CHAPTER ONE

INTRODUCTION

1.1 Overview:

Energy is indispensable for human being, it plays a big role as it the main determiner for human activities. Electricity generation, transportation and heat production for heavy industries in the industrialized countries are based on energy [1]. Production of energy achieved from broad types of feed stocks and sources, these sources can be renewable or nonrenewable sources.

Renewable energy is energy obtained from sources at a rate that is less than or equal to the rate at which the source is replenished [2]. The inversion is nonrenewable sources, which is limited and will finish with continuous consumption. Current energy system based on burning fossil fuel to achieve energy, though fossil fuel has high efficiency and fast response is considered as a dangerous threat to the global environment [1],[2]. Emissions of pollutants that cause the thermal emission phenomena affect negatively in all criteria. In order to reduce this negative environmental impact simultaneously with the increasing demands of energy, future sources system is required to be carbon free. Renewable sources offer these requirements, renewable energy is obtained from many sources such as solar energy, wind energy, geothermal energy, hydro and hydrogen energy. Hydrogen is the simplest element on earth, it consists of only one proton and one electron and it is an energy carrier, not an energy source. Hydrogen can store and deliver usable energy, but it doesn't typically exist by itself in nature and must be produced from compounds that contain it by several techniques.

Fuel cell is an emerging technology, which could allow a clean and cost effective supply of energy on demand on a large scale and in any location, also its one of the most effective methods to transfer chemical energy into electricity [3].

1.2 Problem statement:

Nowadays, the world suffer from fossil fuel emissions that effect on human, animals, and all living creatures' life. Also cause the thermal emission phenomena. There are many methods to solve this problem such as solar - hydrogen. Power generators with or without batteries can serve remote areas where conventional energy grids do not reach, but they have inherent limitations. Batteries can store electricity only for few days, while the very nature of remote areas make the supply of diesel fuel expensive and difficult. These limitations can be overcome by renewable energies specifically solar-hydrogen energy.

1.3 Objectives:

The overall objectives of this project are:

- To investigate the reliability and continuity of supply for the loads.
- To design solar panels to fulfill load demand.
- To develop a computer simulation model of small-scale solar hydrogen systems for remote energy supply with climatic conditions and the profile of the electrical load to be met as inputs.

1.4 Methodology:

The problem of this research solved by calculations for system design then using software MATLAB (SIMULINK) to simulate the cases under this study.

1.5 Project layout:

This thesis is organized in five chapters. Chapter one gives a general introduction about the research, problem statement, objectives of the study and methodology of the research. Chapter two, presents a review on solar-hydrogen systems, highlighting hydrogen production and storage techniques and hydrogen applications in electric generation. Chapter three includes a general introduction about the system operation, case study about the location, system sizing and system modeling. Chapter four projects the simulation results and discussion. Chapter five includes the conclusion and recommendations.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction:

The power system supply is an installation which consists of many components that works together to fulfill load demands by generating electricity. In general, power system supply is divided into two main sections, the first one is connected directly to the electric distribution network which is called grid connection (Grid-Tied), and the second is independent from the electric distribution network ,called off grid or standalone power system supply.

Standalone power system supply is usually used for remote areas where grid extension faces many difficulties. Transmission lines are uneconomical to install due to geotectonic, environmental concerns and other challenges. For these reasons and many others, stand-alone power system supply is needed to overcome these problems in the remote areas. Conventional remote area power supply systems are either exclusively based on fossil fuels or renewable sources coupled with fossil fuel based.

The power generation system from renewable sources is usually solar system or PV/Wind system. Furthermore, with the development of renewable energy technologies, of late hydrogen generation, storage and reuse is being considered as a potential competitor to be added to these sources as a zero-emission fuel that can be used for all purposes. The renewable sources can use water splitting techniques to store the electrical power, the system will be completely sustainable which is called renewable hydrogen system.

There are various combinations of the renewable energy sources are coupled with hydrogen system to supply the remote areas. This study considers on the Solar-hydrogen systems ability to be completely independent from an electricity grid or any form of fossil fuel based back up, which makes it highly suitable to be the power supplier for remote areas. In addition, the lower environmental impact and higher reliability makes it more efficient than conventional battery or diesel-supported systems. Besides the reliability and low maintenance cost (no moving parts) associated with photovoltaic panels makes it a preferable option for remote areas. The solar insolation is more consistent and predictable for a particular location.

As a simple description for the system, Photovoltaic (PV) panels are used to produce electrical power, which drives a Proton Exchange Membrane (PEM) electrolyser to split water into oxygen and hydrogen gases. Hydrogen is stored to be used as a fuel in the PEM fuel cell, which generates electricity at night or when the PV generate insufficient power for the load . This system is a closed loop system, because none of the products or reactants (water, hydrogen and oxygen) are lost to the outside environment [4][5][6].

2.2 System Configuration:

The basic solar-hydrogen system for remote area studied in this project is a standalone system comprising a photovoltaic array, a PEM electrolyser, storage of hydrogen gas and PEM fuel cell. A schematic of the system is shown in Figure 2.1. This means that the main energy source is the solar energy.

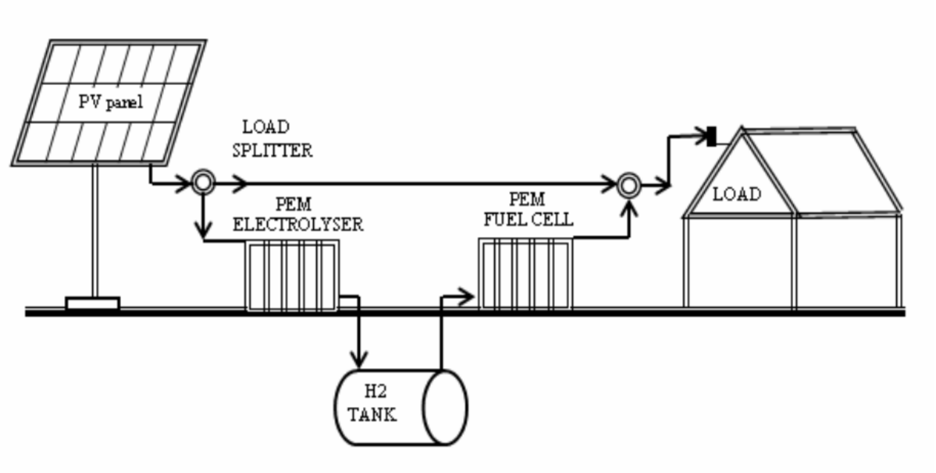


Figure 2.1: A schematic of the solar-hydrogen system [7]

2.3 Solar Energy:

The term Energy is defined as the capacity or ability to do work. Energy, which comes from the sun, is known as solar energy. The output power of sun energy per second is 3.86 x 10^{20} MW consists of heat and light. When the sun heat energy is used, it is known as thermal solar energy, and when sun light energy is used, it is called PV energy. Not all of the sunlight incident from earth's atmosphere arrives at the earth's surface, some of it is absorbed or reflected back before it reaches the ground, which makes the peak intensity of sunlight at the surface of the earth about (1-1.3) kW/m^2. Depends on the area, seasonal radiation and many other factors [8].

2.3.1 Photovoltaic Energy:

Hence the word "photo" means "light" and the term "voltaic" means "electric", Photovoltaic effect is a physical phenomenon responsible for converting light to electricity using special material. This special material is a specific cell named solar cell PV which is basically build from semiconductors like silicon. This cell have the ability to convert sunlight into electricity.

2.3.2 Generation of electricity from PV cell:

This phenomenon (PV effect) is described as follows: Light, which is pure energy, enters a PV solar cell and import enough energy to some electrons (negatively charged atomic particles) to free them. A built-in-potential barrier in the cell acts on these electrons to produce a voltage called PV which can be used to drive a current through a circuit [8]. The exact generation of electricity is shown in Figure 2.2.

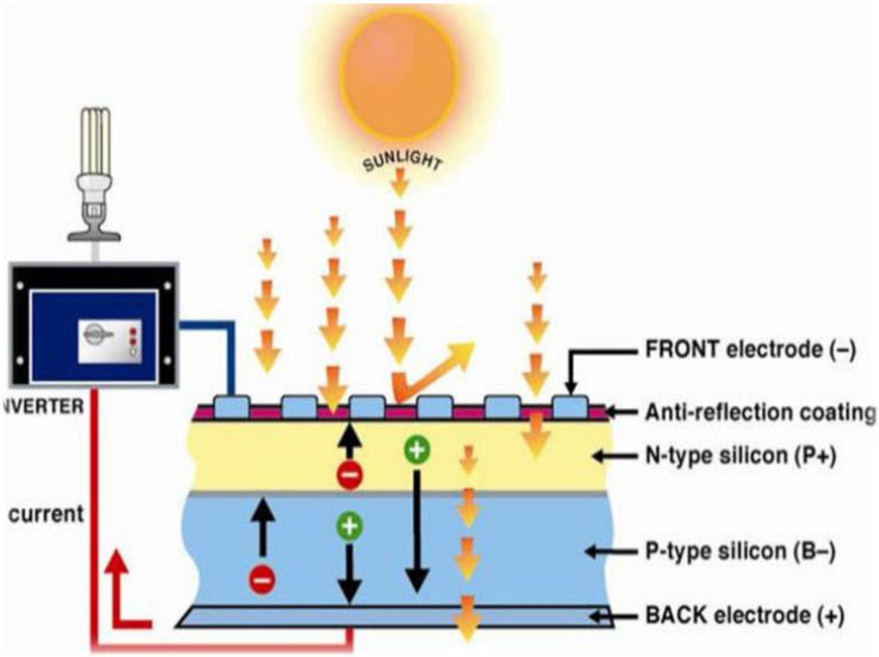


Figure 2.2: PV cell generates electricity

The area around the p-n junction is called the depletion zone where the electrons from the "n-type" silicon, have diffused into the holes of the "p-type" material. Whenever a photon of light is absorbed by one of the atoms in the "n-type", silicon will dislodge an electron which creates a hole. The free electron and the hole produced have sufficient energy to jump out of the depletion zone.

If a wire is connected from the cathode (n-type silicon) to the anode (p-type silicon) electrons will flow (current) through the wire. The electron is attracted to the positive charge of the "p-type" material and travels through the external load creating a flow of electric current. The hole which is created by the freed electron is attracted to the negative charge of "n-type" material and drifts to the back electrical contact.

Generating electricity from the photovoltaic has many advantages such as:

- Unlike conventional power plants using coal, nuclear, oil and gas; solar PV has no fuel costs and relatively low operation.

- The fuel for photovoltaic, sunlight, is practically infinite, free, and easily accessible.
- In PV systems there is no polluting emissions, no noise pollution with lower maintenance costs since there is no moving parts.
- Photovoltaic systems has the capability to supply different sizes of loads (small -medium- large), withier they were connected to the local grid or they were not (stand-alone) or even hybrid systems.

PV system is suitable for a wide range of applications with different sizes. PV system is basically built from cells which is connected together to construct a module, array and solar panel shown in Figure 2.3.

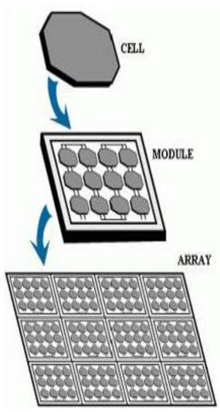


Figure 2.3: Formation of the solar cell from cell to array

2.3.3 Photovoltaic Module and Array:

The solar cell is rarely used individually, because it is not able to supply an electronic device with enough voltage and power, it produces approximately 0.5 Volt DC, and so it can supply small loads like calculators or watches. For this reason, a number of solar cells are electrically connected in parallel or in series in order to achieve as high voltage and power output as possible, which called a photovoltaic module, Figure 2.3 shows the formation of the solar cell from cell to array. The current produced is directly dependent on how much light hits the module. When the cells are connected in series the output voltage is increased, and when it is connected in parallel the amount of current is increased. The solar array or panel is a group of several modules electrically connected in series or parallel combination to generate the required current and voltage and hence the power [9].

2.3.3.1 Types of photovoltaic modules:

The type of module is determined by the cells that compose the module itself. There are common cell technologies, such as:

- Mon-crystalline: As the name implies, these cells that are grown from a single crystal. The production methods are difficult and expensive. These tends to be more efficient (more power in less area) and more expensive [10][7].
- Multi-crystalline: The production process allows multiple crystalline structures to develop within the cell. It is easier to implement it in a production line. It is relatively cheaper than mono-crystalline at the expense of lower efficiency [10][7].
- Thin-film: Uses less silicon to develop the cell (hence the name thin film) allowing leading for a cheaper production costs. But it has also lower efficiency [10][7].

2.3.3.2 Efficiency of PV Modules:

The overall efficiency of the module depends on the cell efficiency and placement within the module, and on the laminating materials used. Typical module efficiencies range between eleven percentage and seventeen percentage for crystalline technologies at Standard Test Condition (STC), most of the commercially available modules are in the lower bound of this range. Thin-film module efficiencies range between six percentage and twelve percentage.

2.3.3.3 Solar Cell Equivalent Circuit:

The characteristics of a PV cell can be explained by creating an equivalent circuit for the solar cell. An ideal solar cell may be modelled by a current source in parallel with a diode. The diode represents the p-n layer and the current source represents the current, which is generated by the photons, and its output is constant under constant temperature and constant incident radiation of light.

In practice, no solar cell is ideal, so a shunt resistance and a series resistance component are added to the model as shown in Figure 2.4, to create the equivalent circuit.

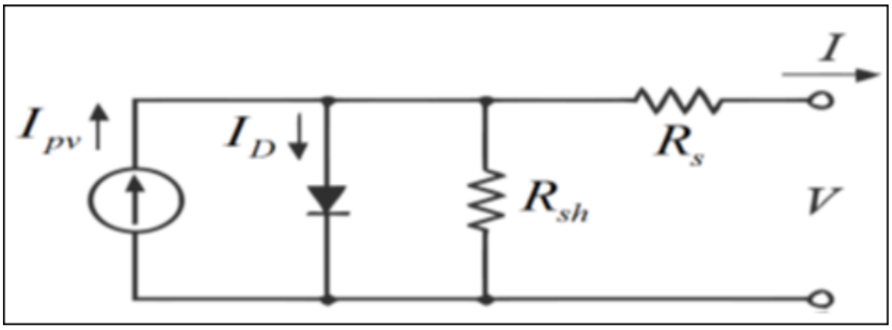


Figure 2.4: Equivalent circuit of the PV [5]

Where:

- I_{PV} is the Photocurrent delivered by the constant current source.
- I_D is the reverse saturation current corresponding to the diode.
- R_s the series resistor that takes into account losses in cell solder bonds, interconnection, junction box.
- R_{sh} is the shunt resistor that takes into account the current leakage through the high conductivity shunts across the p-n junction.

2.3.4 I-V and P-V Curves of the PV module:

Current-voltage (I-V) curve is obtained by exposing the cell to a constant level of light, while maintaining a constant cell temperature, varying the resistance of the load, and measuring the produced current. When an I-V curve is drawn, it normally passes through two points.

2.3.5 Short circuit current (I_{SC}):

This is the current produced when the positive and negative terminals of the cell are short-circuited, and the voltage between the terminals is zero, which corresponds to zero load resistance.

2.3.6 Open circuit voltage (V_{OC}):

This is the voltage across the positive and negative terminals under open-circuit conditions, when the current is zero, which corresponds to infinite load resistance. Figure 2.5 shows a typical I-V curve and the P-V curve. When the voltage and the current characteristics are multiplied, the PV characteristic is produced. The point indicated as Maximum Power Point (MPP) is the point at which the panel power output is max [11].

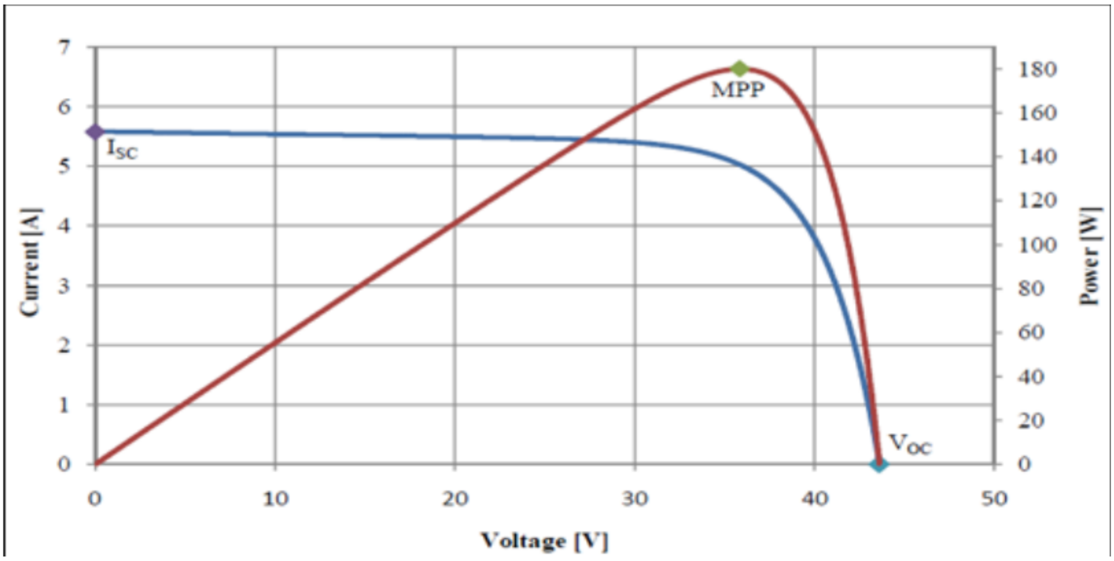


Figure 2.5: The I-V curve of the PV [5]

2.3.7 Solar/Fuel Cell inverter:

Inverters are electronic solid-state devices that is used to transform electric energy from DC to AC [10]. This inverter converts the variable Direct Current (DC) output from the fuel cell or a PV solar panel into a utility frequency Alternating Current (AC) that can supply individual AC loads. The primary switching elements of the inverter are either Silicon Controlled Rectifiers (SCRs) or power transistors called Insulated-Gate Bipolar Transistor (IGBTs).

They are arranged in a bridge circuit and switched (on and off, in the case of transistors) in such a way that an oscillating waveform results [12]. There are different kinds of inverters that can be divided depending on how the PV modules are connected to the inverter and according to the type of the system. The decision on what configuration should be used has to be made for each case depending on the environmental and financial requirements [13]. Inverters can be classified as following:

2.3.7.1 According to how the PV modules are connected is:

- Central inverter
- String inverter
- Module integrated inverter

2.3.7.2 According to the type of the system:

- Stand-Alone Inverters: These inverters operates when they are isolated from the electrical distribution network, this type requires batteries for proper operation. The batteries provides a constant voltage source at the DC input of the inverter.

- Grid-Tied Inverters: These inverters operates when they are coupled to the electric distribution network and therefore must be able to produce almost perfect sinusoidal voltages and currents. The operating requirements for these types of inverters in most cases are determined by the local utilities, yet most utilities rely on existing standards to determine feasible technologies. Some stand-alone inverters can also operate as grid-tied inverters or in combination with other renewable energy sources as part of hybrid power systems. Modern inverters can achieve efficiencies higher than ninety-five percent (especially grid-tied inverters) and are warranted for five to ten years in most cases. Most inverters have efficiencies above eighty-five percent [9].

2.3.8 Load Splitter and control system:

The allocation of the PV power output to the various components of the system according to varying conditions is achieved by using a load splitter. When the PV output is greater than the load [Power of the PV (P_{PV}) >Power of the Load (P_L)], the load is met directly and entirely by the PV array. The surplus power over the load (P_{PV}-P_L) is diverted by the load splitter to the electrolyser for generation of hydrogen gas.

In the other hand if the PV output is less than the load (that is, $P_{PV} < P_L$), then the load splitter ensures P_{PV} is supplied to the load, while the rest of the load (P_L-P_{PV}) must now be drawn from the fuel cell. The splitting of the PV output according to the prevailing conditions can be accomplished by a feedback connection provided through the current voltage regulation channel available in the conventional data loggers.

2.4 Hydrogen energy:

Hydrogen is considered as the most abundant and simplest elements in the universe, its burn is clear, with high efficiency producing water only and zero or near to zero emissions at the using place [9]. Hydrogen is regarded as the most suitable source to replace current fuels in all their presence.

Hydrogen is not available free in nature and its production needs primary materials, these primary materials known as Hydrogen feed stock. Abundant feedstock is affordable to gain hydrogen such as water, fossil fuel (hydrocarbons), and from biomass. Biomass is available from a wide range of sources such as animal wastes, municipal solid wastes, crop residues, short rotation woody crops, agricultural wastes, sawdust, aquatic plants, short rotation herbaceous species, waste paper, corn, and many more. Each one of these feed stocks has its own technologies to produce hydrogen from it.

2.4.1 Hydrogen production technologies:

Generally, hydrogen is produced from two basic sources: the first source is the fossil fuel, this technique includes natural gas, liquid fuel and solid fuel each one of them is subdivided into several methods for hydrogen generation. The second source is to produce hydrogen from renewable sources such as water and biomass, each one of these sources have its own technique of generation [14]. Figure 2.6 illustrates these technologies.

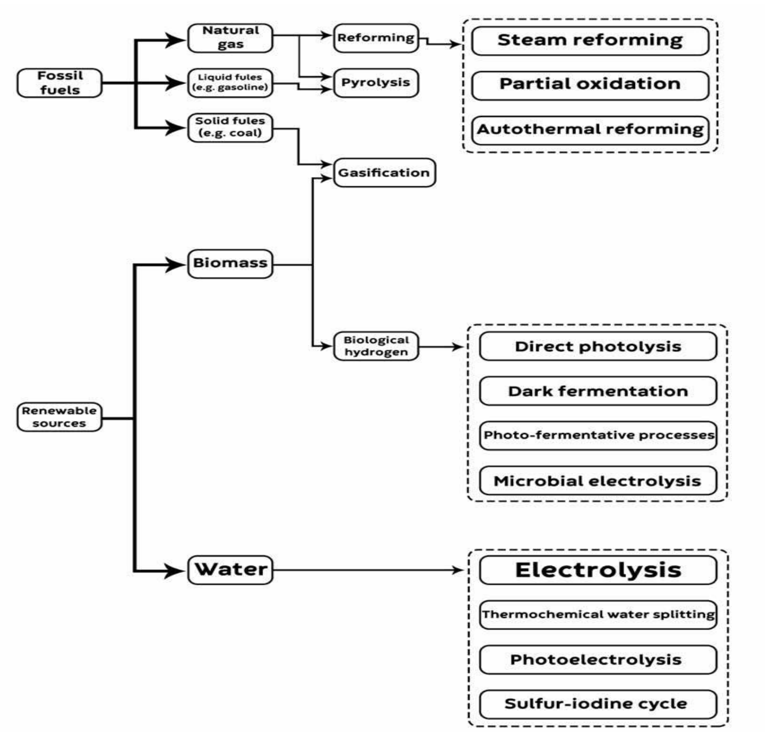


Figure 2.6: Hydrogen production methods

2.4.1.1 hydrogen production from fossil fuel:

Fossil fuels is the fuel which is formed by natural processes of burying dead organisms. Fossil fuel primary include coal, oil and natural gas. There are several technologies of producing hydrogen from fossil fuel, the main technique is hydrocarbon reforming and pyrolysis.

Reforming of hydrocarbon (natural gas) is the most widely used and is the most economical process. This method is a complex process involving many different chemical reactions and catalytic steps with specific temperature degree.

As for solid fuel, the way to produce H_2 is known as coal gasification, it can breakdown almost any carbon-based feed stock into chemical parts. Modern gasifier systems expose coal to hot steam and controlled amounts of air or oxygen under high pressures and temperatures. It occurs at much higher temperatures (1100-1300°C) and uses a wide range of solid feedstock. Coal is the most abundant fossil fuel and the oldest. Coal feedstock is generally much cheaper than CH_4, and this is due to the higher capital investment required for coal gasification.

$$C_S + H_2O + Heat \rightarrow CO + H_2 \Delta H \ (131 \ Kg/mole) \qquad (2.1)$$

Fossil fuel participates with 96% of hydrogen production, which include 48%, 30% and 18% obtained from natural gas, liquid fuels (oil), and coal respectively.

2.4.1.2 Hydrogen production from renewable sources:

Renewable hydrogen includes any technology that produces hydrogen with all energy requirements supplied by renewable energy [15]. There are many processes for H_2 production from renewable sources such as water and biomass.

- Hydrogen production from biomass: Recently, biomass is the most likely renewable organic substitute to petroleum. It is available from a wide range of sources such as animal wastes, municipal solid wastes, crop residues, short rotation woody crops, agricultural wastes, sawdust, aquatic plants, short rotation herbaceous species, waste paper, corn, and many more [16],[17]. For hydrogen generation, the current biomass technologies includes: thermochemical and biological processes [16]. Biological processes are more environmentally friendly and less energy exhaustive.

This process is based on microorganism which operates at ambient temperature and pressure, therefor, less energy is needed, However H_2 production from biological process works in laboratory scale and the practical applications are in need to be improved. In contrast, thermochemical processes are much faster and offers higher theoretical yield of hydrogen with gasification being a promising option based on economic and environmental consideration [18].

- Hydrogen production from water: To produce hydrogen the method of splitting water to manufacture hydrogen and oxygen commercially started since 1890s, researches are progress since then [19]. There are several ways for water splitting, the common method is water electrolysis. In its simplest form it uses an electrical current passing through two electrodes to break water into hydrogen and oxygen [16]. Efficiency of typical electrolysis processes is usually between 30-80%, With some considerations [20].The chemical reaction is shown below:

$$2H_2O \rightarrow 2H_2 + O_2 \quad (2.2)$$

2.5 Electrolyser:

Electrolysers are used widely in industries to synthesize various types of products. A typical electrolyser unit consists of a cathode and an anode immersed in an electrolyte, and generally when electrical current is applied to water, the water splits and hydrogen is produced at the cathode while oxygen is evolved on the anode side via the following reaction [2]:

$$2H_2O + \text{Electrical energy} \rightarrow 2H_2 + O_2 \quad (2.3)$$

An electrolyser converts electrical energy into chemical energy, which produces hydrogen through the process of electrolysis. Electrolysis is an established and well-known method, constituting the most effective technique for water splitting. The reaction, however, is very endothermic thus the required energy input is provided by electricity [21]. The efficiency of this conversion can be quite high-about 90%.

To date, the developed and commonly used electrolysis technologies are alkaline, proton exchange membrane (PEM) and solid oxide electrolysis cells (SOEC) Figure 2.7. In PEM electrolyser water is introduced at the anode where it splits into protons (hydrogen ions) which in turn travel through a membrane to the cathode in order to form H_2, and oxygen which remains back with water [2]. Anode:

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \quad (2.4)$$

Cathode:

$$4H^+ + 4e^- \rightarrow 2H_2 \quad (2.5)$$

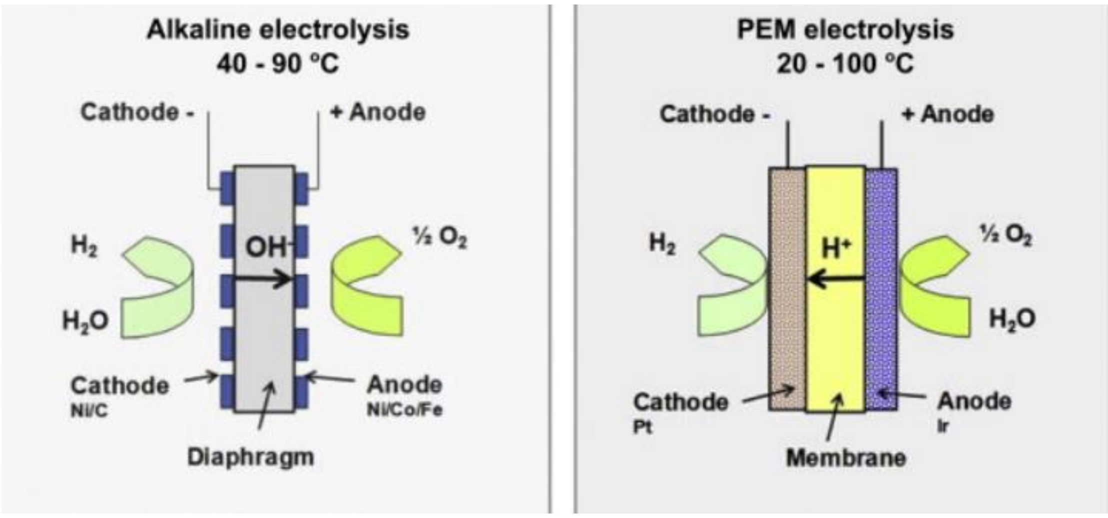
In alkaline and SOEC, water is introduced at the cathode where it splits into H_2 which is separated from water in an external separation unit, and hydroxide ions (OH^-) which in turn travel through the aqueous electrolyte to the anode in order to form O_2 [21]. SOEC systems differ in that part of the electrical energy is replaced with thermal energy, as a result the temperature increases and consequently, the H_2 is left in unreacted steam stream [16].

Anode:

$$4OH \rightarrow O_2 + 2H_2O + 4e \quad (2.6)$$

Cathode:

$$2H_2O + 2e \rightarrow 2OH + H_2 \quad (2.7)$$



(a) (b)

Figure 2.7: (a) Alkaline electrolyser. (b) Proton exchange membrane electrolyser.

2.5.1 PEM electrolyser:

In a PEM electrolyser, a solid polymer membrane acts as the ion-conducting electrolyte, in place of the aqueous solution of an alkaline electrolyser. The polymer membrane conducts the flow of H^+ ions from the anode to cathode where formation of hydrogen molecules occurs. The proton exchange membrane (PEM) successfully eliminates the problems such as continuous circulation of electrolyte, a non-uniform distribution ionic current, and high cell resistance associated with conventional liquid (KOH) electrolytes.

The proton exchange membrane allows the electrolysis process to take place in a solid electrolyte, and has the following additional advantages over conventional alkaline electrolysers [4]:

- Ability to cope with a variable power input.
- Higher purity level of the produced hydrogen.

• Higher rates of hydrogen production per unit mass and volume of the electrolyser unit.

• An option of getting compressed hydrogen directly delivered without the requirement of a mechanical compressor.

• Increased level of safety and ecological cleanliness.

• Lower costs per unit mass of hydrogen produced.

• Regular replacement of liquid electrolyte is avoided, as the electrolyte is entirely solid state and does not degrade.

• An energy efficiency almost 10% higher.

Although extremely pure hydrogen could be simply produced from water by electrolysis, the high consumption of electricity by electrolysers prevents the production cost to compete with other large-scale technologies contributing with a share of about 5% to the total generation. However, if the electrical energy is provided by RES such as hydro, wind and solar, the H_2 produced is the cleanest energy carrier, which can be used to store the excess electricity and improve the plant-load factor and efficiency in small scales [22],[23]. In this way, water electrolysis offers a more sustainable and cost-effective option [24].

2.6 Hydrogen storage:

After producing hydrogen from water electrolysis by using PEM electrolyser, hydrogen must be stored in order to overcome the daily and seasonal discrepancies between energy source availability and demand [25]. Storage of hydrogen is a key to the implementation of hydrogen technology in any of its applications. Hence, hydrogen storage is known as a challenging topic, it is the first element of the periodic table, and it has a low density of 0.09 kg/m^3. The materials used cannot have a strong interaction with hydrogen or any reaction [26]. Hydrogen can be stored in all three phases:

2.6.1 Storage as a compressed gas:

The common method of H_2 storage is by compressing the gaseous hydrogen in high pressure gas cylinders with maximum operating pressure of 20 MPa. Hydrogen vehicle tanks nowadays operate at 5000–10,000 psi [26]. Compressed hydrogen is a highly efficient methodology for hydrogen storage. The energy density considers the volumetric increase with the pressure increase of the gas. Compressed vessels for hydrogen storage can be grouped into:

- Metal cylinder.
- Load-bearing metal liner hoop wrapped with resin-impregnated continuous filament.
- Non-load bearing metal liner.
- Axially and hoop wrapped with resin impregnated continuous filament.
- Non-load bearing non-metal linear axially and hoop wrapped with resin impregnated continuous filament.

The type of metal used in the first to the third systems is usually stainless steel. In the last system, cylinders are made from advanced composite materials and are the most technologically advanced option for lightweight hydrogen storage as compressed gas Figure 2.8, in this type cylinder structure can be divided into two sections: the liner and the composite section. The liner acts essentially as a barrier for hydrogen diffusion through the walls whereas the composite structure ensures the mechanical integrity of the storage container [4].

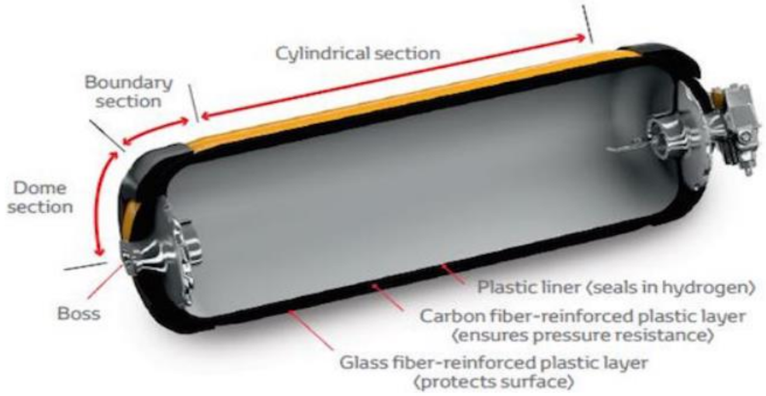


Figure 2.8: hydrogen storage cylinder

2.6.2 Hydrogen Storage in Liquid form:

Liquid H_2 can be stored in cryogenic tanks through a double-step procedure of compression and cooling in a heat exchanger. Because of its low boiling point of 252.87 °C, the work needed is estimated to 15.2 kWh/kg, achieving 70.8 kg/m^3 volumetric density at atmospheric pressure, while the gravimetric density depends on the tank's size. Even with the perfect insulation, the daily boil-off losses of releasing H_2 into the atmosphere are typically rated at 0.4%, 0.2% and 0.06% for storage volumes of 50 m^3, 100 m^3 and 20,000 m^3, respectively [2].

2.6.3 Storage in metal hydrides:

Solid-state storage occurs more effective at storing large amounts of hydrogen at moderate temperature and pressure. , but various metallic alloys have a tendency to adsorb hydrogen. These alloys (collectively termed metal hydrides), form a chemical compound with hydrogen at relatively low pressure (typically in the order of 2-5 bars). In a process of adsorption, a gas molecule interacts with several atoms at the surface of a solid where it is bonded and reversibly released when needed.

Carbon nanotubes are able to store H_2 at quite low temperatures (196.15 °C) and pressures (6 MPa), providing a gravimetric and volumetric density of 10.8 wt% and 41 kg/m^3, respectively. Light metals such as Li, Be, Na, Mg, B, and Al, form a large variety of metal-hydrogen compounds. The gravimetric density is limited to less than 3 wt% and therefore, intense interest has been developed in even lighter metals, complex hydrides. Complex hydrides open a new field of hydrogen storage materials.

2.7 Hydrogen applications:

Hydrogen is an alternative fuel that can replace all present fuels in their presence Figure 2.9. Hydrogen is considered as a clean alternative fuel to the fossil fuels, it is used for generating various forms of energy such as thermal and electricity, by combustion with oxygen. Producing water, unlike the oxidation of fossils that leads to greenhouse gas emission. Hydrogen is lighter than air and diffuses rapidly, its flames have low radiant heat, which can reduce the risk of secondary fire. Besides, It does not explode when ignited as a result of putting it under pressure or low temperature (in compressed tanks), it quickly rises and dissipate [27].

Figure 2.9: Hydrogen applications in transportations, as a fuel for cars

2.8 Electricity generation from hydrogen energy:

Hydrogen energy is in a chemical form, therefore for its utilization as a fuel in domestic, commercial, and industrial applications, or in automobiles and for generating electrical power; the chemical energy needs to be converted into usable forms of thermal, mechanical or electrical energy.

Similar to other fossil fuels, the first step involves the conversion of hydrogen's chemical energy to thermal energy in the form of heat, via combustion with oxygen. Low-temperature catalytic combustion is suited for small household and domestic appliances and high-temperature non-catalytic combustion is suited for electricity generation.

In addition to thermal power plants, a new technology is found to generate electricity from hydrogen. The basic concept of this technology is to combine hydrogen with oxygen in special device generating electricity and water as by-product. This special device is known as fuel cell witch can be used in transportation vehicles, as well as in spacecraft applications [26].

2.9 Fuel cell:

The fuel cell is an electrochemical device that converts the chemical energy into electrical energy. Sir William Grove developed the first fuel cell in 1839. The principle of the fuel cell was discovered by accident during an electrolysis experiment, when he disconnected the battery from the electrolyser and connected the two electrodes together he found a current flowing in the opposite direction consuming the gases of hydrogen and oxygen, he called this the "Gas-Battery". In 1842, he connected a number of gas batteries in series to form a "gas chain" and used the electricity produced to power an electrolyser in order to split water into hydrogen and oxygen.

Modern Fuel cell consist of an electrolyte and two electrodes including the anode which is the negative electrode and the input of the fuel (hydrogen), and cathode the positive electrode which is the input of the oxygen [6]. The electrons produced at the anode from splitting the H_2 atoms into electrons and protons. Those electrons go to the cathode through an external circuit, because of this movement electricity is produced. Then the protons of H_2 reaches the cathode and combines with the oxygen atoms producing water [4].

In a typical fuel cell; a gaseous fuel (hydrogen) is fed continuously to the anode, an oxidant (oxygen) is fed continuously to the cathode. The electrochemical reactions takes place at the electrodes to produce electric current. The overall chemical reaction can be described by the following equations:

At anode: $2H_2 \rightarrow 4H^+ + e^-$ (2.8)

At cathode: $O_2 + 4H^+ + e^- \rightarrow 2H_2O$ (2.9)

Overall reaction: $2H_2 + O_2 \rightarrow 2H_2O$ (2.10)

Outside the fuel cell, the electrons are released from the anode, and returns to the cathode through a load, where the current turns into electric power. Inside the fuel cell, positive ions moves from anode to cathode, or negative ions moves from cathode to anode in the electrolyte to recruit the electrons at the electrodes. The type of the electrolyte and ion species can have various different fuel cells. Meanwhile, the electrode material should be catalytic as well as conductive, porous rather than solid. The catalytic function of electrodes is more important in lower temperature fuel cells and less so in high temperature fuel cells because ionization rates increase with temperature.

2.9.1 Why fuel cells are used instead of batteries?

A fuel cell is similar to a battery that converts chemical potentials to electric power through electrochemical reactions. The main difference between fuel cells and batteries is that batteries carry a limited amount of fuel internally, as an electrolytic solution and solid materials, but fuel cells consume reactants from an external source, which can be constantly replenished. In a fuel cell, the fuel on the anode side and the oxidant on the cathode side react in the presence of an electrolyte. The reactants flow into the cell, and the products flow out of it, while the electrolyte remains within it. Hence, fuel cells can operate continuously without replacement as long as the necessary maintenance is performed.

A battery is an energy storage device, but a fuel cell is an energy conversion device. The maximum available energy in a battery is determined by the amount of chemical reactant stored in it. The battery will stop producing energy when the chemical reactants are consumed. In contrast, the reactants in a fuel cell is replenished from an external source.

Thus, a fuel cell theoretically has the capability of producing electrical energy as long as fuel and oxidant are supplied to the electrodes. In reality, degradation, primarily corrosion, or malfunction of components limits the practical operating life of fuel cells. Fuel cells generate electricity through an electrochemical reaction process, in which the energy stored in fuel is converted into direct current (DC) electricity.

Because fuel cells generate electric energy without combustion, they have many advantages as an energy conversion device:

- High energy conversion efficiency.
- Very low emissions.
- Low noise.
- Fuel flexibility.
- Modular design.

2.9.2 Types of fuel cell:

There are four main types of fuel cells currently being developed. They include Phosphoric Acid Fuel Cells (PAFC), Molten Carbonate Fuel Cells (MCFC), Solid Oxide Fuel Cells (SOFC), and Proton Exchange Membrane Fuel Cells (PEMFC).

Phosphoric Acid Fuel Cells (PAFC) are the most commercially developed type of fuel cell. They range in size from 50 Kw to 500 Kw, and both stationary and vehicle applications are possible. This type of fuel cell operates at 190˚C, and the peak current density ranges around 200Ma/cm2. It generates electric power at more than 40% efficiency, and the startup time is 1 to 4 hours. The PAFCs are being widely used in commercial buildings, airports, and utility power plants [28].

Molten Carbonate Fuel Cells (MCFC) have promised high fuel-to-electricity efficiencies of 50-60%. They operate at 600˚C to 650˚C, so that the fuel can be reformed directly into hydrogen. The MCFCs range in size from 250 Kw to 5 MW with peak current density about 160Ma/cm2, and need a startup time up to 10 hours. The high efficiency and high operating temperature of MCFC units makes them most attractive for base-load power generation, either in electric-only or cogeneration modes [28].

Solid Oxide Fuel Cells (SOFC) can be scaled from Kw-size units to MW-size units for large high-power applications, including industrial and large-scale central electricity generating stations. The high operating temperature of 1000˚C makes it possible to reform fuels to hydrogen internally. Power generating efficiencies in SOFCs could reach 60%, and 80% in co-generation applications [28].

Proton Exchange Membrane Fuel Cells (PEMFC) operate at relatively low temperatures about (80°-120°) ˚C, having high power density up to 700Ma/cm2, and able to vary output power quickly. The PEMFCs range in size from sub-Kw to 500Kw. Because of their high power density and fast response, the most attractive applications are in the automotive industry and portable devices. However, the costs for the proton exchange membranes are relatively high [28].

2.9.3 Proton Exchange Membrane Fuel Cell:

The membrane used here is polymer. It has low temperature below120°C [6]. The low temperature means that only hydrogen rich gas with minimal CO (poison) can be used as fuel. The PEM fuel cell delivers high power density, offers cost and weight, rapid startup and contain no corrosive fluids. The main advantage of using a PEM electrolyser is that it can generate hydrogen at elevated pressure without the need for a separate compressor, and the consumption of hydrogen to regenerate electricity is carried out in a PEM fuel cell. Unlike other fuel cells such as solid-oxide fuel cell, alkaline fuel cells, a PEM fuel cell has the advantage that it operates at low temperature and has relatively higher energy efficiency. It is quite sensitive to the changes in supply rate of reactant which can be controlled as a feedback to the changes in load. Figure 2.10 shows the typical PEM fuel cell.

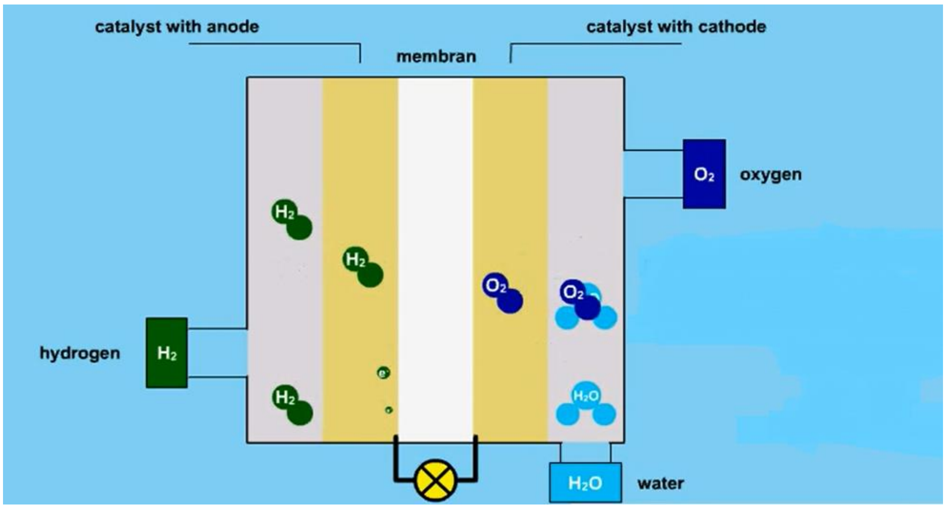


Figure 2.10: PEM fuel cell working process

CHAPTER THREE
METHODOLOGY

This chapter represents the sizing process for the system components. Besides describing a mathematical model for PV panels, electrolyser, hydrogen storage tank and fuel-cell. In addition to that, the system component is simulated using MATLAB (SIMULINK) software.

3.1 Introduction:

Solar-hydrogen is a completely green system, which avails all the energy requirements for home. Solar-hydrogen system is able to be completely independent of an electricity grid or any form of fossil-fuel .Also their lower environmental impact and high reliability makes them suitable more than conventional battery or diesel supported systems.

The personalized home with solar-hydrogen consists of arrays of solar panels, hydrogen system for nighttime power supply and a small electrolyser that uses electricity to break down water into its components hydrogen and oxygen. It requires tanks to store the hydrogen. The storage hydrogen is fed to fuel-cell that combine hydrogen and oxygen to produce electricity and water as shown in Figure 3.1.

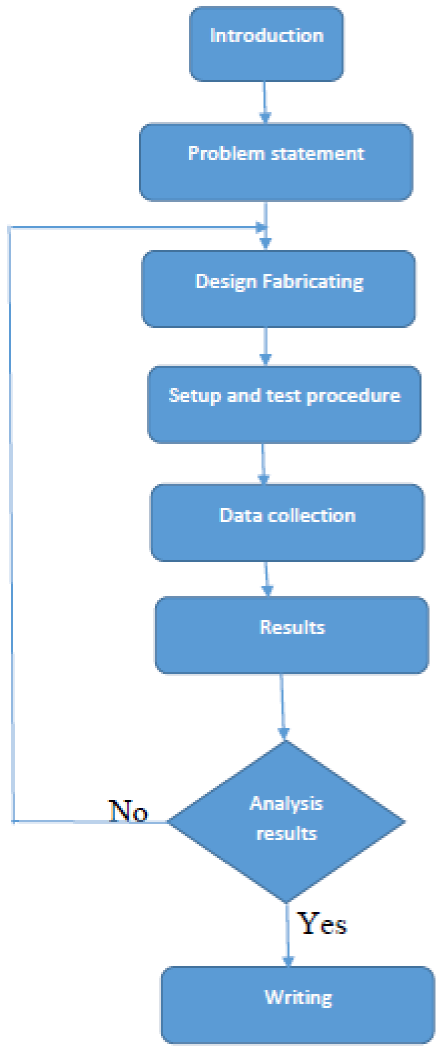


Figure 3.1: Flow chart of the study

3.2 Case Study:

The proposed location is a house in a remote area, which is not connected to the national grid of electricity and is near a water source. The purpose of this project is to design a photovoltaic and hydrogen system to supply this house with electrical power. The studied location faces a serious problem of absence of electricity supply. The issue is the house is far away from the grid and the connection with the national grid faced hard difficulties as mentioned previously.

3.2.1 Location Description:

The solar plant was suggested to be at a location of 28° 22' 9" E Longitude and 12° 39' 33" N Latitude. The annual average of the daily solar radiation on a horizontal surface for this area is 6.183 $KWh/m^2/d$ as shown in Figure 3.2[1].

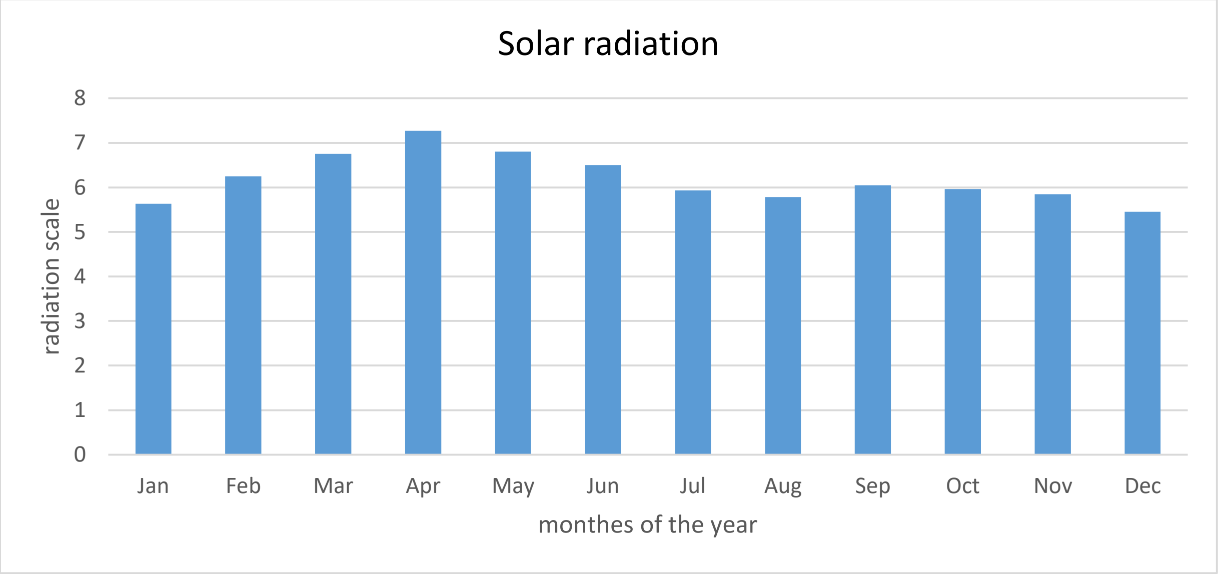


Figure 3.2: Monthly average solar radiation in the area

The average sunlight hours in this area range between 11.2 hours per day in May and 10.4 hours per day in January, this gives a yearly average of sunlight around 3800 hours/year [2]. The temperature of the area under study is measured and shown in Table 3.1 and Figure 3.3.

Table 3.1: Temperature table for the months of the year

Lat12.659 Lon 28.369	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual average
22-year average	22.6	24.5	27.7	29.7	28.2	26.2	24.5	24.4	25.9	27.8	27.0	23.6	26.0
Minimum	17.4	19.0	22.1	24.0	23.9	23.0	21.9	21.5	21.8	22.9	21.8	18.5	21.5
Maximum	28.1	30.3	33.5	35.2	32.2	29.8	27.5	27.9	30.3	32.9	32.6	29.0	30.8

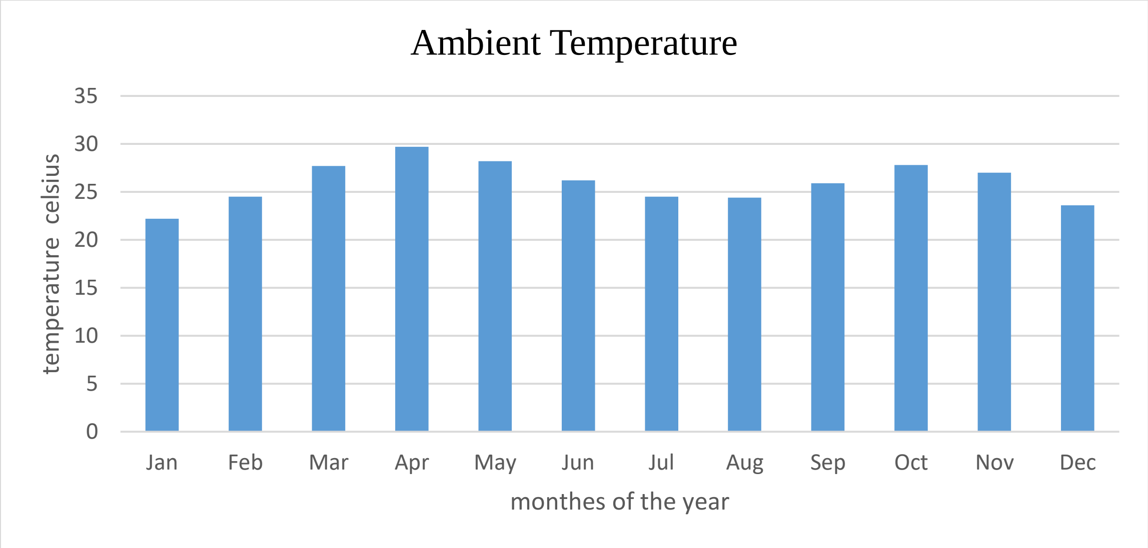


Figure 3.3: Monthly Ambient Temperature for the area

3.3 System sizing:

System sizing is the process used to determine the optimal size of system component to deliver the required electrical energy to the load. The proper sizing of the system is made based on load profile and according to the maximum capacity. As the system is located here in the remote area the modern devices does not exist.

The electrical devices available in the remote areas are itemized with their power ratings and time of operation during the day to obtain the average energy demand in Watt-hour per day. The total average energy consumption is used to determine the required equipment sizes and ratings, starting with the solar array and ending with the sizing of the proper of PEM electrolyser and the fuel cell.

A brief description of the system is as follows, PV modules are connected electrically together in series and parallel configurations and then connected by the load splitter which is connected simultaneously to the storage energy system that consist of PEM electrolyser. Hydrogen storage tank and the PEM fuel cell, since the electrical energy produced by this system is pure DC power the connection must go through inverter in order to provide AC load with the power.

This power must be sufficient to cover the power consumption of the load, but in case of that the sun light may not be available sometimes this condition must be taken into account. The unavailability of this source is caused due to several reasons such as cloudy days, at night, long winter seasons or any other causes represented in failure of PV modules to generate power. In such cases, storing energy system should full fill the load demand.

3.3.1 Load Estimation:

The first step in designing PV system is to find out the total energy consumption of the loads that needs to be supplied by the solar PV system , that is why calculations of the total power consumption demand (in watt-hour per day) for each appliance is made. This can be done by using Table 3.2 to know the hourly consumption of each appliance used, in order to find out their daily consumption (in watt hour per day) according to the duration of using each one of them daily, the electrical loads in home located in area of study are small appliances such as TV, radio and lightings

Table 3.2: Loads of the house in the remote area

Loads	Number of devices	Watts per device	Total watts	Hours	KWH
Fans	5	75	375	24	9
Lamps(2feet)	13	20	260	10	2.6
Sockets	7	10	70	5	0.35
Iron	2	1200	2400	1	2.4
Refrigerator	1	205	205	12	2.46
Television	1	98	98	6	0.588
Radio	1	8	8	4	0.032
Summation			3416		17.43

3.3.2 Sizing of solar system:

After finding out the total (watt-hour per day), calculations must be done to find the total energy required from PV panels. This is done by dividing total appliances Watt-hour per day by the overall efficiency of the system (putting in consideration the various conditions of the load) so as to cover the energy losses in each component in the system such as energy losses in the inverter electrolyser and fuel cell. Besides the efficiency, losing the energy is caused by several reasons, such as temperature degradation and connection losses. Covering these losses will increase the size of PV panels by specific value.

In addition, one of the important factors of PV power is the peak power. Peak power or Nominal power, which is determined according to duration of the solar radiation.

Many assumptions must be made to determine the sizing of the each component in the system.

Assumptions:

- The PV efficiency is assumed to be 80%.
- Inverter converts DC into AC power with efficiency of about 90%.
- The efficiency of the electrolyser is assumed to be 90%.
- The fuel cell efficiency is 90%.

The overall efficiency of the system will be:

$\eta_{overall}$ = 0.8×0.9×0.9×0.9= 0.5832

3.3.3 Sizing of the solar array:

Before sizing the array, the total daily energy in Watt-hours (E), the average sun hour per day (T_{min}), and the DC-voltage of the system (VDC) must be determined. To avoid under sizing, losses must be considered by dividing the total power demand in Wh/day by the product of efficiencies of all components in the system to get the required energy (E_r). So many assumption has been made before the sizing of the suitable solar arrays.

Assumptions:

- The system will be 48 volt to reduce the amount of current flow.
- Average sun hours per day is 6 hours/day.
- The rated current and voltage for each PV panel assumed to be 7.5A and 24V respectively.
- The short circuit current I_{sc} = 8.03 amp
- The safety factor for the charge controller is F_{safe} = 1.25

The average energy demand per day will be divided by the efficiencies of the system components to obtain the daily energy requirement from the solar array.

$$E_r = \frac{E}{\eta_{overall}} \tag{3.1}$$

$$E_r = \frac{17.43}{0.8\times0.9\times0.9\times0.9} = 29.88 \text{ kw}$$

To obtain the peak power, the previous result is divided by the average sun hours per day for the geographical location T_{min}.

$$P_p = \frac{E_r}{T_{min}} \tag{3.2}$$

$$P_P = 4.98\ kw$$

The total current needed can be calculated by dividing the peak power by the DC- voltage of the system.

$$I_{dc} = \frac{P_P}{V_{dc}} \tag{3.3}$$

$$I_{dc} = 103.75\ Amp$$

Modules must be connected in series and parallel according to the need to meet the desired voltage and current, Firstly the number of parallel modules, which equals the whole modules current, divided by the rated current of one module Ir.

$$N_P = \frac{I_{dc}}{I_r} \tag{3.4}$$

$$N_P = \frac{103.75}{7.45} = 13$$

Second, the number of series modules, which equals the DC voltage of the system, divided by the rated voltage of each module Vr

$$N_s = \frac{V_{dc}}{V_r} \quad (3.5)$$

$$N_S = \frac{48}{24} = 2$$

Finally, the total number of modules Nm equals the series modules multiplied by the parallel ones:

$$N_m = N_s \times N_p \quad (3.6)$$

$$N_m = 26$$

3.3.4 Sizing of the inverter:

The used inverters must fulfil the following assumptions:

- The watts rating must be approximately equal to the solar system's watts rating.
- For stand-alone systems, the inverter must be large enough to handle the total amount of Watts.
- The inverter size should be 25-30% larger than total Watts of appliances.
- The inverter size =3.416×1.25= 4 KW.

3.3.5 Electrolyser sizing:

As mentioned previously electrolyser convert water and power (electricity) into Hydrogen and Oxygen. For electrolyser sizing, the required amount of H_2 or O_2 the electrolyser generates is determined mainly by the current, which is supplied to the electrolyser.

Since the current is defined as the flow of electrons and a Hydrogen molecule has just 2 protons and 2 electrons, so when a certain number of electrons put across the membrane (current), it will generate an equivalent number of Hydrogen molecules.

Since electrolyser consist mainly of plates and stacks, these stacks connected in parallel with the DC voltage source and between them a number of series plates or cell is connected, where hydrogen and oxygen gasses are produced.

3.3.6 Sizing of hydrogen storage tank:

After hydrogen is generated this generated hydrogen must be stored for later used, the amount of stored hydrogen depend on how much power that need from this storage system, hydrogen consumption rate and how long this power is need.

3.3.7 Fuel cell sizing:

The chemical reaction happen inside fuel cell is diametrically reverse of the electrolyser reaction. Therefore, fuel cell sizing depend on the amount of hydrogen and oxygen to generate the required electricity for the loads. Firstly the daily load must be supplied by fuel cell should be determined in kwh, then dividing this amount by the number of hours per day, then the size of energy will be determine in KW.

3.4 System modeling:

A schematic of the basic solar-hydrogen system modelled is given in Figure 3.4.

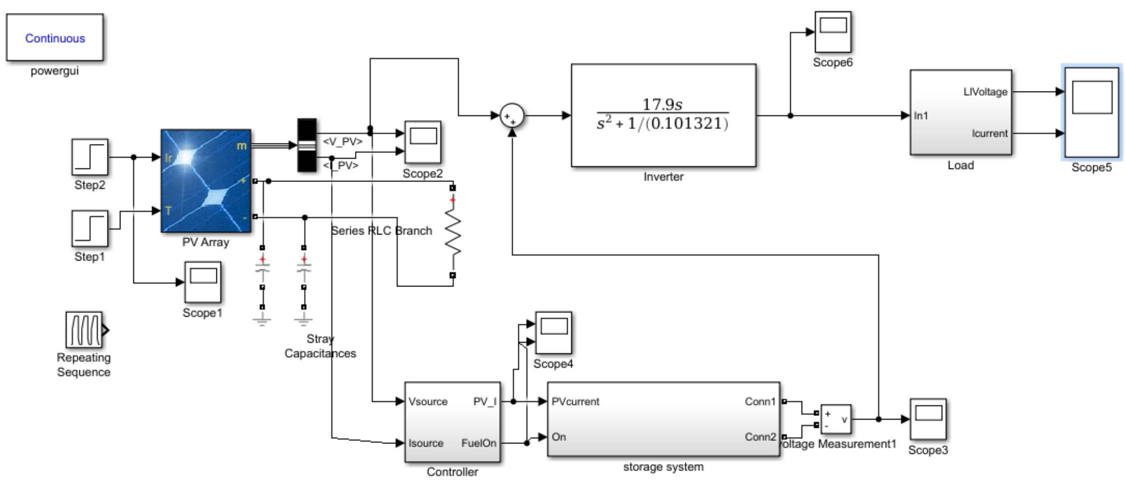


Figure 3.4: overall system model

The model is designed for each component individually to simulate the actual performance of this component and then for the overall solar hydrogen system for various conditions which will be explained later in this chapter Figure 3.5.

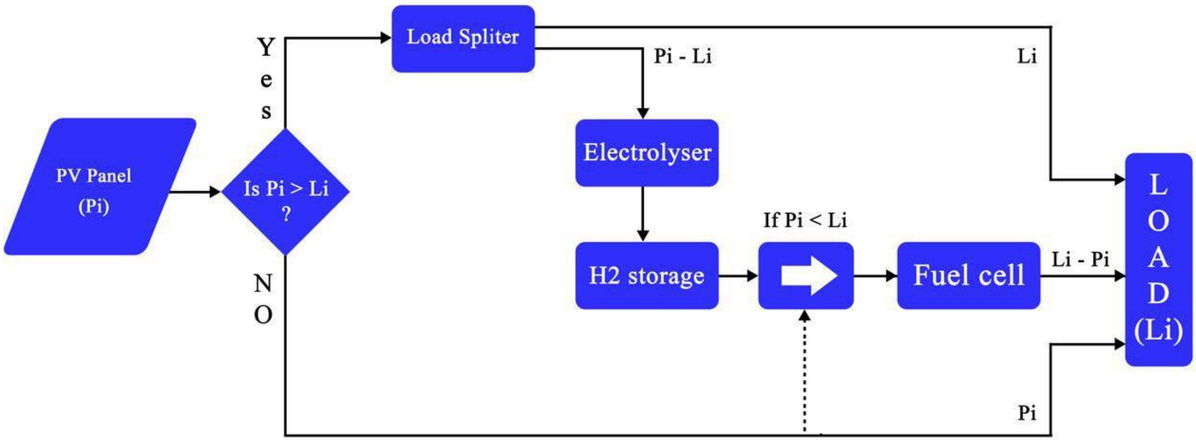


Figure 3.5: flow chart of the model

3.4.1 PV model:

For PV modeling two main parameters should insert to SIMULINK, solar radiation (G) and operation temperature (Top).

The model of solar PV array in SIMULINK in Figure 3.6:

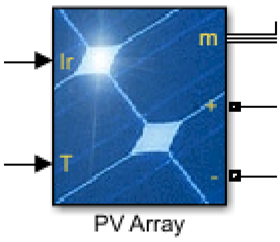


Figure 3.6: PV array model

3.4.2 Electrolyser model:

The electrolyser is presented in mathematical model shows the actual flow rates of hydrogen and oxygen.

$$m_{H2}=2m_{O2}=m_{H2O}= \eta_F \times Ns \times I/n_F$$

$$\eta \mathrm{F} = 96.5 \times e^{\frac{0.99}{I}-\frac{75.5}{I^2}}$$

The model of electrolyser in SIMULINK in Figure 3.7:

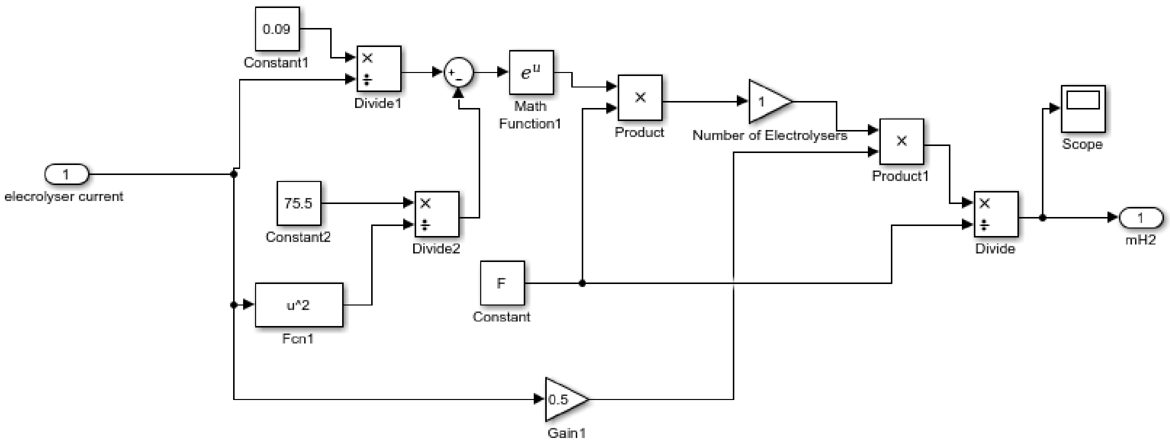


Figure 3.7: electrolyser model

3.4.5 Storage model:

The mathematical model of the storage tank is represent as following equation, the only input of this model is the hydrogen moles (m_{H2}).

$$P= nRT/V \tag{3.7}$$

The model of storage system in SIMULINK in Figure 3.8:

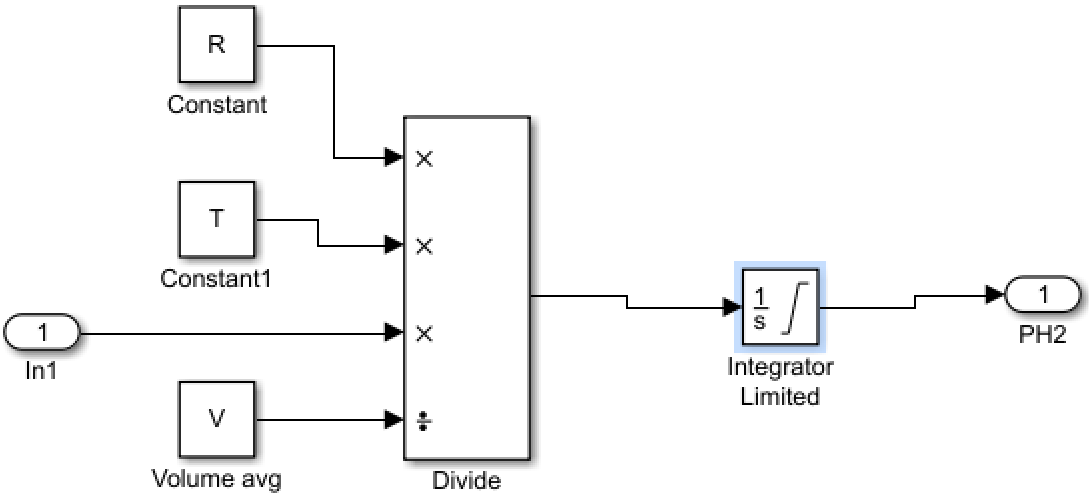


Figure 3.8: storage model

3.4.6 Fuel cell modeling:

The fuel cell is selected from SIMULINK library Figure 3.9, the inputs of it are hydrogen and air (oxygen) gases.

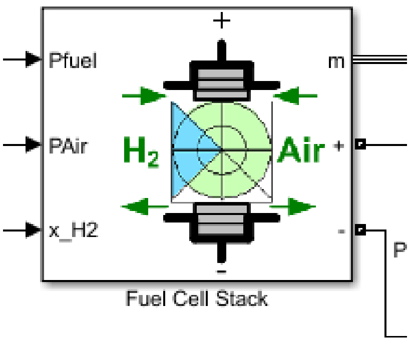


Figure 3.9: fuel cell model

3.4.7 Controlling system modeling:

This system work to manage four main units:

- Power condition unit:

  This unit compare between generation power (Ppv) and load power (Pl) in Figure 3.10, if (Ppv> Pl), load consume power =Pl and the excess power go to electrolyser to split water into hydrogen and oxygen that means the electrolyser switch is on. If (Ppv<Pl) the generation power from PV panels is less than load demand. In this condition, the fuel cell and PV panels work in parallel to fulfill the load demand. That mean the fuel cell switch is on.

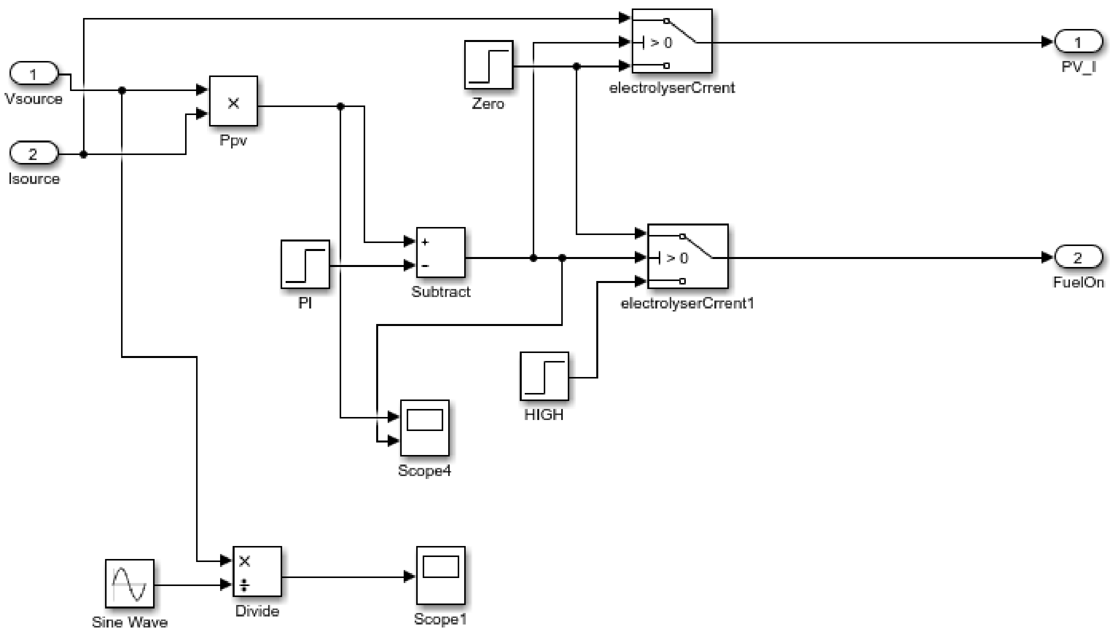


Figure 3.10: The power condition unit model

- Hydrogen pressure unit:

  This unit designed with respect to maximum pressure of hydrogen tank to compare the hydrogen pressure (PH_2) with reference value (maximum tank pressure), if PH_2 equal to maximum pressure value the electrolyser switch is off to stop hydrogen generation as shown in Figure 3.11.

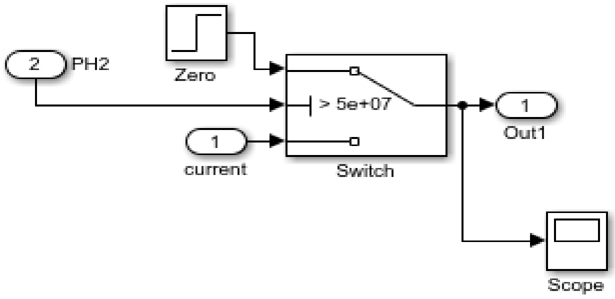


Figure 3.11: hydrogen pressure unit

- Gas flow unit :

  The function of this unit is to stop the air (oxygen) flow to fuel cell unless hydrogen gas enters fuel cell as shown in Figure 3.12.

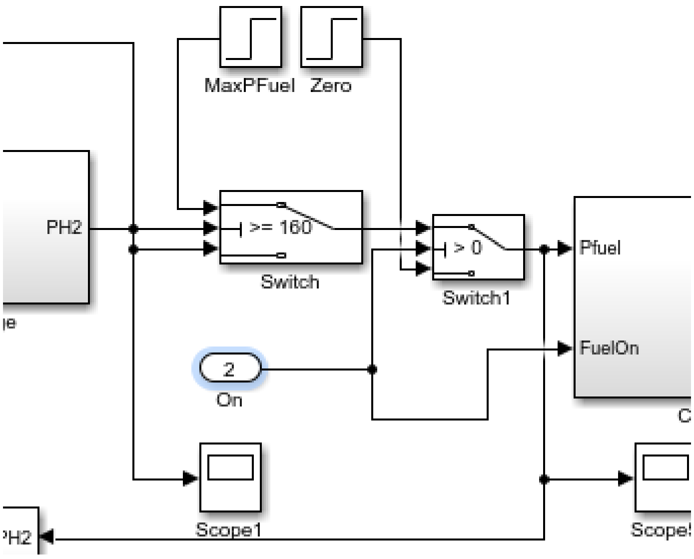


Figure 3.12: Gas flow unit

- Consumption monitoring unit :

  This unit monitors consumption rate of the hydrogen and air to determine the amount of remaining hydrogen inside the tank in Figure 3.13.

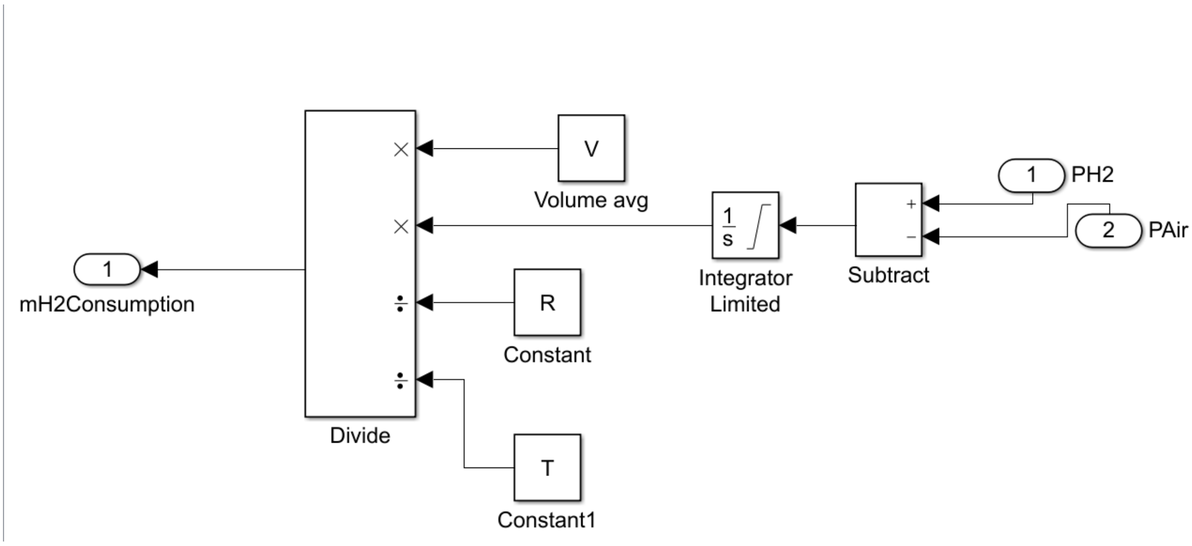


Figure 3.13: Consumption monitoring unit

3.4.8 Inverter model:

The transfer function of the inverter as shown in Figure 3.14 is

$$Z= (\frac{S/C}{S^2+\frac{1}{LC}}) \quad (3.8)$$

$$1/C= \text{gain} \quad (3.9)$$

$$\frac{1}{LC}=\omega^2 \quad (3.10)$$

$$F=\frac{1}{2\pi\sqrt{LC}} \quad (3.11)$$

The gain considered equal to one so 1/C=1, the frequency =0.5HZ so L=1/(4×π^2× 0.25)=0.10132 H.

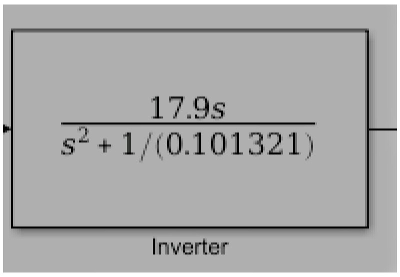


Figure 3.14: Inverter model

3.4.9 Load modeling:

The power of the load should be 3.422 kW, impedance of the load calculated as following:

S =P/p.f (3.12)

S =3.422/0.707=4840.1 KVA

$$s=\frac{Vrms^2}{2\times Z} \quad (3.13)$$

$$Z=\frac{Vrms^2}{2\times s}=\frac{220^2}{2\times 4840.1}= 4.9998=5 \text{ Ohm}$$

$R=X_L-X_C$ (3.14)

Assume:

R=5 Ohm, X_L=10 Ohm, X_C=5 Ohm

L=3.183 H

C=0.06366 F

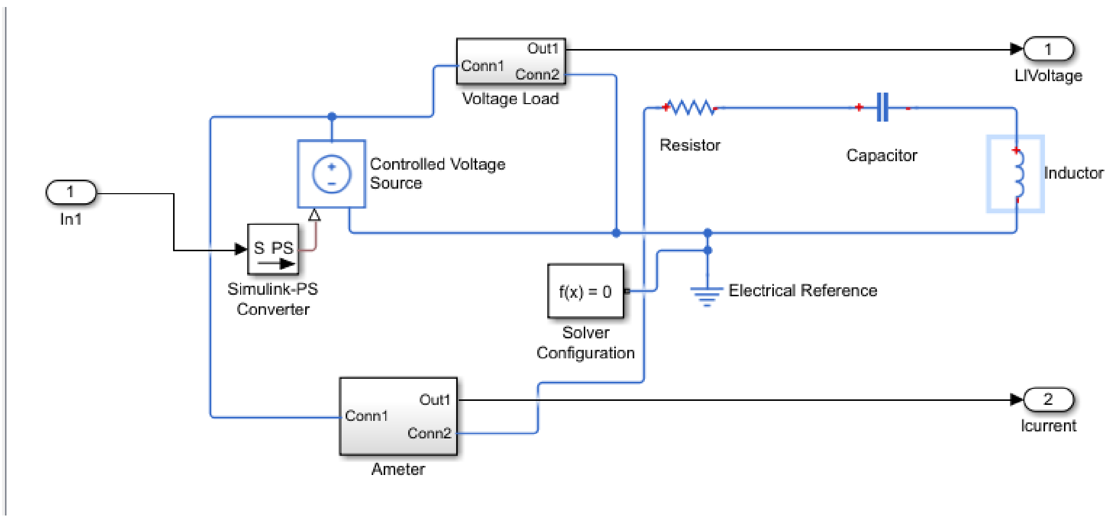


Figure 3.15: load model

CHAPTER FOUR

RESULTS AND DISCUSSION

1.1 Results:

The output results was obtained from MATLAB SIMULINK simulated the system in one mode when $P_{PV} > P_L$, the remaining power (P_{PV}-P_L) was supplied to the electrolyser which generated hydrogen and oxygen. The generated hydrogen is stored for later usage. The overall results is represented as following:

1.1.1 Photovoltaic:

The used radiation was 2.5 kw/m^2/d and the operation temperature was 29°C. The photovoltaic voltage and current in Figure 4.1:

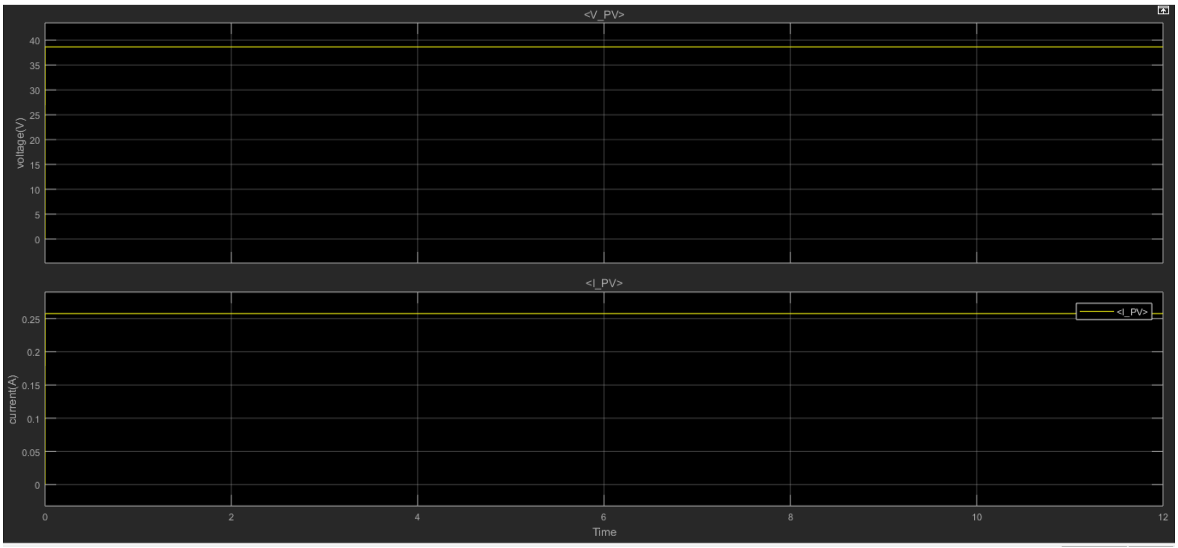


Figure 4.1: photovoltaic voltage and current curves

1.1.2 Electrolyser:

Current flows in the electrolyser, caused because the PV power was greater than the load power.

Number of H_2 moles as shown in Figure 4.2:

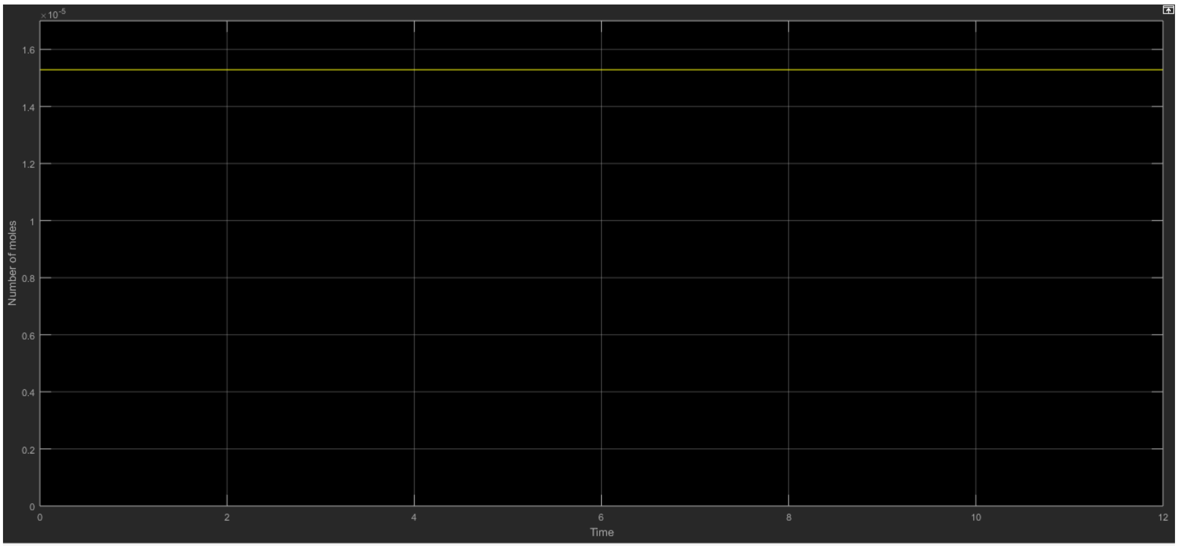


Figure 4.2: Hydrogen moles

1.1.3 Hydrogen storage:

Since the electrolyser produced hydrogen, this hydrogen was stored in the H_2 tank. The stored hydrogen pressure in Figure 4.3:

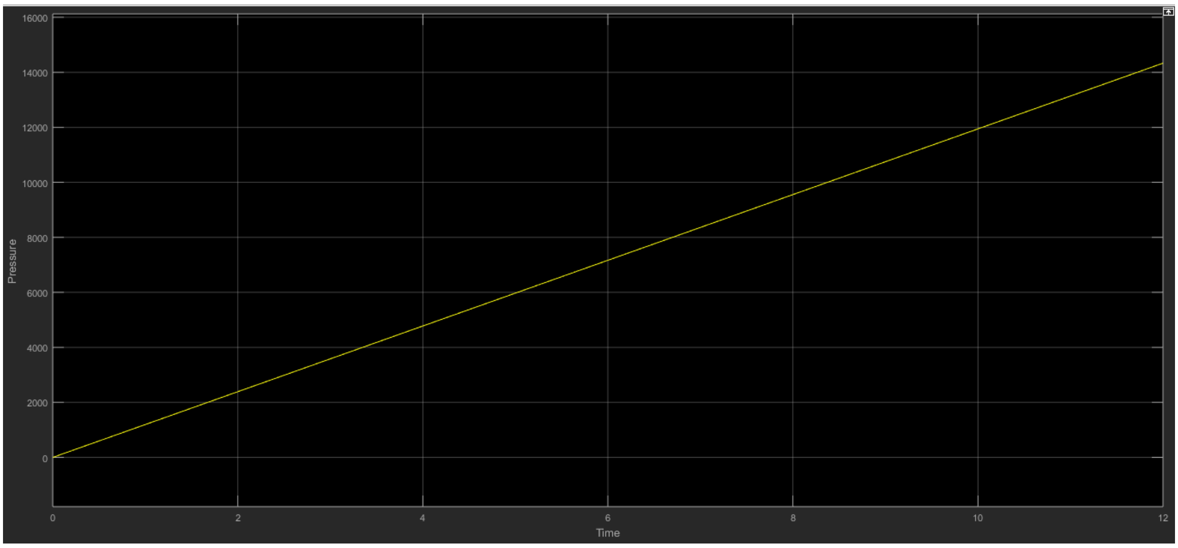


Figure 4.3: Pressure of the delivered hydrogen from the storage

1.1.4 Fuel Cell (FC):

There was no hydrogen entering the fuel cell, because the PV power was entirely feeding the load.

FC voltage and current as shown in Figure 4.4:

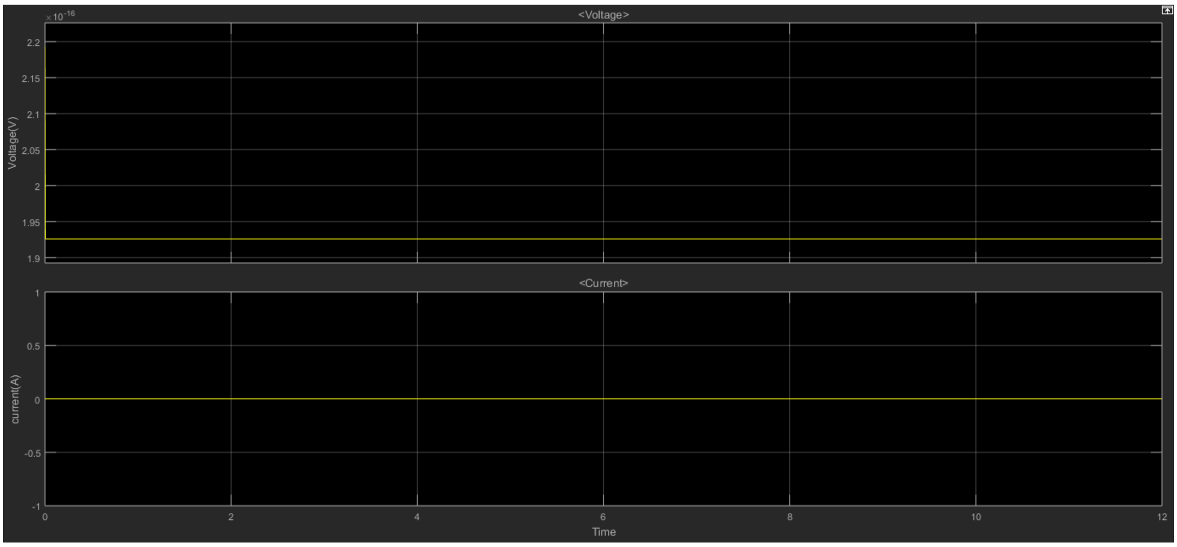


Figure 4.4: Fuel cell voltage and current

1.1.5 Controller:

1.1.5.1 Power condition unit:

It compared between the power value of the PV and load, and the result of this comparison was the electrolyser's power in Figure 4.5.

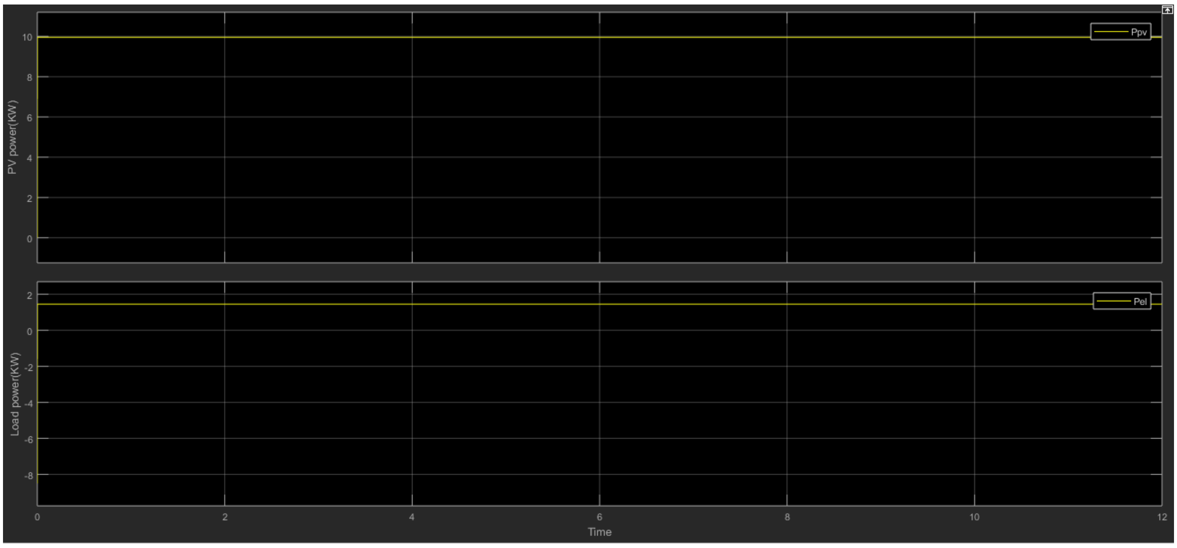


Figure 4.5: PV and electrolyser power

1.1.5.2 Hydrogen pressure unit:

The hydrogen pressure was compared with initial value (5×10^7 Pa) which represents the hydrogen storage capacity as shown in Figure 4.6.

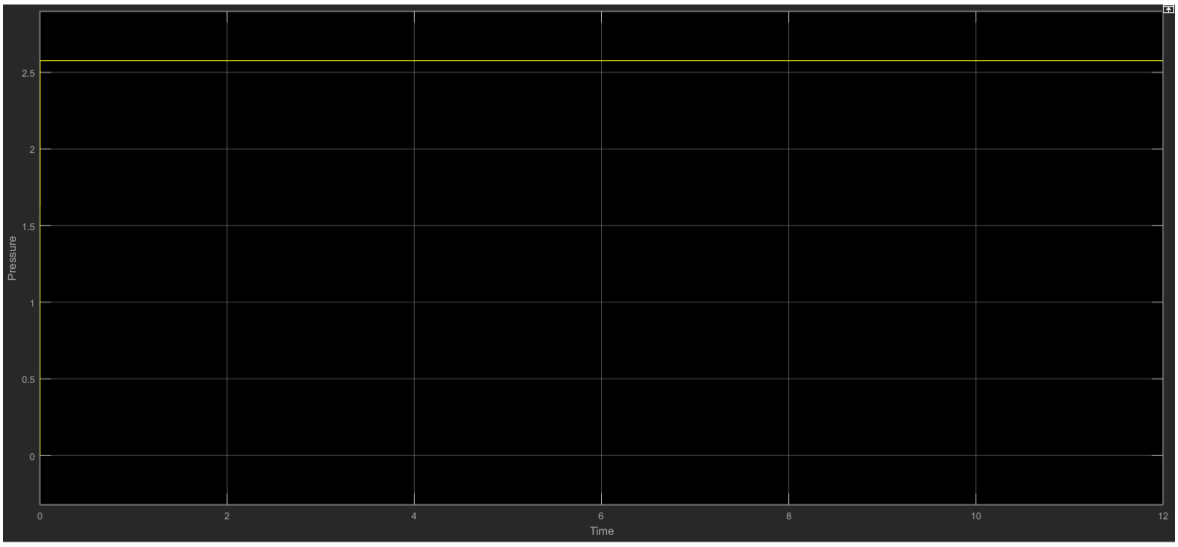


Figure 4.6: Hydrogen storage pressure

1.1.5.3 Gas flow unit:

The result of the gas flow was zero, because there was no air entering the fuel cell, which was connected, with the entering of the hydrogen, Figure 4.7.

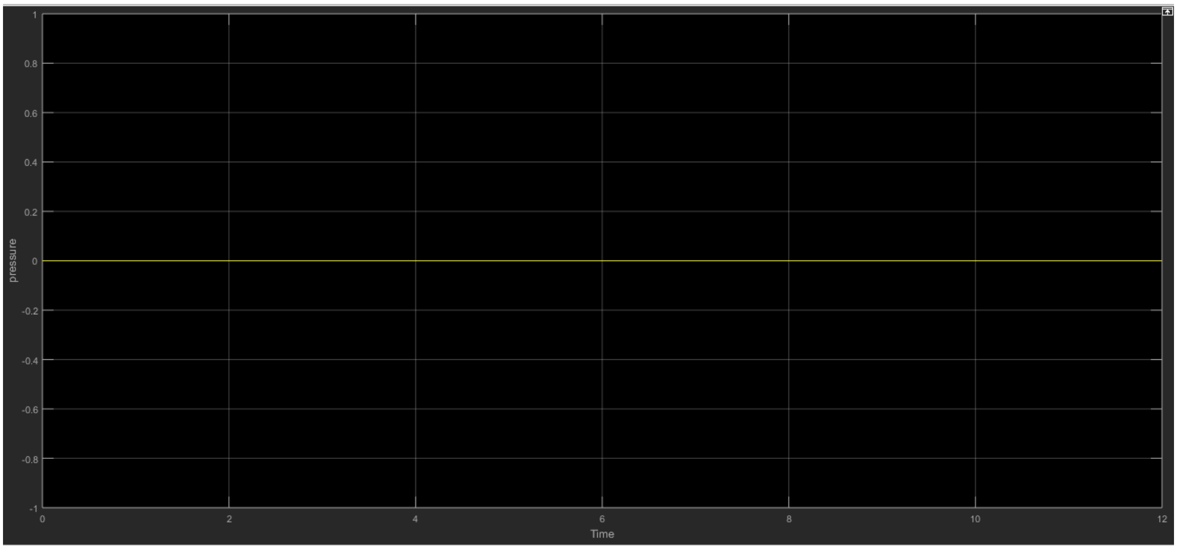


Figure 4.7: pressure of air

4.1.5.5 Consumption monitoring unit:

There was no hydrogen consumed because the fuel cell was not operating.

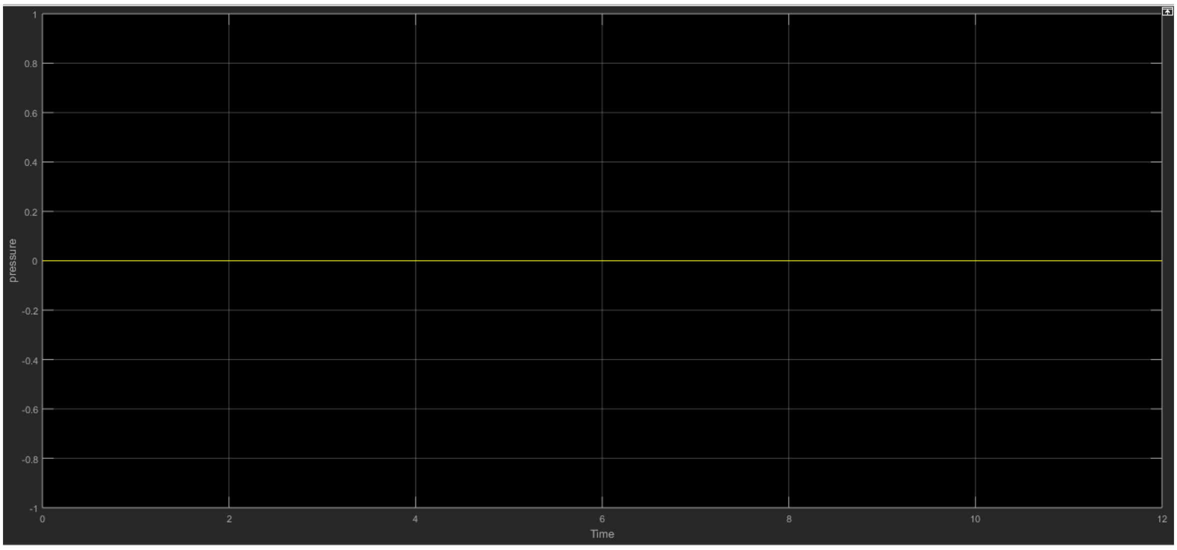


Figure 4.8: pressure of the consumed hydrogen

4.1.6 Inverter:

The generated voltage was converted to 220 volt AC, this is the voltage required to supply the load.

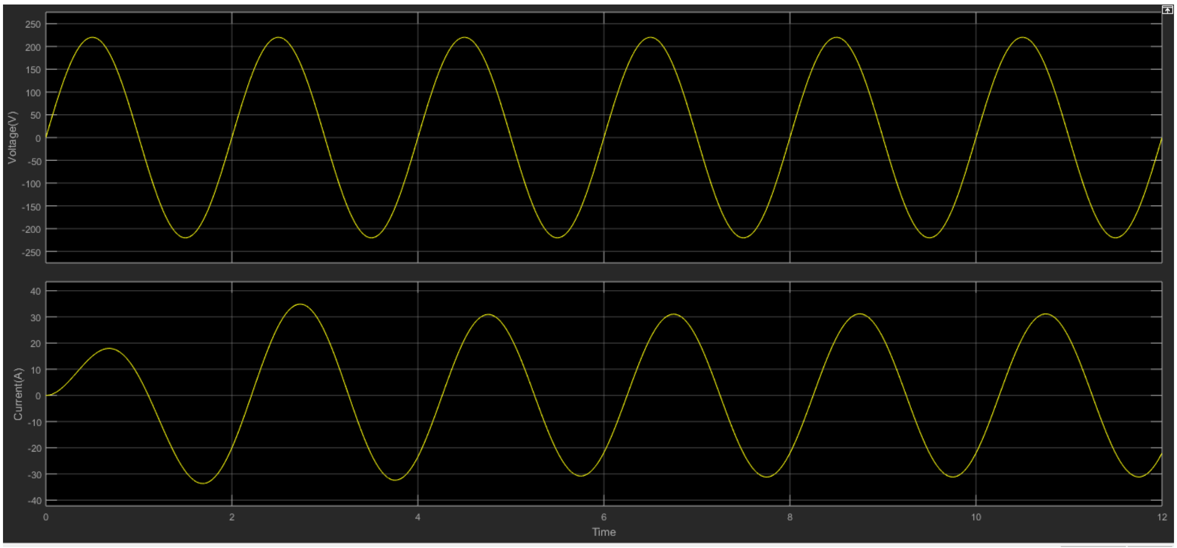


Figure 4.9: The inverters voltage

4.1.7 Load:

According to previous results, the load is supplied by AC power.

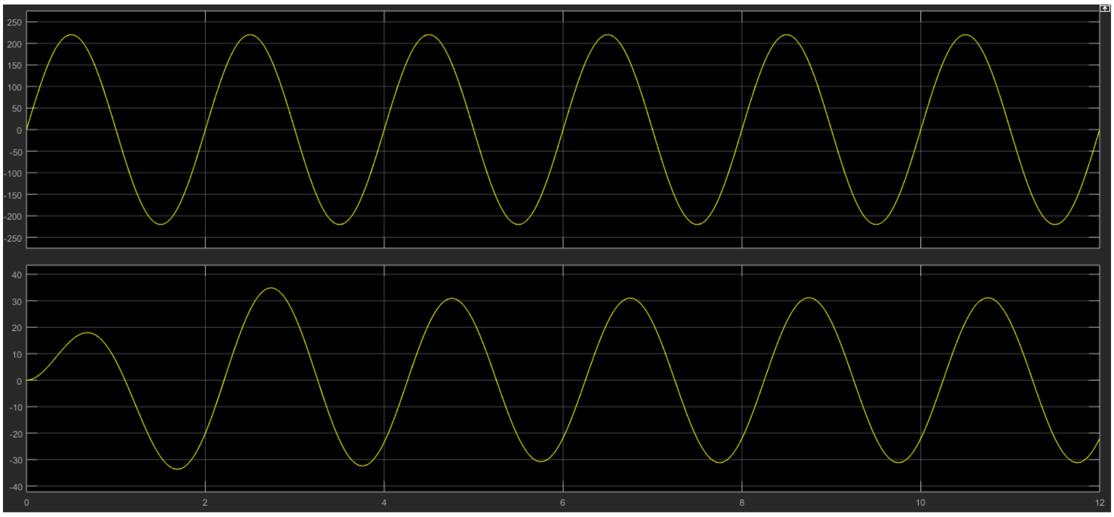


Figure 4.10: Output voltage and current of the load

4.2 Discussion:

The designed system had the ability to supply the load in various conditions according to the PV input parameters (radiation and temperature).

- Figure 4.1 shows that a solar panel generates a certain value of DC voltage and current according to the input parameters of G and T_{op}.
- In figure 4.3 shows that the output pressure from the storage increases with the time.
- Since the PV panels generates a sufficient amount of the power to fulfill the load demands; the fuel cell is of and that is why the fuel cell output current is zero as it is represented in figure 4.4.
- Although the fuel cell is off, the fuel cell voltage is not zero, this was caused by the fuel cell open circuit voltage.

CHAPTER FIVE

CONCLOSION AND RECOMMENDATION

5.1 Conclusion:

Finally, System component is modeled and simulated by MATLAB SIMULINK. The system is controlled for various load conditions using load splitter, which compare generation power with the load demand to determine which energy source must supply the load; PV or fuel cell. The results of PV, electrolyser, storage tank and fuel cell have been obtained and presented in plots and graphs show the performance of each component.

The replacement of the conventional technologies, namely diesel generators and batteries by Hydrogen Fuel cell technology is technologically feasible. It reduces emissions, noise and fossil fuel dependence and increases usage of renewable energy.

5.2 Recommendations:

- The AEM (Anion exchange membrane) elctrolyser has better properties of other elctrolysers. However, AEM needs more tests for future usage.
- Fuel cell technology in general, is a new technology, and is expensive. It needs more investigations to reduce its cost.
- DC-to-DC converter can be used with fuel cell to increase the output voltage.

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APPENDIX A

Used Iron nameplate

APPENDIX B

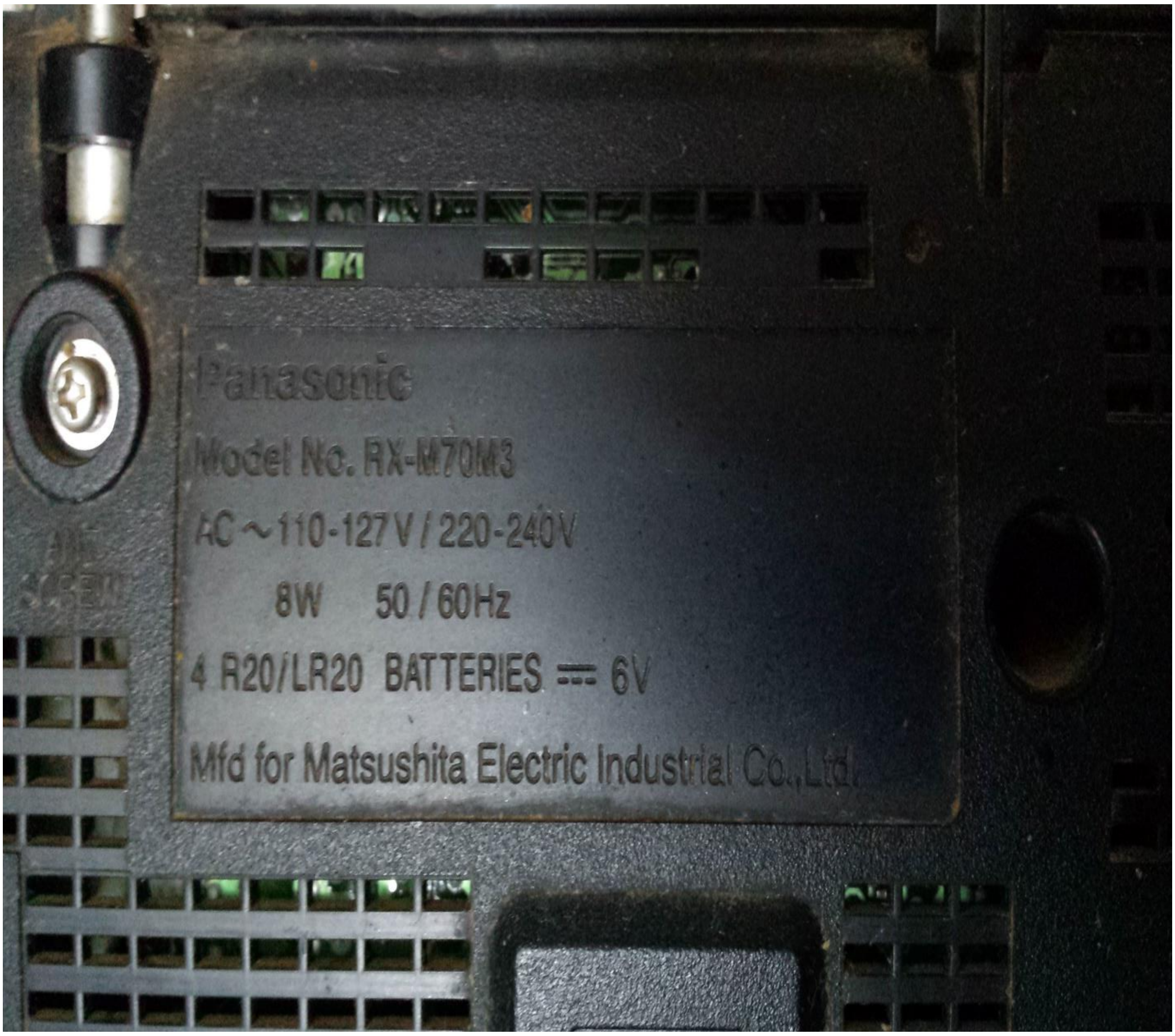
Used Refrigerator nameplate

APPENDIX C

Used Television nameplate

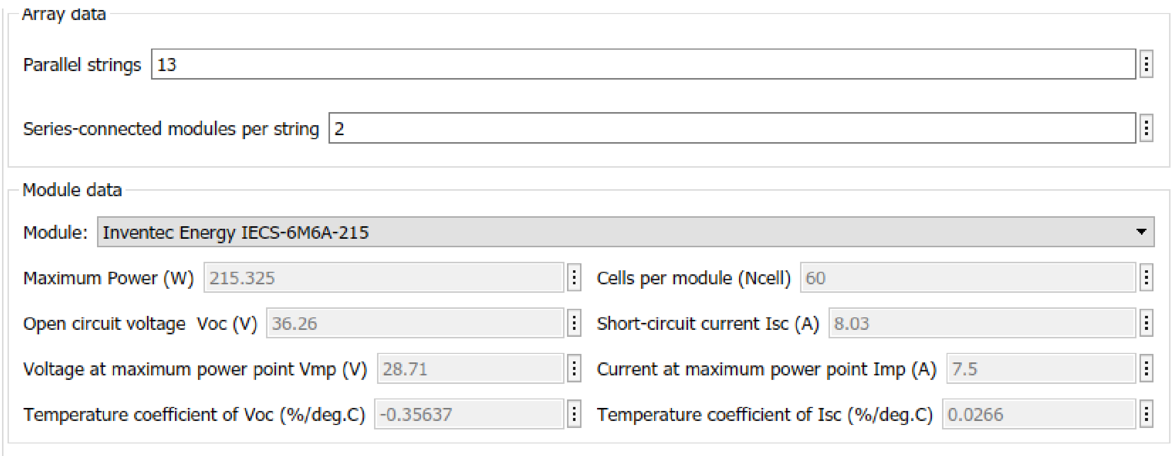
APPENDIX D

Used Radio nameplate



APPENDIX E

PV Parameters



Array data

Parallel strings: 13

Series-connected modules per string: 2

Module data

Module: Inventec Energy IECS-6M6A-215

Maximum Power (W): 215.325

Cells per module (Ncell): 60

Open circuit voltage Voc (V): 36.26

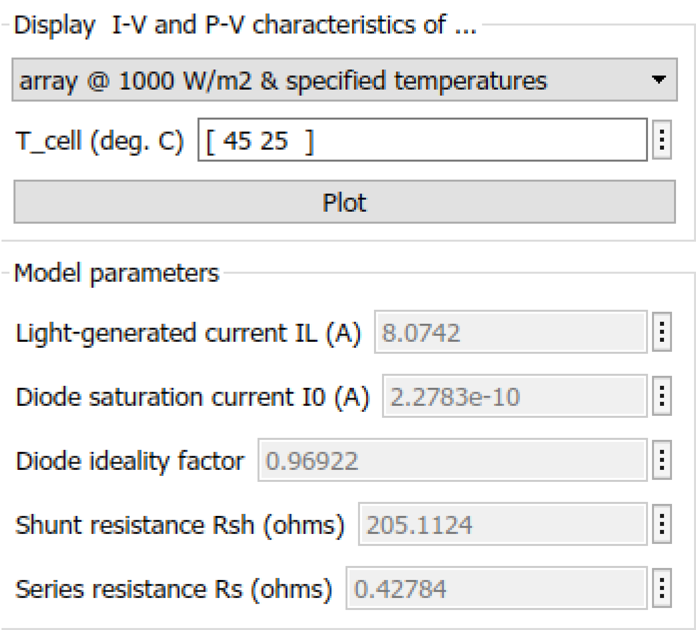
Short-circuit current Isc (A): 8.03

Voltage at maximum power point Vmp (V): 28.71

Current at maximum power point Imp (A): 7.5

Temperature coefficient of Voc (%/deg.C): -0.35637

Temperature coefficient of Isc (%/deg.C): 0.0266



Display I-V and P-V characteristics of ...

array @ 1000 W/m2 & specified temperatures

T_cell (deg. C): [45 25]

Plot

Model parameters

Light-generated current IL (A): 8.0742

Diode saturation current I0 (A): 2.2783e-10

Diode ideality factor: 0.96922

Shunt resistance Rsh (ohms): 205.1124

Series resistance Rs (ohms): 0.42784

APPENDIX F

Fuel Cell parameters