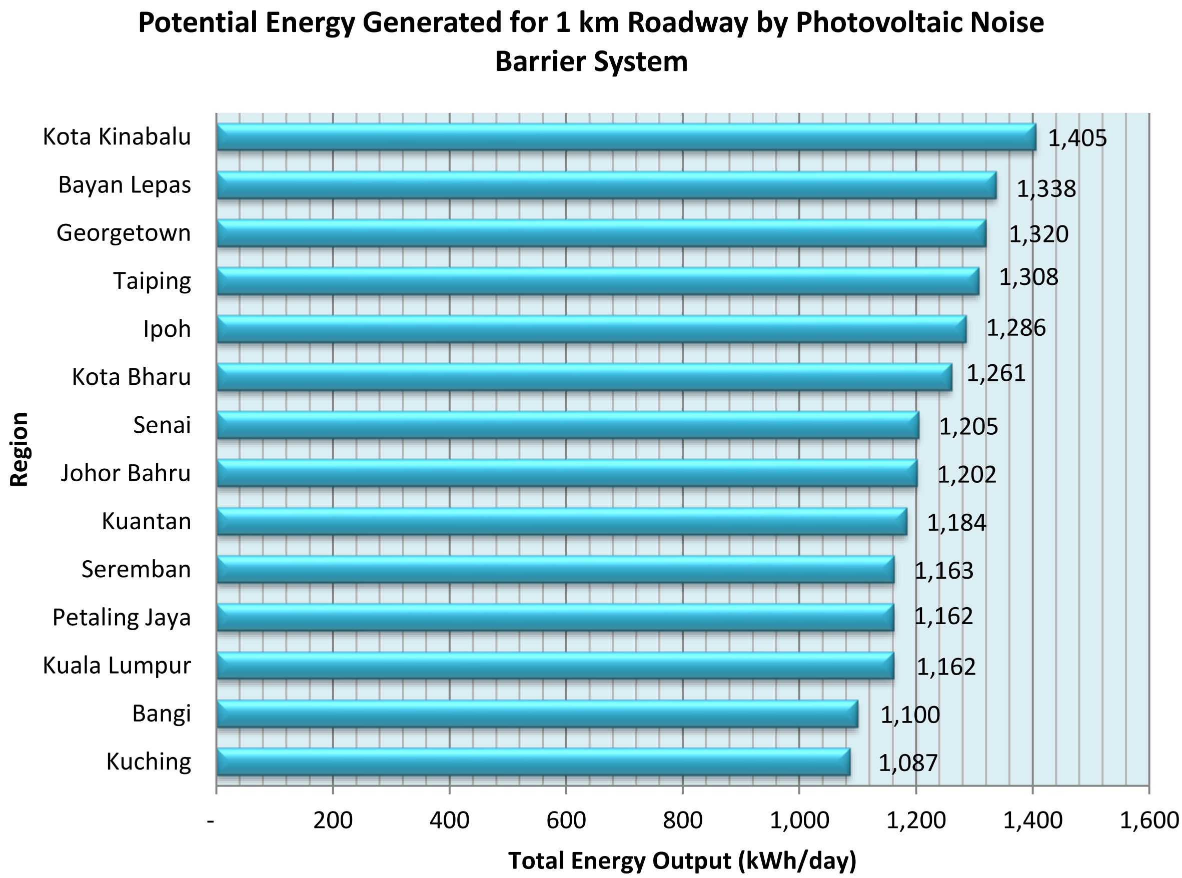


Figure 8: Potential energy generated by 1km of 2 000m^2 area photovoltaic noise barrier energy harvester for major roadways in Malaysia

4.3 COST-EFFECTIVENESS ANALYSIS OF ROAD ENERGY HARVESTIING IN MALAYSIA

Electrical energy generated by each road energy harvesters is not the only parameters used to study the full potential these harvesters to be used in Malaysia. The evaluation must take into account the cost to be invested for each system to generate electricity over their lifetime. In this paper, cost-effectiveness analysis is used as a levelised cost of electricity (LCOE).

4.3.1 Cost-Effectiveness Analysis for Piezoelectric Energy Harvester

Based on Guo et al., (2017) he expressed the LCOE for piezoelectric energy harvester as;

$$LCOE = \frac{Cp + Ci}{Wp \times N \times w \times 365 \times Y}$$

Where;
Cp = cost each PZT unit
Ci = cost of installation
Wp =energy output from each PZT unit per vehicle
N = number of vehicle per day
w = equivalent hit rate
Y = service life

Study done by Urquiza et al., (2016) cited in Guo et al., (2017) estimated that the cost for PZT material is about \$1207 (RM 4700) /m² and installation of PZT system is \$75(RM 300)/m². Since the area of 100m × 0.2m was used which can be embedded with 30,000 PZT cymbals, total cost for installation of each PZT, $C_p + C_i$, is around RM 3.33. Each PZT can generate energy about 0.0012 J (3.33×10^{-10} kWh) and with the traffic volume of Malaysia major expressway varies from 2,310 to 221,066 vehicles as well as equivalent hit rate, w, is assumed to be 100% with 5-15 years of service life, Y, LCOE for the PZT system is calculated as follows;

$$LCOE\text{pzt} = \frac{3.33}{3.33 \times 10^{-10} \times ADT \times 365 \times Y}$$

For service life of 5 to 15 years, average LCOE for PZT is in the range of RM 135.85/kWh to RM 407.56/kWh based on average traffic volume in Malaysia expressway. The distribution of LCOE for each region in Malaysia is shown as per Figure 6. Kuala Lumpur which has the potential to generate highest average electricity output is having the lowest LCOE compared to other regions. As the service life of the system increases, the LCOE becomes lesser. Based on the result, for every kWh electricity generated in Kuala Lumpur by piezoelectric system, the cost is only RM9.38 if the system can last at least for 15 years.

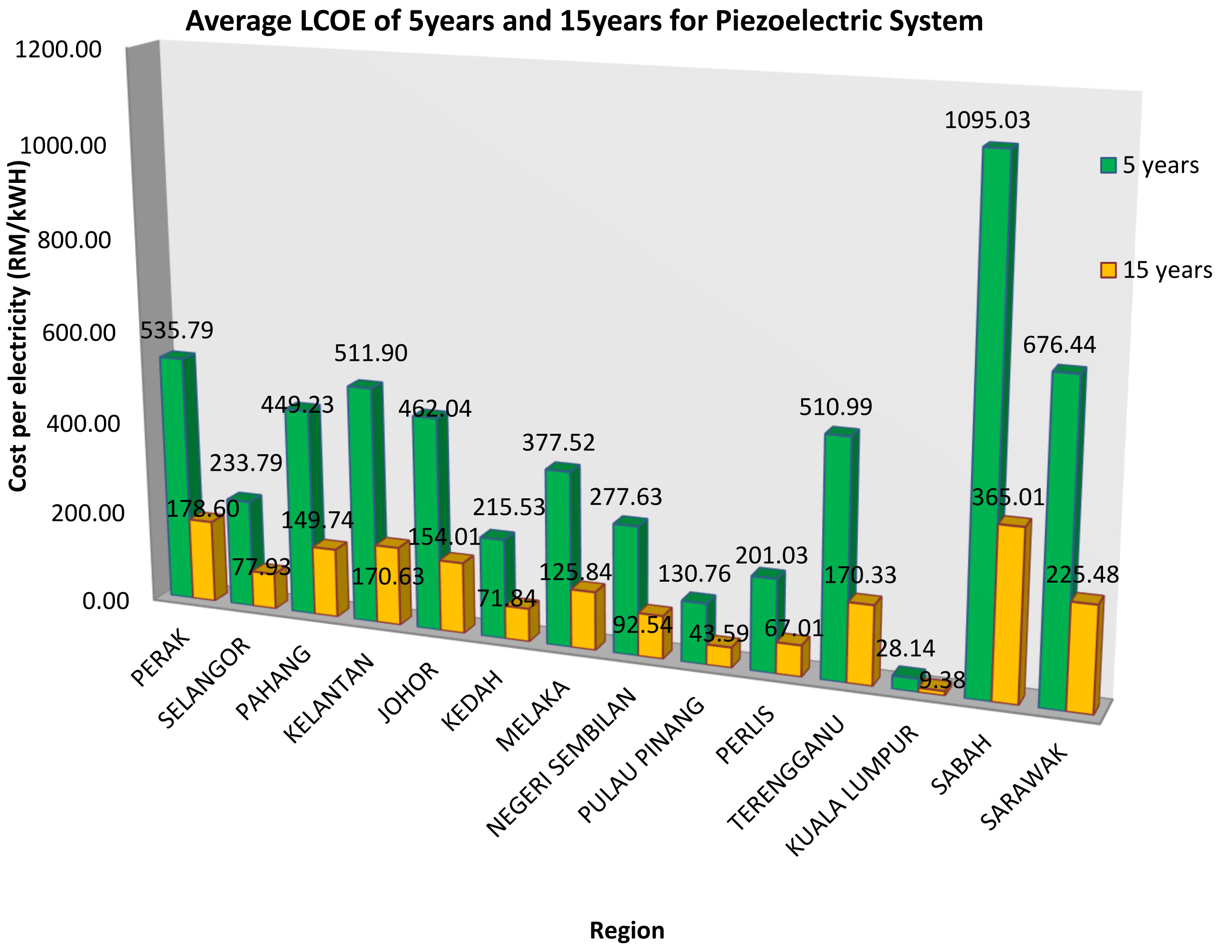


Figure 9: Average LCOE with service life of 5 to 10 years from piezoelectric system

4.3.2 Cost-Effectiveness Analysis for Photovoltaic Energy Harvester

The equation to calculate LCOE for photovoltaic energy harvester is almost similar to piezoelectric energy harvester. It is the total cost of the photovoltaic system divided with total of electrical energy generated over the lifetime.

Embedded photovoltaic pavement was installed by Colas in France with total cost of €5million (RM 24.9million) for a 1km road with area of 2800m^2. It can be assumed that total cost for 1m^2 of embedded photovoltaic is RM 8890. The panels are expected to last for 10 years under heavy traffic and up to 20 years, Y, in less trafficked sites. Therefore, LCOE for the embedded photovoltaic system based on the average energy output in Malaysia (0.375 kWh/m^2/day) can be calculated as follows;

$$LCOE_{\mathrm{pv}} = \frac{8890}{0.375 \times 365 \times Y}$$

LCOE for pavement embedded photovoltaic energy harvester is in the range of RM3.24/kWh to RM6.49/kWh for 10-20 years of service life.

For PVNB, the cost analysis is based on 1995 PV Noise Barrier A27 installed along the (A27 highway at De Bilt, Utrecht in Netherlands. According to PVdatabase (2015), total cost for the system is about €1.1million (RM 5.5 million) with area that cover 550m^2 and consist of 1116 solar modules. It can be assumed that 1m^2 of PVNB will cost about RM9950. The PVNB should be last at least 20 years and with 0.614 kWh/m^2/day average energy output in Malaysia, the LCOE of PVNB can be calculated as follows;

$$LCOE_{\mathrm{PVNB}} = \frac{9950}{0.614 \times 365 \times Y}$$

As for the result, LCOE of PVNB is about RM2.22/kWh as per previous data and some estimation. This value is slightly less than LCOE of embedded photovoltaic due to its better efficiency of generating electrical energy although the cost would be higher than photovoltaic as summarised in Table 3. Note that all the cost estimation is done based on the previous researches for the real project application at different countries. These cost include the materials cost and installation cost which is known as total or the first cost. However, the maintenance and service cost for each energy harvester throughout the life time does not included in the total cost.

Table 3: Summary of evaluation for piezoelectric, embedded photovoltaic, and PVNB in Kuala Lumpur.

	Piezoelectric System	Embedded Photovoltaic System	Photovoltaic Noise Barrier System
Potential Average Energy Output in KL (kWh/m^2/day)	0.0066	0.335	0.581
Potential Energy Output for 1km roadway in KL (kwh/day)	15.85	5000	1 162
Total Area in 1 km roadway (m^2)	2 400	14 000	2 000
Cost of Energy Harvester System per meter squared (RM/m^2)	5000	8890	9950
Total Cost of Energy Harvester System for 1km Roadway (RM)	12 Million	124.5 Million	19.9 Million
LCOE (RM/kWh)	28.14 to 9.38 (5-15 years)	3.43 to 6.86 (10-20 years)	2.35 (20 years)

Based on the result, photovoltaic noise barrier system is more cost-effective than piezoelectric and embedded photovoltaic system. It also found that for Malaysia road pavement, using photovoltaic energy harvester is highly recommended as justified in Table 3, noted that the potential average energy output for each harvesting system is based on the average value from the regions in Malaysia.

CONCLUSION & RECOMMENDATION

Three technologies of road energy harvesting system (piezoelectric, embedded photovoltaic and photovoltaic noise barrier) are reviewed and analysed in depth to be implemented in Malaysia pavement road. Studying their implementation involves the evaluation of criteria such as energy efficiency, prospective cost, and their lifetime. There are advantages and disadvantages for each of road energy harvesters which are discussed in the result to get the information on strength and weakness of the system so they can be improved.

Based on the current estimation of electrical energy generation, it can be conclude that photovoltaic technology which is using photovoltaic noise barrier seems to be the most efficient method to harvest the wasted energy from Malaysia road pavement. PVNB system have the potential to generate the highest amount of energy (0.614 kWh per m^2 per day) compared to other methods and also the most cost-effective systems with LCOE of approximately RM 2.22 per kWh. This preliminary study indicates that solar energy can be harvested potentially much greater compare to stress or vibration energy from the road.

However, further research on this topic should be carried out in order to prove the effectiveness of the available energy harvesting technologies to the real application on site. Information from the previous literature review revealed that assessment on the pavement condition as the impact from the energy harvesting system is not prioritised. Evaluation on the impact of every system to the pavement as well as to the vehicles should be done to ensure the safety of the roadway users. Besides, the output of total potential energy generated by each harvesting system can be improved by using some software such as GIS since the traffic volume and solar radiation are varies for different location of the pavement. GIS software can produce more detailed result through topology and spatial operation which will further explore the potential of the harvesting technologies for Malaysia road pavement.

REFERENCES

Andriopoulou, S. (2012). A review on energy harvesting from roads.

Carder, D., & Barker, K. J. (2007). M7 trial of highway noise barriers as solar energy generators. PUBLISHED PROJECT REPORT PPR178.

Carl, C. (2014). Calculating solar photovoltaic potential on residential rooftops in Kailua Kona, Hawaii (Doctoral dissertation, University of Southern California).

Goetzberger, A., Kleiss, G., Castello, S., Hille, G., Reise, C., Wiemken, E., ... & Gaidddon, B. (1999). Evaluation of the potential of PV noise barrier technology for electricity production and market share. Final report (No. NWS--99091). Department of Science.

Grasselli, U., Schirone, L. and Bellucci, P. “Infrastructures Integration of Photovoltaic Power”, Proceedings of the International Conference on Clean Electrical Power (ICCEP '07), May 2007, Capri, Italy.

Guo, L., & Lu, Q. (2017). Potentials of piezoelectric and thermoelectric technologies for harvesting energy from pavements. Renewable and Sustainable Energy Reviews, 72, 761-773.

Kang-Won, W. and Correia, A., J., 2010. “A Pilot Study for Investigation of Novel Methods to Harvest Solar Energy from Asphalt Pavements”. Korea Institute of Construction Technology (KICT)

Mekhilef, S., Safari, A., Mustaffa, W. E. S., Saidur, R., Omar, R., & Younis, M. A. A. (2012). Solar energy in Malaysia: current state and prospects. Renewable and Sustainable Energy Reviews, 16(1), 386-396.

Ministry of Transport Malaysia, (n.d). *Transport Statistics Malaysia 2015*. Retrieved from Official Portal Ministry of Transport Malaysia: http://www.mot.gov.my/en/resources/yearly-statistic.

Papagiannakis, A. T., Dessouky, S., Montoya, A., & Roshani, H. (2016). Energy Harvesting from Roadways. Procedia Computer Science, 83, 758-765.

Paving the way to tomorrow's energy. (n.d.). Retrieved June 19, 2017, Retrieved from http://www.wattwaybycolas.com/en/.

Poe, C., Plovnick, A., Hodges, T., Hastings, A., & Dresley, S. (2017). Highway Renewable Energy: Photovoltaic Noise Barriers (No. FHWA-HEP-17-088).

PVdatabase, 2015. PV Noise Barrier A27. [online] Retrieved from http://www.pvdatabase.org/projects_view_detailsmore.php?ID=74

Rooij , Rogier van. “Dutch Solar Bike Path SolaRoad Successful & Expanding.” CleanTechnica, 12 Mar. 2017, cleantechnica.com/2017/03/12/dutch-solar-bike-path-solaroad-successful-expanding/.

Roshani, H., Dessouky, S., Montoya, A., & Papagiannakis, A. T. (2016). Energy harvesting from asphalt pavement roadways vehicle-induced stresses: a feasibility study. Applied Energy, 182, 210-218.

Voigt, T., Ritter, H., & Schiller, J. (2003, October). Utilizing solar power in wireless sensor networks. In Local Computer Networks, 2003. LCN'03. Proceedings. 28th Annual IEEE International Conference on (pp. 416-422). IEEE.

Xiong, H., & Wang, L. (2016). Piezoelectric energy harvester for public roadway: On-site installation and evaluation. Applied Energy, 174, 101-107.

Zhang, Z., Xiang, H., & Shi, Z. (2016). Modeling on piezoelectric energy harvesting from pavements under traffic loads. Journal of Intelligent Material Systems and Structures, 27(4), 567-578.

APPENDICES

JADUAL 1.12 : PURATA TRAFIK HARIAN (ADT) DI 63 LOKASI, SEMENANJUNG MALAYSIA, 2006 - 2015
Table 1.12 : Average Daily Traffic (ADT) at 63 Locations, Peninsular Malaysia, 2006 - 2015

BIL *No*	STESEN *Station*	KM	LOKASI *Location*	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
			PERAK										
1	AR 101	106.6	Ipoh - Tanjung Malim (Slim River toll house)	13,555	15,028	13,654	15,038	15,322	14,039	14,431	15,328	16,501	16,736
2	AR 204	78.9	Ipoh - Lumut	20,907	20,778	21,138	23,920	22,389	23,758	25,283	25,942	23,834	26,494
3	AR 301	35.9	Ipoh - Kampar	24,314	23,262	23,050	23,659	31,022	30,311	27,497	26,520	27,126	30,592
4	AR 303	5.6	Ipoh - Gopeng	62,597	64,866	71,205	79,513	84,135	73,487	85,819	77,195	78,210	78,136
5	AR 501	30.4	Ipoh - Kuala Kangsar (500m north of Sg. Siput town)	15,399	17,142	18,036	19,066	19,426	22,500	19,251	20,478	18,578	19,896
6	AR 601	79.7	Ipoh - Batu Hampar - Changkat Jering	10,208	11,989	16,091	16,752	14,128	11,726	19,410	20,588	19,881	20,664
7	AR 603	82.1	Ipoh - Changkat Jering - Semanggol	15,728	15,574	10,034	7,076	10,270	18,646	12,586	12,938	12,531	12,949
8	AR 703	106.3	Ipoh - Teluk Intan - Simpang Empat	23,258	14,351	24,244	25,159	25,365	25,004	28,465	25,469	25,865	27,249
9	AR 801	96.6	Ipoh - Kuala Kangsar - Gerik	4,169	5,319	2,509	2,715	1,724	3,110	3,562	3,487	2,826	3,139
10	AR 803	2.4	Lebuh Raya Timur - Barat	2,906	2,846	2,945	3,078	3,337	3,148	3,944	3,796	3,636	3,293
			SELANGOR										
11	BR 102	3.5	Klang - Port Klang (Jalan Watson)	35,132	42,452	47,817	46,690	52,901	53,983	57,835	56,513	52,563	49,706
12	BR 106	-	300m From The Federal Highway's Junction - North Klang Straits Bypass	109,893	115,023	129,408	122,468	141,121	135,678	140,780	143,223	136,424	131,348
13	BR 203	48.3	Klang - Morib - Batu Laut	6,709	6,324	6,711	7,023	7,101	6,862	7,128	7,777	7,741	7,890
14	BR 405	45.1	Kuala Lumpur - Kepong - Kuala Selangor	21,287	20,631	19,991	20,938	22,822	23,003	23,648	21,278	22,618	21,611
15	BR 501	72.1	Klang - Sabak Bernam	17,455	18,224	17,977	19,773	20,466	21,743	23,370	22,174	22,443	20,838
16	BR 604	21.7	Kuala Lumpur - Kajang	56,808	42,272	57,286	58,929	56,609	57,591	53,689	59,023	54,222	48,737
17	BR 701	58.6	Kuala Lumpur - Kuala Kubu Baru junction (south of junction)	9,896	9,723	12,307	13,209	18,293	13,430	13,320	15,062	15,022	15,536
18	BR 902	19.0	Kuala Lumpur - Karak Highway	141,362	159,324	137,870	150,213	129,345	144,334	151,486	147,449	144,308	129,579
			PAHANG										
19	CR 102	67.0	Kuala Lumpur-Kuantan (along KL-Karak Highway)	19,707	21,061	20,703	22,224	26,109	27,653	28,470	26,509	28,300	30,436
20	CR 403	233.0	Kuantan-Maran	22,293	24,565	23,395	26,064	28,248	29,142	31,138	31,416	31,876	29,856
21	CR 410	32.5	Kuantan-Kemaman	18,840	21,337	20,260	22,249	22,079	23,278	22,911	21,601	22,995	20,827
22	CR 503	262.0	Kuala Lumpur-Kuala Lipis- Kampung Padang Tuanku-Kota Bharu *	6,134	6,427	6,609	6,159	6,253	7,053	7,513	6,985	7,319	8,063
23	CR 603	3.0	Pekan-Nenasi	6,513	6,902	5,746	7,783	8,650	9,761	10,319	11,563	11,535	10,741
24	CR 801	115.0	Kuantan-Karak	11,003	12,106	11,567	11,814	11,771	11,597	13,281	13,328	15,673	14,874
25	CR 805	189.0	Kuantan-Maran	6,832	6,855	6,587	6,761	6,980	8,049	7,088	6,952	6,714	6,389
26	CR 902	-	Kuantan-Segamat (400m. Bkt. Ibam-Rompin junction north bound)	6,634	6,721	7,316	11,634	8,102	8,427	9,545	8,763	9,314	9,985

SUMBER: KEMENTERIAN KERJA RAYA
Source: Ministry of Works

JADUAL 1.12 : PURATA TRAFIK HARIAN (ADT) DI 63 LOKASI, SEMENANJUNG MALAYSIA, 2006-2015 (SAMB.)
Table 1.12 : Average Daily Traffic (ADT) at 63 Locations, Peninsular Malaysia, 2006-2015 (Cont'd)

BIL *No*	STESEN *Station*	KM	LOKASI *Location*	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
			KELANTAN										
27	DR 201	19.3	Kota Bharu - Melor	22,900	35,931	30,696	43,222	31,602	37,939	42,433	32,263	26,043	39,257
28	DR 603	6.1	Km Lebuh raya Timur-Barat	4,807	5,090	5,224	5,296	5,440	5,863	6,275	6,029	6,141	4,716
29	DR 802	61.5	Kota Bharu - Kuala Krai	16,932	18,828	18,707	19,521	20,632	22,308	23,381	21,200	22,523	23,345
			JOHOR										
30	JR 101	142.0	Johor Bahru - Batu Pahat - Muar	11,086	11,727	10,736	12,735	11,162	11,711	14,847	18,659	15,491	13,321
31	JR 104	127.2	Johor Bahru - Yong Peng - Muar	17,891	24,014	32,094	33,381	25,916	40,092	23,361	34,672	32,757	25,310
32	JR 108	116.0	Johor Bahru - Segamat	11,281	12,263	12,557	12,869	12,262	13,025	12,369	11,628	11,521	11,965
33	JR 205	12.7	Johor Bahru - Skudai	199,433	187,867	154,952	218,035	221,084	213,390	162,454	189,292	191,427	178,012
34	JR 218	-	1000m east junction to Masai	45,330	42,184	43,457	46,426	49,309	40,426	47,563	26,552	26,502	29,045
35	JR 305	76.0	Johor Bahru - Ayer Hitam	15,248	15,381	14,708	15,261	14,810	14,894	15,398	13,911	15,847	17,359
36	JR 306	49.5	Batu Pahat - Ayer Hitam - Kluang	31,429	30,231	33,897	33,572	34,964	36,952	39,674	38,053	38,366	41,632
37	JR 404	38.6	Johor Bahru - Kota Tinggi	19,289	19,506	19,417	19,182	20,302	20,106	23,273	22,103	19,750	19,745
38	JR 501	135.2	Johor Bahru - Endau (2.4km north of Mersing town)	17,332	18,563	17,192	16,688	15,598	13,445	13,411	14,412	14,391	14,672
39	JR 503	111.1	Johor Bahru - Kota Tinggi - Jemaluang (500 m south of Jemaluang)	4,049	4,247	4,246	4,477	4,633	4,481	4,490	4,720	4,143	2,856
40	JR 702	60.0	Johor Bahru - Pontian Kecil - Pontian Besar (near Pontian Hospital)	20,095	13,926	17,789	14,480	14,406	12,125	16,772	15,081	14,678	15,945
41	JR 801	199.5	Johor Bahru - Segamat - Batu Anam	12,282	13,880	14,145	14,648	15,237	15,781	15,875	16,826	16,800	17,751
			KEDAH										
42	KR 202	20.6	Alor Setar - Changlun	37,853	37,093	51,314	34,715	30,402	32,311	42,822	47,474	34,003	36,660
43	KR 401	70.8	Alor Setar - Sungai Petani - Butterworth	21,067	20,596	16,123	19,052	24,002	22,195	23,141	23,971	23,672	24,779
44	KR 501	29.0	Alor Setar - Sungai Petani	20,396	21,206	17,586	19,169	19,387	19,618	19,249	18,853	17,797	19,654
			MELAKA										
45	MR 206	22.9	Melaka - Muar	24,404	19,090	14,057	15,501	15,679	16,426	17,044	16,779	17,112	17,182
46	MR 301	25.0	Melaka - Kendong	9,971	10,761	11,057	9,986	11,472	11,465	11,170	15,715	15,665	16,685
47	MR 313	43.5	Melaka - Lubok Cina	7,255	8,730	8,179	7,709	7,858	8,084	8,480	9,097	9,013	11,202

SUMBER: KEMENTERIAN KERJA RAYA
Source: Ministry of Works

JADUAL 1.12 : PURATA TRAFIK HARIAN (ADT) DI 63 LOKASI, SEMENANJUNG MALAYSIA, 2006–2015 (SAMB.)
Table 1.12 : Average Daily Traffic (ADT) at 63 Locations, Peninsular Malaysia, 2006-2015 (Cont'd)

BIL *No*	STESEN *Station*	KM	LOKASI *Location*	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
			NEGERI SEMBILAN										
48	NR 304	21.7	Seremban - Port Dickson	47,909	58,328	68,327	67,092	65,580	46,201	54,394	59,864	62,112	57,613
49	NR 403	42.7	Seremban - Tampin	13,074	13,456	12,990	13,073	12,690	12,565	12,832	12,645	11,459	12,465
50	NR 501	20.0	Seremban - Kuala Lumpur	14,844	15,418	14,329	12,530	12,052	11,964	11,397	10,671	11,810	11,870
51	NR 505	9.3	Seremban - Tampin (500 m outside town area)	39,714	38,284	38,197	33,697	35,708	38,378	57,639	50,484	48,002	47,976
			PULAU PINANG										
52	PR 116	16.9	Butterworth - Taiping	50,151	47,787	53,451	56,601	56,349	60,230	56,932	64,993	48,588	65,716
53	PR 201	11.1	Georgetown - Teluk Bahang (Jln. Keliling Pulau)	22,884	23,061	24,392	24,799	27,334	26,085	28,442	27,106	28,419	24,774
54	PR 203	57.2	Georgetown - Bayan Lepas - Gelugor (Jln. Keliling Pulau)	41,843	40,757	43,232	47,285	50,776	50,950	59,900	62,207	63,049	62,464
			PERLIS										
55	RR 105	3.2	Kangar - Alor Setar (Melalui Simpang Empat)	19,859	21,018	20,769	21,321	21,758	23,234	25,577	26,155	25,092	27,257
			KUALA TERENGGANU										
56	TR 103	61.5	K. Terengganu -Jerteh - Kota Bharu	19,007	18,384	23,357	21,313	24,196	25,551	27,325	27,066	19,490	23,584
57	TR 202	78.9	K. Terengganu - Dungun - Kemaman	20,955	25,215	23,463	29,051	28,602	30,035	27,856	29,864	28,124	28,171
58	TR 305	48.0	Kuantan - K. Terengganu (Jln. Jabor-Jerangau)	4,079	5,116	5,363	5,381	5,590	6,553	7,566	8,036	7,667	4,105
59	TR 402	17.0	K. Terengganu - Kuantan	24,524	39,230	24,933	24,852	25,887	27,451	29,532	31,227	31,686	24,887
60	TR 502	33.0	K. Terengganu - Kg. Ajil - Jerangau	12,216	10,838	13,132	14,701	14,695	12,649	10,092	8,715	8,739	9,561
			KUALA LUMPUR										
61	WR 102	12.1	Kuala Lumpur - Ipoh	150,874	158,754	161,161	214,746	277,797	276,092	252,341	253,179	214,760	211,188
62	WR 103	8.1	Kuala Lumpur - Ipoh	206,484	203,986	205,867	194,287	196,796	209,224	203,277	216,424	192,223	162,596
63	WR 105	8.1	Kuala Lumpur - Seremban Expressway	244,417	258,867	229,713	213,522	201,260	192,649	213,161	206,140	219,336	221,066

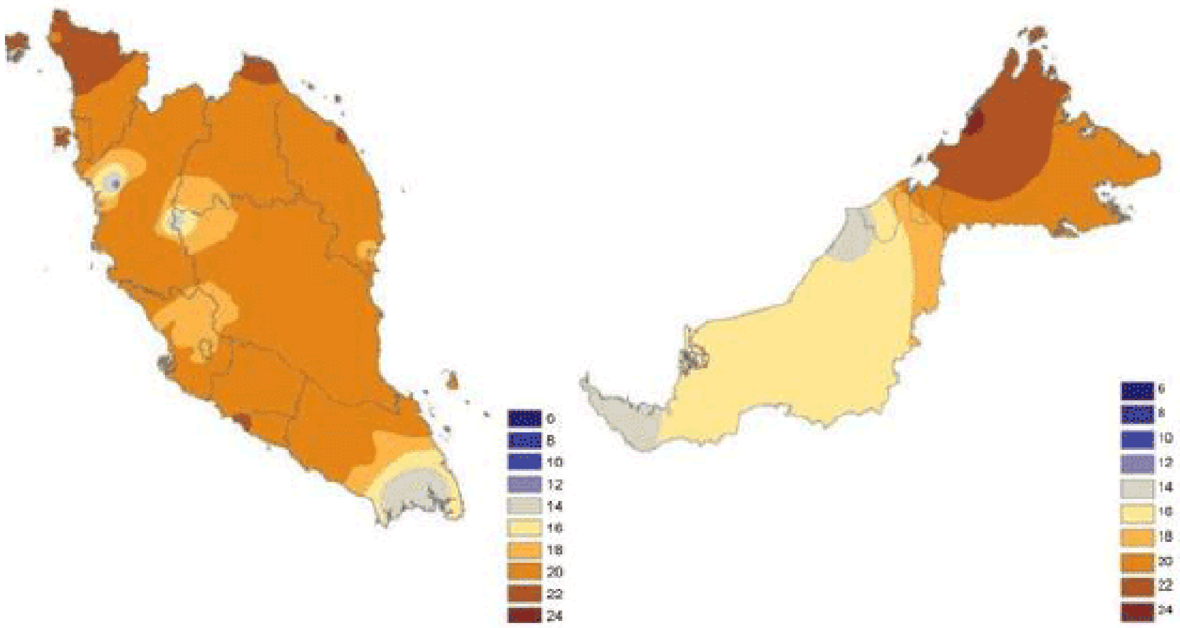
SUMBER: KEMENTERIAN KERJA RAYA
Source: Ministry of Works

JADUAL 1.13 : PURATA TRAFIK HARIAN (ADT) DI 16 LOKASI, SABAH DAN SARAWAK, 2006–2015
Table 1.13 : Average Daily Traffic (ADT) at 16 Locations, Sabah and Sarawak, 2006-2015

BIL *No*	STESEN *Station*	KM	LOKASI *Location*	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
SABAH													
1	HR 101	4.8	Beaufort - Sindumin	7,042	10,773	7,454	4,811	4,924	5,965	5,422	5,694	6,508	6,710
2	HR 104	9.0	Tenom - Toman - Bekuku Highway	4,196	3,879	4,566	4,566	4,294	4,425	2,123	2,450	2,378	2,299
3	HR 201	22.5	Kota Kkinabalu - Papar	3,541	4,932	6,453	7,968	9,370	11,791	14,491	14,406	15,329	15,786
4	HR 202	8.1	Donggongan - Tambunan	4,751	4,685	3,578	3,701	3,835	3,881	3,353	3,839	4,478	4,105
5	HR 204	69.0	Kota Kinabalu - Kudat (100mm From Longtigi Junction)	7,913	11,695	9,855	9,450	11,189	11,138	9,953	13,909	11,923	12,388
6	HR 501	31.4	Tawau - Semporna	10,938	17,009	16,850	9,407	10,074	10,035	10,455	10,327	10,229	11,508
7	HR 504	14.5	Sg. Segama Crossing	7,140	7,423	6,987	6,781	8,294	8,691	7,641	9,407	8,739	6,335
8	HR 506	68.0	20km from Semporna towards Tawau	1,670	3,231	2,585	2,663	2,711	3,074	2,742	2,704	3,087	2,310
9	HR 507	82.0	Tawau - Sandakan (Near Kunak Junction)	7,820	8,170	7,168	8,600	11,141	11,633	9,706	7,831	7,699	6,700
SARAWAK													
10	SR 101	16.1	Bau - Semantan	2,457	2,779	3,188	3,143	3,091	3,504	5,780	3,512	3,582	4,090
11	SR 103	27.4	Kucing - Serian	22,781	21,071	22,225	24,564	30,616	31,112	32,889	27,987	32,808	34,874
12	SR 401	20.0	Bintulu - Sibu	6,779	6,240	7,250	9,808	10,957	14,520	4,342	4,476	5,125	5,841
13	SR 402	29.0	Bintulu - Miri	4,828	4,771	5,924	7,880	8,507	4,178	5,355	9,139	8,677	7,452
14	SR 403	6.2	Miri - Bintulu (before junction to Airport)	10,345	6,882	9,984	11,060	10,506	12,211	11,805	10,865	10,887	12,329
15	SR 503	1.6	Limbang - Brunei Border (Sg.Padaruan)	16,317	15,830	16,319	14,141	19,032	13,519	11,014	12,742	11,150	12,807
16	SR 504	1.6	Lawas - Trusan	3,935	5,235	4,519	5,139	3,653	6,683	6,448	7,243	7,200	7,912

SUMBER: KEMENTERIAN KERJA RAYA
Source: Ministry of Works

Annual average solar radiation in Malaysia (Mekhilefa et al., 2012)



Annual solar radiation in different cities in Malaysia (Mekhilefa et al., 2012)

Region/Cities		Annual average value (kWh/m^2)
1	Kuching	1470
2	Bangi	1487
3	Kuala Lumpur	1571
4	Petaling Jaya	1571
5	Seremban	1572
6	Kuantan	1601
7	Johor Bahru	1625
8	Senai	1629
9	Kota Baru	1705
10	Ipoh	1739
11	Taiping	1768
12	Georgetown	1785
13	Bayan Lepas	1809
14	Kota Kinabalu	1900