AMERICAN UNIVERSITY OF BEIRUT

OPTIMAL ENERGY MANAGEMENT OF PV SYSTEM WITH HYDROGEN TECHNOLOGY

by

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I dedicate this thesis to my family and beloved country Syria.

AN ABSTRACT OF THE THESIS OF

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This thesis addresses the modeling, optimization, and sizing of a grid connected Hybrid Renewable Energy System (HRES) that consists of a Photovoltaic (PV) array that operates as a main source of generation, and two types of back-up systems. The first is a long-term back-up storage consisting of an Alkaline Fuel Cell (AFC) that gets its hydrogen from an Electrolyzer (EL), supplied from the main PV source. The second is an Ultra Capacitor (UC) which is considered as a short-term backup device. After modeling each component an optimal Energy Management System (EMS) was applied in order to minimize the cost of purchasing electricity from the grid and the CO2 emissions. The optimizing method being implemented is based on Linear Programming (LP) and it is subject to a number of constraints which are the power balance equation, upper and lower limits of power delivered by the various devices, ramp rate limits, hydrogen storage limitation, and the UC charge limits. These constraints will assure the reliability and the safety of the system while meeting the load requirements at the lowest cost. The reason behind choosing an LP technique is the linear nature of the objective function and the near linearity of the constraints. In addition to minimizing the cost, this system will allow the hazardous emissions to be reduced by using the clean alternative PV-based power generating system.

The size of the PV modules is selected to give output power that is enough to feed the peak load when the solar radiation is available. The size of other components is set choosing the least solar radiation days of the year which represent the worst days that require the highest sizes of backups. A case study is presented for a village in Lebanon called Anjar where the unreliable nature of the grid is solved using HRES with different scenarios of operation.

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ABBREVIATIONS

AFC: Alkaline Fuel Cell

ANN: Artificial Neural Networks

DP: Dynamic Programming

EL: Electrolyzer

EMS: Energy Management System

FC: Fuel Cell

FLC: Fuzzy Logic Controller

Ga: Genetic Algorithm

HRES: Hybrid Renewable Energy System

LCOE: Levelized Cost of Energy

LP: Linear Programming

MILP: Mix Integer Linear Programming

MPPT: Maximum Power Point Tracking

NOCT: Nominal Operating Cell Temperature

PV: Photovoltaic

PEMFC: Proton Exchange Membrane Fuel Cell

P&O: Perturbation and Observation

R&D: Research and Development

SCC: Social Cost of Carbon

SOC: State of Charge

SOFC: Solid Oxide Fuel Cell

STC: Standard Test Conditions

UC: Ultra-Capacitor

CHAPTER I

INTRODUCTION

Renewable energy systems such as solar, wind and geothermal have been a major success story in the first decade of the 21-st century. As populations grow and industries develop the energy consumptions increase. Moreover, the increasing fossil fuel prices and the hazardous emissions from conventional power plants made the interest in renewable systems increase. Thus, in order to face the increasing electricity demand, grid connected renewable energy sources were suggested. The importance of these systems is that they isolate the economy from fuel price constant increscent and provide clean energy that reduces the dangerous emissions of conventional energy generators.

Hybrid Renewable Energy Systems (HRES) include one or more renewable energy sources with or without traditional energy sources that operate in stand-alone or grid-connected mode. HRES are seen as a way to provide power to remote areas where grid extension is not feasible or economical. However, in grid-connected mode, loads will only partially depend on the grid because clean energy sources with their storage systems will be ready to supply them with power.

One of the widely used renewable energy sources is solar energy. Usually, Photovoltaic (PV) panels use the Maximum Power Point Tracking (MPPT) technique in order to deliver the highest power at each solar radiation and ambient temperature. The output power of a PV array varies with the changes in solar radiation and other climatic conditions. Thus, their fluctuating nature requires storage systems in order to provide energy supply to the load with minimum interruption. Back-up devices such as batteries, fuel cells and ultra-capacitors are recently widely used. However, the real challenge is operating such systems in a way to minimize the fossil fuel utilization using an optimal energy management system in order to get the output from the system's components.

A. Literature Review

Grid connected renewable energy systems have challenges and concerns described by Alsayegh et al [1] , this interconnection will cause voltage flickers and fluctuations since the inputs of renewables vary with weather conditions, the author proposed local supervisory controller strategy in order to monitor and control the renewable energy sources providing optimal supply to the loads while maintaining grid’s stability and renewables’ safety.

The optimal energy management of grid connected HRES is a challenging task. Various Energy Management System (EMS) methods for HRES have been proposed in the literature. In the following, a brief review to some of them is presented.

An optimal power management mechanism for grid connected photovoltaic system with batteries using Dynamic Programming (DP) with a "day-ahead" approach to predict next day’s power schedule is presented by Riffonneau et al [2], where the proposed system helped managing the fluctuation of the PV penetration proposing peak shaving strategy at lowest costs. While Ha Pham et al [3] used mixed integer linear programming (MILP) for demand side management to find the global household energy management. They found MILP to be effective when dealing with the complexity of the problems. Another optimal energy management principle is presented by Zhou et al [4] for PV-hydrogen system in terms of energy efficiency, putting three possible scenarios to the path of PV’s excess power. The authors propose a control strategy that depends on calculating the system efficiency at each path and find the one that will transfer the highest energy.

However, several non-optimal energy management algorithms were implemented using different tools in Matlab environment. Some of them are reviewed in the following. A power management of a grid connected hybrid system consisting of photovoltaic (PV) array and Proton Exchange Membrane Fuel Cell (PEMFC) and Electrolyzer (EL) is represented by Khanh et al [5]. The power management is done for two operating modes, when the system is not heavily loaded and when it is. In both cases the PV works in its maximum power point using Perturbation and Observation (P&O) algorithm and the fuel cell works in high efficiency. When the load is heavy the system can maximize the power generation and minimize the load shedding. However, the system will be more stable when the load is not heavy. Another power management of a system consisting of photovoltaic(PV) generator, proton exchange membrane fuel cell (PEMFC) refueled by an Electrolyzer (EL), and Ultra Capacitor (UC) using Matlab/Simulink is presented by Uzunoglu et al [6]. During the day the PV is the main source of generation. The PV's excess power is used to charge UC bank and the EL in order to use them at night when no solar radiation is available. The system used power control at relevant points to satisfy load demands during the day from PV and at night using FC/UC combination. Li et al [7] show energy management technologies for three stand-alone hybrid PV systems (PV/Battery, PV/FC, PV/FC/Battery) are investigated and compared from the aspects of maximum system efficiency and minimum cost. The PV/FC/Battery system was found to have higher efficiency with lower cost compared with the other systems. Also, Kang and Won [8] proposed another PV/FC/Battery power management system based on minimizing the cost of battery and fuel cell, and maximizing their lifetime. The power management strategy, and in order to increase the lifetime of batteries and fuel cell, will reduce the number of operation modes using time delay elements.

Moreover, Wei [9] presented a power management for a stationary application, the system consists of a stand-alone photovoltaic, fuel cell and electrolyzer. When the PV's output power is high enough to operate the load, the excess power is used to store hydrogen by operating the electrolyzer. Thus, hydrogen will be ready to be used as a fuel to operate the fuel cell during the night. Esmaeili and Shafiee [10] proposed a similar method for a system that has a photovoltaic panel and a wind turbine as primary power sources, hydrogen production cycle of electrolyzer and fuel cell, and an ultra-capacitor. The excess output power is used to produce hydrogen or store it in the ultra-capacitor for later use. The presence of PV panels in addition to the wind power made the system more reliable, where the author compared this system with another one without PV panels. And since the system is a stand-alone system having two main renewable sources made the system more economical. Moreover, Castañeda et al [11] proposed an energy management system strategy for a stand-alone system consists of PV solar panels, a hydrogen system of a fuel cell and electrolyzer, and a battery, using supervisory control that determines the power of each component and decides the proper control step. The rule base implementing this strategy is based on observing the net power (the difference of P_{pv} and P_{load}), hydrogen tank level and battery's State Of Charge (SOC) in order to decide the operating point of system's each component.

While Beltran et al [12] proposed an EMS for a grid connected PV power plant with an energy storage unit, an Ultra capacitor (UC), which provides a fixed amount of power during the day making a system that is reliable and able to compete in electricity markets. This system will decrease the number and the power of units which are on hot standby state, thus making the balance of generation-load easier and more stable. In this paper different EMS configurations were tested for different power patterns, levels, and intervals. Authors found that the optimum EMS for this type of systems is to take hourly constant power intervals, the thing that will decrease the capacity of energy storage units needed and consequently minimizing the cost of the system.

Recently, several intelligent -based energy management systems exist for hybrid renewable energy systems such as fuzzy logic, neural networks and genetic algorithms. This type of energy management is used when there is no enough data about the site.

An Energy management algorithm using a Fuzzy Logic Controller (FLC) for a PV/FC/UC power plant is proposed by Thounthong et al [13]. Takagi-Sugano inference rules were used with seven triangular and trapezoidal membership functions that define the fuzzy input variables. While Natsheh et al [14] proposed an optimized on-line energy management based on a hierarchical controller for PV/FC/Battery system using a (FLC) and Artificial Neural Networks (ANN). The Maximum Power Point Tracker (MPPT) of a PV array is done using feed-forward and back-propagation neural network controller, while the (FLC) is used to decide on the optimum operation of the Proton Exchange Membrane Fuel Cell (PEMFC) and the battery. Another intelligent energy management system which is Genetic algorithm (GA) is used by López and Agustín [15]. GA have been used to find an optimal solution in a hybrid system that consists of Wind/PV/Diesel/FC/Battery. The authors provided a multi-objective design of this system by minimizing cost, pollutant emissions, and unmet load requirements using genetic algorithms.

Another important issue in HRES is the accurate sizing of the components in order to satisfy the load requirements while minimizing the cost. Different optimization techniques were used to optimize the size of the system components. Chedid and Saliba [16] used linear programming to minimize the cost of electricity production while satisfying the load requirements in a reliable way. In [16], sensitivity analysis was use to study the effect of chosen parameters on the optimum design of the system, taking into consideration the maximum available wind and solar areas, and the lifetime of batteries and diesel engines. A similar method was used by Kellogg et al [17] for a hybrid system consisting of a PV modules, a wind turbine, and batteries. The objective was to minimize the annual cost while meeting the required loads. Linear Programming (LP) was used by Chedid et al [18] to solve a multi objective problem while sizing a system of wind, PV and diesel generators. The objectives were minimizing both the cost of the system and the emissions. However, another sizing method was presented by Ai et al [19], where the performance of the system was determined and compared on hourly basis, and the sizing was done by taking the daily average power, or the day of minimum PV power or minimum wind power. Then the matching calculations formed the sizes of the system components.

B. Thesis Contribution

An optimal EMS is presented using (LP) in order to minimize the cost of system operation, that includes the cost of electricity purchased from the grid in addition to the social cost of carbon caused by using conventional power plants plus the cost of operating the renewable sources that includes the annuity on the investment, and the operation and maintenance cost.

A first order temperature model for the transportation losses was developed for an alkaline electrolyzer which was used to determine the characteristic electricity consumption curve. The curve was then linearized to deduce the figure of merit for operating the electrolyzer used in the constraints. A similar modeling exercise was also carried out for the operation of the fuel cell.

Moreover, an hourly load model of the village is developed as a percentage of the peak load using the weekly load profile of the IEEE Reliability Test System [20] and the daily load profiles of typical days in the Lebanese EDL data. The load data is smooth and it is for a one year period.

A case study is also presented for the village of Anjar in Lebanon taking into consideration the unreliable nature of the grid that has hours of blackouts, and replacing this electricity cut offs with clean energy sources. The study is done for one year long data taking an interval of one hour and takes into consideration the different tariffs during the time of day and season.

In the first chapter of this thesis we showed a general literature review on similar topics used in our thesis.

Chapter 2 of this thesis shows a detailed modeling of each component of the HRES, and illustrates the advantages and disadvantages of each one.

In Chapter 3 an overview of the optimization problem formulation is presented. The system will be considered as a linear problem since the objective function is linear and the constraints are near linear.

Chapter 4 explains the methodology used in the thesis and shows the results of a case study done for Anjar. Different scenario tests are shown in this chapter to evaluate their effect on the environment and economics. The simulations are done for one year data.

CHAPTER II

SYSTEM COMPONENTS

The system consists of a Photovoltaic array (PV) as a main renewable energy source. In addition, two types of back-up (storage) systems are used; the first is a long term storage device based on a PEMFC and an EL that supplies hydrogen to the fuel cell through a hydrogen tank, while the second is an Ultra-capacitor (UC), which is a short term storage device. Having these back-up systems will increase the reliability of the system, and at the same time will decrease the loads' dependence on the grid. Moreover, such systems could be used for small power applications such as a single home, or for large ones like a village.

A. Photovoltaic Array

The photovoltaic cells are semiconductors that convert sunlight to electricity. The connection of cells in series and in parallel forms a PV module, a collection of which forms a PV array. The PV array is the main power source of this hybrid system. During the day when the solar radiation is available, the PV array is able to supply the load and the excess output power is used to fill the storage devices. The maximum power at standard conditions (P_{m0}) is usually given by the manufacturer, and the maximum power at other conditions can be obtained from the following equation [21]:

$$P_m = V_m I_m = \frac{V_{oc} I_{sc}}{V_{sco} I_{sco}} P_{m0} \qquad (2\text{-}1)$$

Where

P_m, V_m and I_m: maximum power, voltage and current outputs.

V_{OC}, I_{SC}: the open circuit voltage[V], short circuit current[A].

The open circuit voltage and the short circuit current variation with temperature and irradiance are as follows:

$$V_{OC} = V_{OC0}\left(1 + \frac{V_t}{V_{OC0}} ln\left(\frac{G}{G_0}\right)\right)(1 + \beta_v \Delta T) \qquad (2\text{-}2)$$

$$I_{SC} = I_{SC0}\left(\frac{G}{G_0}\right)(1 + \beta_I \Delta T) \qquad (2\text{-}3)$$

G : Solar radiation [kW/ m^2] in usual operating conditions.

V_{oc0}, I_{sc0} : the open circuit voltage[V], short circuit current[A].

G_0 : Solar radiation [kW/ m^2] in standard conditions.

β_V, β_I : voltage and current temperature sensitivity coefficients [mV/C$^\circ$], [mA/C$^\circ$].

$\Delta T = T_C - T_0$, Where: T_C is the cell operational temperature,T_0 is the standard one=25°C

Where the voltage coefficient is in per unit/°C, and is calculated by dividing the given in mV/°C Celsius by the VOC at standard test conditions (STC).

To get the cell temperature as a relation to the ambient temperature and the nominal operating temperature:

$$T_C = T_a + \frac{NOCT-20}{800} G \qquad (2\text{-}4)$$

k_T : Is the temperature coefficient.

$NOCT$: Is the nominal operating cell temperature.

T_a : Is the ambient temperature.

B. Fuel Cell

It was the middle of the 19-th century when William Grove demonstrated the first fuel cell with limited applications [22]. Then Bacon's work around the 1950s was the step for successful use of fuel cells in later American space application works [22]. This success in space applications was not enough to commercialize fuel cells. However, they became more popular in the last two decades where the increasing demand for renewable energy and the depleting nature of fossil fuels made engineers, economists, environmentalists, and politicians search for additional clean energy generating sources [23].

Fuel cells are electrochemical devices that convert the chemical energy of liquid or gaseous fuel contents into electrical energy. Nowadays, various types of fuel cells are available for different applications depending on their power capacity, which ranges from few watts, such as in mobile and residential applications, to megawatts, like in power plants.

In general, each cell consists of an anode, a cathode, and an electrolyte that separates between them. Electrons move in the external circuit from the negative to the positive side while protons move in the opposite direction within the electrolyte. These movements create an electric current that passes through the membrane. An individual cell gives about 0.7 volts as an output [1]. In order to increase the output a group of cells are connected in series and in parallel to get the required voltage and current values. This group of cells is called a fuel cell stack.

Different types of fuel can be used in the fuel cell, but the most common one is the hydrogen [1]. The hydrogen recombines with the oxygen releasing energy and water.

$$2H_2 + O_2 \rightarrow 2H_2O + Energy$$

The overall reaction in all types of fuel cells is the same. However, the differences between them are in terms of the reactions at the electrodes depending on the electrolyte type used, either acidic or alkaline, and of the temperature of operation. The Alkaline Fuel Cell (AFC) is considered as a low temperature fuel cell with an operating temperature limit of below 80ºC, the Proton Exchange Membrane Fuel Cells (PEMFC) have a range of 80-200ºC. The high temperature fuel cells are the Molten Carbonate Fuel Cell (MCFC) with 650ºC and Solid Oxide Fuel Cell (SOFC) 800-900ºC operating temperature [23].

1. Advantages of fuel cells

Advantages of using fuel cell to generate electricity compared to the conventional sources can be summarized as follows [22]:

a. Efficient

Generating electricity by fuel cells is more efficient than the conventional direct combustion method, since the energy conversion in the fuel cell has a single direct conversion from chemical to electrical energy. In the combustion engines the energy conversion passes through four stages from chemical to thermal then mechanical and electrical. Less energy conversion means decrease in loss which makes fuel cells more efficient with a typical efficiency of 70%.

b. Simple and silent

Fuel cells have few moving parts and they are very quiet no matter what size they are.

c. Low emissions

Fuel cell uses hydrogen as a fuel to produce electricity and pure water. This means that the fuel cell is an environment friendly electricity source with "zero emission" if the hydrogen is produced from renewable resources.

2. *Alkaline fuel cell (AFC)*

Alkaline fuel cells are widely known for space and military applications; it was chosen by NASA to take man to the moon with the Apollo mission in the mid of 1960s [1]. It was the first type of fuel cells that was used in practical applications generating electricity from hydrogen, where it has shown the ability to supply power with high densities [24]. Hence, it will be possible to get higher output voltage by changing the power density for the same volume of the system.

AFC has an aqueous electrolyte, hence the utilized fuel should be free of CO2 since its presence will reduce the number of hydroxyl ions and this will reduce the conductivity of the electrolyte. At the same time carbonates will form and block the pores of the electrodes causing certain blockage on the route of electrolyte [24]. However, the effect of carbonate is for long-term operations and will not appear when operating the fuel cell for short periods. A test of 48 hours done by reference [25] didn't show a degradation in the performance over this period since it wasn't enough for the carbonates to penetrate the pores of the electrodes. Gulzow in [26] did a test with the German Aerospace Center DLR and found that using silver electrodes will solve the problem of blocking the pores. He also suggested changing the electrodes every 800 hour or simply adding water to maintain the hydroxyl ion concentration.

An important advantage of AFC type of cells is the low activation voltage which is the most important voltage loss in low temperature fuel cells [1]. In addition, it has high efficiency compared to the other types of fuel cells, where the advanced AFCs have electrical efficiency of almost 70% [27]. There are some limitations on the temperature of operation that should be below 70ºC for the stack in order to avoid damaging the cell components [27].

An illustration of available hydroxyl ions in electrolyte is represented in Fig.2.1, where OH^-react with hydrogen releasing energy, electrons, and producing water. At the cathode, oxygen reacts with electrons taken from the electrode, and water in the electrolyte, forming newOH^- ions. The reactions are as follow:

Anode: $2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$

Cathode: $O_2 + 4e^- + 2H_2O \rightarrow 4OH^-$

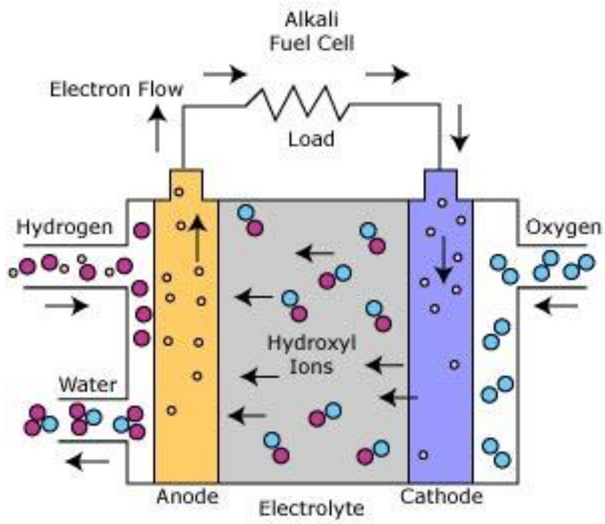


Fig 2.1. Alkaline fuel cell reaction

a. Alkaline fuel cell modeling

Fuel cells typically generate about 0.6 to 0.9 Volts DC per cell. The open circuit voltage is higher, but the internal impedance and losses of the cell, cause the output voltage to decrease as the current increases.

The output voltage of the cell is given by [22] as following:

$$V_{out} = E - V_{act} - V_{ohm} - V_{trans} \qquad (2\text{-}5)$$

E : The reversible open circuit voltage.

V_{act} : The potential associated with the activation losses.

V_{ohm}: The potential associated with the ohmic losses.

V_{trans}: The potential associated with the transport losses.

i. Nernst equation (E)

It represents the open circuit voltage E_0 with an extra term that takes into account the effect of temperature changes and the partial pressures on the reversible voltage. Where E in the equation (2-5) represents the reversible open circuit voltage, it is also called Nernst equation. It is given in the following equation:

$$E = E_0 + \frac{R.T}{2F} \ln(\frac{P_{H2} \, P_{O2}{}^{1/2}}{P_{H2O}}) \qquad (2\text{-}6)$$

WhereE_0 is the open circuit voltage at standard temperature and pressure (STP) and it can be determined from Gibbs energy whose value changes depending on the temperature and the state of the water. Table2.1.shows the value of Gibbs energy for a range of temperatures between 25-1000ºC [1].

$$E_0 = \frac{-Gf}{Z\ F} \qquad (2\text{-}7)$$

Table 2.1. Gibbs energy for different temperatures

Form of water product	Temperature (c)	Gf (KJ/ mol)
Liquid	25	-237.2
Liquid	80	-228.2
Gas	80	-226.1
Gas	100	-225.2
Gas	200	-220.4
Gas	400	-210.3
Gas	600	-199.6
Gas	800	-188.6
Gas	1000	-177.4

Z: number of electrons transferred in a reaction for each molecule.

The equation of E_0 can be applied to other reactions too. But when applying to fuel cell $Z = 2$ since the number hydrogen electrons transferred for each molecule is two.

R : Ideal gas constant =8.314 [J/mole K].

F : Faraday's Constant = 96487 [Coulombs].

P_{H2} P_{O2} P_{H2O} : Partial pressures of hydrogen, oxygen and water respectively.

ii. <u>Activation Losses</u>

Activation losses represent the energy barrier that has to be overcome for the reaction to take place on the surface of the electrodes. The activation voltage representing these losses is given by the Tafel equation:

$$V_{act} = \frac{R\,T_k}{2\,\alpha\,F} \log\left(\frac{i}{i_0}\right) \qquad (2\text{-}8)$$

α : Coefficient in base 10 logarithm form of Tafel equation

i: Current density.

i_0 : Exchange current density at an electrode/electrolyte interface, which is a parameter used in Tefal equation represents the actual current density at net zero current indicating catalytic activity of the electrode.

iii. <u>Ohmic Losses</u>

Ohmic losses are represented by the voltage drop caused by the internal resistance of the cell. They proportionally increase with increment in the current density.

$$V_{ohm} = i\,R_{ohm} \qquad (2\text{-}9)$$

Where the ohmic resistance is given as:

$$R_{ohm} = \frac{t_m}{\sigma} \qquad (2\text{-}10)$$

t_m : Thickness of electrolyte [cm].

σ : Conductivity [S/cm].

iv. Transportation Losses

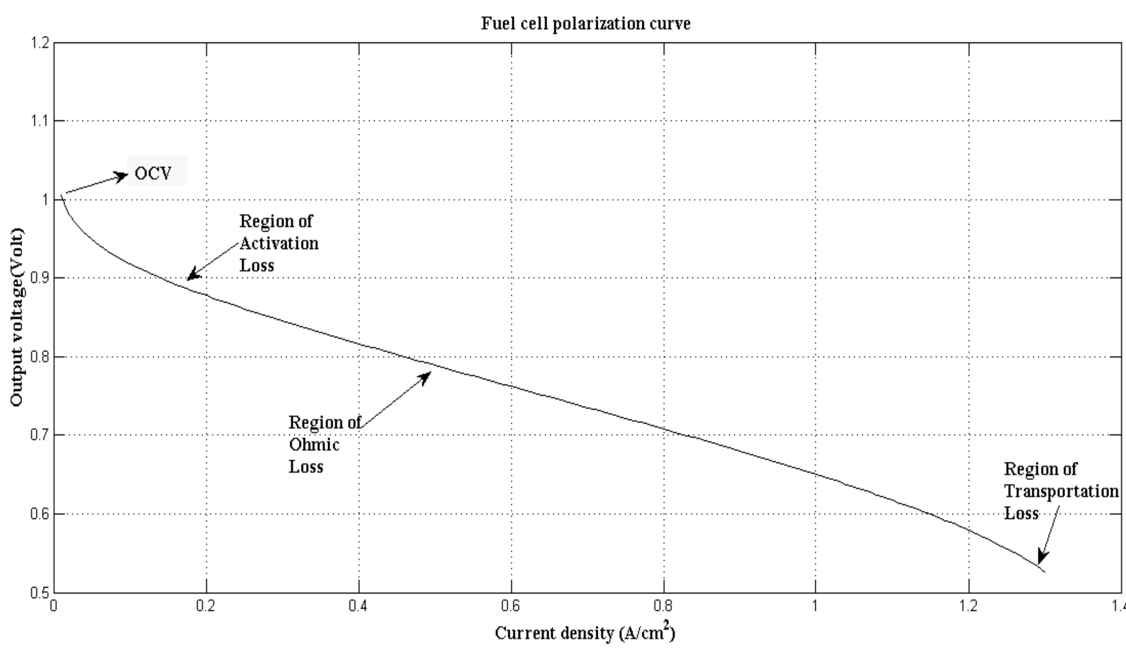
These losses are the result of changes in the concentration of reactants on the surface of the electrode as the fuel used and they are given as:

$$V_{trans} = -B\, log(1 - \frac{i}{i_L}) \qquad (2\text{-}11)$$

B: constant depends on the FC operating state [V].

i_L : Limiting current density [A/cm^2]

Fig.2.2 illustrates the polarization curve that shows the output voltage as a function of the current density of the fuel cell. The voltage starts at the open circuit value then decreases by the



effect of losses mentioned previously.

Fig 2.2. Fuel cell polarization curve that illustrates the effect of voltage losses

Table 2.2 includes the values of parameters used in the above mentioned fuel cell equations, parameter values are taken from [28]:

Table 2.2 Alkaline fuel cell parameters

Parameter	Value
Ideal gas constant, R	8.314 J/mole K
Faraday's Constant, F	96487 coulombs
Temperature, Tc	70ºC
Thickness of electrolyte, t_m	0.0125 cm
Transfer coefficient, α	0.1668
Conductivity, σ	1.235
Exchange Current Density , i_0	3.14 A/cm^2
Limiting current density, i_L	0.5 A/cm^2
Coefficient of transport, B	0.3

We applied these parameters in the above mentioned equations in Matlab in order to get the polarization curve of V-I, this curve includes all losses (activation, ohmic and transportation) for certain temperature of 70ºC, assuming that the fuel utilization is 80% and the anode pressure is 1 [atm]. We also calculated the output power of the fuel cell using the following equation:

$$P_{out} = V_{out} I_{out} A N \qquad (2\text{-}12)$$

A : Fuel cell Area.

N : Number of cells.

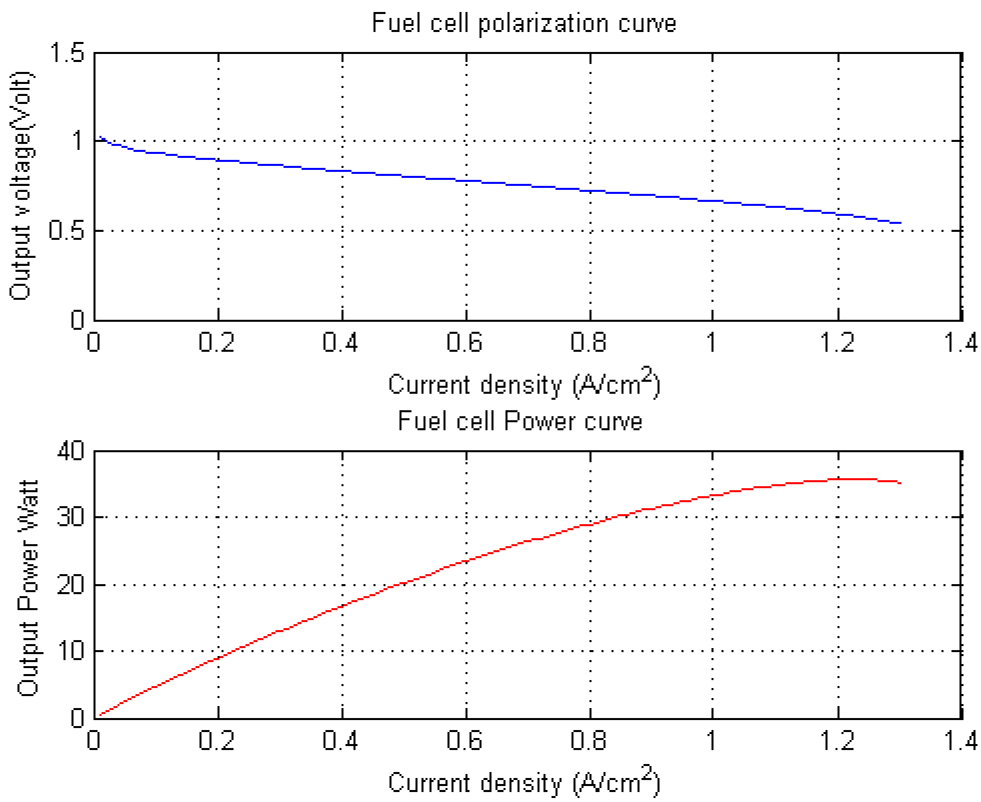


Fig 2.3. Fuel cell polarization curves

<u>b.Effect of temperature on the performance of FC</u>

The performance of the fuel cell increases with the increase in temperature. Despite increases in the ohmic losses, both activation and transportation losses decrease, making the output voltage increase with temperature increment. Run were carried out for different temperatures 60, 70 and 80º C and the corresponding curves are shown in Fig. 2.4.

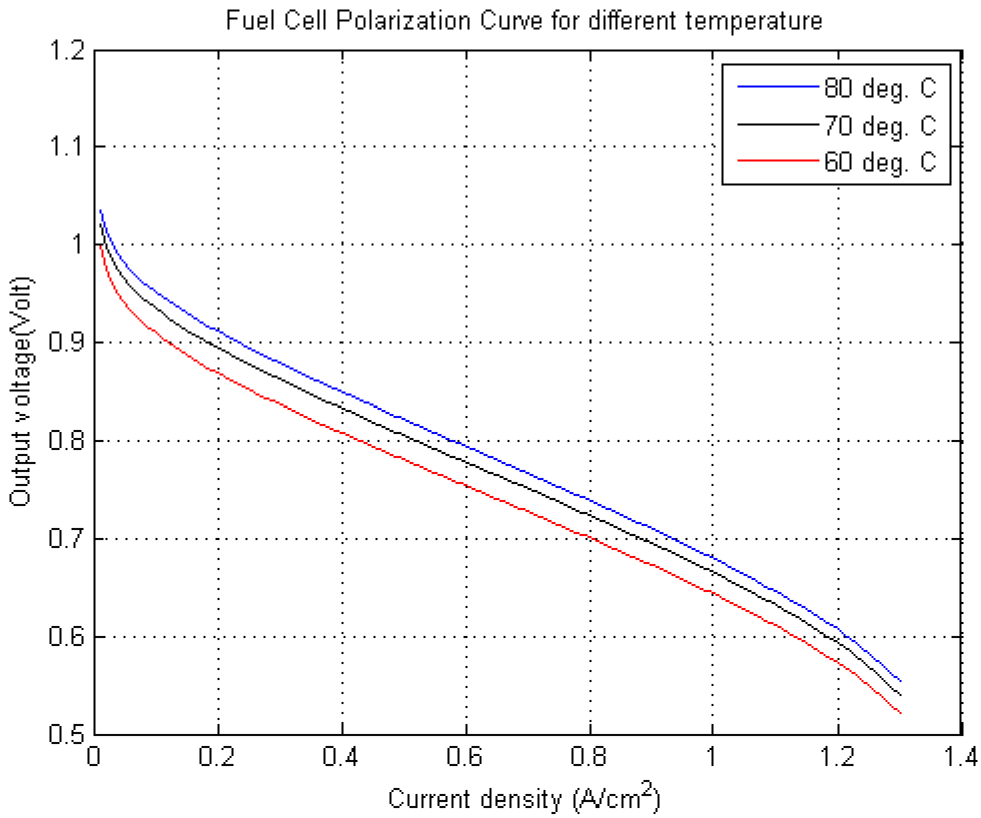


Fig 2.4 Fuel cell polarization curves for different temperature

c.Fuel cell Efficiency

The total hydrogen consumed by the fuel cell which has several cells connected in series is expressed as:

$$mH_2 = \frac{N_c\, I}{2F} \quad \text{[Moles/s]} \qquad (2\text{-}13)$$

Calculating the power produced by the fuel cell at 80ºC with 96 cells and an area of 250cm^2 from equation (2-12).

$$P = 96 * 0.6 * 0.79 * 0.25 * 10^3 = 11376 \text{ W}$$

11376 W corresponds to $\frac{0.079\ (moles/s)}{495\ (moles/kg\ )} = 1.6 * 10^{-4}\ kg/s$

Calculating the energy produced by 1 kg of hydrogen:

$E_{fc} = \frac{11376*10^{-3}}{1.6*10^{-4}*3600}$ = 19.75 kWh/kg of hydrogen consumed

This number represents the figure of merit that will be used in our project as an efficiency indicator. Note that a similar value is found from the curve of mass flow rate versus FC power by taking the slope of the curve in Fig 2.5.

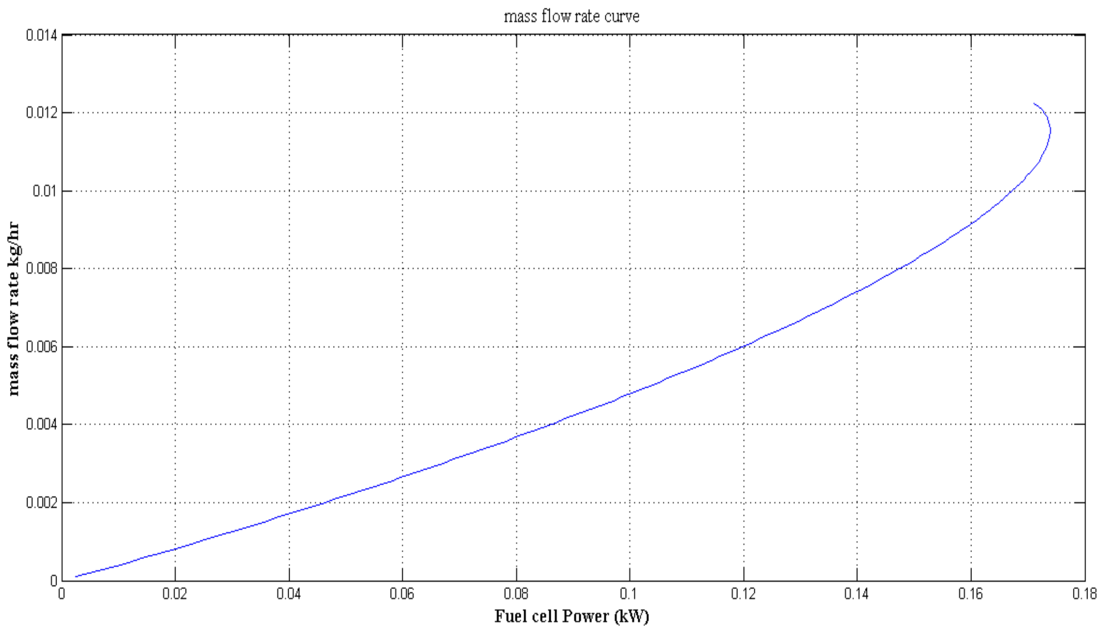


Fig 2.5 Fuel Cell Mass Flow rate curve

C. Electrolyzer

The electrolyzer decomposes the water molecule H_2O into its constituent hydrogen and oxygen by passing a current through its electrolyte in a process which is the reverse of the one that takes place in a fuel cell. The electrochemical reaction in the electrolyzer is shown in the following equation

$$H_2O + energy \rightarrow H_2 + \frac{1}{2}O_2$$

The water splitting is an electrochemical process where the electrical current in the form of electrons received from the external circuit decomposes the water at the cathode into negatively charged hydroxide ions with hydrogen gas released at the cathode. The hydroxide ions migrate to the anode where oxygen is released and water is formed with two electrons produced that travel to the cathode under the effect of the external source. The reactions in the anode and cathode of the water electrolyzer are as [29].

Anode: $$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$$

Cathode: $$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$

Producing hydrogen by water electrolysis is the simplest and most mature way, it has been used since the 1800s [30]. In addition to being the simplest way, it is also the cleanest one as long as the electricity source needed to operate the electrolyzer is coming from a renewable energy source. Water electrolyzers produce very pure hydrogen because the gasses are separated during their transformation at the electrodes [31]. However, and despite all these advantages, only 4% of the world hydrogen is obtained from electrolyzers and the reason behind this low rate is the high energy consumption of the electrolyzer [32].

This hydrogen can be used in different applications such as vehicles, power generation, industrial processes and injection to the natural gas pipelines. Furthermore, the produced hydrogen could be used directly or stored for a later use since the energetic potential of hydrogen makes it convenient for both [33].

The main types of electrolyzers used to produce hydrogen are proton exchange membrane (PEM), alkaline electrolyzer and solid oxide electrolyzer (SOEC). Alkaline and PEM electrolyzers are more mature than the SOECs [34]. Moreover, Research and Development (R&D) gives more focus on the alkaline systems compared to the PEM because of its lower costs [29]. Nowadays different sizes of alkaline and PEM electrolyzers are being manufactured starting from several kilowatts to multi-megawatts, which makes these two types commercially more available than others [34].

In our work the prime purpose of the electrolyzer is to use the excess electricity generated by the solar power to produce hydrogen and store it. The hydrogen produced by an alkaline electrolyzer will be used as a fuel to operate the fuel cell. This produces electricity in order to supply the demand when neither the main renewable source (PV panels) nor the grid are available.

1.Alkaline Electrolyzer

The normal operating temperatures of alkaline electrolyzers are 70-100ºC with pressures of 1-30 bar. The electrolyte used in the conventional alkaline electrolyzers is aqueous potassium hydroxide (KOH) with a solution of 20-30 % water because this range of concentration gives the optimal conductivity and increases corrosion resistance [32]. Moreover, alkaline electrolyzers have an efficiency of 59-70% based on the hydrogen yield [30] .This reasonable efficiency of alkaline electrolyzer illustrates that this technology is currently mature and commercially available one. The availability of alkaline electrolyzers in different sizes makes it feasible to produce hydrogen in different capacities from very small to very large.

It is true that the use of electrolyzers increase the energy consumption but at the same time they help reduce the average cost of electricity purchased [33]. Since the price of electricity varies depending on the time of the day, day of the week, and the season, we can operate it during low demand hours and limit its operation during high demand hours. And we can later use the hydrogen produced by it to serve the customers during peak demand hours, something which will make them able to supply their loads using the hydrogen instead of purchasing it with high prices.

Another challenge facing the widespread use of electrolyzers is the cost of installation and operation. However, using Nickel as an electrode reduces the cost because of its availability and low cost [30]. Electrolyzer cells have two types of designs: they are bipolar and mono-polar. System reliability and flexibility are advantages in mono-polar type cells while there are disadvantages in bipolar cells [30]. Hydrogen production by electrolyzer also needs improvement in maintaining the safety of produced gases since the mixture of hydrogen and oxygen has high flammability, thus, they should be produced and carefully managed. This requires additional effort when designing the membrane of the cell in order to insure the safety of gases produced. Another safety issue facing the operation of electrolyzers is the danger of electrolyte leakage in the connections due to their corrosive effects [30].

a.Alkaline Electrolyzer Modeling

The mathematical model for an alkaline electrolyzer is developed in this section. The water splitting process requires a minimum electric voltage to be applied on the electrodes, it is called reversible voltage which can be determined from Gibbs energy for splitting water and it is calculated as follows.

$$U_{rev} = \frac{\Delta G}{zF} \quad (2\text{-}14)$$

Where ΔG: Gibbs energy which equals to 237 [kJ/mole] at standard conditions (25º C and 1 bar).

z : The number of electrons transferred in a reaction = 2.

F : Faraday's Constant = 96487 [Col].

$U = U_{rev} + \Delta U$ (2-15)

ΔU : The equivalent voltage difference due to losses.

$\Delta U = ri + s \log(ti + 1)$ (2-16)

r: Parameter related to the ohmic resistance of electrolyte [Ωm^2].

i : Current density [Am^2]

s: Coefficient for overvoltage on electrodes [V].

t : Coefficient for overvoltage on electrodes [$A^{-1} m^2$].

Ullberg in [29] found that the ohmic resistance (r) and overvoltage coefficient (t) are temperature dependent. Adding to Ullberg's work, the authors in reference [31] found the temperature dependence expression of coefficient (s). However, in order to find the U-i relationship, we developed a first order temperature model for the transportation losses and did a parameter estimation ignoring the temperature dependence of coefficient (s) since the values given by reference [29] didn't give us identical results. We calculated the equivalent voltage difference due to ohmic and transportation losses and we ended up with the following form of equation:

$\Delta U = (r_1 + r_2 T)i + s \log((t_1 + t_2 T)\, i + 1)$ (2-17)

T : Temperature.

To do the parameter estimation we set initial values of the parameters close to the values estimated by Ullberg:

Table 2.2: Initial values of electrolyzer parameters

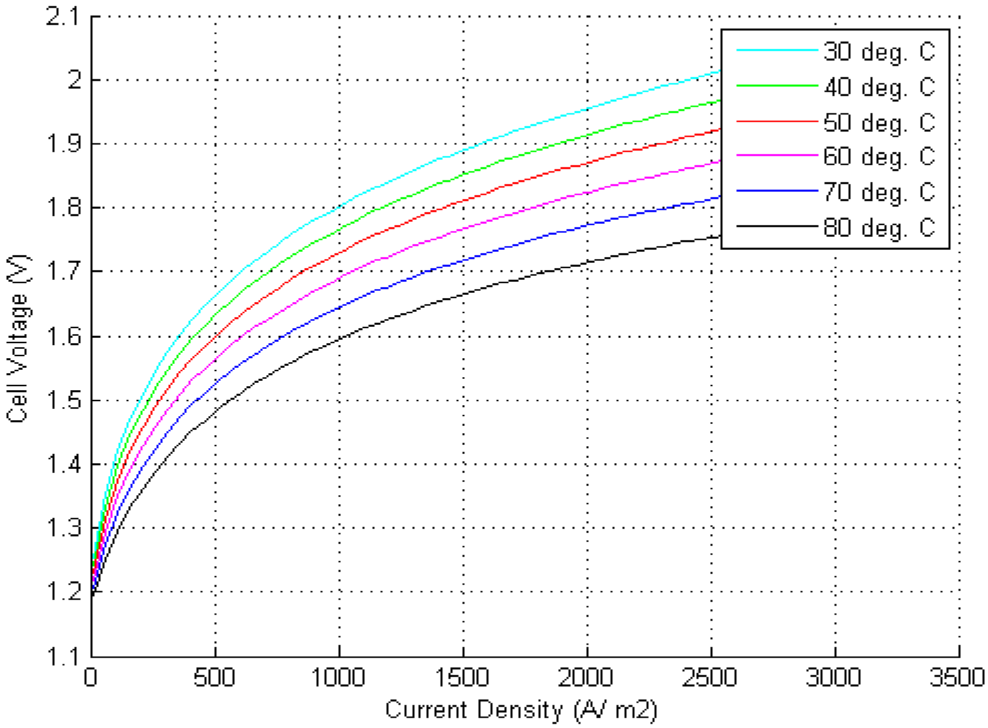
Parameter	Value
r_1 ($\mathbf{\Omega}\, m^2$)	8 x 10^{-5}
r_2 ($\mathbf{\Omega}\, m^2/C$)	-2 x 10^{-7}
S (V)	0.2
t_1 (m^2/A)	0.0114
t_2 (m^2/AC)	-7.25 x 10^{-5}

The estimated values of the parameters used in our model are included in the Table 2.3

Table2.3: Estimated values of the electrolyzer parameters

Parameter	Value
r_1 ($\mathbf{\Omega}\, m^2$)	3.32 x 10^{-5}
r_2 ($\mathbf{\Omega}\, m^2/C$)	-5 x 10^{-7}
S (V)	0.20645
t_1 (m^2/A)	0.0184068
t_2 (m^2/AC)	-0.0001469

We used the experimental data from Ullberg's work [29]. Fig 2.6 shows the polarization curve of electrolyzer for different temperatures. Then, we calculated the sum of square errors between



the experimental voltage differential value and that of the model and plotted them to compare.

Fig 2.6 Electrolyzer polarization curve for different temperatures

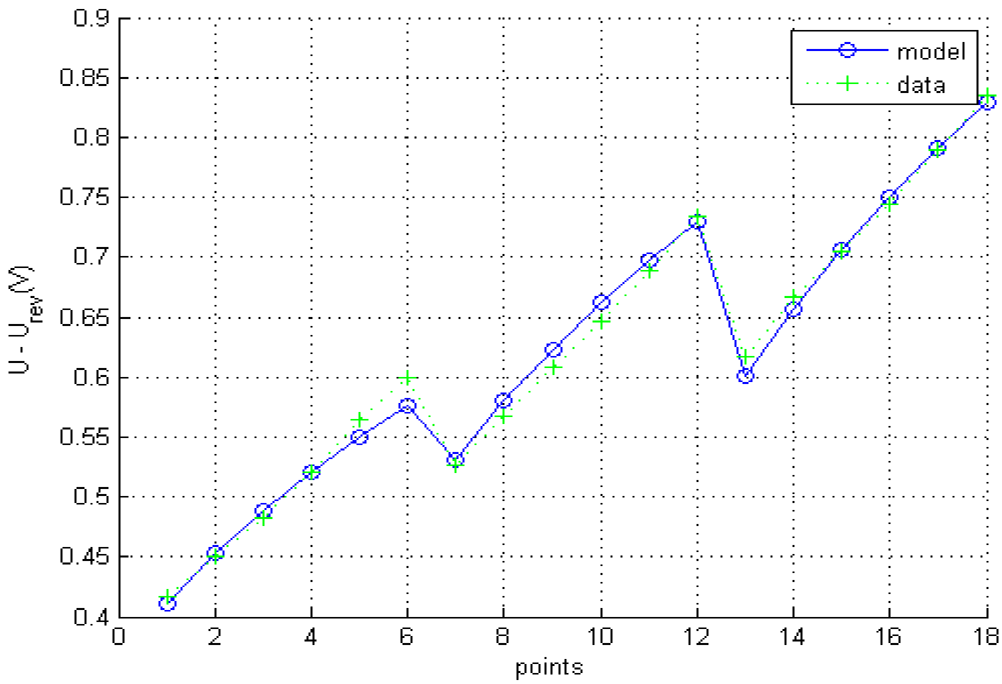


Fig 2.7 Error in Voltage between our model and Ullberg's data

b.Electrolyzer efficiency

The total hydrogen produced by electrolyzer which has several cells connected in series is expressed as:

$$mH_2 = \frac{\eta_f \; N_c \, I}{2F} \qquad (2\text{-}18)$$

Where η_f is the Faraday efficiency and it can be calculated as follows

$$\eta_f = \frac{(I/A)^2}{f_1 + (I/A)^2} f_2 \qquad (2\text{-}19)$$

Where f_1, f_2 are Faraday efficiency parameters and they are equal to [29]:

$$f_1 = 250 \; (mA)^2 cm^{-4}$$

$$f_2 = 0.98$$

Then $\rightarrow$ $\eta_f = \frac{(300)^2}{250 + (300)^2} * 0.98 = 0.997 * 0.98 = 0.9773$

Substituting in mH_2

$$mH_2 = \frac{0.9773*21*0.3*0.25*10^4}{2*96485} = 0.079 \text{ moles/s}$$

Calculating the power consumed by the electrolyzer of (10x 21) cells and Area of $250cm^2$ from equation (2-12)

$$P = 10 * 21 * 1.8 * 0.3 * 0.25 * 10^3 = 28350 \text{ W}$$

28350 W corresponds to $\frac{0.079\ (moles/s)}{495\ (moles/kg\ )} = 1.6 * 10^{-4}\ kg/s$

Calculating the energy consumed to produce 1 kg of hydrogen:

$$E_{ele} = \frac{28350 *10^{-3}}{1.6*10^{-4}*3600} = 49.21 \text{ kWh/kg}$$

This number represents a figure of merit we will use it in our project as an efficiency indicator.

D. Hydrogen Tank

Hydrogen is the fuel of the future and it will be classified as a primary energy carrier in the 21 century [35]. While talking about the hydrogen we are talking about the production, storage and utilization of this valuable energy source.

When the energy crisis in the 1970s happened, the hydrogen economy ideology has changed to give more importance to this valuable and promising future energy source. Nowadays hydrogen is considered as a promising energy carrier since it is able to contribute in solving the energy security and sustainable energy supply problems [30].

Beside water electrolyzers, hydrogen can be produced from natural gas, coal biomass and hydrocarbons. Hydrogen production by water electrolyzers received renewed interest since it’s the cleanest method from the ones mentioned. However, a lot of challenges are facing this method like the need to improve efficiency and decrease cost of production [36].

In our work we are using hydrogen tank to store the hydrogen produced by the electrolyzer to be later used as a fuel to operate the fuel cell. The tank at day one of operation is filled with initial mass of hydrogen and at the same time it has a minimum limit, to prevent shortages in hydrogen, and a maximum limit, to prevent leakage problem.

E. Load Model

We had a load data of one day, with an interval of one hour, from each month in Lebanon from the 1974 yearly book of statistics of EDL. The given loads were as a percentage to the peak load, and the methodology that was used to move from the daily data the one year data is explained in the following paragraph.

From a data of one day we had a profile of a week by multiplying the corresponding weekly peak taking into consideration weekdays and weekends from the IEEE reliability study [20] and scaled it over a week. Table 2.4 shows the assumed daily peak of load in percent of weekly load.

Table 2.4 Daily load in Percent of Weekly Peak

Day	**Peak Load**
Monday	93
Tuesday	100
Wednesday	98
Thursday	96
Friday	94
Saturday	77
Sunday	75

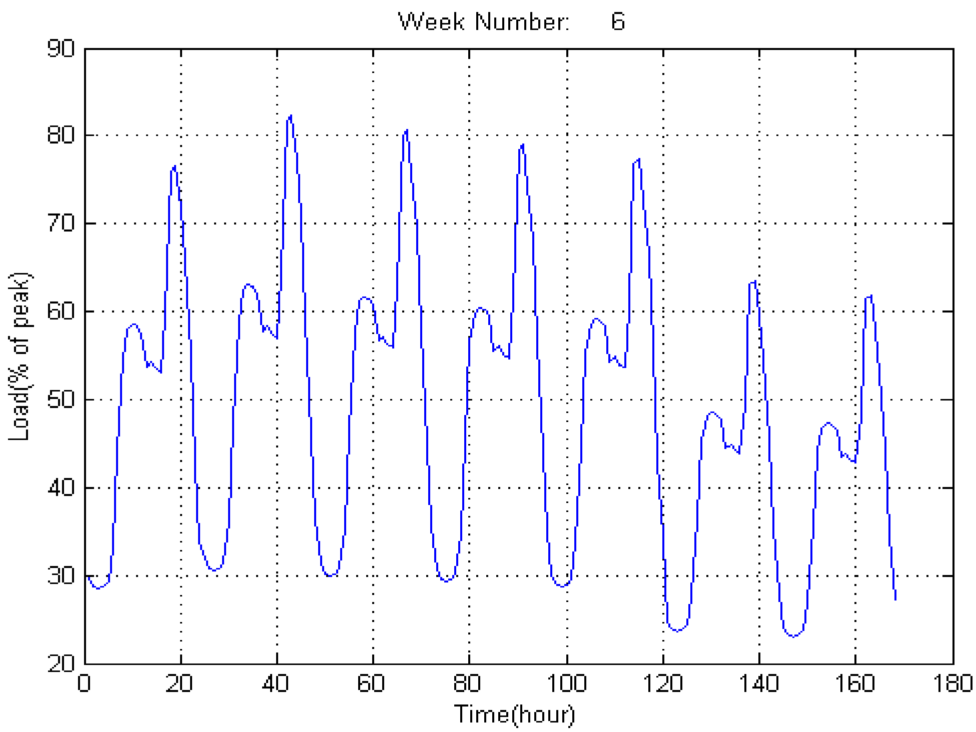


Fig 2.7 Load profile of week number 6

Fig 2.7 represents week number 6 of the year, which is the second week of February. We can notice the demand decreases in the weekends while it is the maximum on Tuesday.

After having the one week profile we considered it as the second week of each month. Then we took the average weighted between these weeks depending on the distance between them in order to find the data of other weeks of each month. Interpolation techniques were used to smooth the edges of day ends and weekends. After getting the data of 364 days we added a day to get a full year data of 365 days that corresponds 8760 hours.

F. Main Grid

Today, the electricity production from the main grid in Lebanon is around 1500 MW while the need is 2400 MW at peak hours, resulting in electricity cuts for hours during the day. The electricity cut offs has a schedule that is repeated every two days as shown in Fig 2.8, where 1 is ON state and 0 is OFF state of grid:

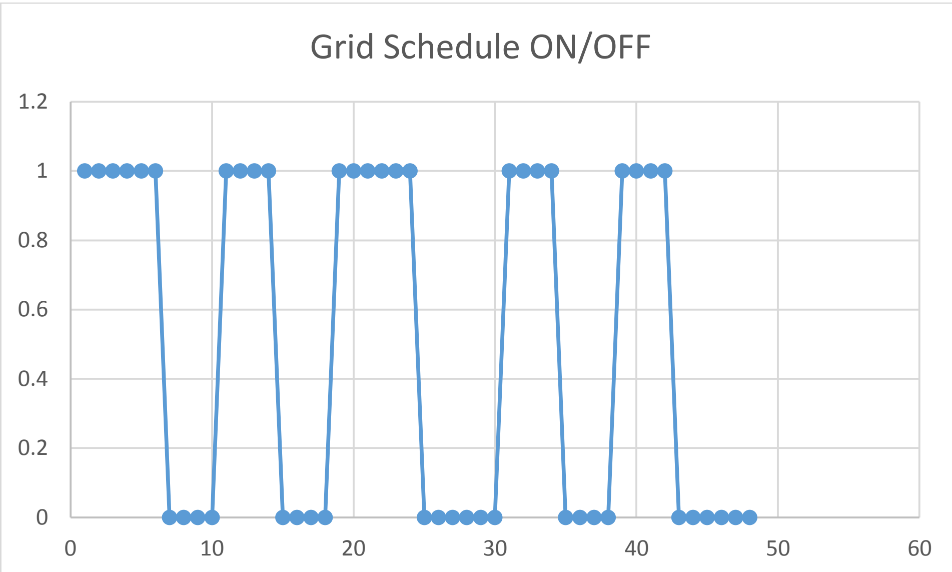


Fig 2.8 Grid Schedule

The certain electricity tariff that was used has different levels depending on the time of day and the season. The tariff has a peak value of 320 LBP at peak hours to be dropped to the day rate of 112 LBP and 80 LBP at night rate. Table 2.5 illustrates:

Table 2.5 Lebanon Electricity tariff for different hours of day

Time of Day- Winter (October 1- March 31)	Time of Day- Summer (April 1-September 30)	Tariff LBP/kWh
Night Rate (from 00:00-07:00)	Night Rate (from 00:00-07:00)	80
Day Rate (from 07:00-16:30)	Day Rate (from 07:00-18:30)	112
Peak Rate	Peak Rate	320

(from16:30- 20:30)	(from18:30- 21:30)	
Day Rate (from 20:30-23:00)	Day Rate (from 21:30-23:00)	112
Night Rate (from 23:00-24:00)	Night Rate (from 23:00-24:00)	80

G. Ultra-Capacitor (UC)

The UC is a power delivering and energy storing device. Capacitors store electric energy by accumulating positive and negative charges (often on parallel plates) on the surface of the electrode, the thing that makes UCs have limited energy storage compared to the batteries [37]. However UCs are able to charge/discharge 100 times faster than batteries with higher power density. In our project, the UC will support the fuel cell specially when having large variations in the load where the fuel cell is not able to cover those quick variations.

CHAPTER III

PROBLEM FORMULATION

A. Problem definition

The diagram of the system components is shown in Fig 3.1. It is a grid-connected hybrid renewable energy system which consists of a photovoltaic array as a main renewable energy source. In addition to two types of back-up (storage) systems; the first one is a long term storage device based on an alkaline fuel cell and electrolyzer, where the electrolyzer produces hydrogen converting the electrical power taken from the DC bus to hydrogen, this hydrogen will be stored in a tank to later be used as a fuel to feed the fuel cell in order to produce electricity. While the second type of back-up system is the ultra-capacitor, which is a short term storage device. The grid is unreliable and its price is time variant. The EMS will find the optimum solution to feed the load from the existing renewable sources.

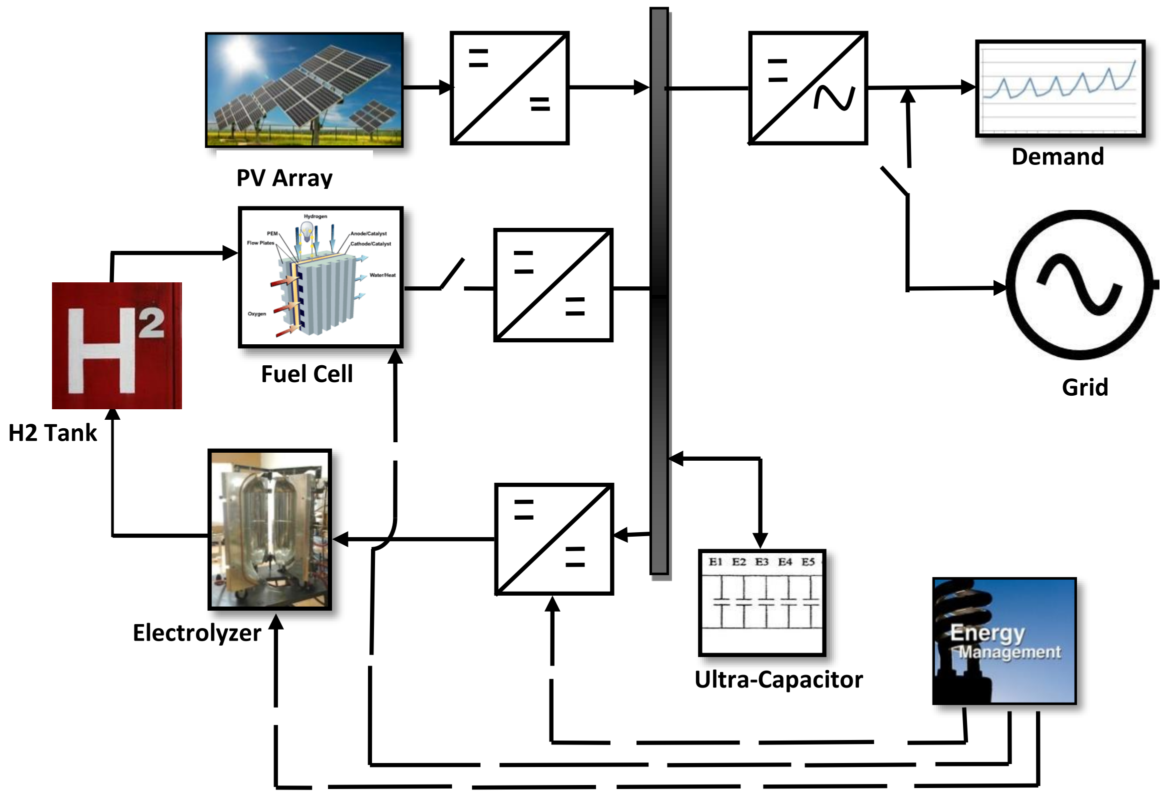


Fig 3.1 Hybrid System Components

B. Optimization problem formulation

The optimization strategy provides an optimal energy management for a grid-connected hybrid renewable energy system in order to minimize the cost of energy obtained from the grid connection supply by getting free energy from the alternative renewable sources while the grid is unavailable. This will minimize the cost of purchasing electricity from the grid while getting reliable and clean power supply that will decrease the CO_2 emissions.

1. System cost

The objective function is the price of operating the system that includes the price of electricity purchased from the grid by the consumer, the cost of carbon cleaning, and the cost of operating both fuel cell and electrolyzer for every hour during a year h =1,..., N. The cost function is a linear relation and it is represented in the following equation:

$$\emptyset = \sum_{t=1}^{N}[P_G(t)\ (\gamma_G + \gamma_{C)}\ \Delta t + P_F(t)\ \gamma_F \Delta t + P_E(t)\gamma_E \Delta t] \quad (3\text{-}1)$$

For all t= 1,..., N where N = 8670 the number of hours per year.

P_G : Power of grid [kW].

γ_G : Grid electricity price and it is time sensitive [$/kWh].

γ_C : Cost reflecting carbon cleaning [$/kWh].

P_F : Power generated by the Fuel cell [kW].

P_E : Power consumed by the electrolyzer [kW].

γ_F, γ_E: Costs of operating fuel cell and electrolyzer respectively [$/kWh].

Δt : Interval =1 hour.

C. Contraints

1. Power balance contraint

$$P_F(t) - P_E(t) + P_{C^+}(t) - P_{C^-}(t) + P_G(t) = P_D(t) - P_{PV}(t) \quad (3\text{-}2)$$

Constraint (3-2) is the power balance constraint and it is the sum of powers generated and consumed in the system. Generated power from the fuel cell, electrolyzer, ultra-capacitor and grid should be equal to the net power which is the subtraction of demand (load) power and the solar power. Where:

$P_{C^+}(t)$: Power supplied from the Ultra-capacitor [kW].

$P_{C^-}(t)$: Power supplied to the Ultra-capacitor [kW].

$P_V\ (t)$: Power generated from the grid [kW].

$P_D(t)$: Demand (load) power [kW].

$P_{PV}(t)$: Power generated by the photovoltaic array [kW].

2. Constraints related to the Fuel Cell

$P_F^{min} \leq P_F \leq P_F^{max}$ (3-3)

$-R_F \Delta t \leq P_F(t) - P_F(t-1) \leq R_F \Delta t$ (3-4)

P_F: Power provided by fuel cell [kW].

R_F: Ramp-rate limit of the fuel cell [kW/s].

Constraint (3-3) determines power level limits on fuel cell operation. While constraint (3-4) is the ramp-rate constraint that prevents the sudden changes in the output power since the chemical reactions inside the cell need time to be done.

3. Constraints related to the Electrolyzer

$P_E^{min} \leq P_E \leq P_E^{max}$ (3-5)

$-R_E \Delta t \leq P_E(t) - P_E(t-1) \leq R_E \Delta t$ (3-6)

P_E: The power consumed by the electrolyzer to produce hydrogen.

R_E : Ramp-rate limit of the electrolyzer [kW/s].

Constraints (3-5) and (3-6) in the electrolyzer are similar to the (3-3) and (3-4) in the fuel cell. The electrolyzer has a range of power that can operate in and also has a range of ramp-rate that is taken into consideration.

4. Constraints related to the hydrogen tank

$m_{H2}^{min} \leq m_{H2}(t) \leq m_{H2}^{max}$ (3-7)

$m_{H2}(t) - m_{H2}(t-1) - P_E(t)\eta_E \Delta t + P_F(t)\eta_F \Delta t = 0$ (3-8)

m_{H2} (t): Mass of hydrogen at moment (t) [kg].

m_{H2} (t -1): Mass of hydrogen at previous moment[kg].

η_E , η_F : efficiencies of electrolyzer and fuel cell [g/kWh].

Constraint (3-7) puts limitations on the level of hydrogen that should be filled in the hydrogen tank. It should not be less than the minimum amount considered in order to make sure we will always have enough amount of hydrogen in emergency cases, it also should not exceed the maximum value considered. While constraint (3-8) tells that the mass of hydrogen at a current time depends on the amount of it in a previous time added to the amount of hydrogen produced by the electrolyzer that has an efficiency of η_E minus the amount of hydrogen consumed by the fuel cell that has an efficiency of η_F. Where, the hydrogen produced by the electrolyzer is the product of its power, a figure of merit, and the time interval. A similar expression is used for the hydrogen consumed by fuel cell.

5. Constraints related to the capacitor

$$P_C^{min} \leq \quad P_C(t) \leq \quad P_C^{max} \qquad (3\text{-}9)$$

$$Q(t) - Q(t-1) + \frac{P_{C^+}(t)\Delta t}{\eta_C} - P_{C^-}(t)\Delta t \eta_C = 0 \qquad (3\text{-}10)$$

Constraint (3-9) determines power level limits on capacitor operation. While constraint (3-10) is related to the capacitor charge and tells that the charge of a capacitor at time (*t*) is equal to the charge at (t -Δt) added to the net charge delivered to the capacitor during time interval (*t*), while accounting for the efficiency of charge and discharge.

No ramp rate constraints for the capacitor will be considered as assumed their ramping capability is very high.

CHAPTER IV

METHODOLGY AND RESULTS

A. Thesis Methodology

LP was used as the optimization technique because the cost function and all constraints are near linear and as such were linearized. LP is easy to implement is used to determine the optimal allocation of the power variables.

We collected solar radiation, weather data and demand data for a village in Lebanon or the Middle East over a year. The system was designed by modeling each component, the demand data was modeled by a time series of demand value over a year, the power available was also modeled by time series for the given value solar radiation and temperature. The fuel cell was modeled by a merit order number specifying the hydrogen consumption per kW of power output. Similarly, the electrolyzer will be modeled by a number determining the hydrogen production per kW of power. The hydrogen available in the tank was calculated. Then, we determined the optimal energy management system of the grid connected renewable energy system using linear programming methodology.

The system size was determined using the trial and error method guided by results obtained using the developed tool for optimal system operation. The objective of the sizing exercise was to satisfy the load demand, and at the same time reducing the electricity purchase from the grid.

B. Case Study

Grid-connected renewable energy sources are provided to supply the demand of a village called Anjar also known as Housh Mousa located in Bekaa Valley, Lebanon. Since the grid is fed from conventional sources that increase carbon emissions to the atmosphere in addition to its unreliable state, we want to decrease electricity purchased from the grid using clean renewable energy sources.

1. Description of the Village

Anjar is 50km from Beirut, a total area of 20$km^2$with a population of around 2400, has a longitude of (33.725ºN 35.92ºE), with an altitude of 950m from the sea level.

The village has three schools, three churches, one governmental building, an athletic and cultural club, a health center, a hotel, restaurants, shops and houses. The village has a high solar irradiation that makes the use of solar energy very beneficial. We will supply this village with electricity using PV panels as a main source with two types of back-up systems in order to support the PV when there is no sunlight and the grid is not available.

To estimate the electricity demand of the village we will start calculating the electrical power needed to supply the loads in the utilities mentioned above. Assuming a family size of 5 persons means we have 600 houses to be fed with electricity. Was considered that $I = 10$ Amperes, $V = 220$ Volts for each house is enough for lighting and supplying the basic applications with electricity, assuming the loads are turned on half of the time and taking a demand diversity factor of 0.5:

$$P_{houses} = IVND = 10 * 220 * 600 * 0.5 = 660\ kW$$

The village has a governmental building that consists of three floors each has10 rooms, each room needs three lamps of 20 watts;

$$P_{govbuilding} = 3(floors) * 10(rooms) * 3 * 200 = 1800\ Watts = 1.8\ kW$$

Each church has 10 chandeliers that consists of 10 lamps with power of 11 watts, then each church need $10 * 10 * 11 = 1100$ watts for lighting. Multiplying with the number of churches which is three:

$P_{churches} = 3 * 1100 = 3.3\ kW$

Concerning the hotel which is a small hotel of 10 rooms, each room needs a refrigerator of 120 Watts, 60 Watts of lighting and 100 Watts for TV. So each room need 120+60+100= 280 Watts. Total power needed for rooms is$10 * 280 = 2.8$ kW. While the corridor needs 10 lamps of 16 Watt. Then, the total power needed for the hotel becomes:

$P_{Hotel} = 2800 + (10 * 16) = 2960\ Watts = 2.9\ kW$

The medical center consists of four rooms, each needs $4 * 20 = 80\ Watts$ for lighting also has two sockets$2 * 175 = 350\ Watts$. So the total power needed for the medical center is:

$P_{medical} = 4 * (80 + 350) = 1730\ Watts = 1.73\ kW$

The village has three schools, each school has almost 15 rooms (classrooms + offices). The room need $40\ Watts$ for lighting, $30\ Watts$ for ceiling fan, one socket of$175\ Watts$. Then$P_{SCH-room} = 40 + 30 + 175 = 245\ Watts$. However, the total power needed for the three schools is:

$P_{school} = 3(schools) * 15(rooms) * 245(W\ per\ room) = 11\ kW$

Assuming an average demand factor of 0.5

$$P_{other} = P_{govbuilding} + P_{churches} + P_{Hotel} + P_{medical} + P_{school}$$

$$= 0.5 * (1.8 + 3.3 + 2.9 + 1.73 + 11) = 10.4\ kW$$

$$P_{tot} = P_{houses} + P_{other} = 660 + 10.4 = 670.4\ kW$$

C. Carbon footprint

Carbon footprint is the total amount of carbon produced directly and indirectly by a person, event or product. Almost 57% of greenhouse gasses emitted to the atmosphere is carbon dioxideCO_2. Burning fossil fuel is the primary source of CO_2in different sectors of transportation, energy, industry and agriculture. For example, when someone drives his/her car the engine burns fuel that emits an amount of $CO_2$to the atmosphere depending on the type of the fuel burnt and the distance. Also burning fossil fuel in order to generate electricity emits a certain amount ofCO_2, this number differs from one country to another depending on the type of fossil fuel burnt and the efficiency of the power plant used to generate electricity. In Lebanon the average CO_2emissions from electricity generation is 0.709 kg/kWh [38].

1. The social cost of carbon

The carbon dioxide is one of the greenhouse gases that prevent block infrared radiation emitted by various processes on earth and thus lead to global warming. Hence, since excessive carbon dioxide emissions have harmful effect on the environment, governments are specifying standards to reduce the carbon emission. Thus it appears that the social cost of carbon (SCC) is an important policy tool that estimates the economic cost of the damages caused by one additional metric ton of carbon dioxide released to the atmosphere [39]. However, there is a wide uncertainty about the SCC differs from one country to another and even in the same country as the parameters of importance change; SCC varing between $9/ton of CO_2in the poorest countries like south Asia to $5,040/ton in the richest ones such as United States of America [40].

The US government uses values of $11, $33 and $52/ton of CO_2[41]. While in Lebanon reports talk about $65 per metric ton of CO_2 in 2009[42]. However, these numbers are really low compared to the effect of these emissions on the climate, in the absence of other analyses they become almost negligible. Hence, when estimating the social cost of carbon we should take into account the effect of these emissions at both present and future periods. Combining different time periods to estimate a value is called discounting, which is the decrement in the value of the money by years [39]. For example 1 dollar today has a higher value than the one received in the future. Especially when applied to the expected environmental damages that will be caused by these emissions on the future generations. The same values used by the US government and after taking discount rates of 1,1.5, and 2% per year and calculated the SCC in 2010 at become $62, $122 and $227 /ton [41].

While the United Kingdom, which is one of the major and pioneer SCC policy makers, estimated a range of $41- $124/ton of CO_2 in 2009 taking average value of $83 [39].

When talking about the impacts of these emissions on the future generations, and since determining the SCC has a lot of impact on decreasing these emissions. Then defining the discount rate should be from the ethical point of view more than the financial aspect [39].

The SCC is increasing every year because the future emissions are expected to produce larger incremental damages as physical and economic systems become more stressed in response to greater climatic changes. However, the growth rate of SCC is also uncertain letting the door to the personal judgment, it ranges from 3% as a central value [43] to 25% [41] where in the latest one the equation of damages on climate is assumed quadratic relation with the temperature change.

Proceeding from the 2009 value of SCC in Lebanon and having a range of growth rates, we will use the following equation to calculate SCC in 2015:

$$P_{Future} = P_{Present}\,(1+i)^n$$

$P_{Present}$: Is the present SCC value that we have \$65/ton of CO_2 (2009 value)

i: The growth rate.

n: Number of periods

In Lebanon the SCC in 2009 was \$65/ton of CO2. Taking a range of SCC growth 3% to 25% the new value in 2015 will be in the range of \$78 and \$248 per ton metric of CO2 using the above mentioned equation.

In this thesis we will use an average value for the SCC of \$210/ton metric of CO_2. Knowing that this is not the value implemented by the Lebanese government, but based on the discussion mentioned above it seems to be a reasonable value to use. The average CO2 emission per kWh for Lebanon is 0.709 kg/kWh [44]. We will calculate the SCC that will be used in our project as following:

$$SCC = \frac{210}{1000} * 0.709 = 0.15 \text{ \$/kWh}$$

D. Sizing of Components

The sizing of the system components was done in a heuristic manner based on common sense. Basically, to satisfy the load demand we used a trial and error method when choosing the sizes of the system components. In the following an explanation is provided of how we chose the sizes for each component and tables of their sizes.

1. PV Modules

The size of the PV modules was selected to give output power that is enough to feed the peak load when the solar radiation is available. PV modules were used to feed the loads, generate hydrogen through the electrolyzer and operate the fuel cell when needed, also used to sell electricity to the main grid.

Table 4.1 illustrates the specifications of used PV modules, where we used SunPower PV modules with rated power of 333 watts for each.

Table 4.1: SunPower Solar Module

SunPower E20/333 Model: SPR-333NE-WHT-D	
Nominal Power (W)	333
Open Circuit Voltage (V)	65.3
Short Circuit Current (A)	6.46
Rated Voltage (V)	54.7
Rated Current (A)	6.09
NOCT (◦C)	45

2. Fuel Cell

The size of other components such as FC, EL, hydrogen tank and UC is set choosing the least solar radiation days of the year which represent the worst days that require the highest sizes of backups. We started with large sizes then checked the results of EMS to minimize some components or maximize others. Then, based on the results from the EMS we would reduce the size the fuel cell if we determine that the largest value of fuel cell observed is significantly smaller than the specified capacity. Otherwise, if the value of the power is always at the upper limit then we conclude that we need to increase the capacity of the fuel cell plant.

Table 4.2 Fuel cell size

Fuel Cell	
$fce.P_{max}$ (kW)	600
$fce.eff$ (kg/kWh)	1/19.7
$fce.cost$ ($)	2000

3. Electrolyzer

Table 4.3 illustrates some of electrolyzer specifications like the rated power, the efficiency and the capitol cost.

Table 4.3 Electrolyzer size

Electrolyzer	
$ele.P_{max}$ (kW)	900
$ele.eff$ (kg/kWh)	1/49.2
$ele.cost$ ($)	1400

4. Hydrogen tank

Table 4.4 illustrates the specifications of hydrogen tank used, it includes the tank size in kg and the capitol cost.

Table 4.4 Hydrogen tank size

Hydrogen Tank	
$hyd.P_{max}$ (kg)	500
$hyd.cost$ ($)	400

5. Ultra-Capacitor

Table 4.5 Ultra-Capacitor size

Ultra-Capacitor	
$UC.P_{max}$ (kW)	300
$UC.P_{min}$ (kW)	-300
$UC.Q_{max}$ (kWh)	600
$UC.eff$	0.85

$UC.cost$ (\$)	350

6. Batteries

We used batteries for scenarios mentioned later in the chapter in order to do a comparison for different components.

Table 4.6 Battery size

Battery	
$Bat.P_{max}$ (kW)	700
$Bat.P_{min}$ (kW)	-700
$Bat.Q_{max}$ (kWh)	5000
$Bat.eff$	0.85
$Bat.cost$ (\$)	200

E. Test Runs

We chose different scenarios and run them for one year on our data, and we did comparisons between these scenarios for both economic and environmental aspects.

1.Base Scenario

In this scenario we assumed that the only available energy source is the grid considering it a reliable source, neglecting all other sources. The run of the scenario is done for one year data. This case is not real for Lebanon.

$$Cost\ of\ objective = Cost\ of\ grid + Cost\ of\ CO2$$

$$Cost\ of\ CO2\ from\ grid\ (\$)\ = Net\ grid\ energy * cost\ of\ CO2$$

Where cost of CO2 is 0.15 (\$/kWh) is the Social Cost of Carbon (SCC), we have explained the calculation of this number in this chapter when we talked about the SCC.

$$LCOE\ (\frac{\$}{kWh})\ =\ \frac{Cost\ of\ objective}{Energy\ Demand}$$

Table 4.7 Results of Base Case

Cost of Objective ($)	797,951.7
Net grid Energy (kWh)	3,281,584
Cost of CO2 from grid($)	492,237.6
LCOE ($ /kWh)	0.243
CO2 emissions (kg)	2,326,643
CO2 emission Saving (kg)	0
CO2 cost Saving ($)	0

For base case the net grid energy is the energy taken from the grid since the energy sold to the grid is zero. Environmentally, this case is the worst one, where all the energy needed is supplied from conventional sources and no renewable energy sources used.

2.Scenario 1

In this scenario we have two energy sources. PV panels plus a reliable grid. Similarly to the base case we did the runs for one year long data. In order to calculate the LCOE we need to calculate the PV annuity, taking into consideration the lifetime of the panel considered to be 25 years with an interest rate of 6%. The capital cost of PV module including inverters and civil works is estimated 2500 $/kW the price of PV module.

$$PV_{investment} = kWp * Cost\ of\ PV$$

$$kWp = number\ of\ modules * \ V_{m0} * \ I_{m0}$$

$= 3500 * 54.7 * 6.09 = 1{,}165{,}930$ Watt

$PV_{investment} = 1{,}165.93 * 2500 = 2914826$

$PV_{annuity} = PV_{investment} * ann_{PV} = 228{,}017$($/year)

Where; $ann_{PV} = \frac{initial\ rate}{1-(1+intitial\ rate)^{-25}} = \frac{6\%}{1-(1+6\%)^{-25}} = 0.078$

$$LCOE = \frac{PV_{annuity} + Cost\ of\ objective}{Energy\ Demand}$$

Table 4.8 Results of Scenario 1

Cost of Objective ($)	370,488
Net grid Energy (kWh)	1,423,293
Cost of CO2 from grid ($)	213,494
PV investment ($)	2,914,826
PV annuity ($/year)	228,017
LCOE ($ /kWh)	0.182
CO2 emission (kg)	1,009,115
CO2 emission Saving (kg)	1,317,528
CO2 cost Saving ($)	197,629

Having PV panels in addition to the reliable grid made the cost of objective drop into almost to the half of the base case cost, since the PV panels will supply the loads when the solar radiation is available and will sell electricity to the grid is case of having excess power. This will decrease the net grid energy because the system is able to sell electricity to the grid. Moreover, the CO2 emissions savings will increase. As we can notice that the LCOE for this case is lower than the one in the base case, because we are getting the solar energy for free.

This scenario is advisable when taking both environment and economic aspects into account, since it has a lot of carbon savings and low LCOE. But, unfortunately this is not a real case for Lebanon that has an unreliable grid.

3.Scenario 2

In this scenario we have PV panels, reliable grid, and batteries. This scenario has batteries as an additional component on scenario 1. In order to calculate the LCOE we need to calculate the battery annuity, taking into consideration a lifetime of 10 years with an interest rate of 6%. Where the capital cost ($Cap_{costBat}$) of a battery is 200 $, and the Operation and Maintenance cost ($O\&M_{Bat}$) is 1% of the capital cost annually.

$$Bat_{annuity} = Bat_{annualcost} + O\&M_{Bat}$$

$$Bat_{annualcost} = Bat_{Pmax} * Cap_{costBat} * ann_{Bat}$$

$$ann_{Bat} = \frac{initial\ rate}{1 - (1 + intitial\ rate)^{-10}}$$

$$O\&M_{Bat} = \frac{1\% * Bat_{annualcost}}{ann_{Bat}}$$

Then the LCOE of the system will be as following:

$$LCOE = \frac{PV_{annuity} + Cost\ of\ objective + Bat_{annuity}}{Energy\ Demand}$$

Table 4.9 Results of Scenario 2

Cost of Objective ($)	313,490
Net grid Energy (kWh)	1,720,021
Cost of CO2 from grid ($)	258,003
PV investment ($)	2,914,826

PV annuity ($/year)	228,017
LCOE ($ /kWh)	0.171
CO2 emission (kg)	1,219,495
CO2 emission Saving (kg)	1,107,148
CO2 cost Saving ($)	166,072

In this case the cost of objective is less than the previous one with more net grid energy and more cost of CO2 since the emission savings are less. However, the LCOE when having batteries is less than not having since the charging procedure is taking place when the grid has low price and the discharging procedure when the grid has high price or when the load are during their peak value. We can follow the time of charging and discharging of batteries for a one day test shown in Fig 4.1. Where $C_n$the net power of the battery, and its negative value represent the charging process that occurs during the lowest grid price (from 0-7 am). And the discharging occurs at the peak time of afternoon till night (16-21pm).

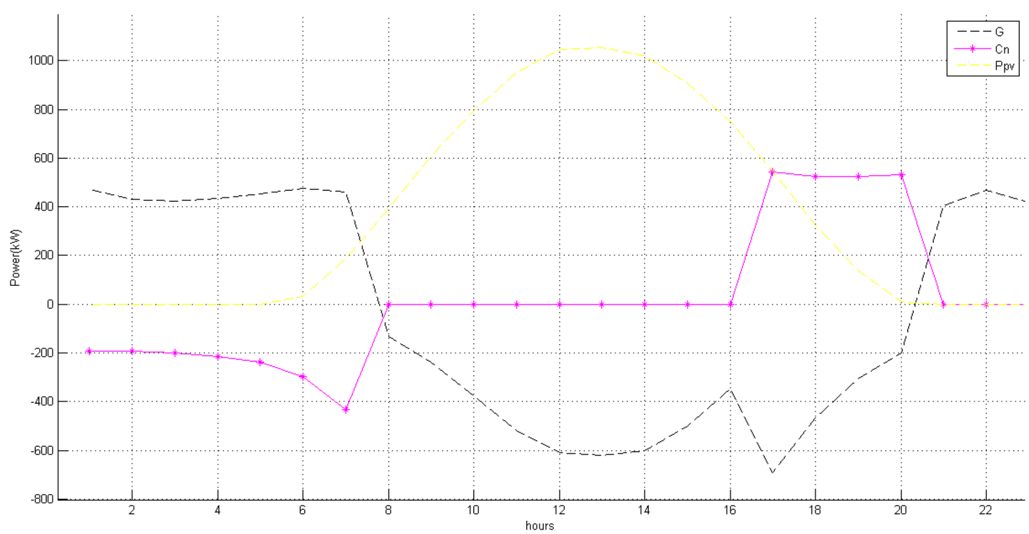


Fig 4.1 Illustration of battery's charging/ discharging hours

Having PV with reliable grid in addition to batteries will lower the LCOE and lower the CO2 savings when compared to the case of not having batteries. Economically this case is the best one but environmentally it is not.

4.Scenario 3

This scenario is similar to scenario 2 except that the grid in this case is unreliable. No changes in the calculations but the results are different.

Table 4.10 Results of Scenario 3

Cost of Objective ($)	491,417
Net grid Energy (kWh)	2,005,821
Cost of CO2 from grid ($)	300,873
PV investment ($)	291,482,6
PV annuity ($/year)	228,017
LCOE ($ /kWh)	0.225
CO2 emission (kg)	1,422,127
CO2 emission Saving (kg)	904,516
CO2 cost Saving ($)	135,677

In this scenario we have higher cost objective, and much higher value for the net grid energy which means we are getting more energy from the grid and increasing the amount of CO2 emissions and lower their savings. In addition to the higher LCOE since the charging of the batteries are occurring whenever the grid is available, even when the price of purchasing electricity from the grid is high. We can notice from the results that this case is worse than the previous one.

The difference between scenario 2 and 3 is the reliability of the grid. The effect of having unreliable grid in Scenario 3 appeared on getting higher LCOE and higher CO2 emissions. Then, the effect of grid reliability was obvious on both environmental and economic aspects.

5.Scenario 4

In this scenario we have PV panels, an unreliable grid, a hydrogen cycle of a fuel cell and an electrolyzer with hydrogen tank, and an ultra-capacitor. In order to calculate the LCOE we need to calculate the annuities of the PV, the fuel cell, the electrolyzer, a hydrogen tank, and the ultra-capacitor, taking into consideration the lifetime of each. Considering 25 year lifetime for both PV panels and hydrogen tank. While 10 year lifetime for others. Where the capital cost of PV module including inverters and civil works is 2500 $/kW the price of PV module. While the capital cost of the system components are as:

The fuel cell cost is 2000$/kW [45], the electrolyzer cost is 1400$/kW [46], the hydrogen tank cost is 400$/kg, and the capacitor cost is 350$. With an interest rate of 6% we did the following calculations:

Calculating fuel cell annuity:

$$FC_{annuity} = FC_{annualcost} + O\&M_{FC}$$

$$FC_{annualcost} = FC_{Pmax} * Cap_{costFC} * ann_{FC}$$

$$ann_{Bat} = \frac{initial\ rate}{1 - (1 + intitial\ rate)^{-10}}$$

$$O\&M_{FC} = \frac{1\% * FC_{annualcost}}{ann_{FC}}$$

The calculation of other components' annuities where done in a similar manner. Where$EL_{annuity}$, $H2_{annuity}$, $Cap_{annuity}$ represent the annuities of electrolyzer, hydrogen tank, and capacitor respectively.

$$LCOE = \frac{PV_{annuity} + Cost\ of\ objective + FV_{annuity} + EL_{annuity} + \ H2_{annuity} + \ Cap_{annuity}}{Energy\ Demand}$$

The results for one year simulation are as following:

Table 4.11 Results of Scenario 4

Cost of Objective ($)	582,659
Net grid Energy (kWh)	2,561,771
Cost of CO2 from grid ($)	384,265
PV investment ($)	291,482,6
PV annuity ($/year)	228,017
Energy Supplied by Fuel Cell(kWh)	728,377
Energy Consumed by Electrolyzer(kWh)	1,814,175
LCOE ($ /kWh)	0.365
CO2 emission (kg)	1,816,295
CO2 emission Saving (kg)	510,348
CO2 cost Saving ($)	76,552

Comparing this case with the one with batteries (scenario 3) instead of hydrogen cycle and ultra-capacitor, this scenario has higher LCOE and this is expected because in this case we have more components. It also has lower CO2 savings since the net grid energy of the grid is higher.

In addition to the one year run, we did runs for the last scenario on our village for one day and one month of summer and winter just to do a comparison between them. Table 4.12 shows results of this scenario for 1 week run in different seasons. Moreover, Fig 4.1 and Fig 4.2 show the power outputs of system components for both January and July weeks.

Table 4.12 Results of Scenario 4 run for 1 week (winter and summer)

	Winter Week (January)	Summer Week (July)
Objective ($)	10628	4650
Net Grid Energy (kWh)	85973	54119
Energy Supplied by Fuel Cell (kWh)	31382	30423
Fuel Cell Usage Factor (%)	31.1	30.2
Energy Consumed by Electrolyzer (kWh)	73455	71062
Electrolyzer Usage Factor (%)	48.6	47

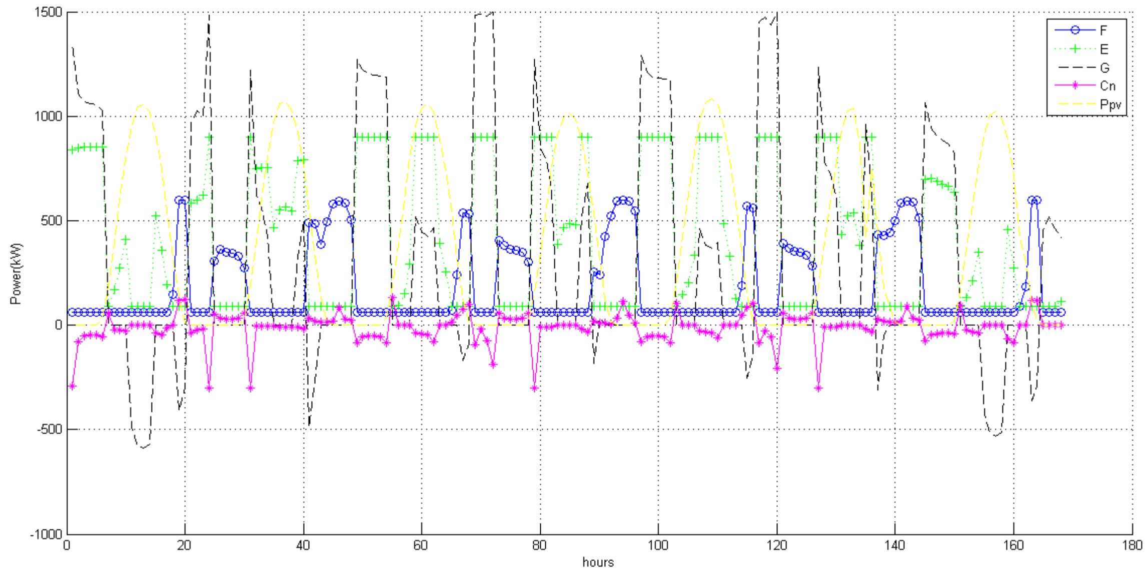


Fig 4.2 One Week Power Results in July scenario 4

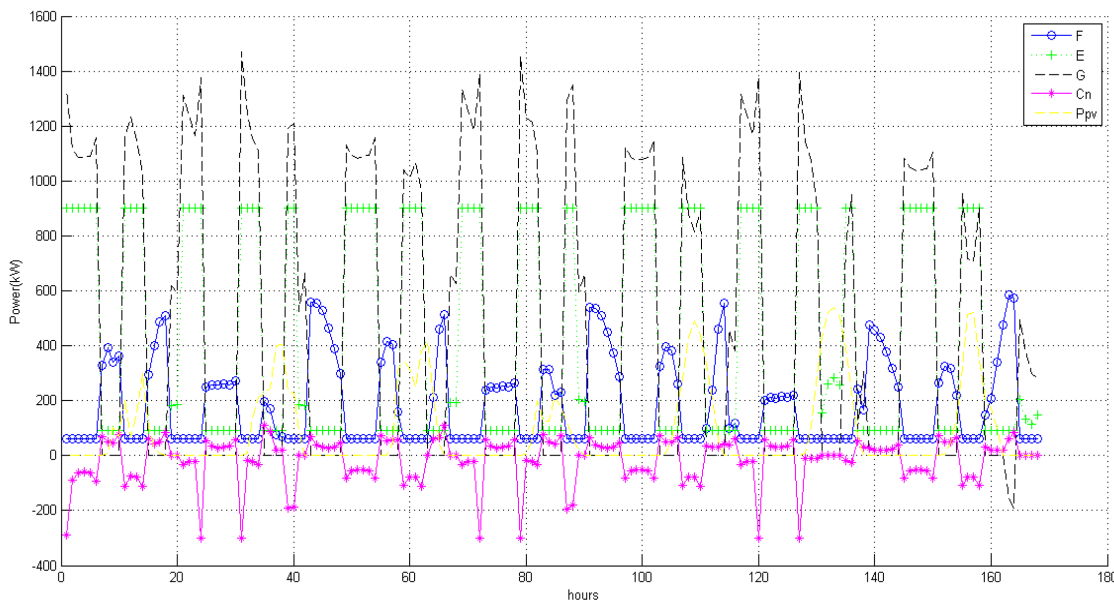


Fig 4.3 One Week Power Results in January scenario 4

Fig 4.2 and Fig 4.3 show power output of all energy sources for one week data in July and January respectively. We can see how the system is able to sell electricity to the in summer since the PV has higher power than its output in January. In January the system is using more UC power than in July. The electrolyzer in winter is working in its maximum whenever the grid is available while in summer it's not always reaching the maximum limits.

We also did runs for the last scenario on our village for one month of summer and winter just to do a comparison between them. Table 4.13 shows results.

Table 4.13 Results of Scenario 4 run for 1 month (winter and summer)

	Winter Month (Jan)	Summer Month (July)
Objective ($)	60,933	32,992
Net Grid Energy (kWh)	268,645	146,203
Energy Supplied by Fuel Cell (kWh)	73,181	48,371
Fuel Cell Usage Factor (%)	16.4	10.8
Energy Consumed by Electrolyzer (kWh)	177,846	115,885
Electrolyzer Usage Factor (%)	26.6	18
CO2 emission Saving (kg)	2,136,173	2,222,985
CO2 cost Saving ($)	320,426	333,447

We can notice that the cost of objective for July is almost the half of its cost in January, because in July there will be an excess power from the PV panels that could be used to operate other system components or could be injected to the grid lower the net grid energy value. In addition to more CO2 emission savings when in summer.

Table 4.14 shows a summary of all scenarios for LCOE, CO2 emissions, CO2 emission savings and CO2 cost savings.

Table 4.14 Summary table for all scenarios

	Base Scenario All from Grid	Scenario 1 PV+ rG	Scenario 2 PV+ rG+ bat	Scenario 3 PV+ uG + bat	Scenario 4 PV+ uG +H2+UC
LCOE ($/kWh)	0.243	0.182	0.171	0.225	0.365
CO2 emissions (kg)	2,326,643	1,009,115	1,219,495	1,422,127	1,816,295
CO2 emission Saving (kg)	0	1,317,528	1,107,148	904,516	510,348
CO2 cost Saving ($)	0	197,629	166,072	135,677	76,552

The best scenario on the aspect of economics was (PV + reliable grid and Battery) where it had the lowest LCOE, while environmentally the best one was (PV + reliable grid) because it had the highest CO2 emission savings. Hence the effect of having even one renewable energy source has a good impact on both the economics and environment.

We did the same scenarios for a lower cost for carbon cleaning, a value of $25/ton metric of CO_2. Since the average CO2 emission per kWh for Lebanon is 0.709 kg/kWh [44].

We will calculate the SCC that will be used in our project as following:

$SCC = \frac{25}{1000} * 0.709 = 0.017$ $/kWh

We got lower LCOE values for each scenario since this value covers the cost of objective that includes cost of carbon cleaning. Since the cost of carbon cleaning is now lower, the cost of objective will become less. Table 4.15 shows the LCOE values for all scenarios.

Table 4.15 LCOE values for low SCC for all scenarios

	Base Scenario All from Grid	Scenario 1 PV+ rG	Scenario 2 PV+ rG+ bat	Scenario 3 PV+ uG + bat	Scenario 4 PV+ uG +H2+UC
LCOE ($/kWh)	0.243	0.125	0.104	0.144	0.254

We can notice that the ranking of LCOE for scenarios that include renewable energy sources didn't change where the best scenario remained scenario2, but the values got lower. For the base case the value for both SCC remained the same since this case doesn't include renewable energy sources that lower the cost of objective. Moreover, scenario 4 that includes the hydrogen cycle remained the one that has the highest LCOE.

F. Conclusion

In this thesis we achieved the modeling, optimization and sizing of grid connected HRES that consists of a PV array that operates as a main source of generation, and two types of back-up systems. The first is a long-term back-up storage is the hydrogen cycle of FC, EL and H2 tank. The second is UC that is considered as a short-term back-up system. The EMS was done using LP technique since the objective function is linear and the constraints were near linear. We did the runs for one year data for a village in Lebanon that has an unreliable grid schedule. However, we applied scenarios for both reliable and unreliable grids. We did comparison for the scenarios applied above on the aspects on environment and economics, where we compared the LCOE and the CO2 emissions for each scenario.

The positive effect of having reliable grid was obvious on both economic and environmental aspects. When the grid was reliable the LCOE was less since the storage devices were charged when the grid had lower price and discharged when the grid had high price.

Moreover, the amount of CO2 emissions (kg) were the highest in the absence of RE sources. And the presence of RE sources had a major effect on decreasing the CO2 emissions. Thus, increasing the CO2 savings.

We used two values for cleaning the carbon, the high price was 210$/ton metric of CO2 and the low price was 25$/ton metric of CO2. The ranking of LCOE for scenarios that include renewable energy sources didn't change. Where the best scenario remained scenario2 that includes (PV, reliable grid, and battery), but the values got lower. For the base case the value for both SCC remained the same since this case doesn't include renewable energy sources that lower the cost of objective. Moreover, scenario 4 that includes the hydrogen cycle remained the one that has the highest LCOE.

The best scenario on the aspect of economics was (PV + reliable grid and Battery) because it had the lowest LCOE for both values of SCC. While environmentally the best scenario was the one that included (PV + reliable grid), since this scenario had the highest CO_2 emission savings compared to the other ones.

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