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Faculty of Graduate Studies

Electrification of Remote Clinics by Photovoltaic – Hydrogen Fuel Cell System

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Dedication

Praise be to Allah, Lord of the Worlds

To the Prophet Muhammad

Blessings and peace be upon him

To my father

To my mother

To my brothers and sisters

To my wife

To my son (Diab), and my daughter (Tlane)

To all friends and colleagues

To my teachers

To everyone working in this field

To all of them,

I dedicate this work

Acknowledgments

It is an honour for me to have the opportunity to say a word to thank Allah alone without partner who helped me to complete this research . I would particularly like to thank the supervisor Prof. Dr. Marwan Mahmoud , who helped me and encouraged me and gave me his time a lot throughout the entire research work.

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الإقرار

أنا الموقع أدناه مقدم الرسالة التي تحمل عنوان

Electrification of Remote Clinics by Photovoltaic – Hydrogen Fuel Cell System .

Declaration

The work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification.

Student's name:	**إسم الطالب:**
Signature:	**التوقيع:**
Date:	**التاريخ:**

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List of Abbreviations

DC	Direct Current
AFC	Alkaline Fuel Cell
EL	Electrolyser component
FC	Fuel cell
I-V	Current-Voltage
MCFC	Molten Carbonate Fuel Cell
MEA	Membrane Electrode Assembly
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracker
PAFC	Phosphoric Acid Fuel Cell
PEM	Proton Exchange Membrane
P-U	Power-Voltage
PV	Photovoltaic generator
SOFC	Solid Oxide Fuel Cell
STC	Standard Test Conditions
STP	Standard Temperature Presser

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Abstract

Palestinian health clinics in remote areas suffer from limited electric networks due to Israeli restrictions and lack of infrastructure fund from National Authorities. Most of these areas are distant from the main medium voltage transmission lines, which makes the unfeasible to connect them to the main electric power grids. Therefore, renewable energy sources could be more clean and feasible solution, especially solar and bio-waste sources. A typical energy consumption pattern for a small health clinic will be used. In addition, the theses would be providing modelling of the proposed system. Experimental results obtained for a reduced scale model parts built in the lab to give insight into the system technical details.

Fuel availability and clean energy production in fuel cells, given its chemical reactions occurs inside as well as production of electricity for unlimited time, are of the main system specifications. This contribution provides a power management strategy for solar and fuel cell system scaled to suite a typical small clinics from rural areas in Palestine The proposed control strategy is based on a logic-based method that consider the states of power supply sources and the demand to combine and switch in between giving priority to the much stable source. In addition, experimental results for system part have been done on scaled system in the lab.

Chapter One

Introduction

1. Introduction

Remote areas far from cities mostly lack water and electric networks. The inhabitants of these areas face considerable difficulties since they have to depend on small inefficient electric diesel generators and obtain their drinking water at expensive cost from tractor tanks. The distance of these areas from the main medium voltage transmission lines (33kV) and their low power demands make it unfeasible to connect them with the main electric power grids.

Solar electric power systems (photovoltaic generators) represent an effective appropriate solution to these villages to cover the power demands of the most necessary equipment such as lighting, TV, computer, water pumps, refrigerators, etc. . . . As known, health clinics that serve all villagers are very necessary. These clinics depend mostly on their own small electric diesel generator or they obtain the electric power from some houses, which posses diesel generators, at very high cost. The electric loads in such clinics are small and consume only small amount of daily energy. The electric loads are mainly represented in lighting (florescent or CFL-lamps), small vaccine refrigerator (196 liter), computer, sterilizer, small water pump, centrifuge, weight and overhead fan [1].

The total daily energy demand of such appliances is relatively low and lies mostly in the range between 2 and 5kWh which can be easily supplied by means of solar photovoltaic generators especially in countries of high solar energy potential as Palestine where the daily average on annual basis exceeds 5.2 kWh/m^2-day while the registered annual sunshine duration exceeds 2800 hours. Providing electric power to isolated rural clinic is not a new application since it has started during the seventies of the last century [2].

A large number of remote health clinics especially in Africa, Latin America and south Asia have been successfully operated by photovoltaic generators with consequently positive impact on the health sector of those areas. However, the new issue in this thesis is the use of a photovoltaic generator with hydrogen and fuel cell instead of using the traditional lead acid batteries as a storage media. The new system with fuel cell is promising to be more efficient and economic than the traditional system [3]. Furthermore the new system is friendlier to environment since it produces no toxic polluting gases as CO_2, CO....etc, and has no lead or mercury in its components [2].

The backup system is the fuel cell which is known with its high efficiency and fast response, fuel flexibility and clean energy production , since chemical reactions occurs inside the fuel cell [4] .In addition production of electricity for unlimited time are of the main system specifications . The photovoltaic generator (PV) produces, during the day light, (variable solar radiation)enough electric power to cover the requirements of the different loads in the clinic while the excess power would be used to supply the electrolyser producing hydrogen .In the night the fuel cell will provide the clinic with the necessary power without using storage batteries.

The system under study in this thesis consists of PV generator and water electrolyser to produce hydrogen, that would be stored in a special storage tank, to be used in periods of low solar radiation by proton exchange membrane (PEM) fuel cell to produce electric power [5].

The main objective of this thesis is to develop a reliable appropriate design for a PV- Hydrogen Fuel Cell system to be used in providing a remote clinic with the total necessary daily energy.

The other objectives are the followings:

- Access to design solar electric power generators that preserve the environment without pollution.
- Identification of the control system that is mostly appropriate and safe for such compound system.
- Determination of the techno- economic feasibility of using fuel cell as backup system instead of storage batteries.

The thesis consists of the six chapters:

Chapter 1	Chapter 1 Provides an introduction to the notion of the Photovoltaic – Hydrogen Fuel Cell System for Electrification of Remote Clinics and the objectives the thesis.
Chapter 2	Studies all the components used in the system, such as photovoltaic, PEM fuel cell, electrolyser and hydrogen storage tank.
Chapter 3	Describes the mathematical modeling for each part of the Photovoltaic Hydrogen Fuel Cell system.
Chapter 4	Experimental results conducted in the laboratory and analysis of the Photovoltaic –Hydrogen Fuel Cell System
Chapter 5	Studies the sizing system and analysis.

Chapter 6 Presents the main conclusion of this thesis and recommendation for future work**.**

Chapter Two

Description of photovoltaic-hydrogen fuel cell system components

2. Description of photovoltaic-hydrogen fuel cell system components

This chapter provides an overview of the main components of photovoltaic-hydrogen fuel cell system. Such a system includes a source of power (PV), a hydrogen generator and hydrogen utilization units. The system provides electrical energy continuously without interruption.

Photovoltaic power generation, which converts sunlight into electricity, and has many advantages, including the inexhaustible it's free and environment-friendly.

The system consists of hydrogen production units called electrolyzers, which operate on hydrogen generation through the separation of the water using photovoltaic as a power source. Hydrogen which is produced by electrolyzer , has the advantage of being highly purified, and without emission of any greenhouse gases.

Battery pack is one of the popular options in energy storage. Stability of battery pack depends on some factors such as: response time of battery, discharge rate, life time and battery life cycle cost. Batteries can be used for daily storage but for seasonal storage, batteries are not practical because of the low storage capacity. As fuel cells can convert hydrogen energy to electrical energy, storing energy, in the form of hydrogen, is another solution for both daily and seasonal storage of electrical energy. Hydrogen tanks are less costly than batteries and despite longer life , they need less maintenance [6].

The figure (2.1) shows the components of a photovoltaic-hydrogen fuel cell system.

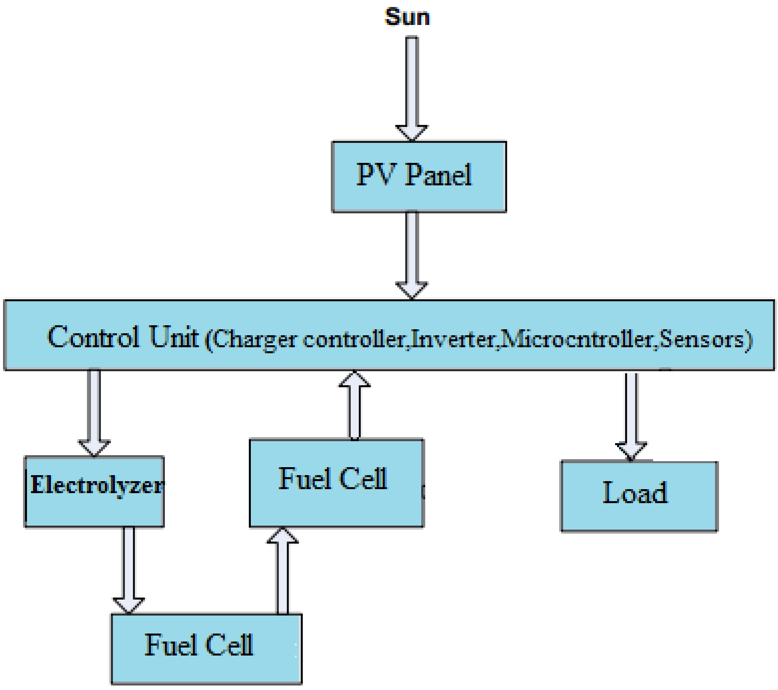


Figure (2.1): Block diagram of the Photovoltaic with fuel cell system.

2.1 Photovoltaic Power Generation

Photovoltaic cells convert solar radiation directly into electrical energy, also known as solar cell. The photovoltaic word refers to "photo" meaning light and "voltaic" refer to generate electrical. The cell is made up of semiconductor material such as silicon. It is composed of a P-type semiconductor and an N-type semiconductor. Solar radiation emitting the photovoltaic cell produces two types of electrons, negatively and positively charged electrons, in the semiconductors. The electric current flows through an external circuit between the two electrodes.

Photovoltaic cells are connected electrically in series and/or parallel circuits to produce higher voltages, currents and power levels. Photovoltaic modules consist of PV cell circuits. A photovoltaic array is the complete power-generating unit, consisting of a number of PV modules. A photovoltaic cell, PV module and array are shown in figure (2.2).

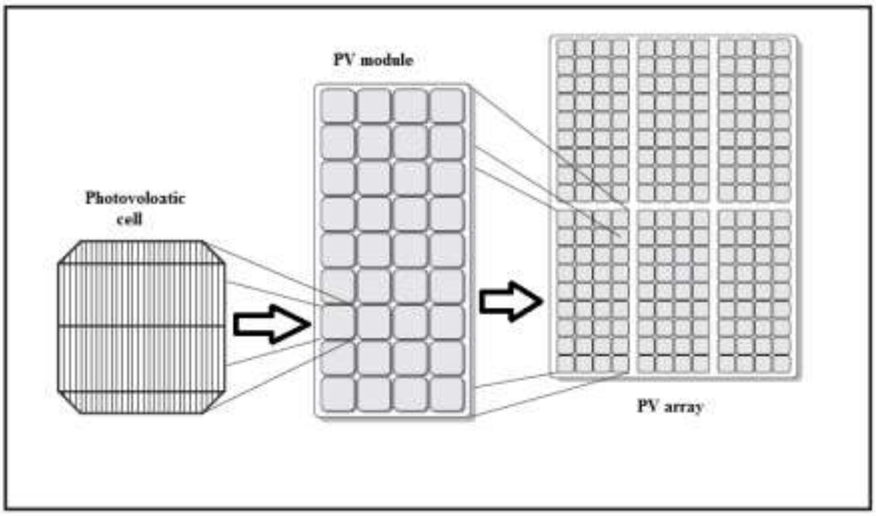


Figure (2.2): Photovoltaic cell, PV module and PV array.

2.1.1 Photovoltaic technologies

Basically, there are three types of technology used in the manufacture of photovoltaic cells: Crystalline silicon (Monocrystalline , Polycrystalline); Thin Film; and Concentrator. These technologies are shown in figure (2.3).

A crystalline silicon photovoltaic cell is manufactured from thin a slice cut of a single crystal of silicon and called (Monocrystalline (Mono c-Si)) whereas other types of less expensive cell and efficiency are called (Polycrystalline or Multicrystalline (Multi c-Si)) , are made of a silicon chips ,scraped from cylindrical silicon crystals and then chemically treated in furnaces to increase their electrical properties .The efficiency range of Crystalline silicon is between 11% and 20%, and represents approximately 85% of the market [7].

Thin film module is made of depositing a thin film of semiconductor material onto a plate of another material such as plastic, steel or glass. These PV cells have an efficiency of between 6-8% and accounts for approximately 4.2% of the global market sales [8]. Commercially, there are more types of thin module depending on the active material are made: Amorphous Silicon (A-Si), Cadmium Telluride (CdTe), and Copper Indium Diselenide (CIGS) [9].

Concentrator photovoltaic (CPV) converts light into electrical energy but focuses the sunlight onto a small area on the solar cell. One of its most important advantages is that it uses less space compared with other technologies and has high efficiency of about 30% [7], but the cost of this technology is relatively expensive.

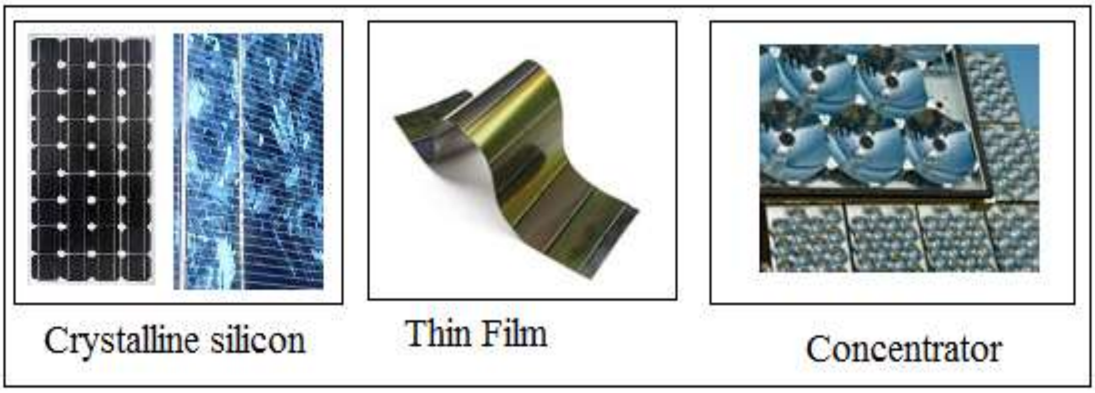


Figure (2.3): Type of Photovoltaic Technologies.

2.1.2 Characteristics of a Photovoltaic module

The performance of a photovoltaic module depends on manufacturing technology and operating conditions (solar radiation and temperature). The curve of current –voltage (I-V) which determines the behavior of a photovoltaic cell is represented in figure (2.3).

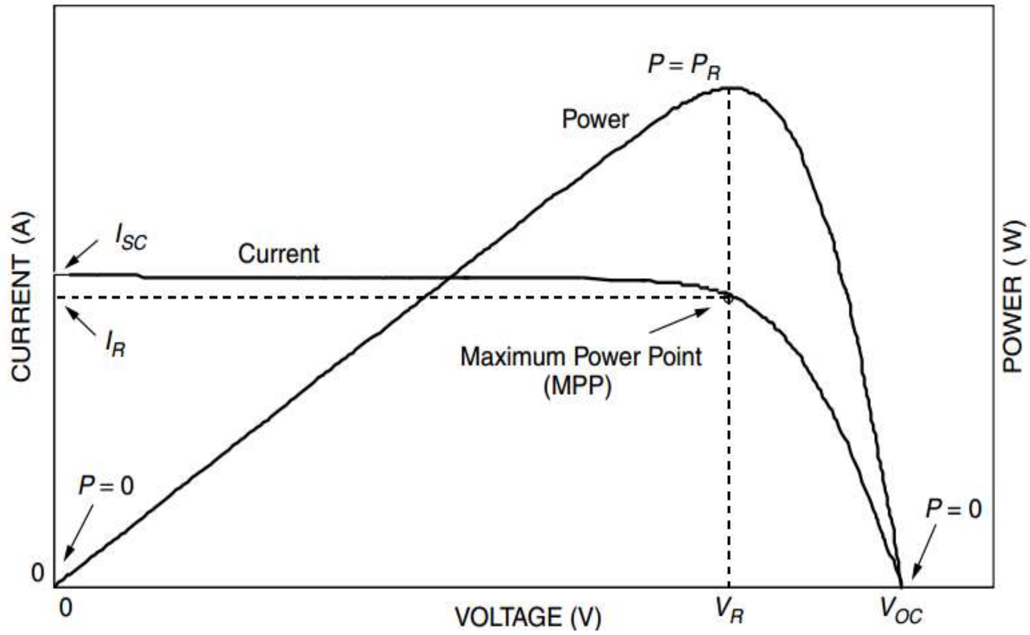


Figure (2.4): The I-V and P-V characteristics of typical PV module [10].

The main electrical parameters that describe the performance of a photovoltaic cell are:

1. Short circuit current (Isc):

   The value of (Isc) can be obtained by connecting the terminals of a module via an ammeter and measuring the current. The value of Isc changes in function of solar radiation and very little of temperature .

2. Open circuit voltage (Voc):

   It’s the voltage of a PV module measured at its terminals at no load.

3. Maximum power point (Mpp):

   The maximum power point of a photovoltaic is a unique point on the (I-V) or (P-V) characteristics and the power supplied in this point is maximum, where measured in Watts (W) .its value can be calculated by the product Vmax and Imax.

4. Fill Factor (FF):

The ratio of output power at maximum power point to the power computed by multiplying Isc by Voc, as illustrated in Figure (2.4).

The FF is obtained according the following equation:

$$FF = Vmpp * Impp / Voc * Isc$$

(2.1)

It is an important performance indicator.

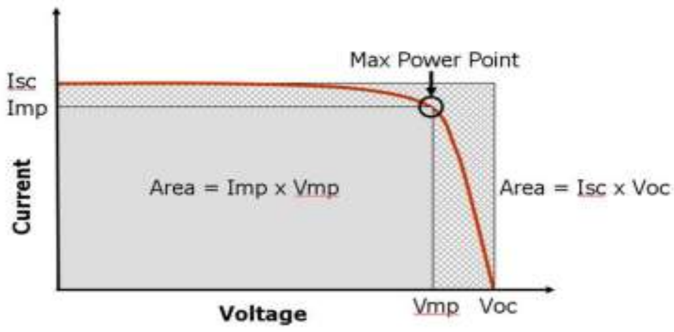


Figure (2.5): The I-V curve of a PV module for defining the FF.

Typically, crystalline silicon photovoltaic FF module is between 0.67 and 0.74

and thin film is 0.7 [11],[12].If the I-V curves of two individual PV modules have the same values of Isc and Voc, the array with the higher fill factor (squarer I-V curve) will produce more power. Also, any impairment that reduces the fill factor will reduce the output power [12].

2.1.2.1 Maximum Power Point

To improve the efficiency of PV systems, various been performed. But, as solar energy is diffuse (less than 1 kW/m²), and photovoltaic cell efficiency is theoretically limited to 44%, efforts need to be strengthened on the energy transfer. This includes the design of the photovoltaic system and the energy management by seeking the Maximum Power Point (MPP).

Large amount of publications can be found on MPPT, and it is not easy to apprehend their differences and to estimate their performances [13].

The position of maximum power point is not known to determine this point used calculation models or by using a logarithms techniques, where vary in terms of complexity and simplicity, implementation, accuracy and the cost. Table (2.1) is shown the famous techniques used and simplicity in implementation [14].

Table (2 1): Techniques of maximum power point tracking .

No.	Methods of MPPT Techniques	Cost (Component ,Sensor, Microcontroller)	Percentage of matching with theoretical value (100%)
1	Constant Voltage (CV)	Low	79.5
2	Short-Current Pulse (SC)	Medium	90.7
3	Open Voltage (OV)	Near to medium	94.6
4	Perturb and Observe (P&O a)	Near to medium	98.9
5	Perturb and Observe (P&O b)	Near to medium	99.3
6	Perturb and Observe (P&O c)	Medium	87.7
7	Incremental Conductance(IC a)	High	98.7
9	Incremental Conductance(IC b)	Near to high	99.5
10	Temperature Methods	High	(90-97)

2 .2 Hydrogen Production From Water

Many of technologies to produce hydrogen one of them is electrolyzer, which is an electrochemical device produced hydrogen from disassociate the water into hydrogen and oxygen by applied the electrical current from power supply (photovoltaic, which is suggested for this thesis).

The electrical current must be direct current (DC) because it flows in one direction .An electrolyzer consists of electrolyte between two electrodes; one electrode is connected to positive of the power supply and produced oxygen. Another electrode is connected to negative of the power supply and produce hydrogen .The amount of hydrogen generated is twice than oxygen, because the one mole of water consists of two moles hydrogen and one mole oxygen. The quantity of gases formed depends on the surface area of electrodes and the value of power supply. The main ways of water electrolysis are Alkaline and Proton Exchange Membrane.

Water electrolysis in the anode place dissociates into protons, electrons, and oxygen is liberated, the protons pass through the membrane. The electrons pass

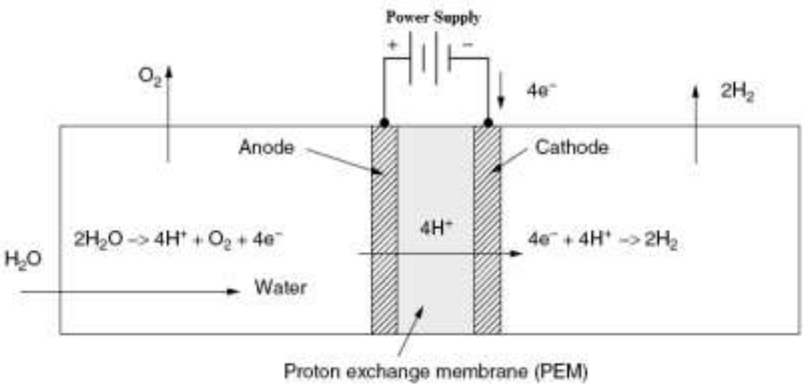


Figure (2.6): Principle of PEM electrolyzer.

through the power supply to the cathode.These electrons combine with protons to form hydrogen. PEM electrolyzer can have an overall efficiency of up to 85% [15].

The overall reaction of the water electrolyzer is:

$$\longrightarrow 2H_2O \qquad O_2 + 2H_2 \tag{2.2}$$

2.3 Hydrogen Storage

Hydrogen is characterized by a low density of 0.08Kg /m^3 under normal conditions, so that its storage is difficult compared with liquid fuels.

Negative aspects of hydrogen and possible risks involved with its usage are primarily because hydrogen is colourless, odourless, tasteless and non-toxic under normal conditions. Hydrogen is potentially explosive; it has extremely low ignition energy, a low viscosity and high combustion, all of which are contributory factors to the hazards associated with hydrogen [16].

It can be stored in many basic configurations such as: compressed hydrogen gas in tanks or liquid hydrogen storage; or metal hydride; or complex chemical hydrides. The various storage types have different characteristics. The selection of a specific storage type depends on these characteristics, and mainly on energy density and cost of each type. Compressed gaseous hydrogen can be stored in pressure tanks at ambient temperature and 200 up to 700bar pressure. The most common materials used for hydrogen tanks are steel and aluminum. From all storage technologies, the compressed gaseous hydrogen has the longest history and cheapest price [17].

2.4 Fuel Cell Technology

The fundamental principle of the fuel cell is to convert chemical energy into electrical energy. A fuel cell is an electrochemical reactor which consumes fuel (in this thesis the fuel used hydrogen) and oxidation oxygen from air to convert the hydrogen and oxygen into pure water and electricity.

2.4.1 Historical development

William Grove in 1839 was first discovered the basic principle of fuel cell by reversing water electrolysis to generate electricity from hydrogen and oxygen .The principle that he discovered remain unchanged today [18].

Grove used four large cells, each containing hydrogen and oxygen, to produce electric power which was then used to split the water in the smaller upper cell.

Commercial potential first demonstrated by NASA in the 1960's with the usage of fuel cells on the space flights [19]. However, these fuel cells were very expensive .Fuel cell research and development has been actively taking place since the1970's, resulting in many commercial applications ranging from low cost portable systems for cell phones and laptops to large power systems for buildings. The following are some applications of fuel cells:

1-Powering portable electronic equipment .

2-Providing off grid and backup power.

3-Powering homes .

4-Powering vehicles .

5-Powerplants .

2.4.2 Functional principle of a Fuel Cell

The basic components of a single fuel cell are two electrodes, separated by an electrolyte**.** A fuel cell is an electro-chemical reactor which consumes fuel (hydrogen) and oxidant (oxygen from air) and converts them into water.

In a fuel cell the equivalent of a combustion reaction takes place, however, At low temperature while separating electron and mass flow, fuel oxidation and oxygen reduction take place which and spatially separated at different electrodes enabling the exchange of electrons. The reactions taking place in the fuel cell are more general in any electrochemical cell that require the transfer of electrons from the reactant to the electrode. These reactions are called redox-reactions. Materials, undergoing oxidation or reduction reactions, are called active materials.

By definition:

Oxidation reactions take place at the Anode.

Reduction reactions take place at the Cathode.

Separation of reaction sites is achieved by insertion of an electronically insulating but ionically conducting phase (electrolyte) between the site of reduction and the site of oxidation. Electrical current in the electrolyte is conducted by electrically charges particles (ions) exclusively. The ionic current is flowing only when the electrons taking part in the reaction are led across an external circuit. The reactions taking place at the electrodes can be described by equilibrium thermodynamic [20].

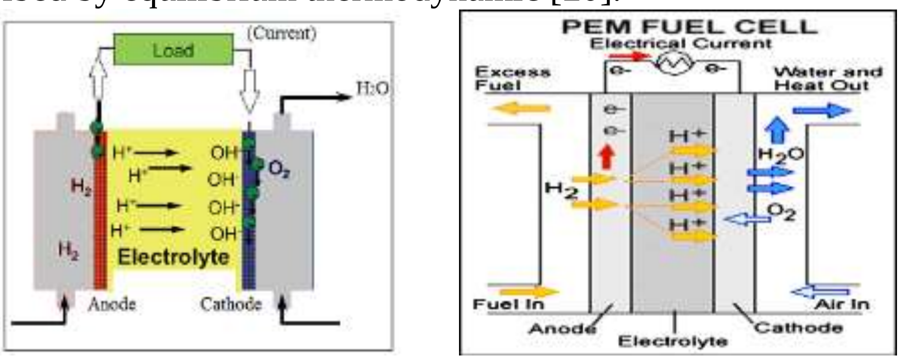


Figure (2.7): Basic principle of a PEM Fuel Cell

The fuel cell, shown in figure (2.4) is described by the following reactions:

Anodic reaction: $H_2 \longrightarrow 2H^+ + 2e^-$ (2.2)

Cathodic reaction: $\frac{1}{2}O_2 + 2H^+ + 2e^- \longrightarrow H_2O$ (2.3)

The overall reaction: $H_2 + \frac{1}{2}O_2 \longrightarrow H_2O$ (2.4)

2.4.3 Fuel cell types

Fuel cell is classified as power generator because it can operate continuously, if fuel and oxidant are supplied. Five categories of fuel cells have received major efforts of research: (1) Polymer Electrolyte Membrane (PEM) fuel cells or PEMFCs (also called PEFCs), (2) Solid Oxide Fuel Cells (SOFCs), (3) Alkaline fuel cells (AFCs), (4) Phosphoric Acid Fuel Cells (PAFCs), and (5) Molten Carbonate Fuel Cells (MCFCs). PEM fuel cells are constructed using polymer electrolyte membranes (notably Nafion) as proton conductor and Platinum (Pt)-based materials as catalyst. Their noteworthy features include low operating temperature, high power density, and easy scale-up, making PEM fuel cells a promising candidate as the next generation power sources for transportation, stationary, and portable applications[21]. The applications of fuel cell depend on the values of the operation temperature and efficiency, the types of the fuel cell as shown in table(2.2).The Proton Exchange Membrane (PEMFC) and the Alkaline (AFC) operate at low temperature .PEMFC are used for the domestic power and mobile applications ,AFC for the space application. NASA first developed PEMFCs for the Gemini mission, but because PEMFCs had water-management problems, alkaline fuel cells were used through the 1990s. Improved PEMFCs promise to be more powerful, lighter, safer, simpler to operate, and more reliable. They will last longer, perform better, and may cost much less than current alkaline fuel cells. PEMFCs use hydrogen fuel and produce only water so pure that NASA plans to use it as drinking water for spacecraft crews. NASA PEMFCs may also produce electricity for spacesuits, airplanes, uninhabited air vehicles, and reusable launch vehicles [19]. At medium temperature the Phosphoric Acid (PAFC) is operated and used for the co-generation application. Molten Carbonate (MCFC) and Solid Oxide (SOFC) are operated at high temperature more than 650C°. These two technologies are used for the high power application.

There are significant differences in relation to temperature between the species used and the efficiency of every kind. To determine the appropriate type depends on the type of applications that would be used.

Table (2.2): Existing fuel cell technologies [22], [18] .

Type of Fuel Cell	Electrolyte	Fuel	Temperature,[°C]	Electrical Efficiency,[%]
PEMFC	Polymer	H2	(20-80)	60
AFC	Potassium hydroxide	H2	(50-200)	60
PAFC	Concentrated phosphoric acid	H2	220	40
MCFC	Molten carbonate melts	CH4	650	45-50
SOFC	Solid oxide	CH4	(500-1000)	60

2.4.4 Advantages and disadvantage of fuel cell

The fuel cell is very important for pollution disposal and greenhouse gases; the only product is water. It has a relatively higher efficiency and operates more silently than diesel engine. Maintenance isn’t complex because there are few moving parts in the system. The operating times are much longer than batteries that to be disposed in hazardous waste landfills [28], the chemical energy to electrical energy is directly converted.

The most important disadvantages of fuel cell, is in dealing with hydrogen in terms of production and storage [23] . In 2009, more than 35% cost reduction has been achieved in fuel cell fabrication [21] , But the cost of manufacturing fuel cells and materials are still higher than conventional sources (fossil fuels) and life time is limited which depends on the membrane[24] .

2.4.5 V-I Characteristics of Fuel Cell

The theoretical voltage for the single PEMFC is about 1.23 V at standard Condition, the V-I and V-P characteristics of a PEMFC are illustrated in figure (2.5), but the actual voltage is less than 1V at open circuit condition and 0.5V at normal condition [10].The cell voltage less than its theoretical voltage due to the losses. The main source of losses can be divided into three; activation polarization dominates at low current densities in area I, is due to the slow charge transfer of the oxygen reduction and is the major source of losses. The second is governed by the ohmic polarization which is due to the resistance of the membrane and the third is bending down of the polarization curves due to the Concentration polarization.

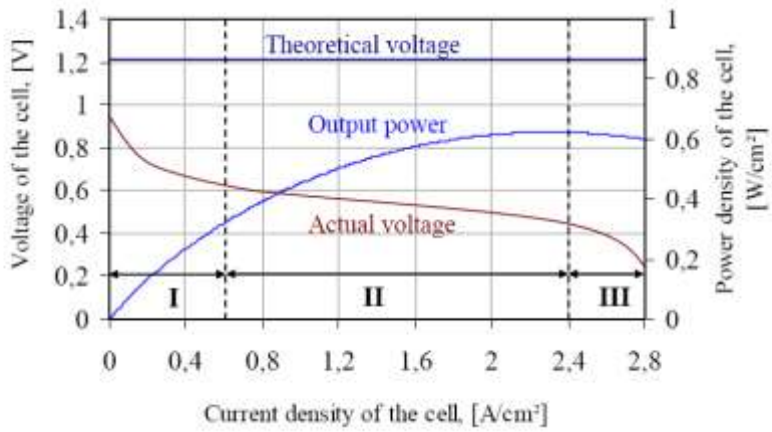


Figure (2.8): The V-I and V-P curves of a PEMFC.

2.4.6 The improvement performance of the PEMFC

The performance of the PEMFC can be improved by:

a) Increasing the temperature of the PEM fuel cell.

b) Increasing Pressure and flow rates of fuel (hydrogen) and oxygen.

2.4.7 PEM Fuel Cell stack

A fuel cell stack consists of a multitude of single cells stacked up so that the cathode of one cell is electrically connected to the anode of the adjacent cell. In this way exactly the same current passes through each of the cells [25]. PEM fuel cells are connected between together in series to increase the voltage, and this structured is known as a stack and shown in figure (2.5).

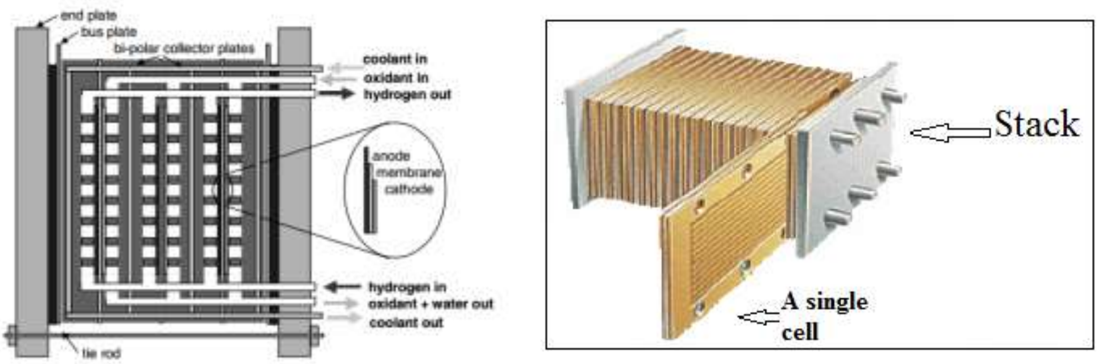


Figure (2.9): A collection of fuel cells (stack) to increase the voltage.

Chapter Three

Modeling of photovoltaic-hydrogen fuel cell system

3. Modeling of photovoltaic-hydrogen fuel cell system

This chapter presents the mathematical modeling for each part of the Photovoltaic Hydrogen Fuel Cell system.

3.1 Modeling of Photovoltaic Generator

Three models are used to describe the equivalent electrical circuit of a PV cell module or array: the one-diode, the two-diode, and the empirical model. The most commonly used configuration is the one-diode model that represents the electrical behavior of the pn- junction [17].

3.1.1 Modeling of Photovoltaic cell

The equivalent electrical circuit of one-diode model consists of a real diode in parallel with a current source. The current source produces the current I_{ph} and the current I_d flows through diode. The current I_L which flows to the load is the difference between I_{ph} and Id and it is reduced by the resistances R_s and R_p [26]. Two resistances, R_s and R_p, are included to model the contact resistances and the internal PV cell resistance respectively. The values of these two resistances can be obtained from measurements or by using curve fitting methods based on the I-V characteristic of PV [27].

The equivalent electrical circuit for a PV cell or module is illustrated in Figure (3.1).

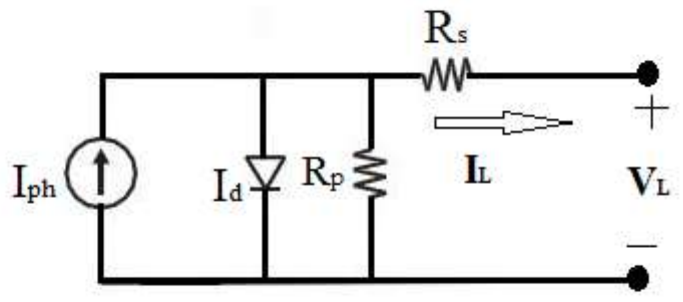


Figure (3. 1): Equivalent circuit of PV cell.

The current source (I_{ph}) depends on the solar radiation and the ambient temperature. The (I-V) characteristics of photovoltaic cell can be determined by the following equations [28].

The terminal current of the model (I_L) is given by:

$$I_L = I_{ph} - I_d - I_p \qquad (3.1)$$

Where,

I_{ph}: photocurrent from photovoltaic cell [A].

I_d: is the current passing through none linear diode [A].

I_p: current through shunt resistance [A].

The photocurrent I_{ph} is a function of solar radiation and temperature, it is determined from equation (3.2):

$$I_{ph} = [I_{sc} + k_I (T_c - T_r)]\, G/G_n \qquad (3.2)$$

Where,

I_{sc}: is the short-circuit of the cell at standard test condition (STC: G_n =1000W/m² and T_r =298.15K) [A].

k_I: is the short-circuit current temperature co-efficient of the cell [A/ K].

T_c and T_r: are the working temperatures of the cell and reference temperature respectively.

G and G_n: are the working solar radiation and nominal solar radiation respectively [W/m²].

The diode saturation current Id of the cell varies with the cell temperature, which is expressed in equation (3.3) as,

$$I_d = I_o\,[\,e^{(q(VL+ILRs)/AkTc)} - 1] \qquad (3.3)$$

I_o: reverse saturation current of the diode [A].

q: is the electron charge [1.6021×10^{-19} C].

V_L: output voltage of the photovoltaic cell [V].

R_s: series resistance of cell[Ω].

A: is the ideality constant of diode depend on the PV technology [1.2-3.3].

k: Boltzmann constant [1.38×10^{-23} J/K].

The shunt current I_p is given by equation (3.4):

$$I_p = (V_L + I_L R_s)/R_p \qquad (3.4)$$

Where R_p [Ω] is parallel resistance .

3.1.2 Modeling of Photovoltaic module

A PV module is the result of connecting several PV cells in series in order to increase the output voltage. The characteristic has the same shape except for changes in the magnitude of the open circuit voltage [27], as shown in figure (3.2).

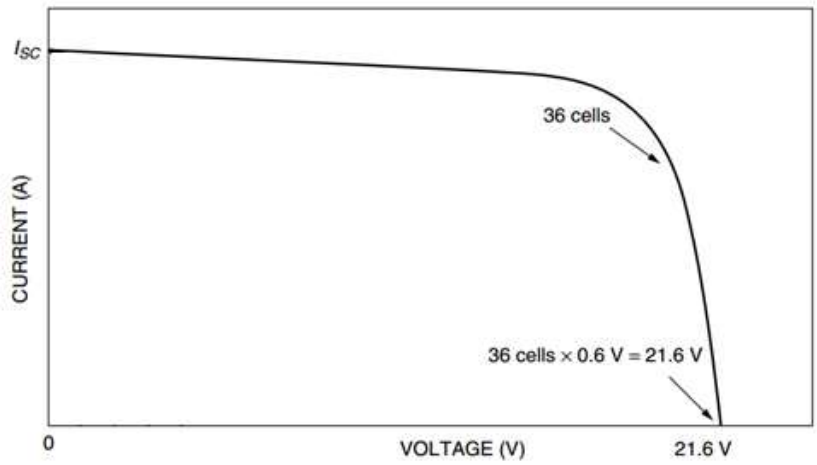


Figure (3.2): The I-V characteristics of a typical PV module consisting of 36 cells connected in series. [10].

The output voltage of a PV module is calculated by:

$$V_{module} = n(V_d - I_L R_s) \tag{3.5}$$

Where

n: is the number of PV cells connected in series in the module.

V_d: is the voltage of the diode of the equivalent circuit of the cell [V].

3.1.3 Modeling of Photovoltaic array

The PV Arrays are composed of some combination of series and parallel of PV modules. The modeling of PV arrays is the same as modeling of the PV module from the PV cells.

Modules in series, the (I–V) curves are simply added along the voltage axis.

The total voltage is just the sum of the individual module voltages [10], as illustrated in Figure (3.3).

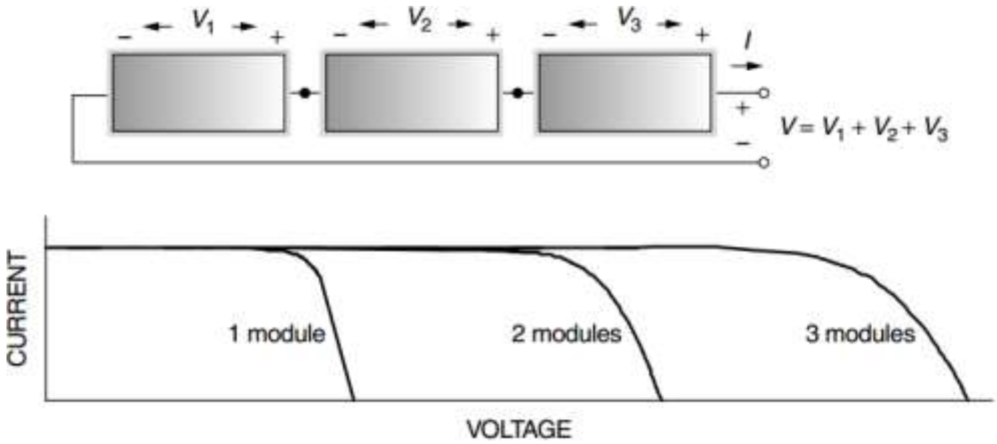


Figure (3.3): The I-V characteristics of 3 PV modules connected in series.

For PV modules connected in parallel the total current is the sum of the currents of the modules whereby the total output voltage is equal to the voltage of one module, as shown in figure (3.4).

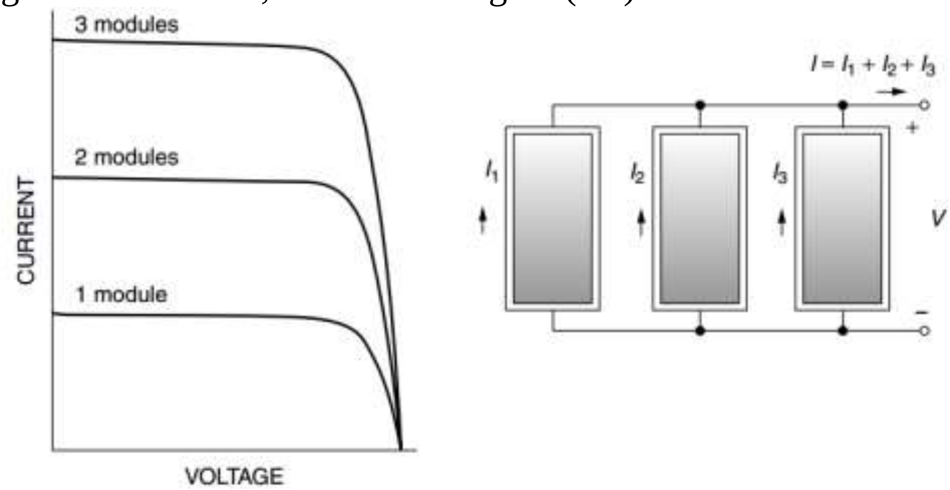


Figure (3.4): The I-V characteristics of 3 PV modules connected in parallel.

Practically the PV array will consist of a combination of series and parallel modules depending on the needed output power of the system.

3.2 PEM Fuel Cell System Model

Modeling of the PEM fuel cell voltage is calculated from the energy balance between chemical energy in the reactants and electrical energy.

3.2.1 Electrical output of an ideal PEM Fuel Cell

A simple theoretical model for a PEM Fuel Cell consists only of an ideal DC voltage source, as shown in figure (3.5).

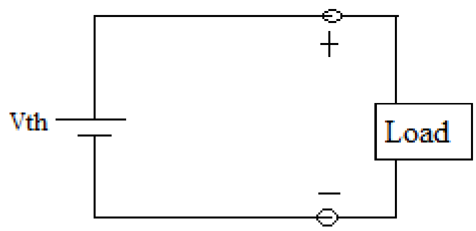


Figure (3.5): A simple equivalent circuit for a PEM fuel cell.

The theoretical voltage V_{th} of the PEM fuel cell at STC can be determine by two mathematical methods, thermodynamics equations and electrical equations.

3.2.1.1 PEM Fuel Cell Thermodynamics

The PEM fuel cell is converting chemical energy to electrical energy. The chemical energy released from the PEM fuel cell can be determined from the change in Gibbs free energy which is the difference between the Gibbs free energy of the product and the Gibbs free energy of the reactants [29]**.** The chemical energy released in a reaction can be thought of as consisting of two parts: an entropy-free part, called free energy G, that can be converted directly into electrical or mechanical work, plus a part that must appear as heat .The “G” in free energy is in honor of Josiah Willard Gibbs (1839–1903), who first described its usefulness, and the quantity is usually referred to as Gibbs free energy [10]. The chemical reaction is:

$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O_{(\ell)} \qquad (3.6)$$

Where (ℓ) indicate the water in liquid state .

The theoretical voltage value V_{th} of the PEM fuel cell can be determined by the equation (3.7):

$$V_{th} = -\Delta G/nF \tag{3.7}$$

Where

ΔG (Change free Gibbs energy): is the maximum possible amount electrical that a fuel cell can be produced [J/mol].

n : is the number of electrons participation in reaction and in fuel cell is two electrons.

F: is Faradays constant [96485.309 C/mol].

The change in free Gibbs energy is the difference between the electrical energy and heat. In chemical reactions, the difference between the enthalpy (H) of the products and the entropy (S) of the reactants tells us how much energy is released or absorbed in the reaction. The enthalpy of H_2O depends on whether it is liquid water or gaseous water vapor [10] ,as illustrate in table (3.1).

Table (3.1): Enthalpy (H) and entropy (S) at 1atm, 298.15K for selected substances [30] .

Substance	State	H^o (kJ./mol)	S^o (kJ./mol − K)
H	Gas	217.9	0.114
H_2	Gas	0	0.130
O	Gas	247.5	0.161
O_2	Gas	0	0.205
H_2O	Liquid	-285.8	0.0699
H_2O	Gas	-241.8	0.1888

When the result is liquid water the enthalpy is -286J/mol. The equation (3.8) shows the relationship between electrical energy (ΔH) and heat (TΔS) with the change in free Gibbs:

$$\Delta G = \Delta H - T\Delta S \tag{3.8}$$

ΔH: is the change in enthalpy [J/mol].

T: is the temperature at STC [K].

ΔS: is the change in entropy [J/K/mol].

Substituting equation 3.8 in equation 3.7 the value of Vt_h of the PEM fuel cell at STC which is 1.229V .

3.2.1.2 PEM Fuel Cell electrical equation

The theoretical voltage (V_{th}) across the two electrodes is:

$$V_{th}=P/I \tag{3. 9}$$

Where

P: electrical output power delivered [W].

I: output current [A].

The electrical power can be estimated by the following formula:

$$P = W_e \times r \tag{3.10}$$

Where,

W_e: is the maximum electrical output of H_2 at STC [237.2 kJ/mol].

r: the rate of flow H (mol/s) .

The value of current can be estimated by the following formula:

$$I = q \times N \times n \times r \tag{3.11}$$

Where

N: Avogadro's number ($6.022*10^{23}$ molecule/mol).

Substituting the equations (3.10) and (3.11) in equation (3.9) the value of V_{th} of PEM fuel cell at STC which is 1.229 V.

The ideal theoretical voltage V_{th} of PEM fuel cell can be determined by using two methods (thermodynamics and electrical equation), in the two methods the V_{th} is 1.229V as shown in figure (3.2).

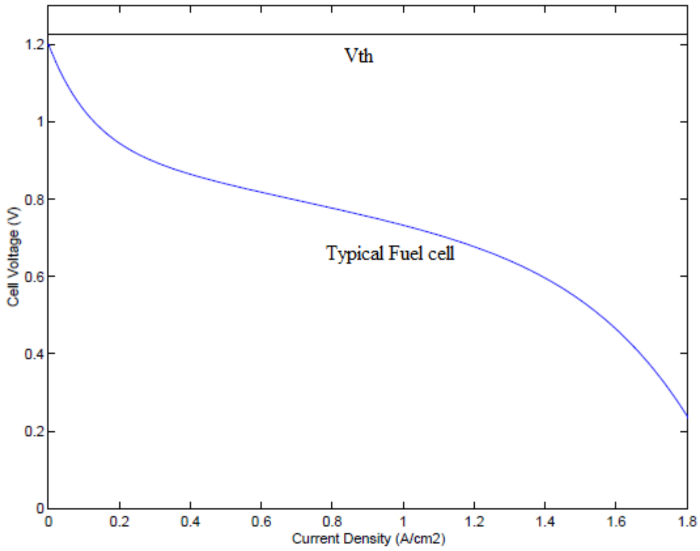


Figure (3.6): The V-I characteristic of PEM fuel cell.

3.2.2 Actual PEM Fuel Cell

The actual fuel cell voltage V_{actual} is lower than the theoretically voltage V_{th} due to various losses .There are three main sources of losses:

1) Activation losses.
2) Ohmic losses.
3) Mass transport losses.

A equivalent circuit for the fuel cell is consisting of a voltage source in series with some internal resistance shown in Figure (3.7).

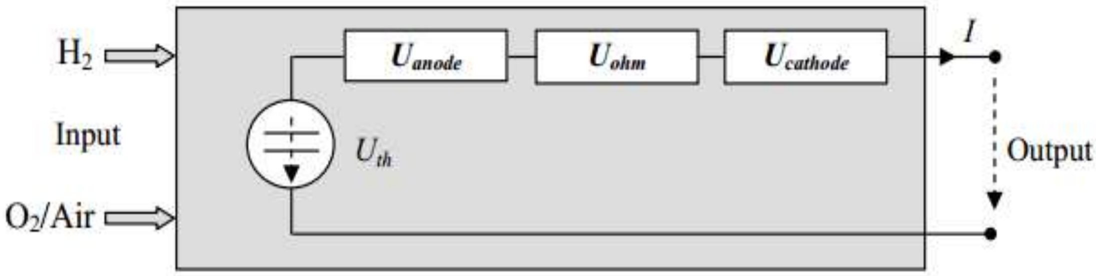


Figure (3.7): An equivalent circuit of the actual PEM fuel cell.

In general actual voltage of PEM fuel cell generates only about 60–70% of the theoretical maximum.

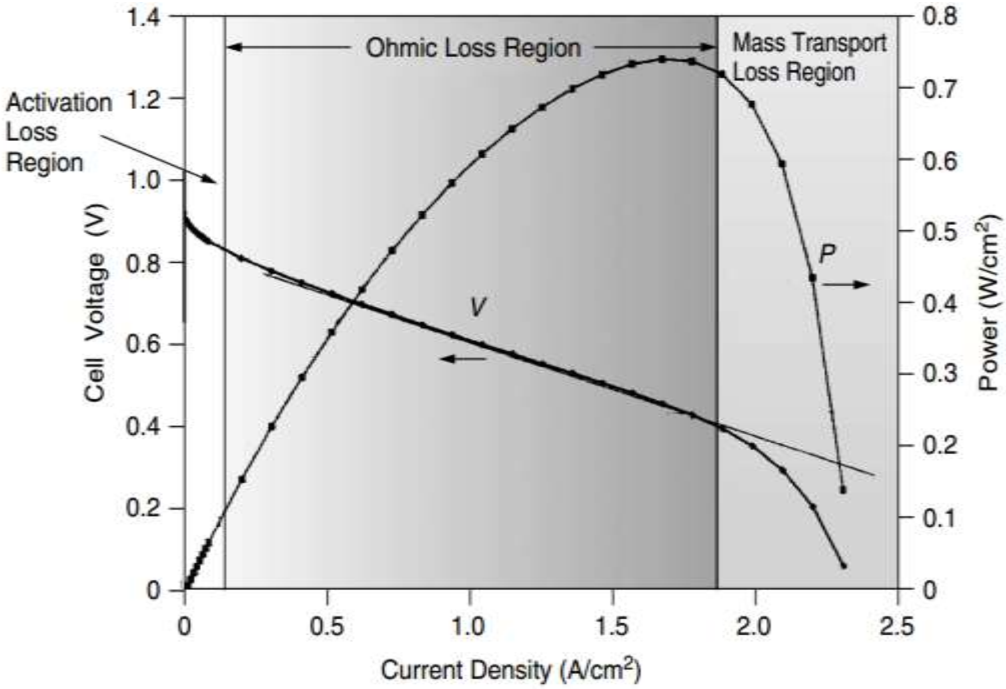


Figure (3.8) : The P-V of the PEM fuel cell[10].

The power at zero current, or at zero voltage, is zero, there must be a point somewhere in between at which power is a maximum. As shown in the figure (3.8), that maximum corresponds to operation of the fuel cell at between 0.4 and 0.5 V per cell .Over most of the length of the fuel cell I –V graph, voltage drops linearly as current increases.

The output voltage of the PEM fuel cells is defined by the equation (3.9) [30]:

$$V_S = N\left(V_{S0} + \frac{RT}{nF}\, In\left\{\frac{P_{H_2}\left(\frac{P_{O_2}}{P_{atd}}\right)^{1/2}}{P_{H_2O_c}}\right\} - L\right)$$

(3.9)

Where

V_S: Stack output voltage [V].

N: Number of cells in stack.

V_{S0}: Cell open circuit voltage at standard pressure [V].

(RT/nF): The Tafel slope, usually in the range from 0.03 to 0.12 V for 24◦C.

R is the universal gas constant, F is Faraday’s constant, T is the operating temperature and n=2 is the number of transferred electrons.

P_{H2}: Partial pressure of hydrogen inside the cell.

P_{O2}: Partial pressure of oxygen inside the cell.

P_{H2Oc}: Partial pressure of gas water.

Pstd: Standard pressure.

L: Voltage losses.

3.2.2.1 Activation losses

Activation losses result from the energy required by the catalysts to initiate the reactions. The relatively slow speed of reactions at the cathode, where oxygen combines with protons and electrons to form water, tends to limit fuel cell power.

The effect activation losses on the V-I characteristics is shown in figure (3.7).

The voltage at zero current, called the open-circuit voltage, is a little less than 1 V, which is about 25% lower than the theoretical value of 1.229 V [10].

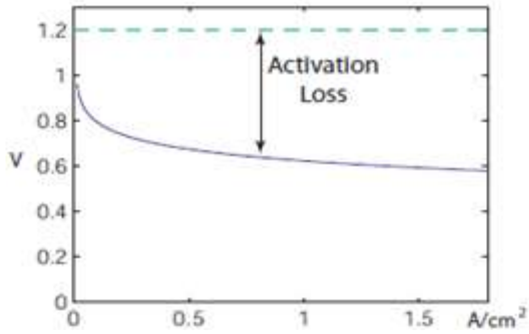


Figure (3.9): The V-I characteristics of PEM Fuel Cell affected by the activation losses.

3.2.2.2 Ohmic losses

Ohmic losses result from current passing through the internal resistance posed by the electrolyte membrane, electrodes, and various interconnections in the cell. Another loss, referred to as fuel crossover, results from fuel passing through the electrolyte without releasing its electrons to the external circuit.

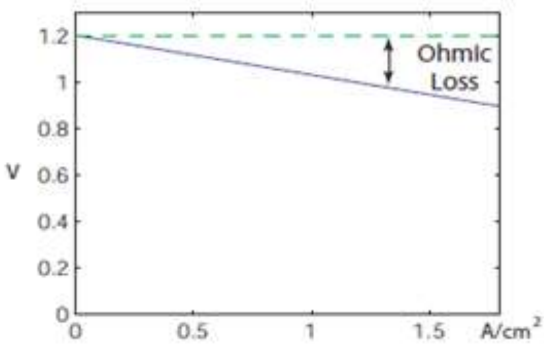


Figure (3. 10): The V-I characteristics of PEM Fuel Cell affected by the ohmic losses.

3.2.2.3 Mass transport losses

Mass transport losses result when hydrogen and oxygen gases have difficulty reaching the electrodes. This is especially true at the cathode if water is allowed to build up, clogging the catalyst.

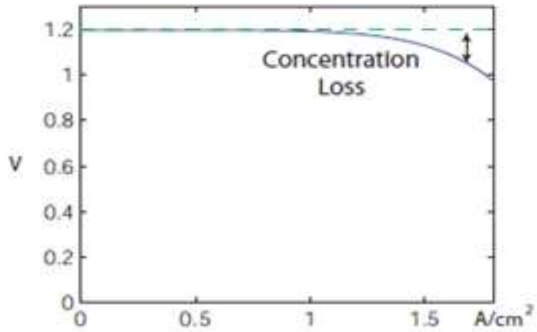


Figure (3.11): The V-I characteristics of PEM Fuel Cell affected by the mass transport losses.

Chapter Four

Experimrntal results and analysis of photovoltaic-hydrogen fuel cell system

4. Experimrntal results and analysis of photovoltaic-hydroge fuel cell system

In this chapter, the evaluation of the system components (photovoltaic, electrolyzer, fuel cell) was performed, the efficiency of each component was measured .Practical experiments on the characteristics and performance of the system components was carried out under the variable load.

For the purpose of this study, a lab unit (PEMFC) produced by HELEX company," Solar and Hydrogen Fuel Cell Trainer " illustrated in figure (4.1) is used. The unit will be exposed to experiment tests to present the function of the system.

Figure (4.1): The Emona HELEX adds in module.

4.1 Basic Specifications of the Photovoltaic Panel

The panel output is a DC voltage when illuminated by either sun or lamp.

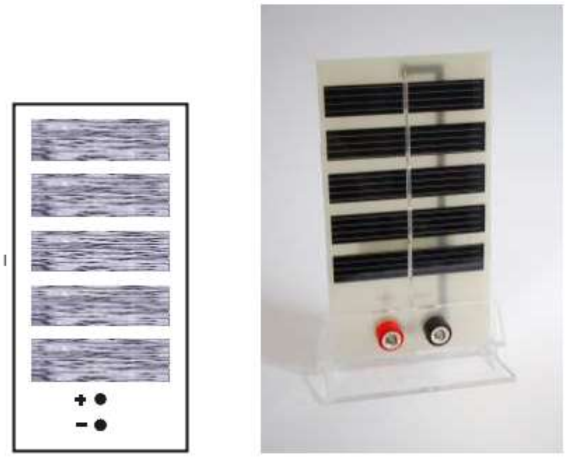


Figure (4.2): Photovoltaic Panel.

Each PV panel includes 5 silicon cells, connected in series as shown in figure (4.2).The specification of PV Panel used in experiment is illustrated in table (4.1).

Table (4. 1): Photovoltaic Panel Specifications

Number of Cells Per Module	5 silicon cells, series
Voltage at Maximum Power point	2.4V DC
Current at Maximum Power point	200mA DC
Power Output	0.48W
Cell Area	37.2cm²(12*62*5)
Open Voltage circuit	2.8V at 1000W/m²
Short Current Circuit	250mA at 1000W/m²

4.2 The I-V Characteristics

In order to measure the (I-V) and (P-V) characteristics of the used photovoltaic panel, a variable load was connected to the PV panel as illustrated in figure (4.3). The solar radiation intensity on the surface of the PV module was measured to 580 W/m^2. The obtained results are illustrated in table (4.1).

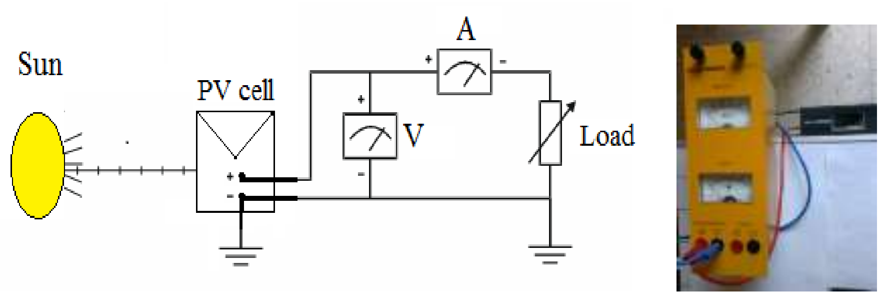


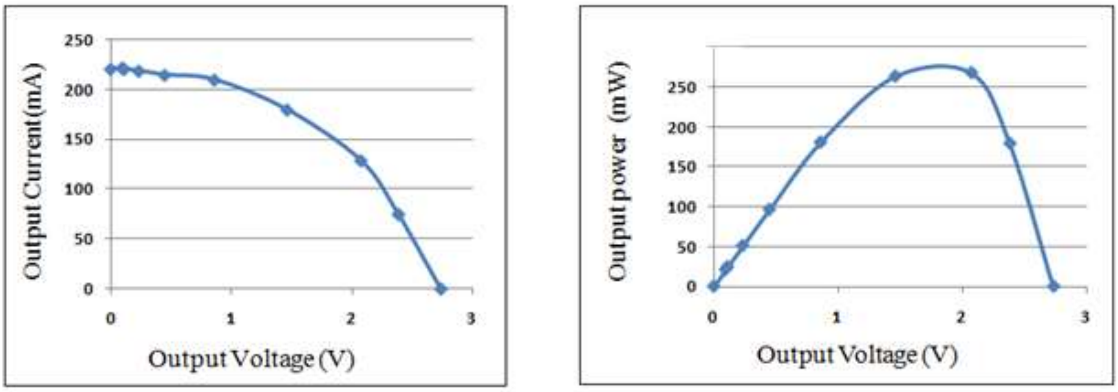
Figure (4.3): Measuring circuit for determination of the I-V and P-V characteristics of a PV module.

From the measured data in table (4.2) the Vmpp is equal 2.073V and Impp is equal 129mA and the maximum power point (MPP) is 267.4mW under the condition 580W/m^2 and the room temperature amounting to27 °C.

Table (4.2): Measured data for PV CELL (G=580W/m^2)

Load (Ω)	**voltage (V)**	**Current (mA)**	**Power (mW)**
Open circuit	2.736	0	0
32	2.384	75	178.8
16	2.073	129	267.417
8	1.461	180	262.98
4	0.859	210	180.39
2	0.447	215	96.105
1	0.233	219	51.027
0.5	0.111	221	24.531
0.25	0.095	222	21.09
Short circuit	0	221	0

Figure (4.4.a) illustrates the (I-V) characteristics of photovoltaic cell and the (P-V) of photovoltaic as shown in figure (4.4.b), the (I-V) and (V-P) depending on the measured data.



(a) The (I-V) Characteristics **(b) The (P-V) characteristics**

Figure (4.4): Characteristics of photovoltaic module at ($G=580W/m^2$).

4.3 Hydrogen Production

With reference to the thermodynamics data the amount of hydrogen can be obtained from decomposition water under standard temperature pressure (STP: 0 °C, 1 atm, and 22400 ml). For hydrogen one mol occupies (22400 ml) . As in our system, the volume of hydrogen is (10ml).

So, 10 mol H_2 = (10/22400 moles of H_2) =0.00045 moles of H2.

One mole of water occupies 18 ml, from the equation ($2H_2O_{(l)} \dashrightarrow O_{2(g)} + 2H_{2\,(g)}$) that once as much H_2O is needed to create the amount of H_2,

So 0.00045 moles of H_2O needed to create the 10 ml of H_2 =0.00045 mol H_2,

And 0.00045 mol H_2O ×18 ml=0.0081 ml of H2.So,10 ml $H_{2\,(g)}$ =0.0081 of $H_2O_{(l)}$.

Therefore, the volumetric ratio of $H_{2\,(g)} : H_2O_{(l)}$ is 1234 :1.

4.3.1 Basic Specification of Electrolyzer

The type of elctrolyzer used in experiment is Polymer Electrolyte Membrane (PEM), the specification is shown in table (4.3).

Table (4.3): PEM Electrolyzer Specifications.

Power Consumption	800mW
Required Voltage	1.4 to 1.8V DC
Maximum Current	0.5A DC
Rate of Hydrogen Production	3ml/h (at 0.5A)
Consumption of Distilled Water	0.1ml/h (at 0.3A)
Maximum Storage Capcity	10ml H_2 and 10ml O_2

4.3.2 The Efficiency of Electrolyzer

The method used in this thesis to produce hydrogen is electrolysis of water. The type of the used electrolyzer is proton exchange membrane (PEM). This PEM is covered from both sides with catalyst material on either as shown in figure (4.5).

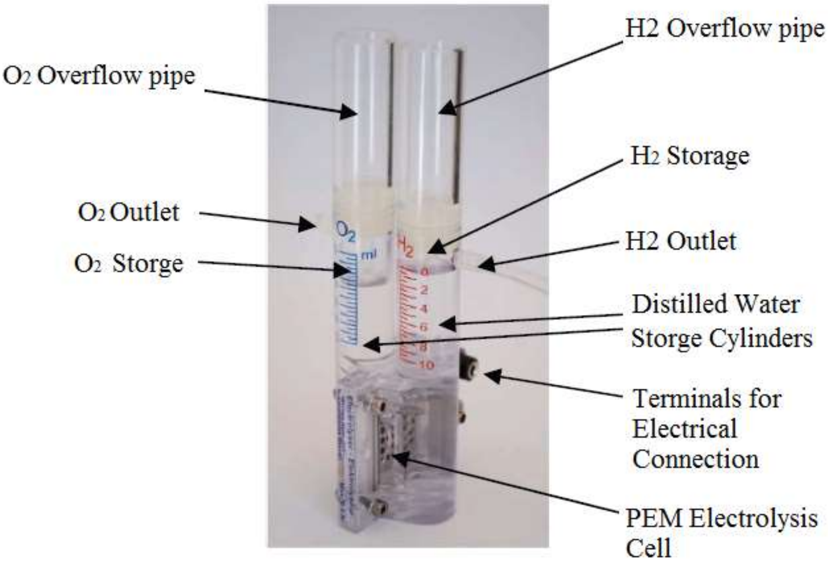


Figure (4.5): The PEM electrolyzer used in the experiments to produce H2 and O2.

The chemical reaction at the anode and cathode is as follows: At the anode, the water decomposed into positively charged hydrogen ions (H+) and Oxygen. The electrons are produced at the anode by this oxidation reaction:

$$2H_2O_{(\ell)} \longrightarrow O_{2(g)} + 4H^+_{(aq)} + 4e^-$$

(ℓ, g and aq are liquid, gas and aqueous)

At the cathode, addition of 4e to hydrogen in aqueous state is produces hydrogen gas. Four electrons with four ions of H2 are required to produce two moles of hydrogen gas:

$$4H^{+}_{(aq)} + 4e^{-} \longrightarrow 2H_{2(g)}$$

The chemical overall equation for the electrolyzer is transfer of 4 electrons through the circuit, two molecules of hydrogen gas are created and one molecule of oxygen gas is created as previously illustrated in figure (2.13):

$$2H_2O_{(l)} + 4e^{-} \longrightarrow O_{2(g)} + 2H_{2(g)}$$

The theoretical decomposition voltage for electrolyzer is 1.23V but the actual voltage value is higher due to the following reasons:

1- Electrode material.

2- Texture of electrode surface.

3- Type and concentration of electrolyte.

4- Current density and temperature.

The difference between theoretical and actual voltage is called over voltage and must be made as low as possible.

A current source was used to supply the PEM electrolyzer for studying of its performance and characteristics. The circuit of experiment is shown in figure (4.6).

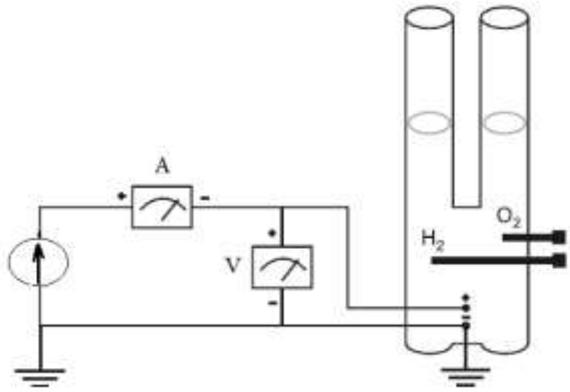


Figure (4.6): Current source supplying the electrolyzer .

The efficiency of the electrolyzer can be determined by:

$$\eta_e = E_H / E_{el} \qquad (4.1)$$

Where

η_e : Efficiency of the elctrolyzer.

E_H : Energy content of the hydrogen generated .

E_{el}: Electrical energy used to produce that hydrogen.

The energy content of H_2 at normal temperature pressure NTP (NTP: 25 °C, 1 atm, and 22400 ml) and a volume of 22400 ml is equivalent to 286 kJ. In this case where 10 ml H_2 was produced the energy content is 119 J. The electrical energy can be calculated as follows:

$$E_{el} = V \times I \times t \qquad (4.2)$$

Where,

V: Terminal voltage of the current source.

I: Current supplied to electrolyzer.

t: Time needed to produce 10 ml of hydrogen gas.

The values of V, I and t where measured. The measuring results with the respective calculated values of E_{el} and η_e are illustrated in table (4.4).

Table (4.4): Measuring results of V,I,t, E_{el} and η_e for production (10 ml H2 $\longrightarrow$ E_H = 119J).

No.Test	Time (s)	Current (mA)	Voltage (V)	Eel J (W.s)	efficiency (%)
1	306	247	1.77	133.78	88.9
2	310	247	1.76	134.76	88.3
3	324	248	1.83	147.04	80.9
4	309	248	1.75	134.11	88.7
Average	312.3	247.5	1.77	**137.42**	**86.7**

The measured average value of electrical energy to produce 10 ml H2 is 137.42 W.s, which results an efficiency of electrolyzer amounting to 86.7%.

To determine the I-V Characteristics of the electrolyzer an adjustable voltage source, was used .The voltage was increased from 1.2V at an increment of 0.05 V each 20 seconds .At end the corresponding current of the electrolyzer was measured as illustrated in table (4.5).

Table (4.5): PEM Electrolyzer performance.

Voltage at PEMEZ(V)	Current into PEMEZ(mA)
1.2	0
1.25	0
1.3	0
1.35	0
1.4	0
1.45	4
1.5	24
1.52	70
1.55	94
1.6	120

It should be mentioned that the hydrogen bubbles started forming at V=1.45V. The measuring circuit for determining the I-V characteristics is shown in figure (4.7).

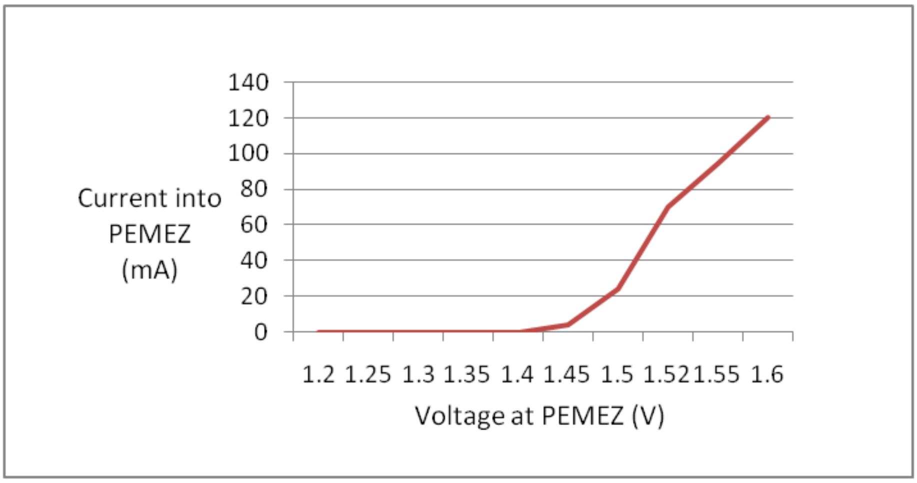


Figure (4.7): I-V characteristics of the PEM elctrolyzer.

The I-V characteristics of PEM electrolyzer is shown in figure (4.7). The current increases exponentially with voltage increasing. The voltage must be kept less than 1.8 V otherwise the electrolyzer will be destroyed as indicated in the datasheet.

4.4 The Voltage-Load Characteristics of Fuel Cell

The type of fuel cell utilized in this thesis proton exchange membrane fuel cell (PEMFC).The basic specifications is shown in table (4.6).

Table (4.6): PEM Fuel Cell Specification

Type	Polymer Electrolyte Membrane (PEM) Hydrogen
Membrane	Catalyst Material 0.4 mg/cm2 Pt
Rate of Hydrogen Consumption	7ml/min (at 1.0 A DC)
Voltage Output	0.4 to 1.0V DC
Output Power	0.5W
Input Terminals	2*Oxygen tube terminals 2*Hydrogen tube terminals

The PEMFC consists of electrolyte between two electrodes, inlets and outlets for H2 and O2 as well as electrical terminals for connecting of the load as illustrated in figure (4.8).

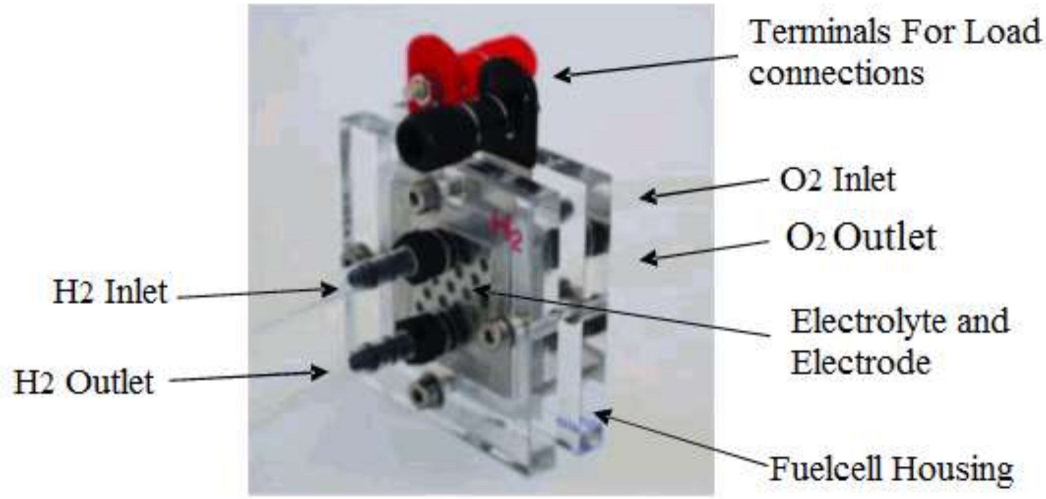


Figure (4.8): The PEM Fuel Cell**.**

The maximum theoretical output voltage of fuel cell which is a result of reaction between H_2 and O_2 is 1.23V.This value is obtained as discussed in chapter three. This theoretical voltage isn't reachable because the various losses happen during in practical actual application.

The decrease of these losses can be achieved by:

1- Improvement the catalyst materials.

2- Used high conductive materials.

3- Optimized electrodes structure.

The connection of the experiment equipment for measuring the characteristics of the PEM fuel cell is shown in figure (4.9).

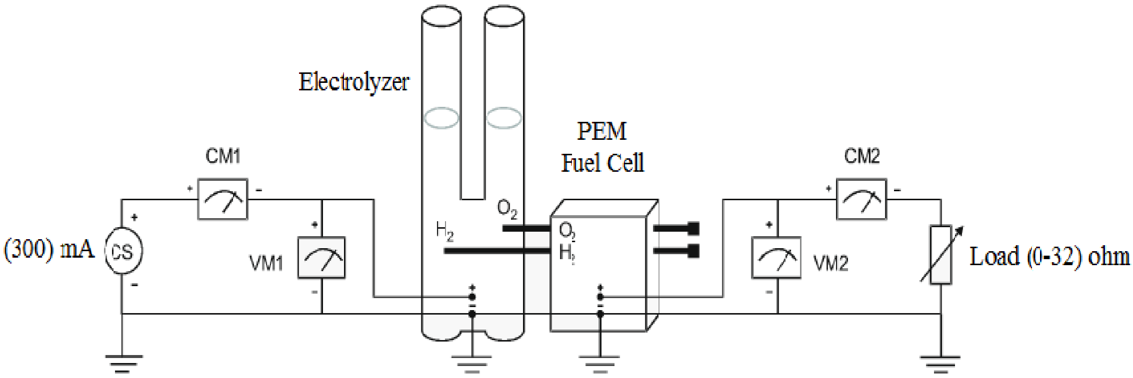


Figure (4.9): (PEM) Fuel Cell connection with the electrolyzer , load and measuring devices

Both sides of elcetrolyzer are filled with distillated water and connected to the current source. When the hydrogen gas is formed and the stored capacity is 10 ml the current source must should be switched off. At this time started the experiment for the characteristics of the PEM fuel cell, changing the value of the load and record the values voltage and current for the PEM fuel cell .All thisvalues are shown in table (4.7).

Table (4.7): The output current and voltage of PEM fuel cell at different loads.

Load (ohm)	**current (mA)**	**voltage (V)**
open circuit	0	0.825
32	23	0.752
16	44	0.724
8	82	0.683
4	148	0.631
2	245	0.556
1	360	0.457
0.5	512	0.346
0.25	631	0.239

The shape of the obtained experimental (V-I) of the PEMFC is shown in figure (4.10) and the maximum voltage of the PEMFC is less than theoretical voltage 1.23 , which is correct due to the mentioned losses .

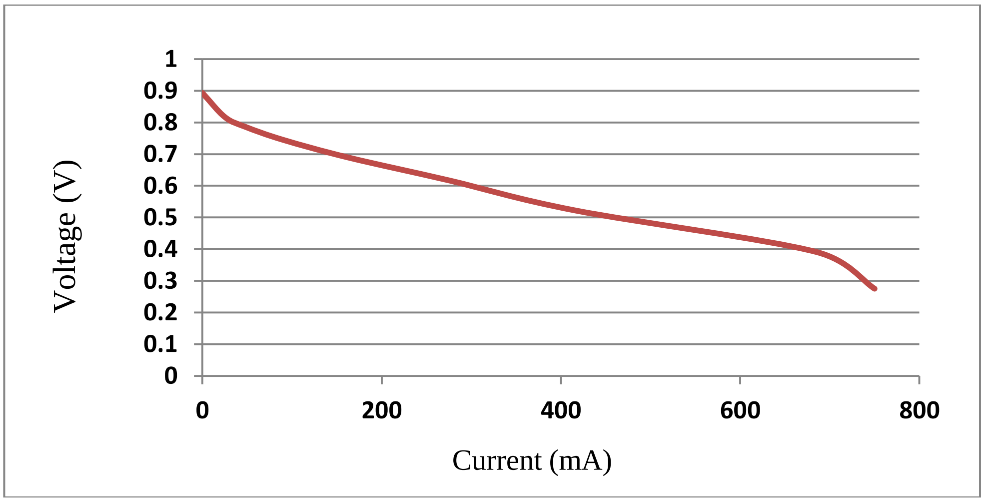


Figure (4.10): The (V-I) characteristics of PEMFC.

The PEMFC maximum output power is achieved between (0.25 and 2) ohm and this shown in figure (4.11) .The maximum power point drops after the fuel cell has consumed the remaining gas within its casing. The rate of consumption of gases is not constant and is affected by the power delivered to the load. The output power would drop when prevent the gas flow into device.

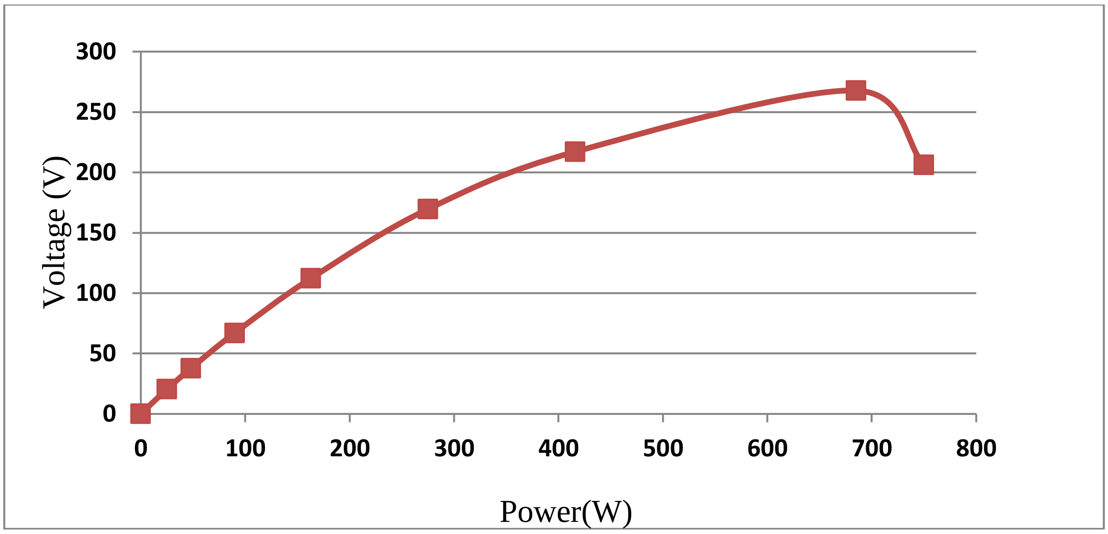


Figure (4.11): The relationship between the output power of PEMFC and voltage through variation of the load.

$$\eta_{fc} = E_{el} / E_H \tag{4.3}$$

Where

η_{fc}: Efficiency of the PEM fuel cell.

E_{el} : Electrical energy generated from the PEM fuel cell (Power*time).

E_H : Energy content of the hydrogen .

The electrical energy output delivered to the load from the PEMFC is equal (47J) and from the experiment the hydrogen is 10 ml ,so the energy contained in it is equal (119J). Therefore the efficiency of the PEM fuel cell is 39.5%.

4.5 Practical Connection of Fuel Cells

Fuel cells can be connected series or parallel to increase the output power, where multiple of identical fuel cells are packaged together is known as stack.

To produce a higher output voltage from fuel cells there is one way, the fuel cells have to be connected in series and the experiment circuit is shown in figure (4.12).

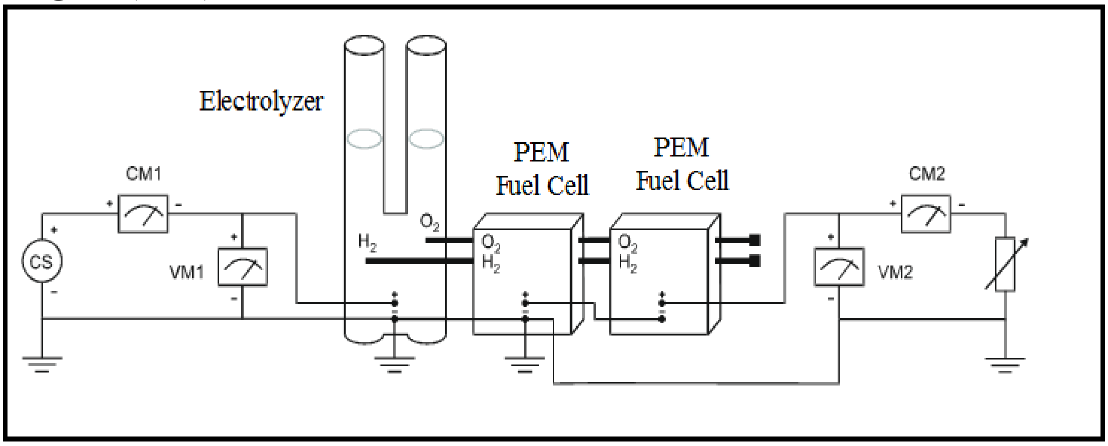


Figure (4.12): Two PEM Fuel Cell connected in series.

Both fuel cells are connected in series and supplied with hydrogen and oxygen from the electrlyzer. The electrical terminals of fuel cells are connected in series.

To produce a higher output current from fuel cells, they must be connected in parallel.The experiment circuit is shown in figure (4.13) and the inlets and outlets for gases are the same connections as in series but the connection of the electrical terminals of the fuel cells is parallel through diodes .Using diodes is very important because the current would flow from the fuel cell output with higher output voltage value into the fuel cell with the lower output voltage ,this current flow in fuel cell must be avoid otherwise the fuel cell will be destroyed.

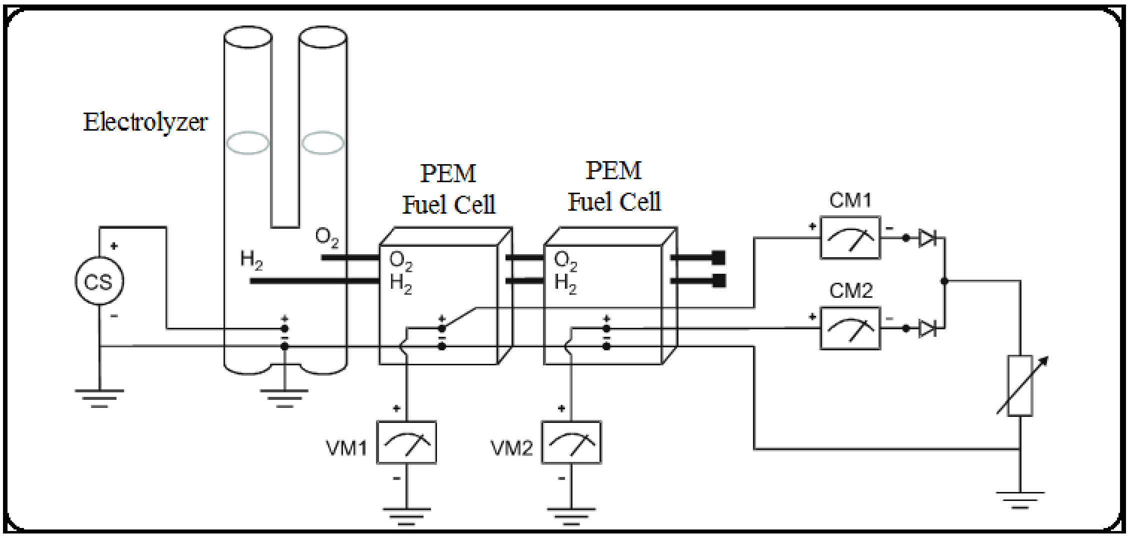


Figure (4.13): Two PEM Fuel Cell are connected in parallel.

Both fuel cells are connected in parallel and supplied with hydrogen and oxygen from the electrlyzer. The electrical terminals of the fuel cells are connected in parallel. The current readings from the output of the fuel cells are about double than one fuel cell.

Chapter Five

Sizing photovoltaic module and fuel cell stack

5. Sizing photovoltaic modul and fuel cell stack

This chapter focuses on sizing of the PV array and the PEM fuel cell depending on the load and solar radiation.

5.1 Electrical Appliances at Health Clinics

The energy demands of a health clinic and the climate condition will be critical factors in the selection of the most appropriate renewable electrification technology. The electrical devices used in rural health clinics are listed here after:

1- Vaccine Refrigeration, vaccines are stored for up to one month and require a stable temperature between 0°C and 8°C, Once the vaccines have been exposed to temperatures outside this range, potency is forever lost[15].

2- Lighting, electric light greatly improves emergency treatment, birthing, maternity care, surgery, administrative tasks, and other medical functions.

3- Blood Chemical Analyzer, it's a medical device that analyses blood sample by count the cell number (red blood cells, white blood cells and platelets) and Hemoglobin concentration. This device consists from diaphragm pump, photo cell, suction and aperture.

4- Sterilization, Sterilization requires rather high temperatures, approximately 120°C.

5- A microscope apparatus and a microscopic method that uses the microscope apparatus for examining a sample or a specimen, such as but not limited to a tissue sample or a tissue specimen.

6- A centrifuge is a piece of clinics equipment, generally driven by an electric motor that puts an object in rotation around a fixed axis, applying a force perpendicular to the axis. It’s used to separate of blood samples according to density of the components from each other. [33].

7- Blood chemistry analyzer, used to measure the concentration of some solute materials in blood such as blood sugar concentration and urea concentration.

This device needs AC voltage to for its operation.

Table (5.1) shows the common equipment types used in rural health clinics including typical power ratings. The time of day power needed and the peak power demand have an impact on the sizing of equipment [32].

Table (5. 1) :Electrical loads of the small health clinics

Equipment	**Quantity**	**Power (W)**	**Time (Hours**	**Total Energ**
Refrigerator-Vaccine	1	60	10	0.6
Refrigerator-Non-med	1	300	5	1.5
Centrifuge	2	242	4	1.94
Microscope	2	20	6	0.24
Blood Chemical Analyzer	1	88	4	0.35
Hematology Analyzer	1	230	4	0.92
Small electrical application (Radio +Mobile charger)	1	230	2	0.46
Tube -Fluorescent	4	40	8	1.28
Desktop Computer	1	230	4	0.92
Total				**8.2**

5.2 System Sizing of Small Clinics Electrification

The photovoltaic generator produces power, when solar radiation is sufficient, for electric power demands different loads while the excess power will be stored and partially used for hydrogen production. When solar radiation is absent, the fuel cell will provide the necessary power .In this thesis, the load profile of a rural clinic and the average daily solar radiation in Palestine are considered in the system design.

5.2.1 Load Demand

A typical daily load curve for a small clinic is given in figure (5.1). The maximum consumed power during a day is 670W and energy consumption is 8.2kWh/day.

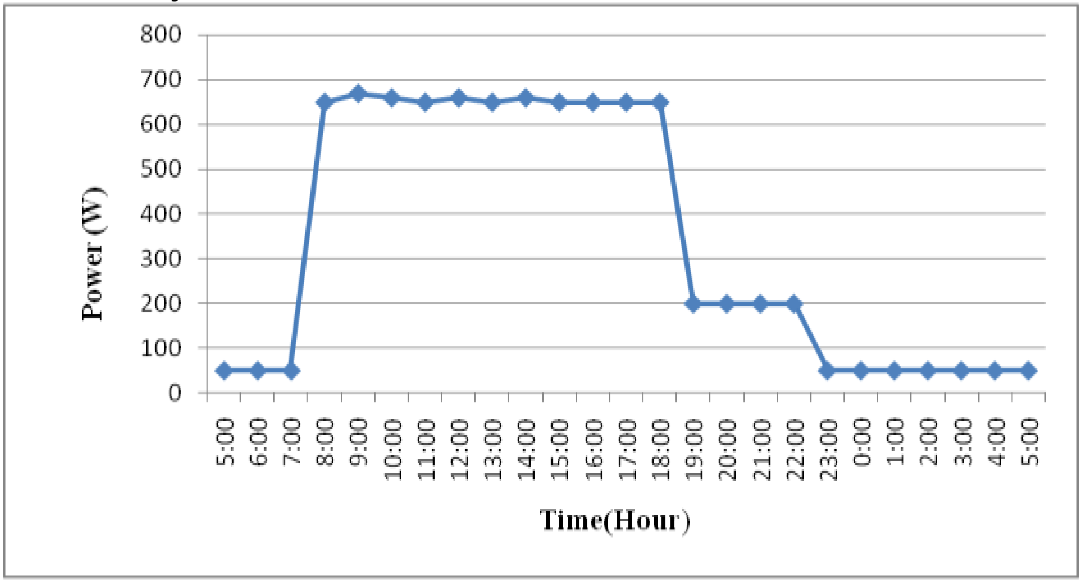


Figure (5.1): Daily load curve of small clinics**.**

5.2.2 Solar radiation

The geographical location of Palestine is within a considerably high solar belt represented in 5-6 kWh/m^2 –day. The daily average of solar radiation in Palestine amount to 5.4 kWh/m^2 –day .

5.2.3 Sizing the PV generator

The important parameters for system sizing are the average daily solar radiation energy and the load consumption. These parameters can be used to calculate the peak power of the PV generator.

The size of PV generator can be determined by the equation (5.1):

Area of PV=Ed / [ASR* η_{pv} *η_{ch} *η_{IN} *η_{el}*η_{fc}]

Ed: daily energy consumption.

ASR: average daily solar radiation.

η_{pv} :efficiency of photovoltaic.

η_{ch}: efficiency of charger controller.

η_{IN}: efficiency of Inverter.

η_{el}: efficiency of electrolyzer.

η_{fc}: efficiency of PEM fuel cell.

5.2.4 Sizing of the PEM Fuel Cell

The PEM fuel cell supply is required when there is not enough solar radiation and in the night. Fuel cells use hydrogen as fuel under normal temperature conditions. Its power can be calculated according to the maximum load required.

5.2.5 Sizing an Electrolyser

The rated power of the electrolyzers can be calculated by the equation (5.3):

$$P_{el} = P_{PV} - P_{L,min} \quad (5.3)$$

P_{el} : rated power of the electrolyzer.

P_{PV}: output power of PV modules.

$P_{L,min}$: minimum of the clinic load .

5.3 Case study

A typical solar radiation pattern is for one average day at southern Palestinian villages shown in Figure (5.2) [34]. The solar radiation is obtained for 24 hour on 24/4/2012, and the solar radiation average in this daylight (6:30 AM to 19:30 PM) is 0.538 kW/m².

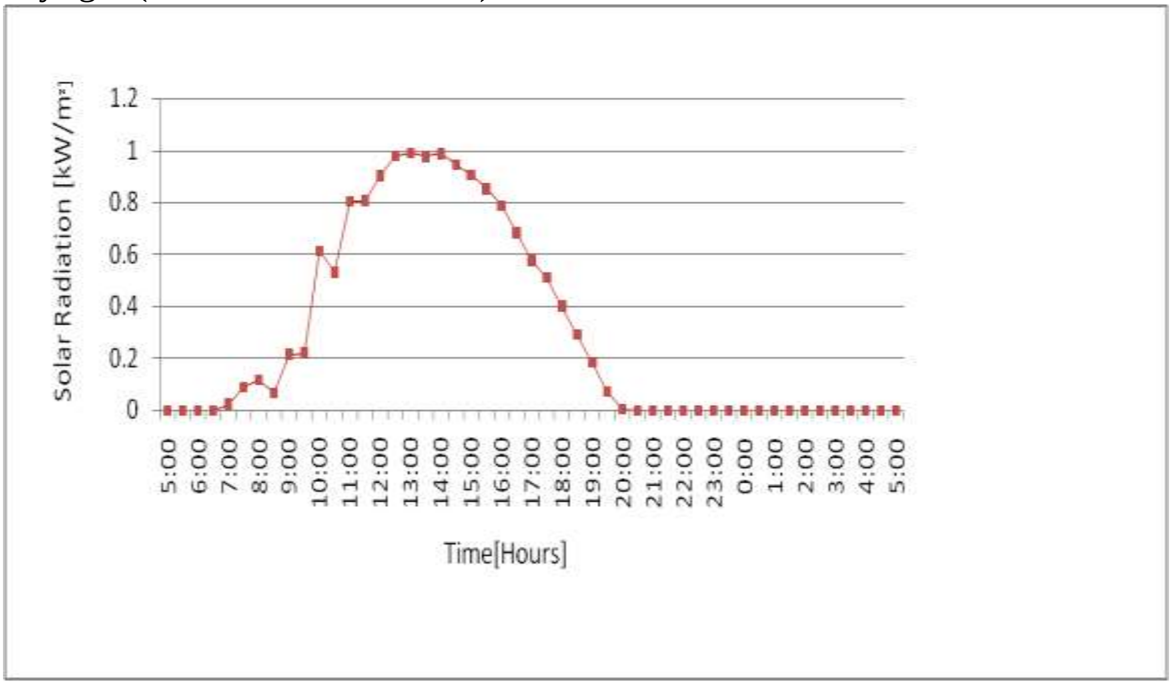


Figure (5. 2): Solar radiation pattern obtained on 24/4/2012.

The day is classified into three periods for operating the system:

1- Morning (5:00 AM – 8:30 AM): in this period of day the sun rise and the solar radiation will increase slowly so the fuel cell will provide the needed low power demand.

2- (8:30 AM – 6:30 PM): during this period the solar radiation will increase to reach its maximum values. Thus the power output from the PV generator can meet the load demand until the solar radiation decreases the sunset. During this period the Fuel cell still shutdown.

3- During the time (6:30 PM – 5:00 AM): where no sunlight exists, the PV power output is zero. The fuel cell must give the required power to meet the load demands.

5.3.1 Power management strategy

The main aim for the applied Power Management Strategy (PMS) in the adopted system is to satisfy the load requirements of the clinic use. The operation of the fuel cell should satisfy the load pattern requirements in terms of duration and power level for the various operation times.

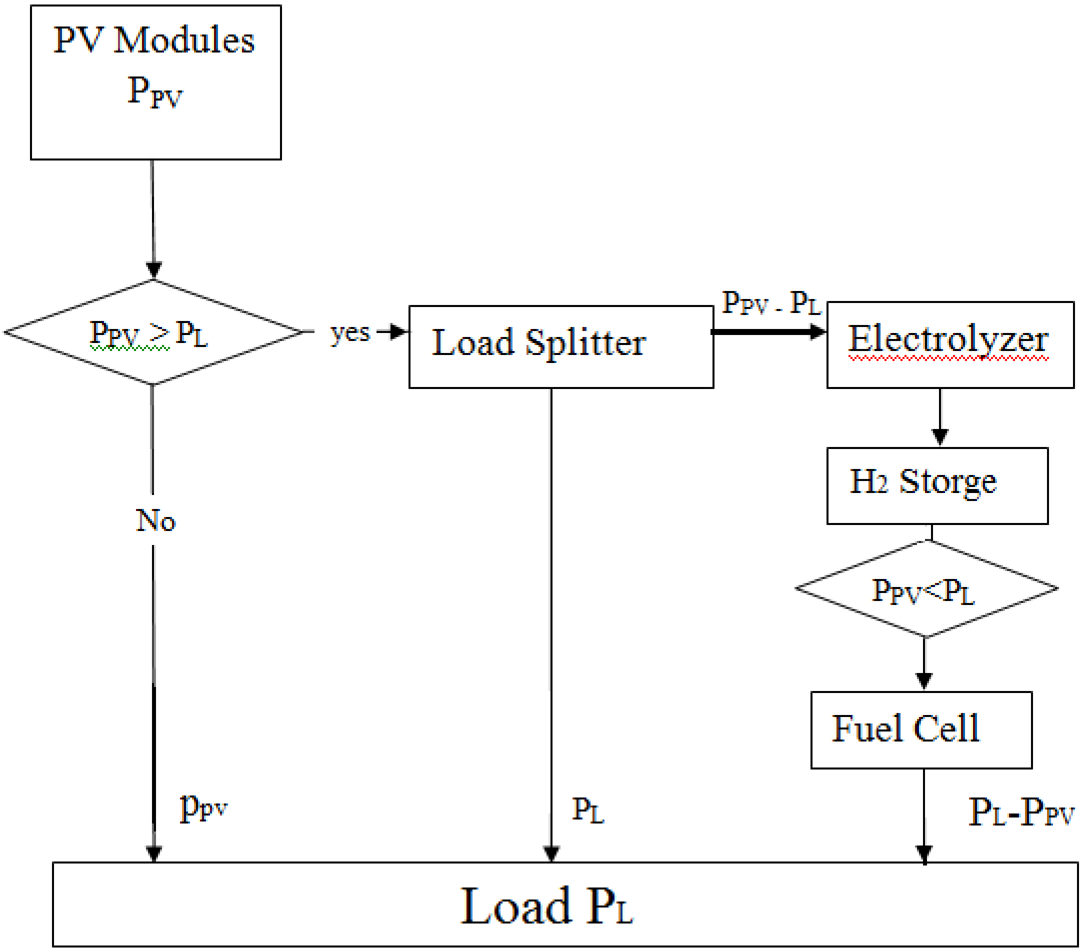


Figure (5.3): Logical block diagram for PMS.

The adopted PMS is must be built to provide the operating modes under variable weather conditions to ensure the satisfaction of the power requirements. The logical block diagram for PMS is shown in Figure (5.3). It is built on the bases of power sources states and load demand pattern with the priority given to solar energy supply, thus if power difference between solar and load P < 0, based on instantaneous power supply, then the necessary power to satisfy the load is provided by the fuel cell. The PV modules provides the necessary power to meet the total load demand, and the excess power from the PV modules will provides the electrolyzer to produce the hydrogen .

To determine the size of the PV modules during the day is divided into two periods, the first period is the period of solar radiation sufficient to provide the load demand. The following illustrate calculate the size of the solar generator required in this period:

The energy consumed in this period is 7150kWh, The area of photovoltaic needed to supply the clinic load is about 11.6 m^2 and using Mono-crystalline with module area 1.67m^2 , and the number of modules to installation is 7 module, as illustrated in table (5.2).

Table (5.2): Specification of PV module

Parameter	Nominal Value
Peak Power (W)	250
Maximum Power Point Voltage(V)	48.5
Maximum Power Point Current(A)	5.15
Open Circuit Voltage (V)	58.1
Short Circuit Current(A)	5.58
Size of Module (mm)	1580*1058*46

Figure (5.3) shows the output power of the 7 PV modules and the load demand.

Table (5. 3): The size of the PV modules during the period of solar radiation.

Ed (kWh)	ASR (kWh/m^2)	η_{pv}(%)	η_{ch}(%)	η_{IN}(%)	Area of PV(m^2)	No. module
6950	5400	14.5	90	85	11.6	6.94

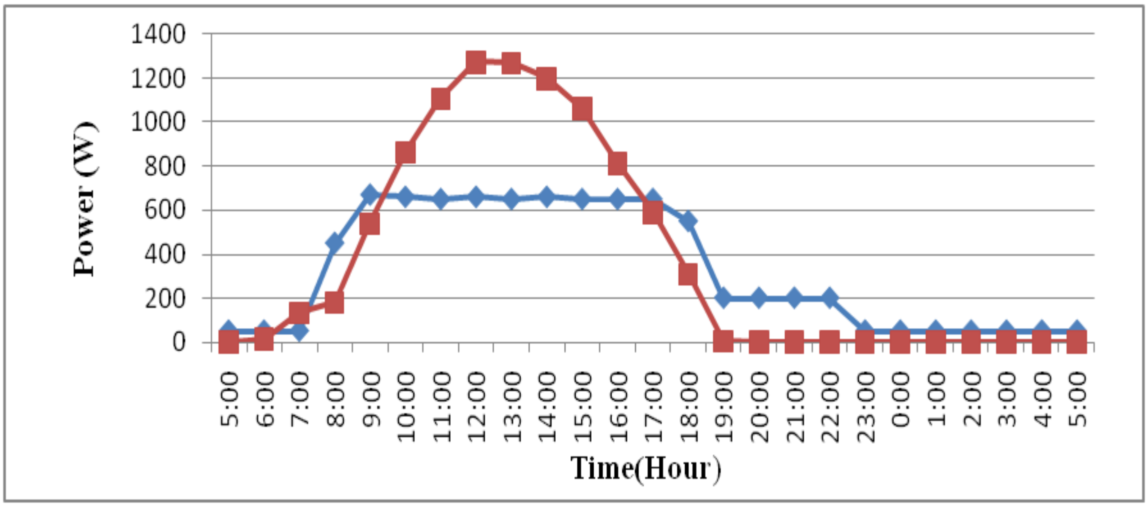


Figure (5.4): The load demand and the output power of the PVgenerator.

Figure (5. 5): The demand load after provides of PV modules.

The exceeded energy of PV modules in the first period is 1.166 kWh, which used in the second period and the output energy of fuel cell is 0.460 kWh. The second period the fuel cell provides the demand load which is 1.920 kWh, and the maximum consumption is about 270W ,the size PEM fuel cell is P_{fc}=300W. This mean the rated power of fuel cell is 300W.

Stack electrical efficiency for commercial fuel cell is about 40%, nominal power is 300 W and operating temperature of fuel cell is 30°C performances as given in Table (5.2).

Table (5.4): PEM Fuel Cell Specifications

Parameter	Nominal Value
Nominal Stack Power (W)	300
Nominal Stack Voltage(V)	43
Nominal Stack Current(A)	7.2
Nominal Stack Efficiency (%)	40
Number of cells	42

To determine the size of the PV generator must take into account the efficiency of electrolyzer and the efficiency of the PEM fuel cell. The area of photovoltaic needed to supply the clinic load is about 7.16 m^2 and using Mono-crystalline with module area 1.67m^2 , and the number of modules to installation is 4 module, as illustrated in table (5.5).The figure (5.3) shows the output power of the 4 PV modules and the demand load .

Table (5.5): Parameter of sizing PV modules with PEM fuel cell.

Ed (kWh)	ASR (kWh/m^2)	η_{pv} (%)	η_{ch} (%)	η_{IN} (%)	η_{el} (%)	η_{fc} (%)	Area of PV(m^2)	No. module
1460	5400	14.5	90	85	85	40	7.16	4.29

The volume of hydrogen production during the day 24/4 is shown in figure (5.5).

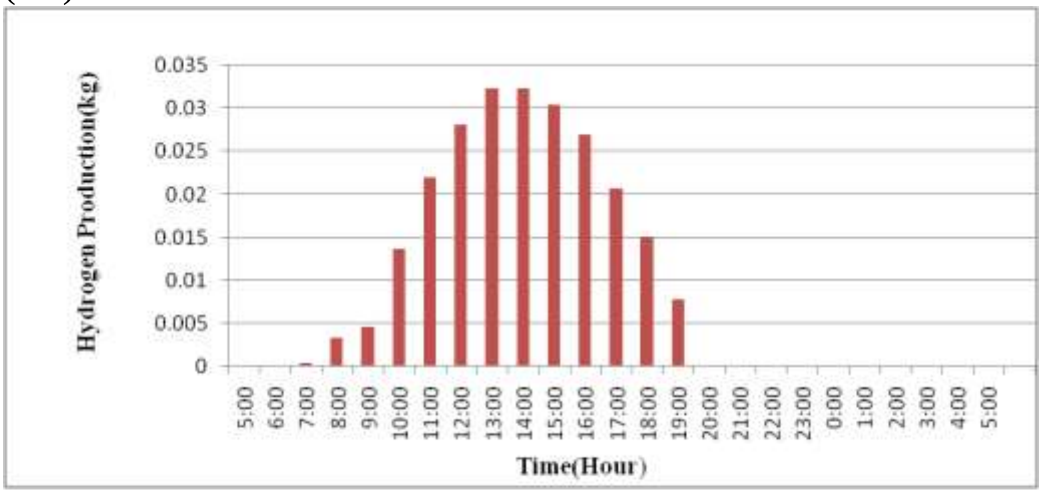


Figure (5. 6): The volume of Hydrogen production.

The total necessary PV modules amount 11.3 modules there for we use 12 modules with following connections to produce a nominal DC voltage of 48V for supplying of the electrolyzer and electrical appliance in the small clinics.

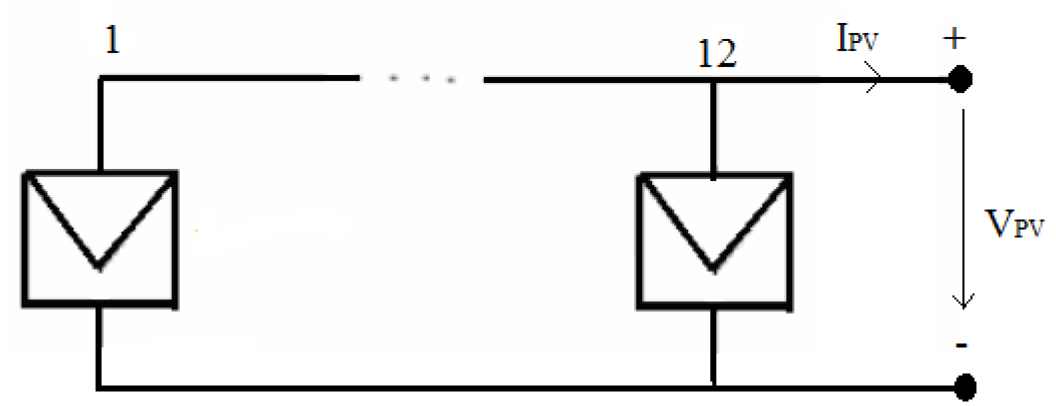


Figure (5. 7): Connection of the PV modules to build the PV generator

The above PV generator figure (5.7) has an open circuit voltage and short circuit 58V and 5.58A which correspond to a peak power of 3kW.

5.4 Cost Comparison between Fuel Cell and Battery

The capacity of the battery can be determined by the equation (5.):

C_{AH}=Ed/ [DOD* η_B*V_B] (5.)

C_{AH}: Ampere hour capacity.

DOD: Depth of discharge.

η_B: efficiency of battery.

V_B: voltage of battery.

The C_{AH} for one day needed to supply the load 8.2kWh is 804Ah, for two days C_{AH} must be doubled (1608Ah) .The number of batteries is 24

(2V/100Ah) where each two batteries have to be connected in series to deliver 24V at the output of the storage system.

The specification of the fuel cell is illustrated in table (5.6).

Table (5. 6): Specifications of PEM fuel cell.

Parameter	Nominal Value
Nominal Stack Power (kW)	1.26
Nominal Stack Voltage(V)	24.3
Nominal Stack Current(A)	52
Nominal Stack Efficiency (%)	46
Cost($)	4500

In table (5.7) illustrated the prices the component for each system

Table (5. 7): Comparison of the total cost between two systems.

	Cost system with Battery($)	Cost system used Fuel cell ($)
Photovoltaic	1575	3500
Battery	13440	-
Electrolyzer	-	1000
Fuel cell	-	4500
Total	15015	9000

In the table (5.7) the cost of using fuel cell is less storage battery, the difference of the costs of the two designs is 6015 $.The system depending on battery has higher cost storage for long intervals is required .The system of fuel cell can store energy for long time at lower cost since storage of produced hydrogen is in tank.

Chapter Six

Conclusion and Future work

6. Conclusion and future work

6.1 Conclusion and Recommendation

Main purpose of this thesis is to investigate electrification of health clinics far from the electric grid, by environment friendly system consisting of photovoltaic generators and fuel cells. The advantages of this system in comparison of using storage batteries are represented in the lower cost and in protection the environment. Clinics need electrical power throughout the day without a break because they contain vaccines and this system supplies electricity to the clinic load daytime and night without interruption.

During the process of the fuel cell experiments show that it should be supplied with hydrogen for three minutes before taking readings because membrane initially need to stimulate the production of electricity and in order that the fuel cell operates at nominal efficiency. Distilled water should be used in the electrolyzer where the membrane is put in the process of separating water into hydrogen and oxygen. Non- distilled water leads to the destruction of the membrane of the electrolyzer.

In this system the electrolyzer to produce hydrogen consumes a part of electrical energy generated from PV, and can be dispensed with using other elements. Fortunately, hydrogen can be generated from bio-waste material available locally using economic technologies.

6.2 Future Work

This thesis establishes a new direction for research in Palestine related to Fuel cell and PV systems. Studies that can be carried out in the future are summarized in the following:

1- Management process control of pressure and flow of hydrogen gas through the electrical and mechanical system.

2- Design a control system to regulate the functioning of the system depending on the load demand.

3- Feasibility study for fuel cells and compare with other systems for different applications.

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[28] S. Sheik Mohammed-a, **Modeling and Simulation of Photovoltaic module using MATLAB/Simulink,** International Journal of Chemical and Environmental Engineering October2011,Volume2, No.5, Salalah, Sultanate of Oman.

[29] Jay Tawee Pukrushpan ,**Modeling and Control of Fuel Cell Systems and Fuel Processors**, A dissertation submitted in partial fulfillment of the requirements for the degree of the Doctor of Philosophy, 2003, University of Michigan.

[30] Andrea, E.; Ma ˜nana, M.; Ortiz, A.; Renedo, C.; Egu´ıluz, L.I.; P´ erez, S.; Delgado, F**,A simplified electrical model of small PEM fuel cell** , University of Cantabria, Cantabria, Spani .

[31] http://www.sciencedirect.com/science/article/pii/S1364032109000872 [Access Date 12-9-2013 (1:30 PM)] .

[32] http://tools.poweringhealth.org/[Access Date 12-6-2013 (12:30 PM)]

[33]http://www.frankshospitalworkshop.com/equipment/documents/centrifuges/wi kipedia/centrifuge.pdf[Access Date 12-8-2013 (11:00 PM)]

Appendixes

Appendix (A)

Solar Cell and Hydrogen Fuel Cell Trainer

Introduction

The HELEx™ Solar and Hydrogen Fuel Cell Trainer Add-in Module for NI ELVIS
HELEx, the Solar-Hydrogen Electricity Experimenter, as its name implies, is used to help students learn about sustainable energy generation and characteristics. The Emona HELEx add-in module is fully integrated with the NI ELVIS platform and NI LabVIEW environment.

Overview
For many years the ancients would marvel at the power of the sun and wonder at how such immense forces could travel such great distances and power both the tiny and the enormous forces which drive our living planet. Today we understand a great deal more about what powers our sun and we stand at the doorway of our own journey towards harnessing the power of sunlight for our own varied uses.

Understanding how the photon affects the electron to affect the molecule and back again, to power our electrical devices is a broad ranging and fascinating endeavour. As well we are learning how to utilise that most simple of elements, hydrogen, as a source of clean and sustainable energy. The same energy that powers the sun can be used in our devices to power our modern world.

The Emona HELEx Add-in Module along with kit components including: Photovoltaic Cells, Hydrogen Fuels Cells and Electrolyzer, which when patched together to implement 17 sustainable energy experiments.

The ETT-411 Experimenter will introduce students to these concepts, through hands-on exercises, observation, measurement and LabVIEW based data processing, and provide them with the fundamental, underpinning knowledge needed for the future.

Components of the HELEx Kit
The ETT-411 HELEx Kit includes the following components:

ETT-040 : Universal Base Board
ETT-411 : HELEx Circuit Board
ETT-411-01 : patch lead set
ETT-411-02 : lux meter adaptor
ETT-411-03 : electrolyzer
ETT-411-04 : 2 x photovoltaic solar cells
ETT-411-05 : PEM hydrogen fuel cell
ETT-411-06 : dismantlable fuel cell
ETT-411-07 : 0.1mg Pt membrane kit
ETT-411-08 : safety glasses
ETT-411-09 : Silicone Tube and Stopper Set
ETT-411-10 : Black card (for PV cells)
ETT-411-11 : 125mL wash bottle
ETT-411-12 : User Manual
ETT-411-13 : Lab Manual
ETT-411-14 : CD-ROM
ETT-411-15 : travel case
ETT-411-16 : accessories tool set

Only one of either of the following LAMPS:
ETT-4110010 Desk Lamp 120V, or
ETT-4110020 Desk Lamp 220V

The Emona HELEx Add-in Circuit board mounted on the ETT-040 Universal Base Board

Required Equipment

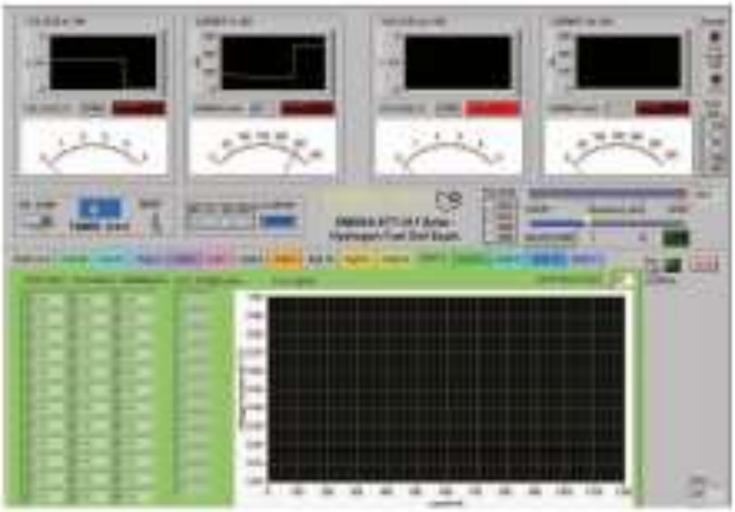
The ETT-411 HELEx Kit requires the following additional equipment and materials:

1, NI ELVIS I/II/II+ platform
2, Personal Computer
3, NI LabVIEW
4, *Distilled water : approximately 125mL

* It is imperative that ONLY distilled is used in the electrolyzer, If distilled water is not used, the electrolyzer will be damaged beyond repair,

NI LabVIEW™ and HELEx™

The Emona HELEx add-in module is fully integrated with the NI ELVIS platform and NI LabVIEW environment, The HELEx Soft Front Panel provides a customized experiment screen for each experiment in this manual,



The Emona HELEx Soft Front Panel,

- Measurement functions include: voltmeters, current meters, timer, luxmeter and electronic load,

- Control of voltage and current sources,

- Experiment panes for each chapter of this Lab Manual,

HELEx™ VIs are provided in the supplied CD-ROM so that the student has the ability further enhance the experiment capabilities of the HELEx hardware, by utilizing the resources of NI LabVIEW as well as integration with NI's wide range of tool kits.

How to handle, install and power up HELEx™

Handling HELEx

When holding UBB and HELEx, always hold the circuit board by the edges, as illustrated.

Only hold UBB and HELEx by the edges

How not to hold UBB and HELEx

Ensure NI ELVIS Prototype Board Power OFF

Before installing the HELEx add-in module in the NI ELVIS PROTOTYPE PCI SLOT, always check the PROTOTYPING BOARD POWER switch is in the OFF position.

Ensure Prototype Board Power is OFF

Installing HELEx on NI ELVIS

When installing the HELEx add-in module in the NI ELVIS PROTOTYPE PCI SLOT, always carefully check the alignment is correct before pushing HELEx into position.

Carefully align HELEx with the NI ELVIS socket

Check for correct bracket alignment

Carefully push HELEx into position

Power up HELEx

After DATEx is correctly positioned, turn the NI ELVIS Prototyping Board Power switch ON.

Turn NI ELVIS Prototype Board Power ON

CURRENT METERS

Two independent DC current meter inputs are provided on the HELEx board. Display of the current readings is on-screen, within the HELEx Soft Front Panel (SFP) window.

USE

Two DC current meters are supplied on the HELEx board. They are labeled *CM1* and *CM2*. These ammeters use two of the sampled analog voltage inputs available on the NI ELVIS unit. They have differential inputs and can be connected in reverse direction without damage (though the REVERSED lamp lights up to indicate the error).

The current reading is simultaneously displayed in three formats:
(i) Analog meter with pointer
(ii) Digital reading, and,
(iii) As a slowly moving real time strip chart.

Current meters CM1 and CM2 have 3 ranges,
0 to 300mA, 0 to 1A and 0 to 3A DC

Notice that in the top right-hand corner of the HELEx soft front panel (SFP) there are some display option switches. The following notes explain their function.

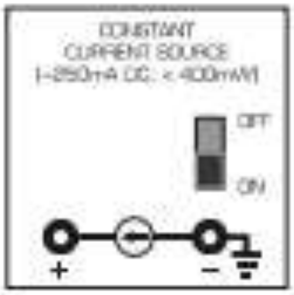
Smooth switch: Selecting this option performs a three-point moving average on all four data signals displayed (that is, on VM1, VM2, *CM1* and *CM2*). This is useful for determining an average value for any rapidly changing unstable signals.

BASIC SPECIFICATIONS (HELEx board and SFP)

Analog Input 0 to 3A DC, in 3 ranges, differential input;
Resolution 1mA;
Accuracy <=1000mA +/-(1% + 2digits), and >1000mA +/-(2% + 10digits);
Internal Resistance 0.1 ohm, +/-1%
Display via HELEx SFP: analog meter, digital meter and strip chart

CURRENT SOURCE

A low power, constant DC current source is used to operate the Electrolyzer.



USE

The HELEx board provides a well regulated source of DC current. It is specifically designed to run the Electrolyzer at a safe and reliable operating point.

The only control provided is an ON/OFF slide switch.

CAUTION: This CONSTANT CURRENT SOURCE must not be used for any other purposes or with any equipment other than the Electrolyzer supplied with the HELEx Kit, or the RESISTIVE DC LOAD supplied.

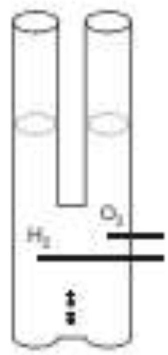
BASIC SPECIFICATIONS (HELEx board)

Constant Current Output approx. 250mA DC at 1,6V DC
Power Output <400mW
Control ON/OFF switch
Current and voltage limited

ELECTROLYZER

The HELEx Electrolyzer is used to create hydrogen and oxygen gas by decomposing water into its constituent parts, being oxygen and hydrogen.

Only distilled water may be used. Only the HELEx Solar Cells or HELEx CONSTANT CURRENT SOURCE may be used as the source of electricity to operate the Electrolyzer.



WARNING:

THIS PEM ELECTROLYZER MAY ONLY BE FILLED WITH DISTILLED WATER.

USING TAP WATER OR ANY OTHER LIQUID COULD DESTROY THE ELECTROLYZER.

WARNING:

NEVER OPERATE WITHOUT DISTILLED WATER.

USE

The HELEx Kit includes one PEM electrolyzer which implements the following chemical process of electrolysis:

$$2H_2O_{(l)} \rightarrow O_2 + 2H_2$$

The PEM electrolyser uses a proton conducting polymer membrane coated with catalyst material on either side as the central component. PEM electrolysers can have efficiencies of up to 85%.

The following figure identifies the component parts of the electrolyzer.

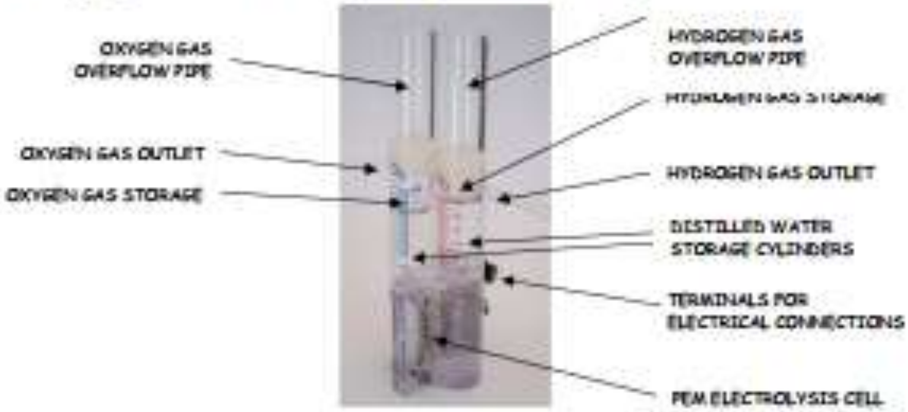


Fig.1 - PARTS OF THE PEM ELECTROLYZER

FILLING WITH DISTILLED WATER

Before the Electrolyzer can be used it must be filled with approximately 50mL of distilled water.

Use the wash bottle supplied with the HELEx Kit for filling the Electrolyzer.

Pour distilled water into the wash bottle. Place the wash bottle pipe into the OXYGEN OVERFLOW PIPE and then the HYDROGEN OVERFLOW PIPE and squeeze the bottle to fill the required amount of distilled water.

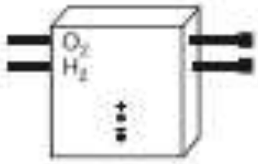
For normal use in class and for operation of up to one hour, fill both storage cylinders up to the 0mL marks.

BASIC SPECIFICATIONS

Type Polymer Electrolyte Membrane (PEM) electrolyzer
Filling Liquid distilled water ONLY
Power Consumption 800mW maximum
Required Voltage 1,4 to 1,8V DC
Maximum Current 0,5A DC
Output Terminals oxygen tube terminal and hydrogen tube terminal
Rate of Hydrogen Production 3,5ml/min (at 0,5A DC)
Consumption of Distilled Water 0,1ml/h (at 0,3A)
Maximum Storage Capacity 10ml H_2 and 10ml O_2
Electrical Terminals 4mm red (positive) and 4mm black (negative)
Dimensions 85x65x35mm

HYDROGEN FUEL CELL - PEM fixed

The HELEx Hydrogen Fuel Cell uses an electrochemical process to directly generate electricity from hydrogen and oxygen. This fuel cell is classified as a Polymer Electrolyte Membrane (PEM) type fuel cell.



USE

Fuel cells are highly efficient electrochemical electricity generators. The basic principle behind the fuel cell is the direct generation of electricity using a fuel (e.g. hydrogen) and an oxidant (oxygen) in an electrochemical process.

A fuel cell consists of two electrodes and the electrolyte. The anode is supplied with the fuel and the cathode with the oxidant. The electrolyte is the material in between and connects the two electrodes. The fuel is "oxidized" at the anode and electrons are released. The electrons released during this process flow via the attached external circuit to the cathode. Here the oxidant is "reduced" by absorbing electrons. The flow of electrons through the external circuit can be used to perform useful work.

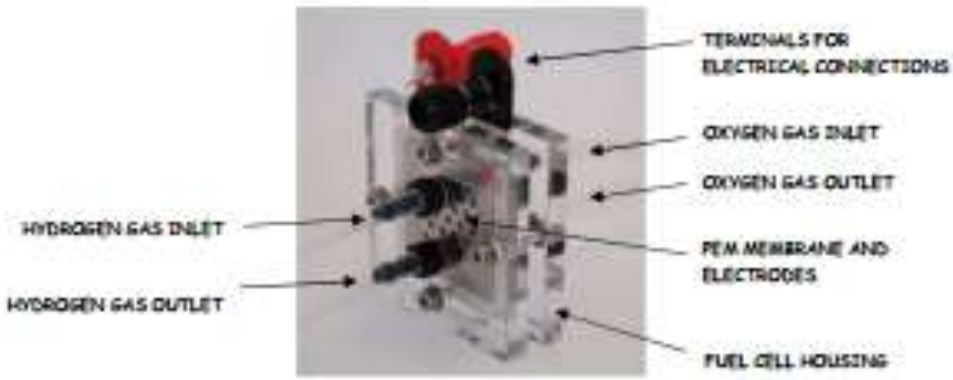
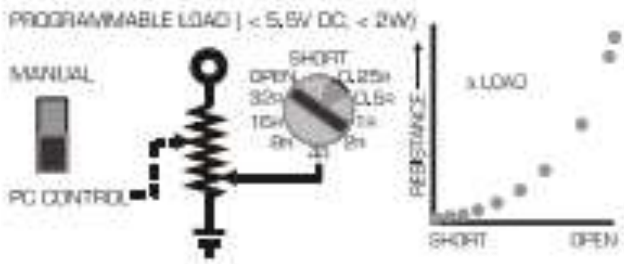


Fig.2 - PARTS OF THE PEM HYDROGEN FUEL CELL

RESISTIVE DC LOAD

The HELEx board provides a variable resistance or load, called PROGRAMMABLE LOAD, that is both manually adjustable via the board or controllable via NI LabVIEW from the HELEx Soft Front Panel (SFP) in a variety of ways.



USE

The PROGRAMMABLE LOAD has two switch selectable modes of operation. These are selected on the HELEx board itself:

MANUAL : where the resistance value is set via the finger adjustable rotary switch on the HELEx panel. One red LED on the LOAD curve will illuminate for each position of the rotary switch,

RESISTANCE RANGE : resistance range varies from 0 Ohms (short circuit) through to 32 Ohms and Open Circuit,

PC CONTROL : where the resistance values are set on-screen, via the HELEx SFP. There are 4 options for PC-CONTROL of the PROGRAMMABLE LOAD:

SLIDE - The resistance is set by the on-screen slider;

TAB - The resistance is set by the currently selected tabbed experiment on the SFP;

SLOW sweep - The resistance value increments constantly over the entire range, at a preset rate;

FAST sweep - Like the slow mode, but increments constantly over the entire range at a faster rate.

LED DISPLAY : the LED display on the HELEx board is arranged to show the changing resistance of the load in a proportional manner. That is, for resistances of 0,25, 0,5 1, 2 Ohms etc, the LEDs are close together. When the resistance changes between 8, 16 and 32 Ohms, the LEDs are spaced further apart.

In PC-CONTROL mode the LEDs are approximately indicative of the resistance range only. Precise resistance values should be taken from the SFP.

GROUNDING : the PROGRAMMABLE LOAD on the HELEx board has one end permanently connected to ground (0 volts), as indicated on the LOAD panel. There is no need to make a separate ground connection and no terminal is provided for such a connection.

WARNING: the PROGRAMMABLE LOAD is specifically designed to be used ONLY within HELEx experiments. Any other use may cause permanent damage to the LOAD.

BASIC SPECIFICATIONS (HELEx board and SFP)

Operation manual (rotary switch) and fully programmable under NI LabVIEW VI control
Load Circuit one input with load resistance to Ground
Resistance (Load) Values:
MANUAL control 10 steps - 0, 0,25, 0,5, 1, 2, 4, 8, 16 and 32 ohms, open circuit.
PROGRAMMABLE control 240 steps - 0 to 60 ohms in 0,25 ohm steps, and open.
Tolerances 0,25 +/-30%, other values +/-10%
MAXIMUM Allowable Input Signals <2W, +5,5V DC, DC Voltage ONLY
Display on HELEx Board 10 LEDs
Display via HELEx SFP digital readout

SOLAR PHOTOVOLTAIC CELLS

Two solar panels are included in the HELEx Kit. Each panel will output a DC voltage when the panel is illuminated by either sun light or the HELEx Kit Lamp.

USE

Each HELEx solar panel includes 5 silicon cells, permanently connected in series.

The HELEx solar panels may be used individually or patched together in series or parallel. The solar panels will normally be used to provide a source of electricity for the Electrolyzer.

> **WARNING: OVER HEATING OF THE SOLAR PANEL**
>
> WHEN USING THE LAMP TO ILLUMINATE THE SOLAR PANELS, ALWAYS ENSURE THE LAMP IS MORE THAN 30cm (12 inches) FROM THE SOLAR PANEL. OTHERWISE PERMANENT DAMAGE MAY OCCUR.

BASIC SPECIFICATIONS

Number of Cells Per Module 5 silicon cells, series
Voltage at Maximum Power Point 2.4V DC
Current at Maximum Power Point 200mA DC
Power Output 0,48W
OPV Cell Area 37,2cm^2 (12x62mm x 5)
V_{oc} = 2,8V, I_{sc} = 250mA at 1000W/m^2 incident power
Module Dimensions 80x135x52mm
Output Terminals 4mm red (positive) and 4mm black (negative)

STOPWATCH / TIMER

On-screen controllable stopwatch and timer with digital readout in 1 second increments.

USE

TIMER is started, stopped and reset via on-screen switches.

BASIC SPECIFICATIONS (HELEx SFP)

Timing counts up in 1 second increments.
Control includes start/stop and reset buttons
Display via HELEx SFP digital readout

VOLTAGE METER

Two independent DC voltage meter inputs are provided on the HELEx board. Display of the voltage readings is on-screen, within the HELEx Soft Front Panel (SFP) window.

USE

Two DC voltage meters are supplied on the HELEx board. They are labeled VM1 and VM2. These voltmeters use two of the sampled analog voltage inputs available on the NI ELVIS unit. They have differential inputs and can be connected in reverse direction without damage (though the REVERSED lamp lights up to indicate the error).

The voltage reading is simultaneously displayed in three formats:
(i) Analog meter with pointer
(ii) Digital reading, and,
(iii) As a slowly moving real time strip chart.

Voltage meters VM1 and VM2 have 2 ranges, 0 to 2.5V and 0 to 5V DC.

Notice that in the top right-hand corner of the HELEx soft front panel (SFP) there are some display option switches. The following notes explain their function.

Smooth switch: Selecting this option performs a three-point moving average on all four data signals displayed (that is, on VM1, VM2, CM1 and CM2). This is useful for determining an average value for any rapidly changing unstable signals.

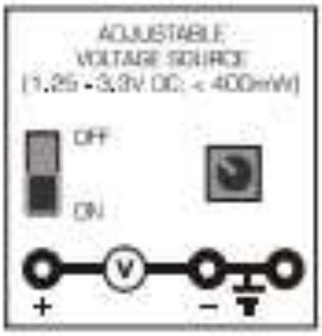
Scale switch: Selecting this option changes the scale of the VM signal displays only, halving the maximum range and thus doubling the viewing resolution. This is useful for viewing low-level signals more easily.

BASIC SPECIFICATIONS (HELEx board and SFP)

Analog Input +/-10V DC, differential input
Maximum Resolution 10mV;
Accuracy +/-(1% +2 digits);
Input Resistance 2kohm, +/-5%
Display via HELEx SFP analog meter, digital meter and strip chart

VOLTAGE SOURCE

A low power, variable DC voltage source is used in conjunction with the HELEx Electrolyzer and Solar Cells.



USE

The HELEx board provides a well regulated source of DC voltage. It is specifically designed to be used with other HELEx Kit components.

Two controls are provided: an ON/OFF slide switch and a finger adjustable knob to set the required output voltage.

CAUTION: This VOLTAGE SOURCE must not be used for any other purposes or with any equipment other than the HELEx Kit.

BASIC SPECIFICATIONS (HELEx board)

Adjustable Voltage Source approx. 1.24V to 3.3V DC
Power Output <400mW
Short Circuit Protection voltage and current limited
Control ON/OFF switch

HELEx™ SOFTWARE INSTALLATION & SFP OPERATION

Installing NI DAQ and NI ELVIS software

Before installing the EMONA HELEx software, ensure that the NI DAQ and NI ELVIS software has been correctly installed as per the accompanying NI DAQ and NI ELVIS user instructions.

When an NI ELVIS unit is connected to a PC it will automatically run the Instrument Launcher panel as shown below. This is not used by HELEx and can be closed.

Using NI MAX (Measurement and Automation Explorer), confirm the Device Number of the NI ELVIS unit connected.

Installing the EMONA HELEx software

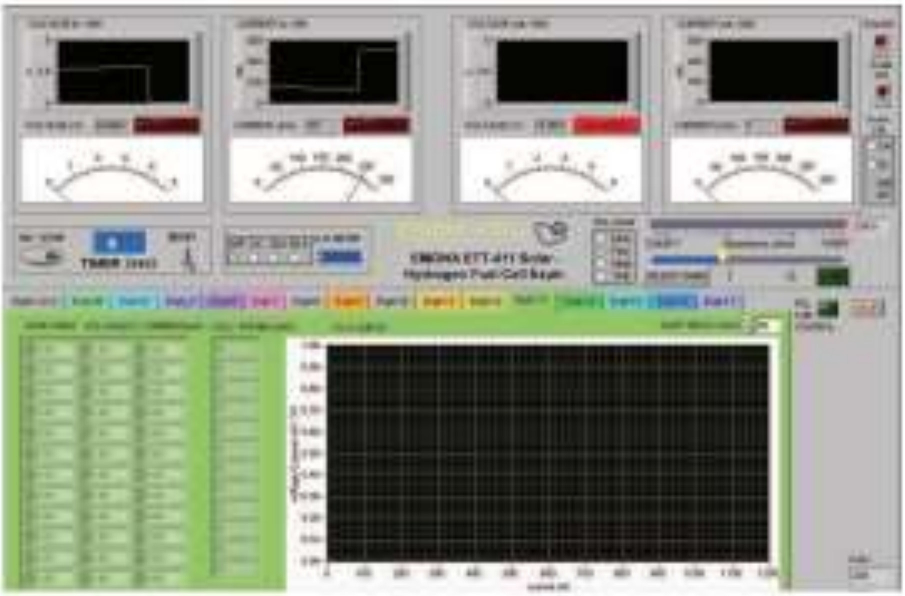
The CD-ROM supplied with the HELEx Kit includes the following items:

- HELEx-Main SFP (Soft Front Panel).
  A large SFP which allows specific HELEx switches and knobs to be controlled on-screen and includes TABBED control panels for each experiment in the Lab Manual.
- HELEx low level VIs for control of the individual HELEx modules.
  These VIs can be used by any LabVIEW program to control any of HELEx's variable parameters.
- Example LabVIEW programs which demonstrate LabVIEW control of the HELEx.
  A selection of simple example programs for using HELEx block functions.

The HELEx CD-ROM also includes a soft copy of the Lab Manual.

- Emona HELEx Lab Manual in PDF format

Installation procedure
Insert the CD-ROM in your PC drive, open the CD-ROM directory and run **HELEx-setup.exe**



Using the HELEx SFP

To launch the HELEx SFP go to START > click on HELEx SFP.

Enter, into the Dialog Box, the appropriate Device Number for your NI ELVIS unit.

As the SFP screen shot above shows, there are four customized meters which graphical and numeric output as well as control panel for the electronic load, and a number of customized data input/output display panels (selected by tabs) for the numerous experiments in this manual.

These instruments take their signals directly from the HELEx board via the EMONA ETT-040 Universal Base Board, into the ELVISmx circuitry, and after processing by LabVIEW are displayed on screen as required.

PROGRAMMABLE LOAD under PC CONTROL mode

Use the mouse left button to click and drag the slider to the desired position. The resistance values are set on-screen, via the HELEx SFP. There are 4 options for PC-CONTROL of the PROGRAMMABLE LOAD:

SLIDE - The resistance is set by the on-screen slider;

TAB - The resistance is set by the currently selected tabbed experiment on the SFP;

SLOW sweep - The resistance value increments constantly over the entire range, at a preset rate;

FAST sweep - Like the slow mode, but increments constantly over the entire range at a faster rate.

TABBED EXPERIMENTS

Experiments in the Lab Manual each have their own specific data entry and display tables, selectable via on-screen TABs. Some TABBED experiments include automated measurement and displaying of data. These experiments also have provision for varying the sample rate.

Confirming PC-to-HELEx™ Communications

To confirm that the on-screen mouse control signals are being passed from the PC through the NI-DAQ to NI ELVIS and the HELEx add-in module, do the following:

Select SLIDE mode on the SFP and click and drag the slider.

As the slider is varied, the communications LEDs should flicker on-and-off.

If the LEDs (A, B, D) flicker, then communication signals are being passed from the PC through to the HELEx.

If the communications LEDs do not flicker, then the check the following:

1. That the correct DEV number is selected for the NI-DAQ in the HELEx SFP.
2. That the HELEx SFP is "running".
3. That the PROTOTYPING BOARD POWER switch is in the ON position.
4. .That the PC, NI-DAQ and NI ELVIS are connected correctly.
5. That the NI ELVIS virtual instruments are functioning correctly.
6. That the HELEx add-in module is correctly positioned and plugged-into the NI ELVIS PCI slot.

HELEx communications LEDs

Running the HELEx SFP without NI ELVIS

In order to run the HELEx SFP when your PC is not connected to NI ELVIS unit, you will need to create a simulated NI ELVIS unit. This is useful when you wish to enter data and create plots with values taken during an earlier lab session.

Creating a simulated NI ELVIS unit is achieved using NI MAX (Measurement and Automation Explorer).

- Run NI MAX and select the simulation option as shown in the figure below. Select a USB-6251 (Mass Termination) device.
- Enter the allocated Device Number for the simulated device into the HELEx SFP Dialog box when required.

Distilled Water
"Steam - distilled water" is available from large grocery stores at low cost.

DO NOT USE: tap water, filtered water or de-mineralized water.

USA Lamp
Philips 90W, 120V PAR38, SP10 Halogen Long Life Bulb (1300 lumens) "SPOT"

Ref: www.bulbamerica.com Part #: 230698

EU Lamp
Radium 120W, 230V PAR38 SPOT or similar.

Appendix (B)

PEM Fuel Cell Datasheet

H-300 H-SERIES PEM Fuel Cell SystemLeightweight, efficient, low cost, high power densities, semi-integrated 200W fuel cell system.

Opening new possibilities for integration and innovative application development.

Including:

- Connections and tubing

- Electronic valves

- Electronic control box

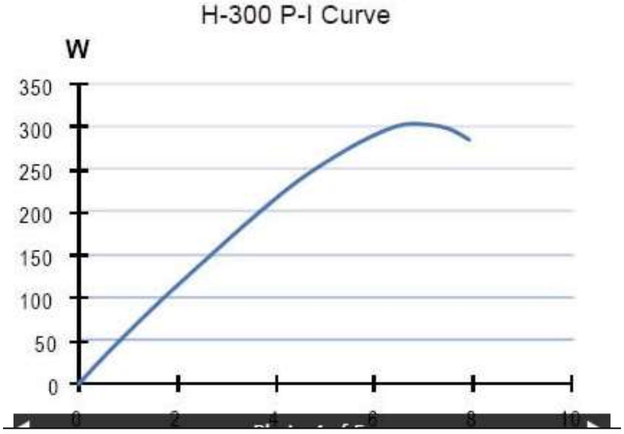
- 300W stack with blower

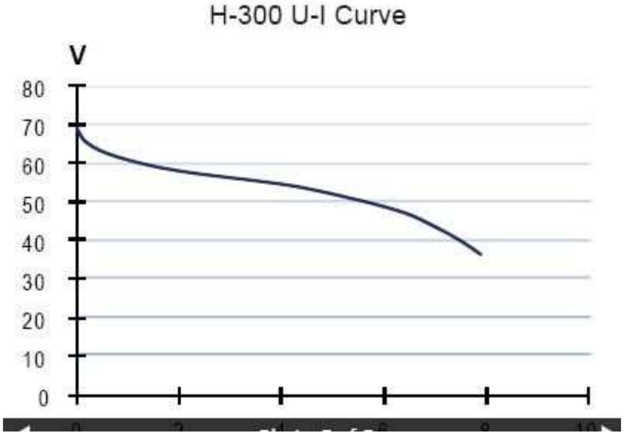
- Fuel cell ON / OFF switch

- SCU ON / OFF switch

- Manual

[redacted]





Details

H-300 Technical Specification

Type of Fuel Cell...................... PEM

Number of Cells........................ 72

Rated Power............................. 300W

Rated Performance................... 43V @7.2A

Output Voltage Range............... 39 - 69V

Weight (with fan and casing)....... 2kg / 4.4lbs

Size (mm / in.)........................ 104x280x90 / 4.1x11x3.5

Reactants............................... Hydrogen and Air

Rated H2 Consumption............. 4.2l/min 259in^3/min

Hydrogen Pressure..................... 0.4 - 0.45Bar / 5.8 - 6.5PSI

Purging Valve Voltage................. 12V

Blower Voltage..........................4 - 12V

Controller weight.......................362.4g / 0.8lbs

Controller size (mm / inch)......... 88x133x40 / 3.5x5.28x1.6

Hydrogen supply valve voltage.... 12V

Ambient Temperature................. 5 - 35°C / 41 - 95°F

Max. Stack Temperature............ 65°C / 149°F

Hydrogen Purity........................ 99.999% dry H_2

Humidification.......................... Self-Humidified

CoolingAir............................... Air (integrated cooling fan)

Start up Time........................... <30s @ 20°C / 60°F

System Efficiency...................... 40% @ 43V

Additional Information

Weight	2.0

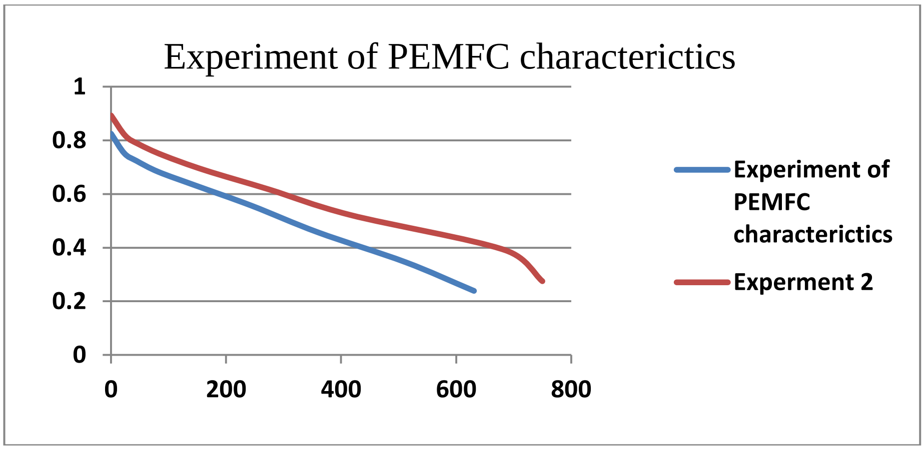
Appendix (C)

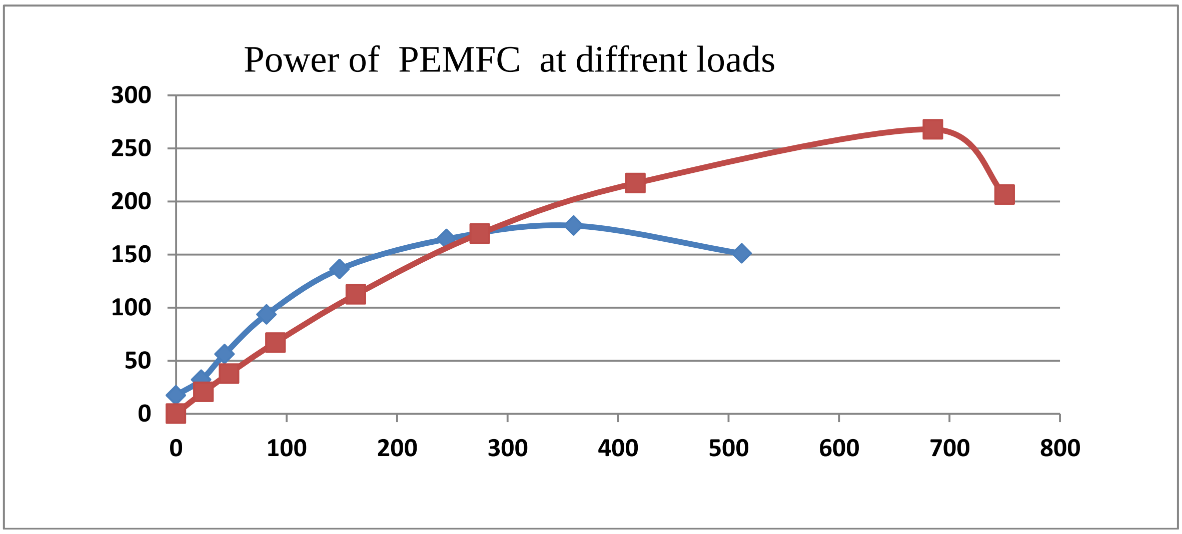
Solar Radiation and Load

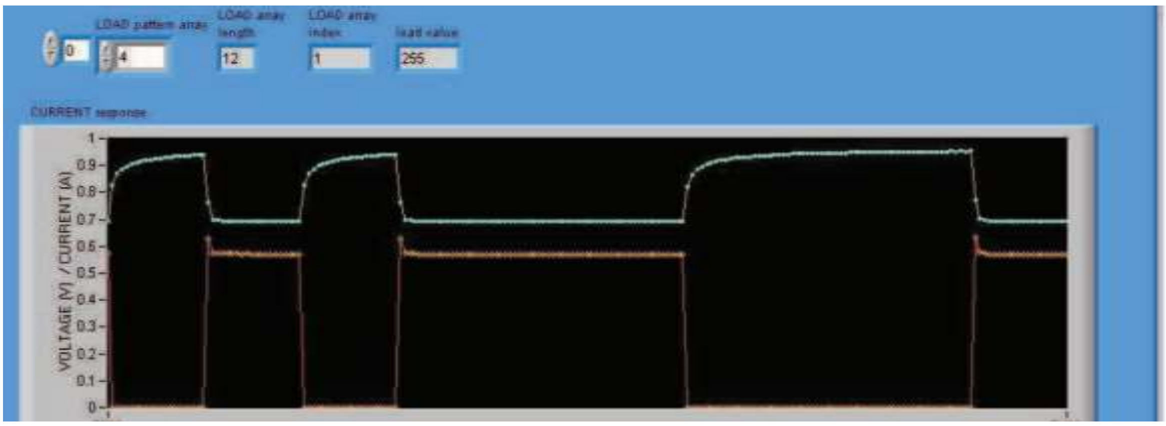
Time	Load	Solar Rad.

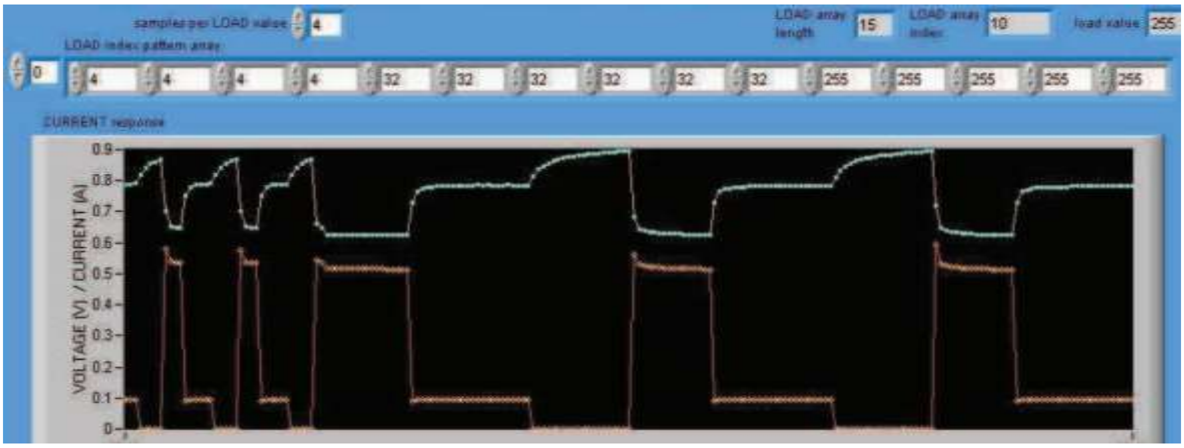
Appendix (D)

Experiments of PEMFC


Experiment of PEMFC characterictics
1
0.8
0.6
0.4
0.2
0
0
200
400
600
800
Experiment of PEMFC characterictics
Experment 2


Power of PEMFC at diffrent loads
300
250
200
150
100
50
0
0
100
200
300
400
500
600
700
800


CURRENT response
VOLTAGE (V) / CURRENT (A)



Varied step load profile response of fuel cell

Appendix (E)

PV module and PEMFC Stack Datasheet

جامعة النجاح الوطنية
كلية الدراسات العليا

تزويد العيادات الصحية في المناطق النائية بالكهرباء باستعمال أنظمة الخلايا الشمسية وخلايا الوقود العاملة بالهيدروجين

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قدمت هذه الأطروحة استكمالا لمتطلبات الحصول على درجة الماجستير في هندسة الطاقة النظيفة وإستراتيجية الترشيد بكلية الدراسات العليا في جامعة النجاح الوطنية نابلس فلسطين.
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الملخص

العيادات الصحة الفلسطينية في المناطق النائية تعاني في الغالب من عدم وجود الشبكات الكهربائية بسبب القيود الإسرائيلية وعدم توفرالبنية التحتية من السلطات المحلية. معظم هذه المناطق هي بعيدة عن خطوط نقل الجهد المتوسط الرئيسية ، مما يجعل ربطها مع شبكات الطاقة الكهربائية الرئيسية غير عملي. ولذلك، يمكن لمصادر الطاقة المتجددة وخاصة الطاقة الشمسية وخلايا الوقود تمثل حلولا أكثر نظيفة وموثوقة و مجدية . ويتضح نمط استهلاك الطاقة نموذجية من عيادة صحية مقترح. وتعرض النتائج التجريبية التي تمت للنظام الذي بني في المختبر لإعطاء نظرة ثاقبة على التفاصيل الفنية نظام .

توفر الوقود وإنتاج الطاقة النظيفة عن طريق خلايا الوقود ، وإعطاء التفاعلات الكيميائية التي تحدث في داخل الخلية وكذلك إنتاج الكهرباء لمدة غير محدودة ، هي من المواضيع الرئيسية للنظام في هذه الأطروحة . تقدم الأطروحة أيضا استراتيجية لإدارة الطاقة لنظام الخلايا الشمسية والوقود لتغطية الطلب على الطاقة الكهربائية من عيادة صغيرة نموذجية في المناطق الريفية في فلسطين . وتستند استراتيجية الرقابة المقترحة على الطريقة المستندة إلى المنطق الذي يعتبر مركز مصادر إمدادات الطاقة والحمل يتطلب الجمع بينها والتبديل في ما بينها و إعطاء الأولوية للمصدر أكثر استقرارا .وأخيرا ، تمت دراسة النظام من حيث المقارنة المالية بين استخدام بطاريات و خلايا الوقود لتزويد العيادات الريفية بالكهرباء في هذه الأطروحة . وقد وجد أن استخدام خلايا الوقود هو أكثر جدوى اقتصاديا.