# FINITE ELEMENT ANALYSIS OF HYBRID ENERGY HARVESTING OF PIEZOELECTRIC AND ELECTROMAGNETIC

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## ABSTRACT

Harvesting energy from ambient vibrations is a highly sought after method because of the wide range of available sources that produce vibration energy applicable from industrial machinery to human motion application. This report studied the implementation of harvesting energy from two technologies to form a hybrid energy harvester system. These two technologies involves are relate to the piezoelectric harvesting energy as well as the electromagnetic harvesting energy. A finite element model was developed by using the Ansys software with the harmonic analysis solver to analyze and examine hybrid harvesting energy system. The variance dimension of geometry on the bimorph piezoelectric cantilever beam is also being implemented in order to study the performance of the beam relating to the difference perspective of dimension. The proposed length of the cantilever beam was 16.5$mm$ and 36.5$mm$ with the width of 6.35$mm$, 12.7$mm$, and 19.05$mm$. Both power output generated from the magnet and the piezoelectric is then combined to form one unit of energy. The result shows the system generate the maximum power output of 14.85$\mu W$ from 100$Hz$, 4.905$m/s^2$, and 0.6$cm^3$ for resonance frequency, acceleration, and the volume respectively from the selected sample of the energy harvester design. The NPD result of 10.29 $kgs/m^3$compared with other literature also can be used in energy harvesting system for vibration application.

# ABSTRAK

Penuaian tenaga daripada getaran ambien merupakan kaedah yang sangat dicari-cari kerana terdapatnya rangkaian yang luas untuk menghasilkan tenaga getaran. Ia juga boleh dihasilkan dan digunapakai dalam pelbagai cabang aplikasi bermula daripada jentera-jentera atau mesin yang terdapat di kawasan perindustrian sehinggalah pengunaan dalam sistem pergerakan tubuh manusia. Laporan ini mengkaji pelaksanaan tenaga penuaian daripada dua teknologi untuk menghasilkan satu sistem penuai tenaga hibrid. Implementasi kajian menggunakan kaedah "model unsur terhingga" (FEA) telah dijalankan dengan menggunakan perisian Ansys sebagai alat bantuan untuk membantu menyelesaikan analisa harmonik dalam kerangka sistem tenaga penuaian hibrid. Kedua-dua teknologi yang digabungkan dalam sistem ini adalah berkaitan dengan teknologi penuaian tenaga daripada piezoelektrik serta elektromagnet. Terdapat pelbagai variasi dimensi geometri yang dicadangkan pada rasuk julur piezoelektrik bimorph mengikut beberapa sampel. Perkara ini dilakukan untuk menguji prestasi sistem tenaga penuaian hibrid mengikut pemboleh ubah dimensi. Kedua-dua pengeluaran kuasa yang dijana daripada magnet dan piezoelektrik ini kemudiannya digabungkan untuk membentuk satu unit tenaga. Daripada kajian yang telah dijalankan, sistem hibrid ini telah menghasilkan maksimum pengeluaran kuasa sebanyak 14.85$\mu W$ dari 100$Hz$, 4.905$m/s^2$, dan 0.6$cm^3$ frekuensi resonans, pecutan, dan isipadu sampel yang terpilih daripada rekaan penuai tenaga. Hasil NPD menunjukkan sebanyak 10.29 $kgs/m^3$ dapat diperoleh daripada sistem ini dan jumlah ini telah dibandingkan dengan hasil daripada kajian-kajian yang dilakukan daripada penyelidik-penyelidik yang lain. Secara tuntasnya, sistem penuaian tenaga hibrid ini boleh digunakan dalam sistem penuaian tenaga khusus untuk aplikasi getaran.

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| | |
|---|---|
| $A_{in}$ | Input acceleration |
| b* | Strain related to vertical displacement of the beam |
| c | Speed of light |
| $C_p$ | Capacitance of the piezoelectric device |
| d | Piezoelectric strain coefficient |
| D | Electric displacement |
| E | Electric field |
| f | frequency |
| k | Coupling coefficient |
| P | Power |
| R | Load resistance |
| $t_c$ | Thickness of the piezoelectric material |
| V | Voltage |
| $Y$ | Young’s Modulus |
| $\omega_n$ | Natural frequency of the system |
| ω | Driving frequency |
| δ | Mechanical strain |

| | |
|---|---|
| $\Phi_B$ | Rate of change of magnetic flux |
| ζ | Mechanical damping ratio |
| $\varepsilon$ | Total induced EMF |
| ε | Dielectric constant of the piezoelectric material |
| σ | Mechanical stress |

# LIST OF ABBREVIATIONS

| | |
|---|---|
| AC | Alternate Current |
| CAD | Computer Aided Drafting |
| CAE | Computer Aided Engineering |
| DC | Direct Current |
| EH | Energy Harvester |
| EMF | Electromagnetic Field |
| FE | Finite Element |
| MEMS | Micro-electromechanical Systems |
| NdFeB | Neodymium Iron Boron |
| NPD | Normalized Power Density |
| PE | Piezoelectric-Electromagnetic |
| PV | Photovoltaic |
| PZT | Piezoelectric Material |
| VEH | Vibrational energy harvesting |

# CHAPTER 1

# INTRODUCTION

## 1.1 BACKGROUND OF PROJECT

The terms of harvesting energy can be referred as the process by which the energy is derived from the ambient source, captured and being stored. Solar, wind, and thermal energy are the common ambient energy sources used for energy harvesting. As the sources of energy are becoming more scarce and expensive, the energy harvesting is receiving more global interest and is currently a growing field.

In today's world, energy harvesting plays a crucial role in supplying the energy to various application such as small wireless autonomous devices. For example, the Vibrational energy harvesting (VEH) with micro-electromechanical systems (MEMS) generators based might be able to provide several amount of energy in microwatts of electrical power. MEMS are micro-electromechanical systems comprising of computers linked to tiny mechanical and other devices like sensors, valves, gears, and actuators, embedded in semiconductor chips based on silicon as shown in Figure 1.1.

With the rapid development of microelectronic devices in military, medical, and civil applications, a traditional bulky battery can no longer meet the needs of advanced sensing technology due to its limited service life and difficulty in replacement. Hence, much attention should be place for research and development in sustaining the power requirement for autonomous wireless and portable devices. Energy harvesting has becoming one of the best option for the implementation in order to fulfil the condition as stated. Currently, the technological advancements have made the energy harvesting become much more deployable since the devices introduced in commercial nowadays were using the ultra-low power components. Figure 1.2 shows the number of transistors per chip doubling every two years.

**Figure 1.1:** Typical implementation of microstructure device using the piezoelectric inside the shoe as the power generator

Source: Ville Kaajakari (2010)

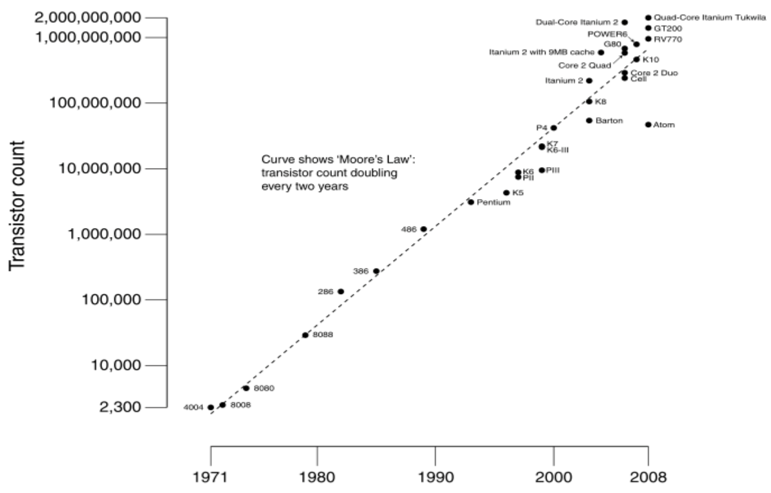


**Figure 1.2:** CPU transistor counts for the year 1971-2008.

Source: Wgsimon (2008)

## 1.2 PROBLEM STATEMENT

Vibration energy are generated from any perceivable activity and usually seen as the noise. However, if the energy were scavenged at the certain level of resonance frequency, it can produce the power output in which can be implemented to any useful application especially in the milliwatt power levels application as such in the MEMS technology. Several studies has been conducted by the scholars regarding on the energy harvesting system by using the electromagnetic and piezoelectric transduction. These research employ these two technologies to develop the hybrid harvesting energy systems in order to capture the ambient source of energy from the vibration.

## 1.3 OBJECTIVES

This research is made to fulfill objectives:

i. Model hybrid energy harvesting system of piezoelectric and electromagnetic using harmonic analysis in Ansys software.
ii. Analyze hybrid energy harvesting system with different width and length of bimorph piezoelectric beam to produce power from the mechanical strain

## 1.4 SCOPE OF PROJECT

To fulfill above, the scope of project study are:

i. Model hybrid harvesting energy using the piezoelectric and magnet material
ii. Bimorph piezoelectric cantilever beam is used with dimension as follows:
    a. Width : 6.35mm, 12.7mm, 19.05mm
    b. Length : 16.5mm, 36.5mm
iii. Simulation using the harmonic analysis in Ansys software to produce the deflection of the beam and voltage output of the piezoelectric bimorph beam.
iv. The project required to be accomplished within the 6 month of period based on the Gantt chart schedule proposed (Appendixes A).

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 ENERGY

By definition, energy is the capacity of a physical system to perform work (Rouse, 2005). Energy exists in several forms such as heat, kinetic or mechanical energy, light, potential energy, electrical, or other forms. According to the law of conservation of energy, the total energy of a system remains constant, though energy may transform into another form. The SI unit of energy is the joule (J) or newton-meter (N.m) in which it is also the SI unit of work. In electrical circuits, energy is a measure of power expended over time. In this sense, one joule (1 J) is equivalent to one watt (1 W) dissipated or radiated for one second (1 s). A common unit of energy in electric utilities is the kilowatt-hour (kWh), which is the equivalent of one kilowatt (kW) dissipated or expended for one hour (1 h).

### 2.1.1 Source of Energy

Figure 2.1 shows the energy sources can be classified into two types, nonrenewable energy and renewable energy. Nonrenewable resources, such as fossil fuels and nuclear material, are removed from the earth and can be depleted. These resources have been the most used type of energy in the modern era. Renewable resources, such as wind, water, solar, and geothermal, come from sources that regenerate as fast as they are consumed and are continuously available. Some, such as biofuel produced from food crops and other plants, are replenished every growing season. In the early part of the twenty-first century, renewable sources have become more popular as nonrenewable sources have begun to be depleted. Though it is becoming a trend that more and more people care about where the energy that we use comes from, we are not sufficiently informed to have a well-founded opinion. People seem to be in favor of solar, wind and hydroelectric power, but it is highly questionable how reliable our sources of information are.

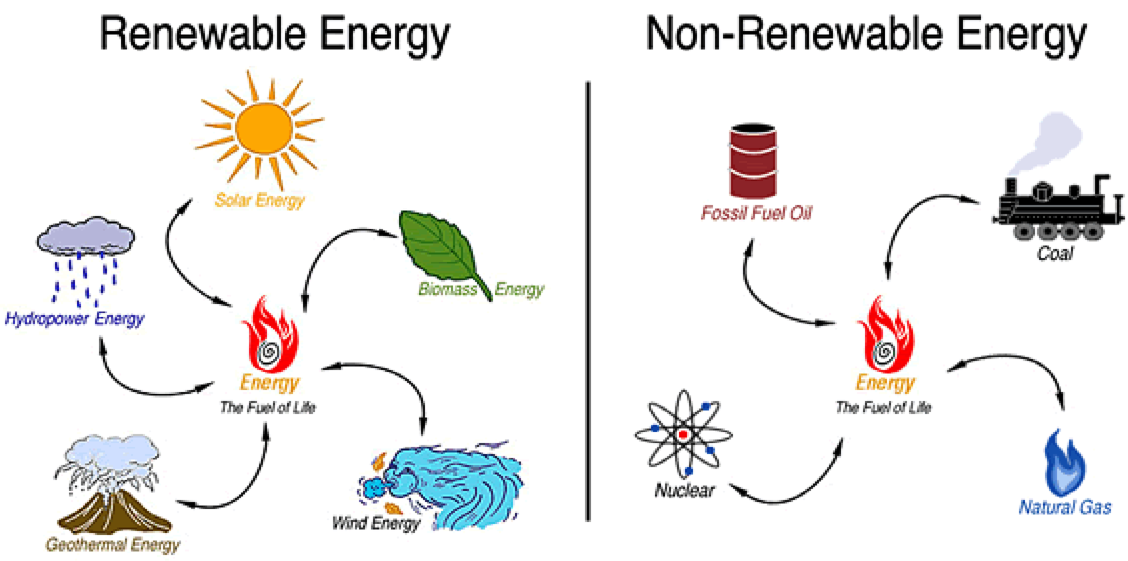


**Figure 2.1:** Two forms of energy, renewable energy and non-renewable energy.

Source: Types of Energy (2005)

### 2.1.2 Electrical Energy

Electrical energy results from the movement of an electrical charge, and is commonly referred to as simply “electricity.” There are two types of electrical charge as illustrated in Figure 2.2, called positive and negative. If two electrically charged objects are brought close to one another, they will experience a force. If they have different charges, they will attract one another. If the charges are the same either both positive or negative, the force will act to push the objects away from one another. This repulsion or attraction is known as the electromagnetic force, and it can be harnessed to create a flow of electrical energy.

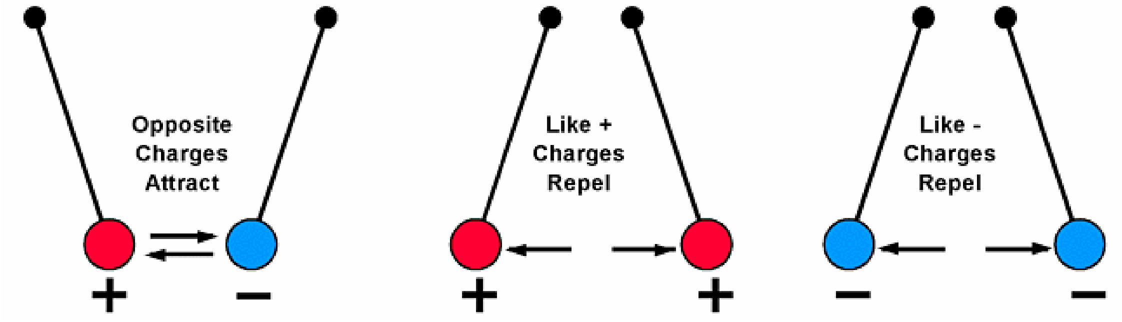


**Figure 2.2:** Two kinds of electrical charge. The protons are said to be positive (+). The electrons are said to be negative (-).

Source: Luciano (2014)

Most electricity is generated by devices that convert rotational motion into electrical energy, using the same principle as an electric motor, but in reverse. The movement of coils of wire within a magnetic field produces an electric current. Commonly, the heat which often generated by the burning of fossil fuels is used to produce steam that powers a turbine to provide the rotational motion. In a nuclear power plant, nuclear energy provides the heat. Hydroelectric power uses the movement of water under gravity to drive the turbine. Electricity for small, low power devices is often supplied by batteries. The energy produced from the chemical reaction inside the batteries generate a relatively small electric current. They always generate a direct current, and therefore have a negative and a positive terminal. Electrons flow from the negative to the positive terminal when a circuit is completed.

### 2.1.3 Faraday's Law

In 1831, Michael Faraday discovered that, by varying magnetic field with time, an electric field could be generated. Faraday law is one of the most basic and important laws of electromagnetism. This law finds its application in most of the electrical machines, industries and other field. The theory of Faraday's law of electromagnetic induction describe any change in the magnetic field of a coil of wire will cause an electromagnetic force (EMF) to be induced in the coil. This EMF induced is called induced EMF and if the conductor circuit is closed, the current will also circulate through the circuit and this current is called induced current. Figure 2.3 illustrates the phenomenon known as electromagnetic induction.

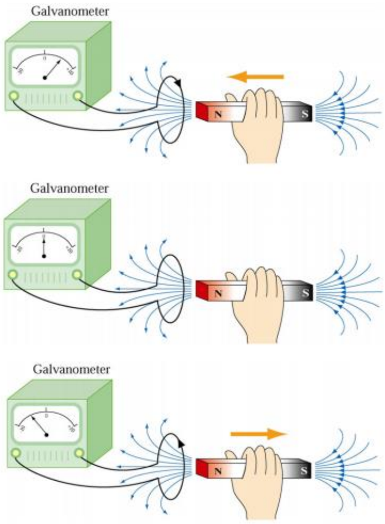


**Figure 2.3:** Electromagnetic Induction

Source: Liao (2004)

Method to change the magnetic field can be done by doing as follows:

1. Moving a magnet towards or away from the coil
2. Moving the coil into or out of the magnetic field
3. Changing the area of a coil placed in the magnetic field
4. Rotating the coil relative to the magnet

Faraday's law of induction may be stated as follows:

- The induced EMF **ε** in a coil is proportional to the negative of the rate of change of magnetic flux $\Phi_B$:

$$\varepsilon = \frac{d\Phi_B}{dt} \tag{2.1}$$

- For a coil that consists of N loops, the total induced EMF would be N times as large:

$$\varepsilon = \frac{Nd\Phi_B}{dt} \quad (2.2)$$

### 2.1.4 Lenz's Law

Lenz's law is a common way of understanding how electromagnetic circuits obey Newton's third law and the conservation of energy. Lenz's law is named after Heinrich Lenz, and describe the law as if an induced current flows, its direction is always such that it will oppose the change which produced it (Liao, 2004). Lenz's law is shown with the negative sign in Faraday's law of induction which indicates that the induced voltage $\mathcal{E}$ and the change in magnetic flux $\Phi_B$ have opposite signs as shown in the Eq. (2.3).

$$\varepsilon = \frac{-Nd\Phi_B}{dt} \quad (2.3)$$

The minus sign in the equation is important as it means that the EMF creates a current I and magnetic field B that oppose the change in flux $\Phi_B$. The direction of induced current can be determined by using the right-hand rule (Lenz Law of Electromagnetic Induction, 2011). If the fingers of the right hand are placed around the wire so that the thumb points in the direction of current flow, then the curling of fingers will show the direction of the magnetic field produced by the wire as shown in Figure 2.4.

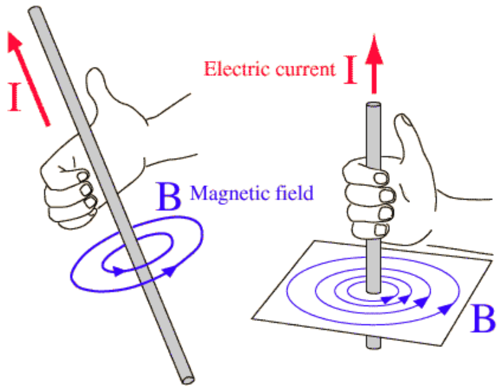


**Figure 2.4:** Determination of the direction of induced current by the right-hand rule

Source: Lenz Law of Electromagnetic (2011)

## 2.2 FUNDAMENTAL OF ENERGY HARVESTING

The term "energy harvesting" refers to the generation of energy from sources such as ambient temperature, vibration or air flow. A typical energy harvesting system starts with an energy collector or transducer device and depends on the type of energy one is trying to convert. These are typically solar or photovoltaic cells for light energy, piezoelectric for pressure, kinetic for movement, inductive for rotational or motion, thermoelectric for heat or temperature differential, and electromagnetic. The energy harvesting system is quiet significant as it has the potential to replace the batteries for small, low power electronic devices. Figure 2.5 illustrate the key components of a simple energy harvesting system to convert and store the ambient energy into electrical energy. The stored electrical energy can then be used by various sensor nodes for applications such as sensing, actuating, or sending wireless signals.

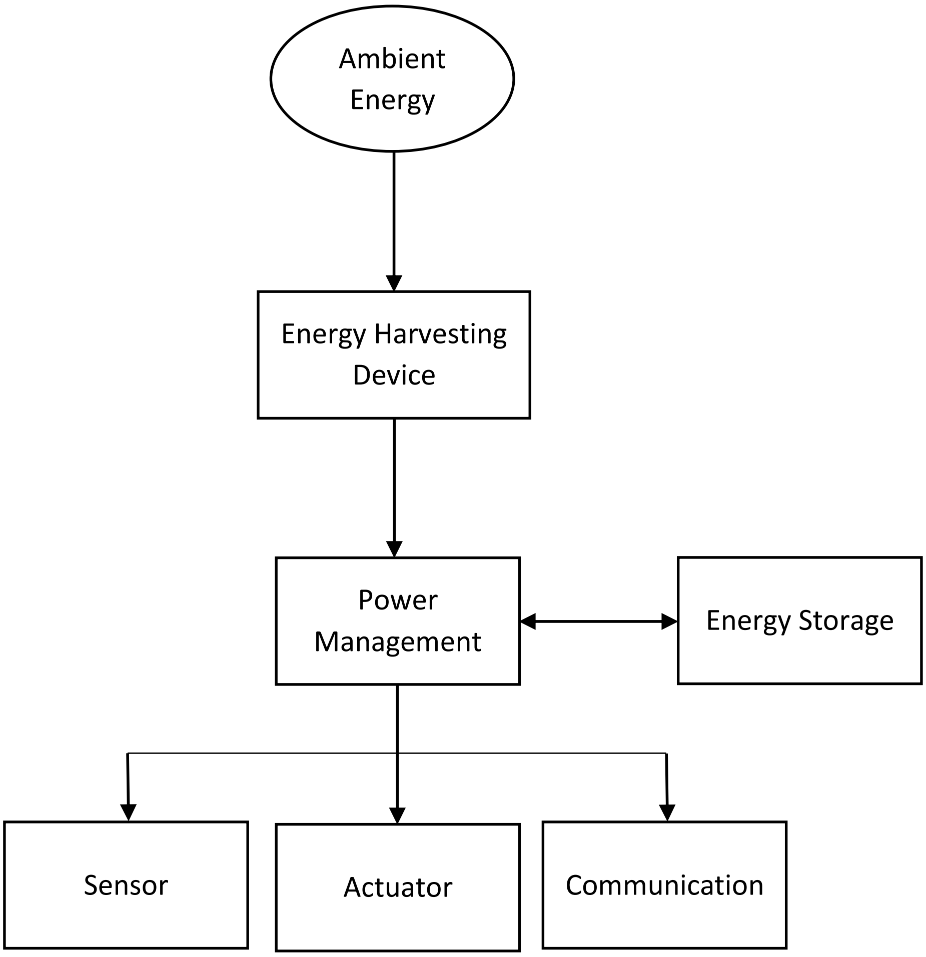


**Figure 2.5:** Generic sensor node architecture

Source: Berder (2015)

## 2.3 TYPES OF ENERGY HARVESTING

It is important to note, that all energy sources are virtually unlimited and can be harvest from various sources. The most common types of energy harvesting are photonic, thermal, and vibrational.

### 2.3.1 Photonic

Common photonic harvesters rely on solar energy drawn with the use of photovoltaics. Solar cell is the basic component for harvesting the sunlight using solar photovoltaics and commonly made from semiconductors as shown in the Figure 2.6.

Figure 2.7 shows when a solar cell is exposed to sunlight, the photons (sunlight) strike and ionize the semi-conductor material causing its outer electron to break free of the atomic bonds. Due to the semiconductor's structure, the electrons are force to move in one direction, creating a flow of electrical current.

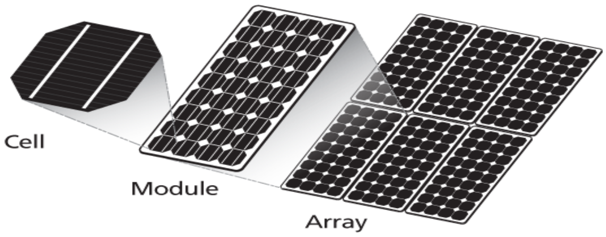


**Figure 2.6:** The difference between Photovoltaic Cell, Module, and Array

Source: Solar PV Cell Module Array (2014)

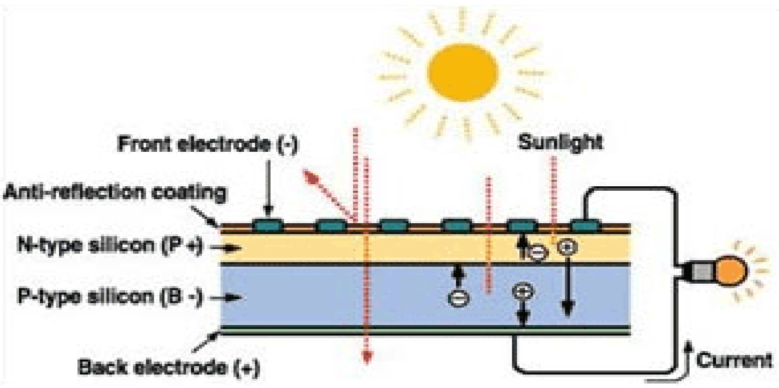


**Figure 2.7:** The process known as the "Photovoltaic Effect" to produce the electricity.

Source: Lambardo (2014)

According to Kwang (2014), solar cells are not 100% efficient because some spectrums of the sunlight are being reflected, some are too weak to create electricity (infrared spectrum) and some create heat energy instead of electricity (ultraviolet spectrum) Susceptibility to pollutants such as dust that blocks light from the cells may further impede their efficiency. The fragility of photovoltaic devices is still yet another concern.