AMERICAN UNIVERSITY OF BEIRUT

SUSTAINABLE SELF-SUFFICIENT METHANOL VILLAGE

by
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AN ABSTRACT OF THE THESIS OF

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The increase of the CO_2 concentration in the air is causing a rise in the Earth temperature known as global warming, this phenomenon is expected to increase in the coming years due to the growth in power demand. On the other hand the main sources of energy today depend mainly on oil, gas and coal, which are being depleted. The prices of these resources are expected to rise compounded with further demand. The solution proposed in this thesis would be to use renewable energy from the sun in a desert area to produce energy. Thus this thesis investigates the technical and economic feasibility of creating a self-sufficient village in desert areas (North Africa or Middle East) to use decentralized solar energy and transform into a green energy product, methanol, which can be exported using existing transportation tanker systems. This system would involve several subsystems to desalinate water through reverse osmosis, then produce hydrogen through electrolysis, and green methanol to be exported. The system would harvest its energy from solar radiation or other renewable resources. The system would also need to support the community in terms of its vital needs for water and energy to be self-sufficient. In this thesis, the components of the system would be optimized in term of operation and sizing. Given the components' sizes, the operation of the system is simulated using Simulink to produce methanol at the minimum possible cost using single-step dynamic programming (SSDP). Optimization of the hybrid power source is implemented in the simulation. The components' optimum sizing of this hybrid system is obtained using the ordinal optimization (OO) technique. The best cost we obtained to produce green methanol using this proposed method was higher than methanol market cost, usually obtained from fossil fuels. Further investigation was made to show how carbon credit and other factors can play role in increasing the value of green methanol to have an economical and profitable system. In addition to reducing the amount of carbon dioxide emissions there are other benefits for the idea like reducing the unemployment rate and enabling a poor community to improve its living standards through access to energy.

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CHAPTER I. INTRODUCTION

A. Opening Statement

From the beginning, mankind used sustainable energy systems like biomass by burning wood for example, or wind to rotate the mill, or water flow to rotate a wheel, and the sun to provide heating during winter, they used also these kinds of energy sources to travel from one place to another and for other mechanical activities that may require a rotating body.

Lately (from 250 years and onwards), the world entered the period of industrialization, where the main source of energy this time was fossil fuels which became available in large scale. Today, around 85% of the energy used in the world is taken from fossil fuels, which is mainly used to generate electricity, for mobility, and other usage. However there has been a great drawback for the usage of fossil fuels as their combustion produces primarily CO_2 gas. Due to the great dependence of the world on fossil fuels there was a great increase in the concentration of CO_2. Its percentage raised in the atmosphere by 44% (from 280 ppm in the preindustrial era to 402.3 ppm in October 2016 [1]). Figure 1 shows recent monthly averages in parts-per-million (ppm) of CO2 in the atmosphere.

This increase in CO_2 average had a severe effect on the global climate, as it increased the temperature of the atmosphere year after year. This effect is referred to as “greenhouse gas effect” which became of great importance to all the world. The main effect of this increase in the temperature is the melting of ice in the north and south poles, and many of the world coastal cities are in danger of being flooded with water. Another consequence of the increase in greenhouse gases is drought. The year 2016 was the hottest year on record according to NOAA and NASA and other institutions as shown in figure 2 [2].

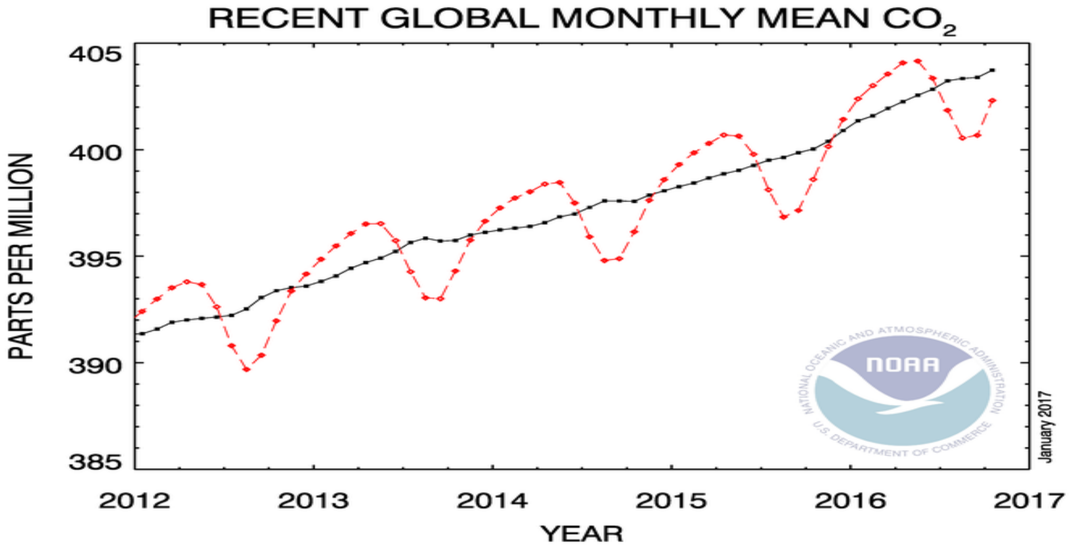


Figure 1: Global Monthly Mean CO2. The last four complete years plus the current year. The dashed ***red line*** *with diamond symbols represents the monthly mean values, centered on the middle of each month. The* ***black line*** *with the square symbols represents the same, after correction for the average seasonal cycle [1].*

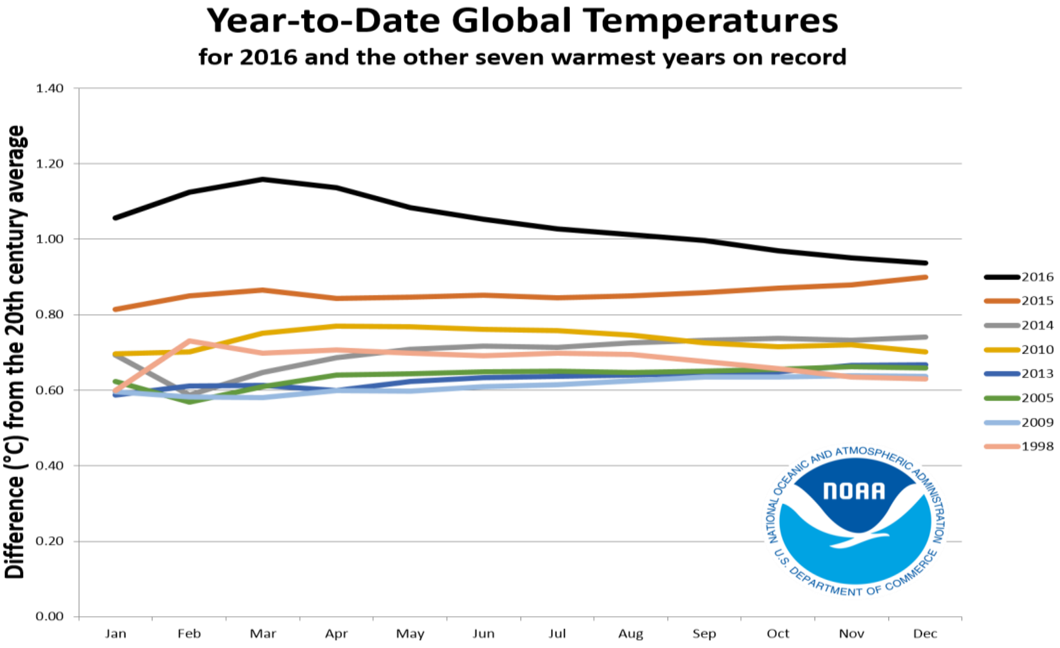


Figure 2: Warmest years on the record.

Beside all the negative environmental impacts mentioned above, the depletion of the fossil fuels is another problem facing the world as is not possible to stop the industrialization process.

It is estimated that around 40% of the CO_2 emission comes from coal or natural gas plants [3]. If we can capture these emissions from thermal power plants and use the captured CO_2 in the production of hydrocarbons substituents, it would be profitable from the environmental point of view.

Therefore an urgent and sustainable solution is needed to overcome all of the above mentioned problems. Scientists started to look for the solar power in the deserts, as it is abundant, sustainable and can produce enough energy to satisfy all the world with the needed energy. The research on this topic led to the project “DESERTEC” that consists of taking solar power from the Sahara to feed Europe with the needed energy through a super grid that connects Africa with Europe to distribute electricity over thousands of kilometres. The project was ambitious and the scientists expected that it would feed Europe by 15% of its power demand by 2020 [4]. This was planned for electricity, but the researchers also expected to use electricity instead of coal, oil and gas. Therefore electricity would be the first carrier of power, and it would be used for transportation, cooking, heating, cooling and other usages. Therefore all kinds of energy can be derived from an electrical power source.

The uncertainty of the renewable energy sources and the load demand may have a large effect on the load frequency fluctuations and on voltage regulation in the electric grid. The greater the fluctuation the greater the unbalance in the network would be. That is why that researchers proposed to connect very far areas extended over many continents (Europe and Africa) to make the required balance between the energy provided and the demand. Knowing that a great amount of electricity can be produced in the deserts of Africa from a clean source like the sun. The electrical linking of two continent (or maybe more) was expected to have a positive effect in balancing the fluctuation of the renewable energy sources as well as energy consumption.

Today, the world electricity production is approximately 24,000 TWh/year in 2015 according to [5]. The world population is growing very fast and there is an increasing energy demand per capita, which may lead to an expected global electricity consumption of approximately 48,000 TWh/year in 2050 according to the World Energy Council [6] as shown in Figure 3. In the same manner the primary energy usage is expected to increase from around 550EJ/year in 2010 to reach 700 EJ/year in 2050 [6]. Figure 4 demonstrates how the primary energy would consist of more renewable and less coal, the main objective being to decrease CO_2 emissions. This means that capacities of 4755 GW (1 EJ/year $\cong$ 31.7 GW) of primary power have to be newly installed to respond to the increase in energy demand. The above numbers are only approximate and are based on an optimal scenario, and ignore the efficiency factors of power plants. For example in the future if we produce hydrogen from electricity then the efficiency factor for transferring fossil fuel into electricity and that for transferring the electricity into hydrogen when taken into account it will mean that the above mentioned numbers have to be higher. Although, by ignoring these factors that are different from plant to another and from one technology to another, the above number gives a guide estimation of the additional capacities that have to be installed in the very short time of 40 years.

For illustration, it is known that 1 GW is approximately the electrical power of a typical nuclear power plant. To build and run 5000 additional nuclear power plants (fission or fusion) in the next 40 years (i.e. 0.4 new reactors per day) is simply impossible from the point of view of the qualified manpower that is needed to do so. Therefore, to add 5000 GW of power, PV modules would be the only possible action to take place, although the chemical elements needed for the production of the modules which are already rare would be further significantly reduced.

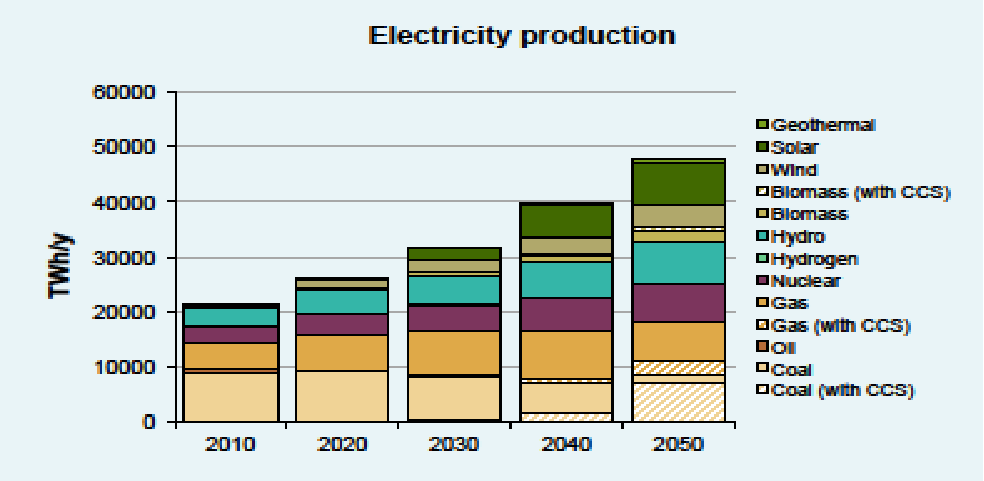
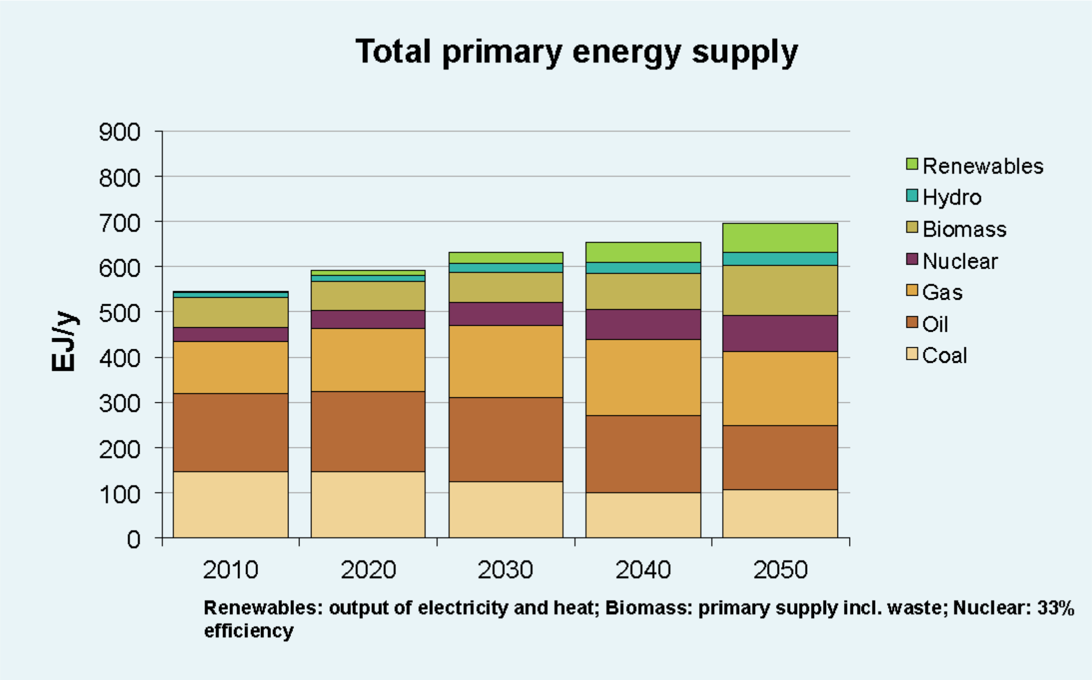


Figure 3: The world electricity demand may increase in the coming 35 years by about 100% from an average of 24000 TWh/year to about 48000 TWh/year [5].



Renewables: output of electricity and heat; Biomass: primary supply incl. waste; Nuclear: 33% efficiency

Figure 4: The expected increase in the primary energy supply from 550EJ/year to around 700EJ/year [6] notice the increase in expected renewable usage (1EJ/year=31.7GW).

From above, we can conclude that the future energy system will not be defined by what technology is possible only, but also by what technology is available in the short time and is feasible from the point of view of human and material resources.

The future of the energy would not be from the fossil fuels which are the main cause of pollution and CO2 emission and their limited amounts are being depleted and will run out soon. Fossil fuels should rather be replaced by other energy carriers (for electricity production and transportation). One of the possible replacement can be the synthetic fuels: liquid like methanol, gaseous like hydrogen, or electricity. Electric power will be of great importance, as the already available networks can transport and distribute electric energy in a very efficient and simple way. In addition the increased demand for electric power by the increase in world population and the increasing use of electric home appliances, as electric power will be a prime choice even for home heating and cooling.

However for transport applications, where it is very important to have a high storage of energy, another carrier could become more important than electricity. It is the elemental fuel, hydrogen, which is expected to be a great source of energy in the future. For this reason, efficient ways to produce hydrogen and other synthetic fuels using renewable energy sources largely available in desert areas must be studied with a techno-economic analysis of their feasibility.

Desert is an immense source of solar irradiance. The solar radiation that the sun delivers to an area at the edge of the earth atmosphere is 1.37 GW/km^2. Using current technology of PV Panels, the technically accessible power is 340,000 GW [7], which exceeds the world energy consumption (which is 550 EJ/year or 17,500 GW) by a factor of 20. This is based on latest average efficiency of 12% of the PV panels to convert solar irradiation into electrical power. The area of desert that is subject to this study are the areas with high direct solar radiations. Areas not suitable for solar energy technology, e.g. mountain areas, are excluded in this estimate. Figure 5 shows a map of those desert areas that are well suited for standard PV technology. The figure shows more electric consumption in USA, Europe and Japan while in opposite to Africa and South America where there is shortage of electric power despite the availability of the desert areas very rich in solar irradiance.

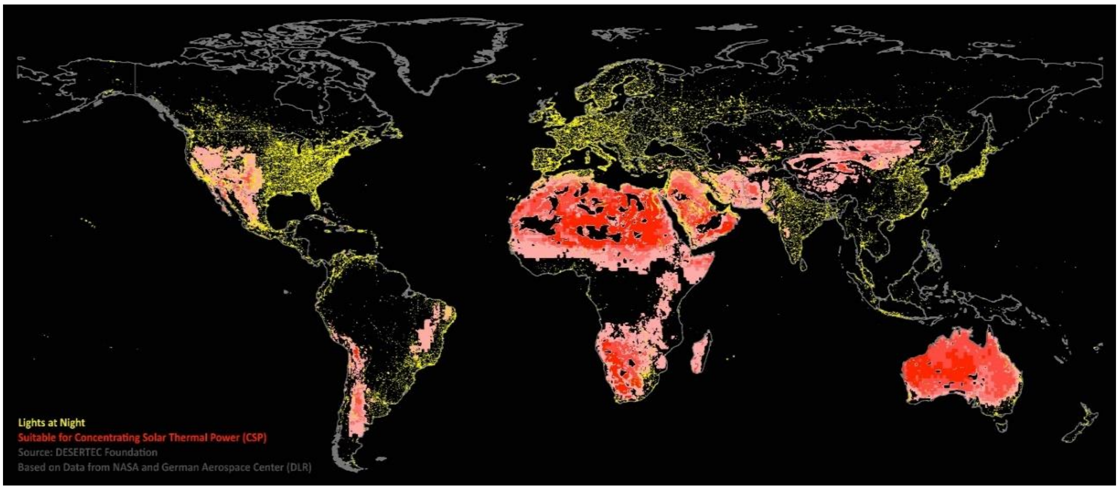


Figure 5: The red colour indicates desert areas that are well suited for solar power plants due to large direct solar irradiation. Overlaid is a satellite image of the earth at night. The yellow lights indicate the areas with concentrated electricity consumption (Source: DESERTEC; based on data from NASA and DLR).

Methanol is widely used in the chemical industry. It is used to produce Formaldehyde, MTBE (methyl tert-butyl ether), and acetic acid. Furthermore it has great combustion properties and thus can be used in transportation as a fuel. Also methanol is less polluting than other fuels. It can be used by mixing it with gasoline. For example M85 is 85% methanol and 15 percent gasoline. M100 can be used also as pure methanol fuel for cars and it is more efficient. Although methanol by itself is toxic and may cause blindness or death. It can be dehydrated to produce DME (dimethyl ether) which is substitute for Diesel. Thus, if methanol is produced from renewable sources of energy, it will allow for the CO_2 to be recycled [3].

The idea is to produce a source of energy (methanol) from renewable energy which does not have any carbon dioxide emissions. This source can be easily distributed and stored since it is liquid under ambient conditions.

B. **Literature Review**

1. ***Desertec:***

On 30 October 2009 the German companies (EON, RWE, Siemens, Deutsche Bank and Munich Re) and the Desertec foundation signed an association of Desertec industrial initiative (DII) [8]. The estimated total cost of the project was about 400 billion euro. It was mainly to transport the solar energy from the Sahara through the electricity grid to Europe. Gerhard Knies, the coordinator of the Trans-Mediterranean Renewable Energy Corporation said “within 6 hours deserts of the world receive more energy from the sun than human kind consumes within a year”. It was planned for this project to provide the EU with 15% of its electricity energy by 2050 as shown in Figure 6. This would be a great solution for many problems starting with reducing the CO_2 emissions to the drought by producing more water through the desalination of the sea water, to reduce the unemployment rate and to solve the problem of the climate change.

2. ***The Fall of Desertec:***

However, this promising project which was expected to solve all of the above mentioned problems did not survive [9]. Siemens pulled out of the project.

The main reason for this action was the reduced subsidies on the solar energy by the governments. The lesson learned from Desertec are enormous, Jenny Chase, an analyst at Bloomberg New Energy Finance in Zurich, Switzerland said “I think it’s something that will be achieved organically, bit by bit, which will probably be cheaper, easier and achieve the same results.”

There are other factors that caused this fall [10]. Political issues played a key role in this failure. It was not accepted to feed Europe with power and to leave the place where this power is produced without electrical energy. On the other hand it was not accepted also to pay to build energy sources outside your own territory in places you don’t have any control on.

Figure 6: Solar thermal power plants offer one option for supplying Europe with electricity through the DESERTEC project.

This brings the idea that having decentralized source of energy is better than having a centralized one. A decentralized source has a lower investment cost and will be small enough to allow a bit-by-bit, or organic, development and testing on the system. The cost benefit of such decentralized small solar power production would be easier to study and implement. At last in the desert where there is very low population density local power generation is far better than building a network to transport the power delivered by the solar panels.

Based on the above we are going to study a decentralized system for producing an energy product, green methanol, from the solar power available in deserts, taking into consideration all of the ambitious targets included in Desertec, however, with a different perspective.

3. ***Electrolysis***

Although hydrogen is one of the most commonly-found elements in the universe, it rarely exists as an independent molecule on our planet. Most of the time, it is bound to other elements or molecules to form compounds like water, carbohydrates, hydrocarbons and DNA acids. Obtaining hydrogen is not easy and usually requires energy to break the bonds connecting it to other elements. One process is water electrolysis in which electric energy is used to split water into hydrogen and oxygen to regain the potential chemical energy stored in the hydrogen molecule. Hydrogen and oxygen combine to yield energy and water in a fuel cell which works in the reaction opposite to that of the electrolysis.

Hydrogen production can be performed through water electrolysis, where electricity separates the water molecules into hydrogen and oxygen in a device called electrolyser. The device which re-combines hydrogen and oxygen in order to convert the chemical energy stored in them into electricity is called fuel cell.

Michael Faraday was one of the forerunners to start conducting a systematic study on electrolysis. According to [26] he proposed the two laws of electrolysis:

- The quantity of the elements produced during electrolysis is directly proportional to the amount of the electricity passing through the electrolytic cell.
- With a given quantity of electricity, the amount of the elements produced is proportional to the equivalent weight of the element.
-

4. *Reverse Osmosis*

Reverse Osmosis (RO) is a process used to demineralize water, to clean brackish water or to desalt seawater. The process consists in recovering water from a saline solution pressurized by pumping it into a closed vessel to a point greater than the osmotic pressure of the solution. Thus, the solution is pressed against a membrane so that it is separated from the solutes (the dissolved material). The portion of water that passes through the membrane has a strongly reduced solute concentration and is called permeate. The remaining water (or brine) is discharged with a higher salt concentration than the feed in solution.

In the last years, significant advances in the membrane technology have allowed an essential improvement in the filtering quality and a simultaneous general reduction of costs. Hence, RO plants have today lower energy consumption, investment cost, space requirements and maintenance than other desalination processes [29].

5. *Methanol Production*

Van dal et al [3] described the process of methanol production through CO_2 capture. The process is designed and simulated using Aspen Plus. Figure 7 below shows this simulation showing the temperature and pressure at each stage.

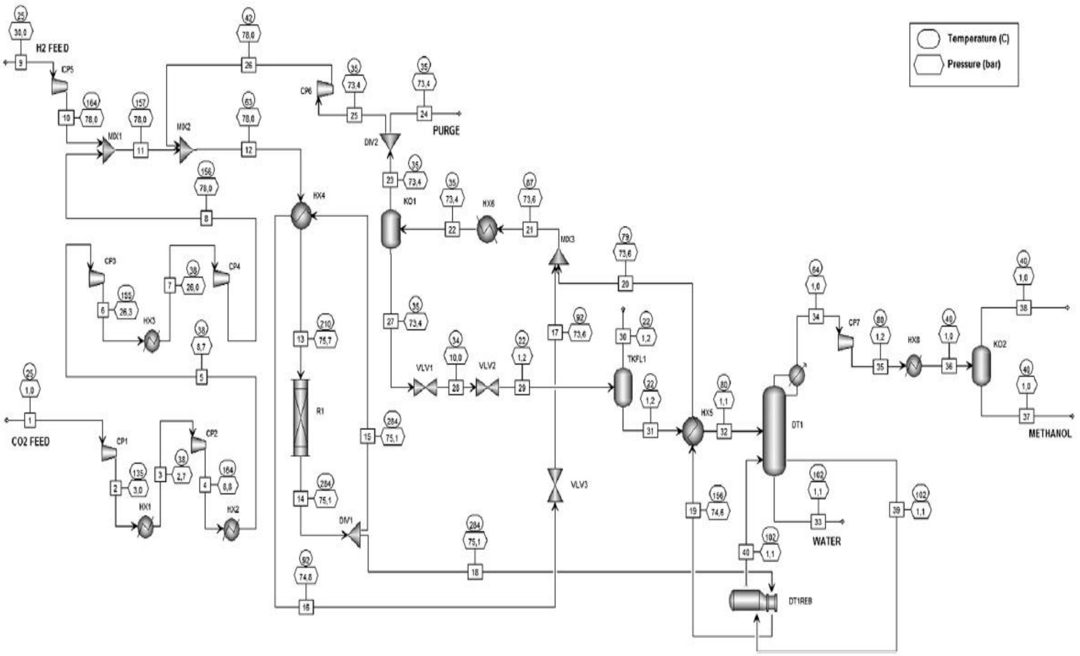


Figure 7: Methanol production simulation as in [3]

CO_2 Feed enters at 25 °C and 1bar then it is compressed to 78 bar in a series of compressors and heat exchangers to cool it. Hydrogen gas feed enters at 30bar and 25 °C. It is then compressed by a single stage to 78 bar. The two feeds are mixed in MX1 and MX2. It is then heated to 210 °C at HX4 and then injected to the fixed bed adiabatic reactor R1. The gases leaving the reactor are then divided by DIV1 into two streams: 60% to heat the new feed to HX4 and the rest goes to the reboiler DT1REB. The two streams are then remixed in MIX3 and cooled to 35 °C by HX6. Methanol is separated from the non-reacted gases in a knock out drum KO1. The output of KO1 is called crude methanol then it is expanded to 1.2 bar in two valves (VLV1 & VLV2). Then it is heated by HX5 to 80 °C and then sent to distillation column DT1. The water comes out at the bottom of the column at 102 ^{o}C while methanol comes out at the top at 1 bar and 64 ^{o}C in gaseous form. Methanol is then compressed and CP7 and cooled HX8 to 40 ^{o}C. The non-reacted gases come out at the top of the knock out drum KO2. Methanol in the liquid form comes out at the bottom of KO2.

Atsonios et al [11] provided a technical and economic analysis of methanol production by using the utility grid as source of power. Excess electricity is used to provide H_2 gas and methanol at low cost, and in order to do that the study considered the storage of the hydrogen gas in tanks. Kourkoumpas at al [12] provided a better estimation of the methanol cost of production which reached about $500 per ton of methanol by the Public sector, again depending on the extra energy in the grid (when the price of electricity is low). However they did not take into consideration the operational requirements of the methanol plant. For example one can’t run the methanol plant for one hour when the electricity is low and then close it for one hour only when the electricity cost is very high.

6. *Operational optimization technique*

The optimization of energy management for fuel cell and battery energy in a hybrid vehicle was described by Karaki et al [14]. While Karaki et al [13] described how to use ordinal optimization to determine the sizes of components of a fuel cell hybrid car. Majed et al [15] used single step optimization to reach a near optimal operation solution which we will be using in this paper along with ordinal optimization to get the near-optimum sizes of the methanol production system components.

C. **Thesis Contribution:**

The project proposed in this thesis will study the operation and design of decentralized self-sufficient solar-based power system in the desert to produce a valuable energy product, green methanol.

It is assumed that the plant will be manned by a community that will have access to water and energy as byproducts of the plant operation. The main income of the community is from the sale of the highly valuable energy product which is essentially carbon neutral. Methanol production is fixed at 50 ton/day from hydrogen available in a high pressure storage tank. Hydrogen is produced through electrolysis at a rate proportional to the solar irradiance and at a maximum capacity of 3000 kg/h. Extra hydrogen gas is stored in the hydrogen tank. The size of the hydrogen tank is selected to give the minimum methanol production cost. The water needed for electrolysis is taken from seawater that is desalinated through reverse osmosis (RO) to provide also the water required for living by the residents of the village or community. These residents are responsible to run the methanol production plant, the electrolyser and the hybrid power system. The hybrid power system is composed of solar panels, batteries and a fuel cell plant. The operation of the fuel cell and batteries is optimized and then the sizing of the components of the hybrid power system is optimized using ordinal optimization.

The proposed system will provide water and electricity to places of need in North Africa or elsewhere first before considering the idea of providing Europe with power. It will also help create work opportunities in these areas for people living there. Thus, reducing the high level of migration from Africa and Middle East to Europe, where most of them are dying in the sea before reaching Europe. The project is investigating the technical and economic viability of a self-sufficient community where the residents are provided with electricity, water and salaries to get their needs. They would also be producing a prime energy product that will help reducing CO_2 emissions all over the world by getting power from a clean and sustainable source. Transform the renewable energy in these areas into a source of energy that can be sold and easily transferred to all over the world. The study will focus on producing hydrogen by electrolysis, then stored in underground reservoirs and finally transformed into methanol by synthesis. This system could be done on a relatively small scale and based on an independent investment, and therefore would not be affected by the political relation between countries. The idea itself could be built in different places and countries among North Africa, Western Sahara, Yemen and the Middle East, which would create a competitive market among the energy producers. This would lead to reduced prices of energy and a continuous development and improvement of the system to be more profitable. This would stimulate more research on the topic for having "clean energy wells" spread all over the deserts and will increase the energy security in the world by having another sustainable and distributed sources of energy available for use.

CHAPTER II. POWER PLANT

In this chapter we discuss the power plant used to provide the required electrical energy for the different processes of the methanol production system. This power plant would consist of several components: PV panels, backup batteries and hydrogen fuel cells.

A. **Components Description**

The components of the power plant are the PV panels where we would describe their method of operation and the output power relation with the irradiance level and ambient temperature. For the backup batteries we would give a brief explanation of the work of Li-ion batteries and their charge and discharge characteristics. Regarding the fuel cell, the process of operation would be described and the relation between hydrogen demand and power delivered given.

1. ***Photovoltaic panels & Hybrid power stations***

The inputs to this block are the solar irradiance, the ambient temperature, the power demand of all the other systems (methanol plant, electrolyser, residents and RO), The sizes of the PV panels peak power, batteries energy and fuel cell power, and the last input is the hydrogen tank level which will be used to decide the if the hydrogen for the fuel cell can be taken from the tank or should be bought from outside. Regarding the outputs of this block are waste energy is the lost (extra) energy from the solar panels, Battery energy which represents the total energy given by the batteries during one year, fuel cell energy that is the energy given by the fuel cell during one year. Also operational cost which stands for the cost of operation using the batteries and the fuel cell, it should be noted that this output is used just to validate the program used to make the operation optimization and not as indication to the operation cost. Energy load represents the total energy of the load for one year. Energy shed is the energy that cannot be supplied by our power plant and should be bought from outside. Batteries state of charge represents the state of charge of the batteries at every hour during the year. Manpower demand represents the total manpower demand of the power plant. Hydrogen consumption stands for the total hydrogen consumption by the fuel cell during one year from the hydrogen tank. Finally hydrogen extra consumption stands for the hydrogen that needs to be bought from outside for the fuel cell.

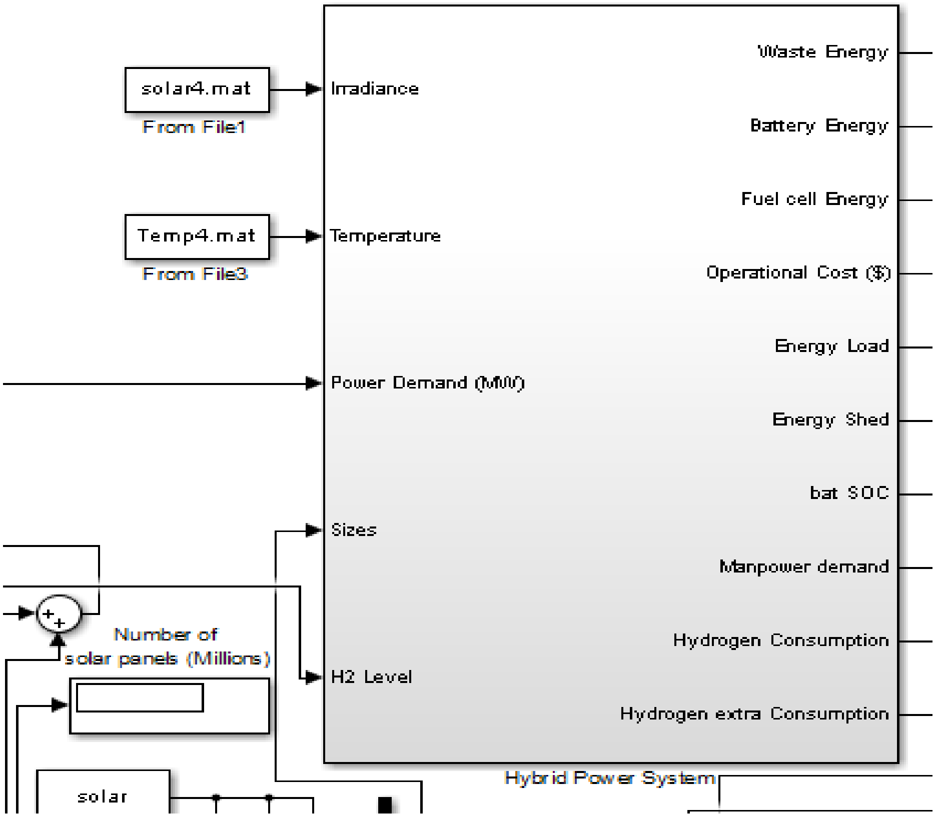


Figure 8: Photovoltaic panels and hybrid power system (backup batteries & Fuel Cell)

f. PV Power System

Photovoltaic cells produce electricity directly from solar radiation, mainly light. The photovoltaic effect was discovered by Becquerel in 1839 and developed as power source in 1954 by Chapin, Fuller and Pearson using silicon doped with impurities. A photovoltaic cell gets its current from holes and electrons created by the solar radiation photons, which get accelerated by the electric field present across the PN junction. Efficient power utilization depends on the efficiency of power generation in the cell, and the dynamic load matching with the external circuit done by using DC-to-DC converters as a “maximum power point tracking” interface.

When a photovoltaic (PV) cell is illuminated and connected to a load, a potential difference (V) appears across the load and a current (I) circulates. The cell functions as an energy converter from light into electricity delivered to the load. The photons reaching the interior of the cell with energy greater than the band gap, generate electron-hole pairs that become current carriers. Some of these carriers will find themselves in or near the depletion region and are accelerated by the strong electric field, to form the photonic current (I_p). Other carriers will recombine and contribute to diode or dark current as governed by the Shockley equation:

$$I_D = I_0(\exp\left(\frac{V}{mV_T}\right) - 1 \tag{2.1}$$

The load current is the difference between the photonic and the diode current such that $I = I_v - I_D$ which when combined previous equation yields:

$$I = I_V - I_0(\exp\left(\frac{V+IR_S}{mV_T}\right) - 1) \tag{2.2}$$

Note that $V + IR_S = V_D$ and that the constant m=1 at high current and m=2 at low current. A fair model representing the operation of the cell occurs when m=1.3. The saturation current I_0 is difficult to measure and the I-V equation may be more usefully written in terms of the open-circuit voltage (V_{OC}) and the short circuit current (I_{SC}). The short circuit current is nearly equal to the photonic current $I_V \approx I_{SC}$ (R_S is very small) and at open-circuit conditions the previous equation reduces to:

$$0 = I_{SC} - I_0\left(\frac{\exp(V_{OC})}{mV_T}\right) - 1 \qquad (2.3)$$

$$V_{OC} = mV_T \ln(\frac{I_{SC}}{I_0} + 1) \qquad (2.4)$$

A very useful expression of the *I-V* characteristics is obtained by getting I_0 from (2.3) and replacing it in (2.2) rearranging and taking the natural logarithm:

$$V = V_{OC} + mV_T \ln\left(1 - \frac{I}{I_{SC}}\right) - IR_S \qquad (2.5)$$

The above equation may be used to plot the *I-V* characteristics at different solar irradiance levels. The open-circuit and short-circuit tests are usually given by manufacturers at standard conditions: G_0=1000 $\mathrm{Wm^{-2}}$ and T_0=25°C. The values for the panels of Hyundai 250$\mathrm{W_p}$ as in [16] are V_{OC0} = 37.5 V, and I_{SC0}=8.7A. The open circuit voltage and short circuit current vary with irradiance levels and temperature. At other irradiance levels and at a cell temperature rise above 25°C, i.e.

$$\Delta T = T_C - 25 \qquad (2.6)$$

The short-circuit current I_{SC} at a given irradiance G and temperature T_C is given by:

$$I_{SC} = \left(\frac{G}{G_0}\right) I_{SC0} + \beta_I \Delta T \qquad (2.7)$$

The dependence of V_{OC} on solar irradiance is obtained through using (2.4) at the given cell conditions and then at standard conditions, after some manipulation and judicial simplifications the following equation is obtained:

$$V_{OC} = V_{OC0} + \beta_V \Delta T + mV_T \ln(\frac{G}{G_0}) \qquad (2.8)$$

The maximum power at any solar irradiance is $P_m = V_m I_m$ is delivered from the PV cell when the equivalent load resistance is ideally matched such that $R_L = V_m/I_m$. As the solar irradiance changes then the values of V_m and I_m will change and to take maximum power from the cell the effective load resistance has to be changed using special switching dc-dc converters. The efficiency at the maximum point, at any irradiance, is given by:

$$\eta_m = \frac{V_m I_m}{GA} \qquad (2.9)$$

For the PV cell data given above, the values of V_m and I_m are V_m= 30.5 V and I_m= 8.2 A. give an efficiency figure at standard conditions of η_m = 15.5%. At lower solar irradiance the efficiency decreases. The efficiency of a PV cell decrease with an increase in cell temperature Eq. (2.5) suggests that as V_{oc} increases then V_m also increases. By differentiating Eq. (2.3) with respect to T we obtain:

$$\frac{dV_{OC}}{dT} = \frac{V_{OC}}{T} - \frac{\left(\frac{mkT}{qI_0}\right) dI_0}{dT} \qquad (2.10)$$

The derivative usually negative as the second term is dominant one. The cell temperature (T_C) depends only on the ambient temperature and solar irradiance as follows:

$$T_C = C_T G + T_a \qquad (2.11)$$

Where

$$C_T = \frac{NOCT - 20}{800} \qquad (2.12)$$

And *NOCT* is the normal operating cell temperature given by the manufacturer test for an ambient temperature of 20^{o}C (*NOCT* ≈ 46^{o}C).

The input to the PV system block in our system is the Irradiance and the atmosphere temperature for one year. Another input is the peak power of the PV panels (size) to be installed which is an input to the program for optimization purposes. At each hour the power from the PV panels is calculated based on the data taken from [16] and B_P (power coefficient with temperature) is calculated to be:

$$\beta_p = \frac{\beta_i}{I_{m_0}} + \frac{\beta_v}{V_{m_0}} \tag{2.13}$$

Thus the output power of the PV is:

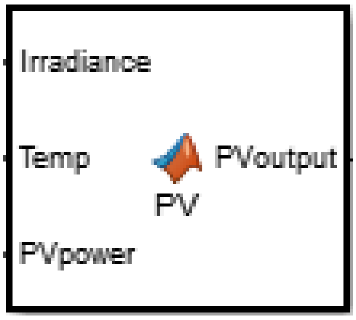
$$P_{PV} = \frac{G}{G_0}\left(1 + \beta_p (T_C - T_0)\right) P_m \tag{2.14}$$

The PV system cost is estimated to be 0.6\$/W_P as the price is between 0.4 and 0.5 \$/W_P adding to it different variables of land cost and other costs (around 20%) we reach 0.6\$/W_P.

The annuity cost would be derived from net present value:

$$A = P\,\frac{i(1+i)^n}{(1+i)^n - 1} \tag{2.15}$$

Where (n) is the number of years for the project which is 25 years and (i) is the interest rate selected to be 5%.



```
function PVoutput = PV(Irradiance,Temp,PVpower)

% Test Temperature degrees C
T0 = 25;

Vm0= 30.5;
Im0= 8.2;

G0= 1000;         % Maximum irradiance (W/m²)
NOCT= 46;         % Nominal operating cell temperature (°C)
Bv= -0.34;        % Voltage sensitivity to temperature (V/°C)
Bi= 0.052;        % Current sensitivity to temperature (A/°C)
CT= (NOCT - 20)/ 800;    % Cell Temperature Coefficient
```

```
Tc = CT * Irradiance + Temp;          % Cell Temperature (ºC)

Bp = Bi / Im0 + Bv / Vm0;
PVoutput = (Irradiance/G0) * (1+Bp*(Tc-T0)) * PVpower;

end
```

Figure 9: Simulink block for PV modules and the code used inside it

Figure 9 shows the PV module block used in simulink program for system simulation. The input to this block are the irradiance and temperature at every hour, while the PV power represent the size of PV power in terms of the peak power. The output of the PV module block is the output PV power calculated based on Equation 2.14.

g. Batteries

Li-ion batteries currently have an unmatchable combination of high energy and power density, along with a high efficiency, which allow their use in various electric grid applications, to improve the quality of energy harvested from wind, solar, geo-thermal and other renewable sources. This is contributing to their widespread use for building a sustainable energy economy. Li-ion batteries have certain fundamental advantages over other chemistries. Firstly, Li has the lowest reduction potential of any element, allowing Li based batteries to have the highest possible cell potential. Also, Li is the third lightest element and has one of the smallest ionic radii of any single charged ion. These factors allow for higher charge capacity per ion, the additional charge significantly reduces their mobility [31].

A significant shortage of Li is unlikely in the near future. The amount of Li available on the Earth's crust is sufficient to power a global fleet of automobiles. Li is used in the cathode and electrolyte, which make up only a small portion of the overall cost; the cost of processing and the cost of cobalt in cathodes are the major contributing factors.

A wide range of battery modeling approaches depend on what details are desired from the model, including experimental, electrochemical, and electric circuit-based models. Equivalent circuit models are simple and can represent steady-state and dynamic battery behavior. An equivalent circuit approach is preferable for modeling stationary battery behavior because of its faster simulation time. The R_{int} equivalent circuit model contains a constant voltage source in series with resistor, as shown in Figure 10. In Figure 10 $i(t)$ represents the battery's internal dynamic current (A), R_O represents the battery's internal ohmic resistance (ohms), V_{batt} represents the terminal output voltage of the battery, and V_{OC} represents the applied input voltage to the battery. The terminal voltage output for the R_{int} model is shown below:

$$V_{batt}(t) = V_{OC} - R_O * i(t) \tag{2.16}$$

This model does not include the battery SOC directly; however, the battery SOC can be represented as a function of the open-circuit voltage. Other equivalent circuits in the literature model the effects of polarization in the battery using RC parallel circuits. Although these models may be more accurate then the R_{int} model, the differential equations that represent capacitors require greater simulation times. This cost outweighed the benefits for our purpose, so we selected the R_{int} equivalent circuit.

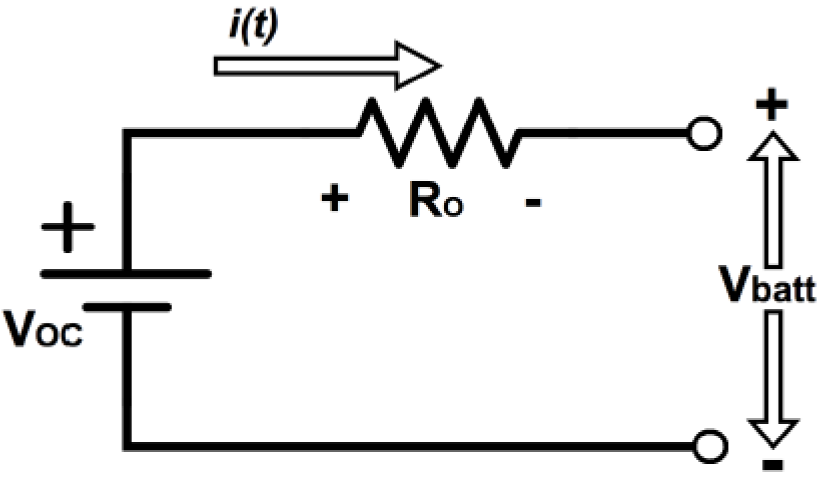


Figure 10: Circuit diagram of R_{int} equivalent circuit model

To validate the battery model accuracy against the manufacturer's discharge curve, a steady-state current was used as an input. The simulation results of the steady-state validation were superimposed on the original manufacturing data as shown in Figure 11.

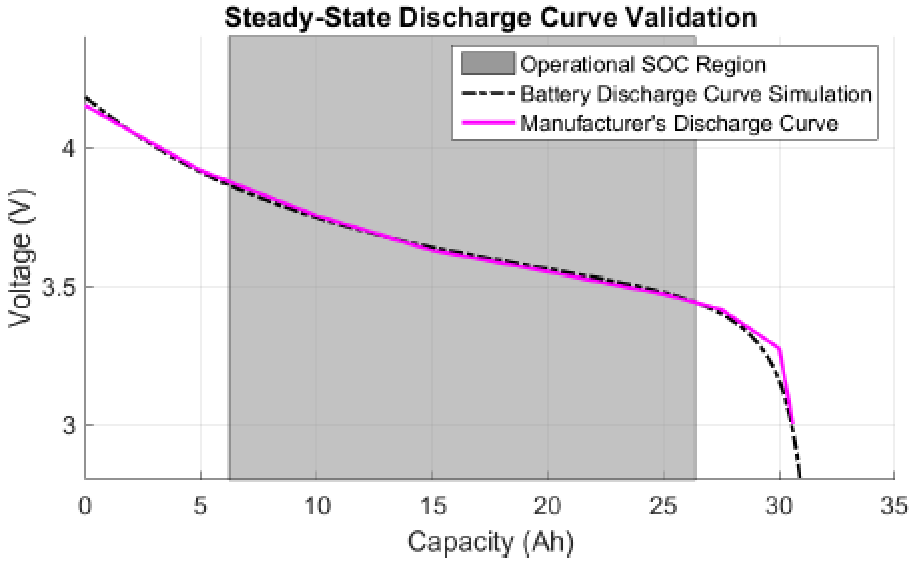


Figure 11: Steady-state discharge curve output plotted against the manufacturer's data at a rate of current equals to the current required to drain the battery in one hour.

In Figure 11 the shaded region represents the operational SOC range of the battery model. The accuracy of the fit between the simulated curve and manufacturing curve is most crucial within the allowable SOC range for the battery, which was selected to be between 20% (6.2 Ah) and 85% (26.35 Ah). As shown in Figure 11, the error between curves within the chosen allowable SOC range for the battery is negligible. Upon verifying the fit between the experimental battery manufacturing data and the simulated discharge curve, the steady-state simulation parameters are used to predict the dynamic behavior of the battery.

In the field of electrochemistry, it is conventional to model batteries in terms of current and voltage. However, in modeling a stationary battery for demand-side management scenarios in power and energy systems, it is more useful to express the battery model in terms of power and energy. The type of experimental data that is provided about a given battery can vary depending on the battery manufacturer [30]. Figure 12 shows the battery scaled charge power curve with the relation between power to internal power of the battery, from which we can take the coefficients of the curve [13].

In our design the input to the battery block as shown in Figure 13 are the size of the energy of the batteries taken in MWh and the previous *SOC* ,which is taken as a feedback from the output of the operation optimization block, and initial SOC_O also the battery scaled charge power curve from which we can take coefficients of the power to internal power and internal power to power curves, which is shown in Figure 12 as taken from [13], taking into consideration cubic order curve fit. The value of these coefficients are calculated at time = 0 then it is feedback every time step back to the input, since these values will not change during the simulation. The coefficients are [-0.435, -1.014, -0.002, 0] to transfer from power to internal power, and [-0.425, -0.995, -0.002, 0] to transfer from internal power to power. SOC maximum and minimum are output of the batteries block along with the batteries current SOC, these are used by the operation optimization block to control the limit of energy the battery can give. The maximum power a battery can give is taken from [17] to be 0.2 maximum SOC for lithium ion batteries. The cost of the batteris is about 200 $/KWh [32].

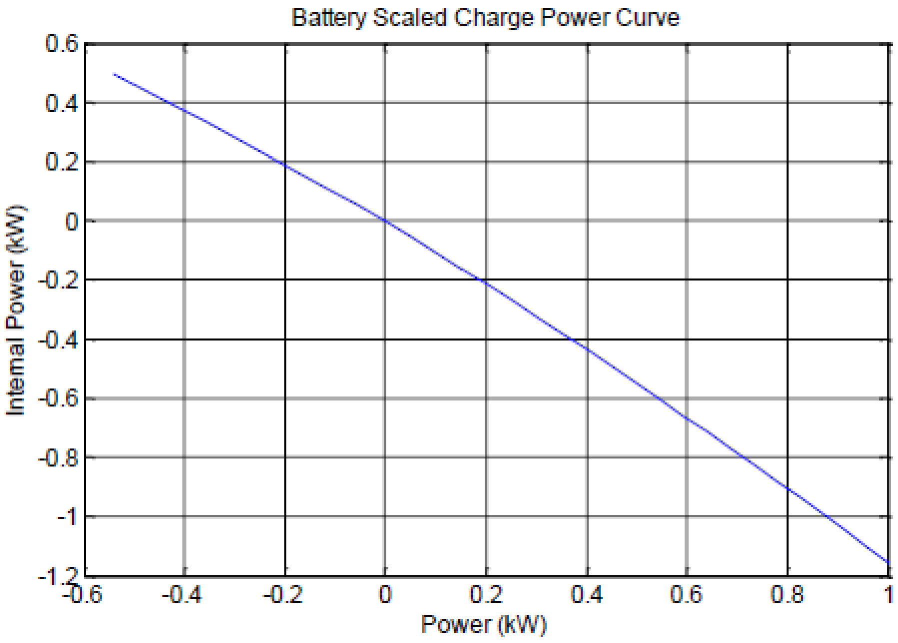
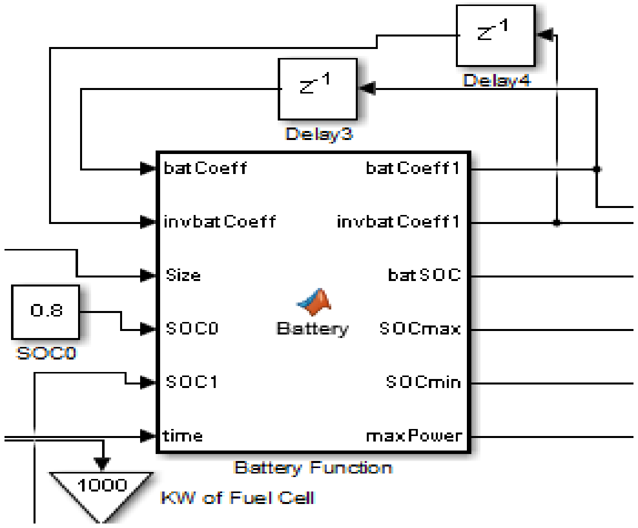


Figure 12: Backup Batteries Power vs Internal power characteristics



```
function [batCoeff1,invbatCoeff1,batSOC,SOCmax,SOCmin,maxPower]   =
Battery(batCoeff,invbatCoeff,Size,SOC0,SOC1,time)

SOCmax=Size;    % Maximum SOC
```

```
SOCmin=0.4*Size;  % Minimum SOC
maxPower=0.2*SOCmax;  % Maximum battery power

if time==0

batSOC=SOC0*Size; % Fisrt time take the initial value of SOC then Take
the new value of SOC

    % Battery Charge Map Model
% Saft Li-ion 6Ah 3.65V
batData= [ ...

% P(W)     Q(W)
 -381.0974  363.4200
-293.6634  282.6600
-207.6478  201.9000
-123.2444  121.1400
  -40.6158   40.3800
         0         0
   40.1442  -40.3800
  119.0356 -121.1400
  196.1523 -201.9000
  271.6566 -282.6600
  345.7426 -363.4200
  418.5946 -444.1800
  490.3491 -524.9400
  561.0578 -605.7000
  630.6425 -686.4600
  698.8647 -767.2200
  765.2837 -847.9800  ];

% Calculate power at the busbar if the dc-dc converter efficiency is
96%
convEff= 0.96;

Pbus= batData(:,1);
Qbat= batData(:,2);
iP= find(Pbus >= 0);
iM= find(Pbus <  0);
Pbus(iP)= Pbus(iP)* convEff;
Pbus(iM)= Pbus(iM)/ convEff;

% [Pbus, Qbat ]

batCurve= [Pbus, Qbat ];

batPmax=  max(batCurve(:,1));
% batPmin= -min(batCurve(:,1));

% Scale curve to one kW for use in different sizes
batLen= length(batCurve);
batCurve(1:batLen,2)= batCurve(1:batLen,2)/ batPmax;
batCurve(1:batLen,1)= batCurve(1:batLen,1)/ batPmax;

% Rescale battery charge map to current battery size (kW)
batCurve(1:batLen,2)= batCurve(1:batLen,2)* maxPower;
batCurve(1:batLen,1)= batCurve(1:batLen,1)* maxPower;
```

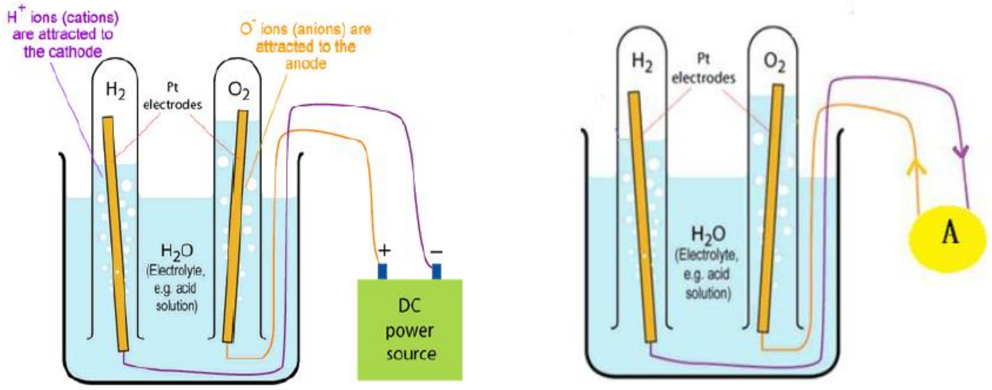
```
% Create smoother curve by fitting it to a cubic
[batCoeff, ~] = CurveFit(batCurve(:, 1),batCurve(:, 2), 'cubic');

[invbatCoeff, ~]= CurveFit(batCurve(:,2),batCurve(:,1),'cubic');

batCoeff1=batCoeff;
invbatCoeff1=invbatCoeff;

else
    batSOC=SOC1;
    batCoeff1 = batCoeff;
    invbatCoeff1=invbatCoeff;

end

end
```

Figure 13: Simulink block for batteries and the code used inside it

h. Hydrogen Fuel Cell

In 1839, the scientist William Grove demonstrates the basic principle of the fuel cell by using the experiment shown in figure 14a and 2.7b. In Figure 14a the water is being electrolyzed into hydrogen and oxygen by passing an electric current through it. In Figure 14b, the electrolysis is reversed – hydrogen and oxygen are combined to produce an electric current. However, the produced currents are very small and it is due to :

- The low contact area between the gas, the electrode and the electrolyte.
- The large distance between the electrodes



(a) (b)

Figure 14: The electrolysis of water (a), Reverse electrolysis

Another way of explaining the process of fuel cell is by saying that hydrogen fuel is being combusted as shown by the equation:

$$2H_2 + O_2 \longrightarrow 2H_2O$$

However, electrical energy is produced instead of heat energy

To solve the small current problem, flat electrodes are used and a thin electrolyte is placed in between as shown in Figure 15. The structure of the electrodes is also made porous to increase the contact area between the gas, electrodes and electrolyte. Fuel cells work as electrical batteries but instead of supplying solid or liquid fuel in the battery, hydrogen gas is pumped into the cell. The reaction between the hydrogen and the oxygen producing an electric current depends on the different types of fuel cells.

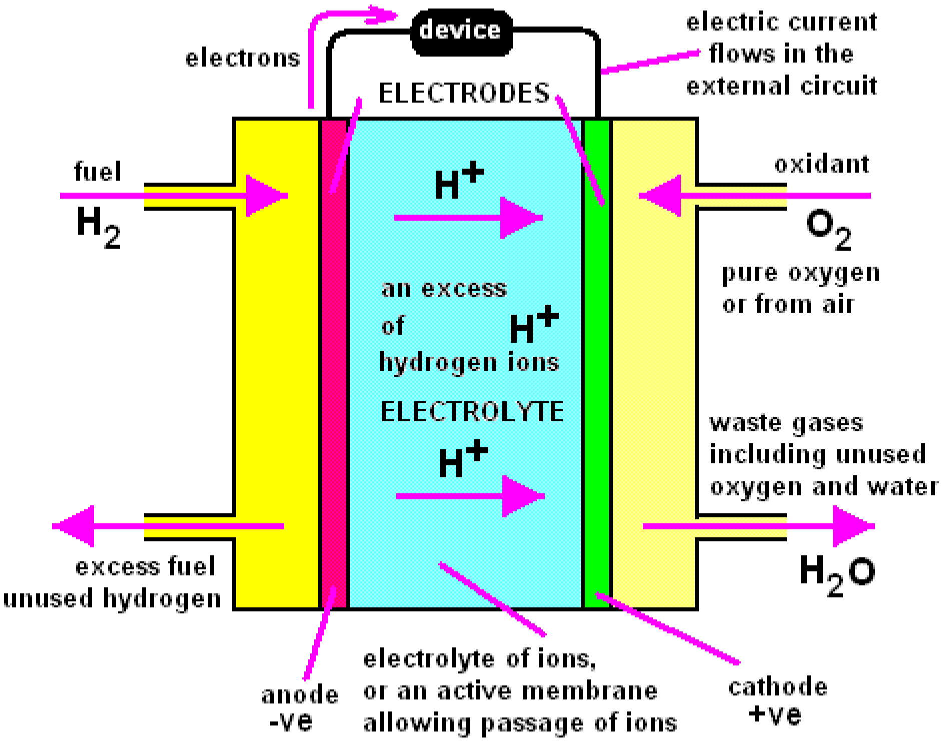


Figure 15: Basic cathode-electrolyte-anode construction of a fuel cell

As the hydrogen reacts, it releases energy at the anode. However the reaction has the ‘classical’ energy form shown in figure 16. Hence ‘activation energy’ should be supplied to get over the energy hill. The reaction will proceed slowly unless at very high temperature as is the case for the fuel cell reactions.

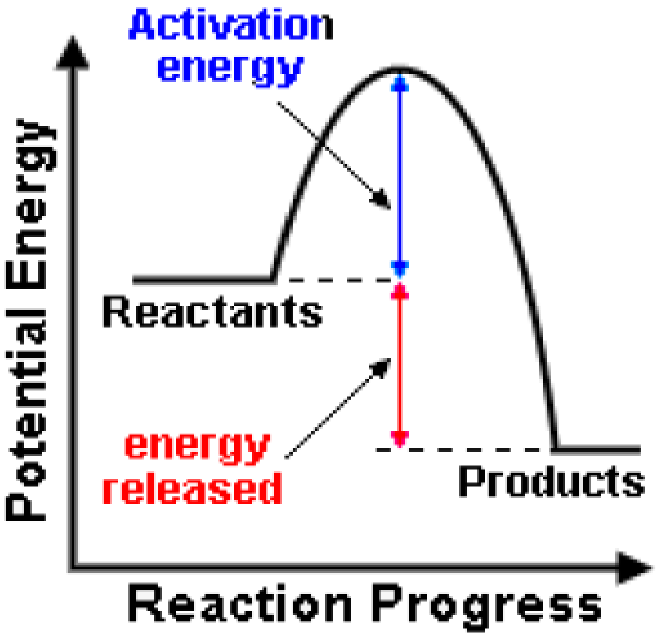


Figure 16: Energy diagram of an exothermic reaction

To improve the speed of the fuel cell reactions and hence increase the current, three ways are used:

- The use of catalysts
- Increasing the temperature
- Increasing the electrode area

This reaction, which involves fuel or oxygen in its gaseous state with a liquid or solid electrolyte and the electrode, is called three phase contact. Indeed, the rate of the reaction varies proportionally with the area of the electrode. To increase the performance of the fuel cell design, modern fuel cell electrodes have a microstructure to increase the effective surface area to hundreds or even thousands times their real ‘length x width’. In addition to these improvements, electrodes should include catalyst and withstand high temperature in corrosive enviroment.

The voltge of a fuel cell is small (0.7 V) when a current passes through it. To produce a usefull voltage multiple fuel cells should be connected inseries, and this structure is known as ‘stack’. The simplest way to connect the anode of one cell to the cathode of the other one as shown in the Figure 17.

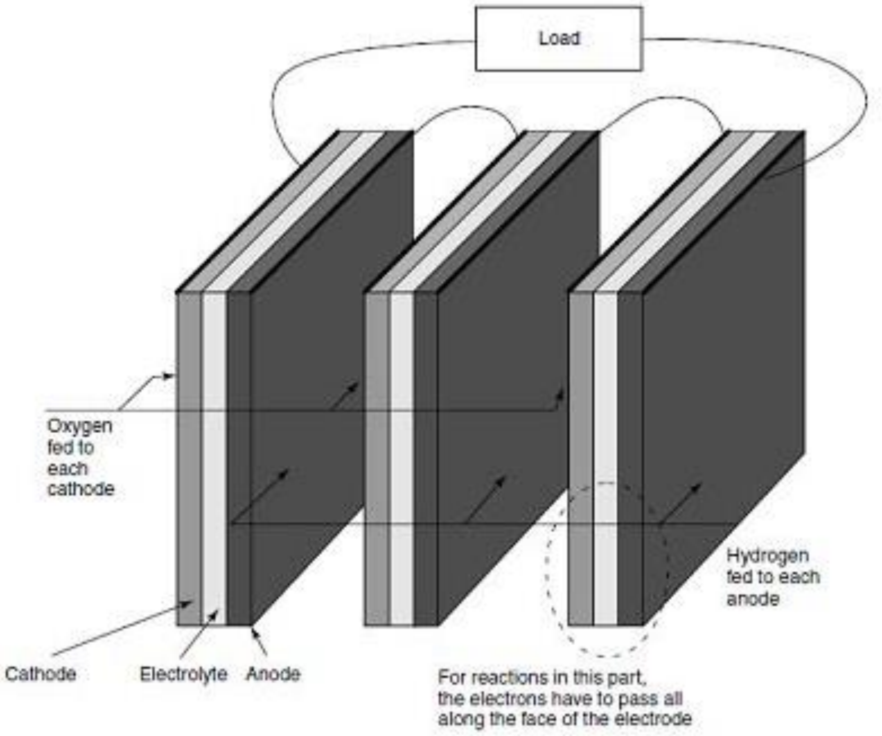


Figure 17: Simple edge connection of three cells in series

The problem with this method is that even if the electrodes are good conductors, each cell is operating at ≈ 0.7 V, i.e. a small voltage drop is important. That’s why this method is not used. An alternative method of cell interconnection is the ‘bipolar plate’. This makes connection all over the electrode surfaces, i.e. the cathode of one cell is connected with the anode of the next cell. It also feeds oxygen to the cathode and fuel gas to the anode as shown in Figure 18.

To connect multiple cells in series, ‘bipolar plates’ are used. These cell interconnects have a particular design that make good electrical contact with the surface of each alternate electrode. There are channels cut in them to let the gases flow over the surface of the electrodes, also to optimize the electrical contact, the contact points should be large enough but that will diminish the good gas flow over the electrode.

Another way is to make these points small but abundant, but that will make the manufacturing complex and costly. Hence, the ideal bipolar plate should be thin in order to minimize electrical resistance and to make the fuel cells stack small, even if this model can narrow the channels for the gas flow and make the pumping of the gas more difficult.

Figure 18: Grooves to let gas flow over surface of electrodes

The electrodes of the fuel cell are porous and this property would allow gas leaking of the edges. That's why we should seal the edges by fitting a sealing gasket around each electrode, to form a stack from such assemblies as shown in Figure 18.

The arrangement shown in Figure 19 is called external manifold: the fuel and the oxygen are supplied to the electrodes through these manifolds. However it has two main disadvantages:

- It is hard to cool the system: It is difficult to supply a cooling fluid through the cells. In practice, air is passed over the cathodes at a higher rate than the demand by the cell, although it is efficient, it is considered as waste of energy.

- The gasket around the edge of the electrode is not evenly pressed down: The gasket is not pressed firmly onto the electrode and this causes a leakage of the reactant gases.

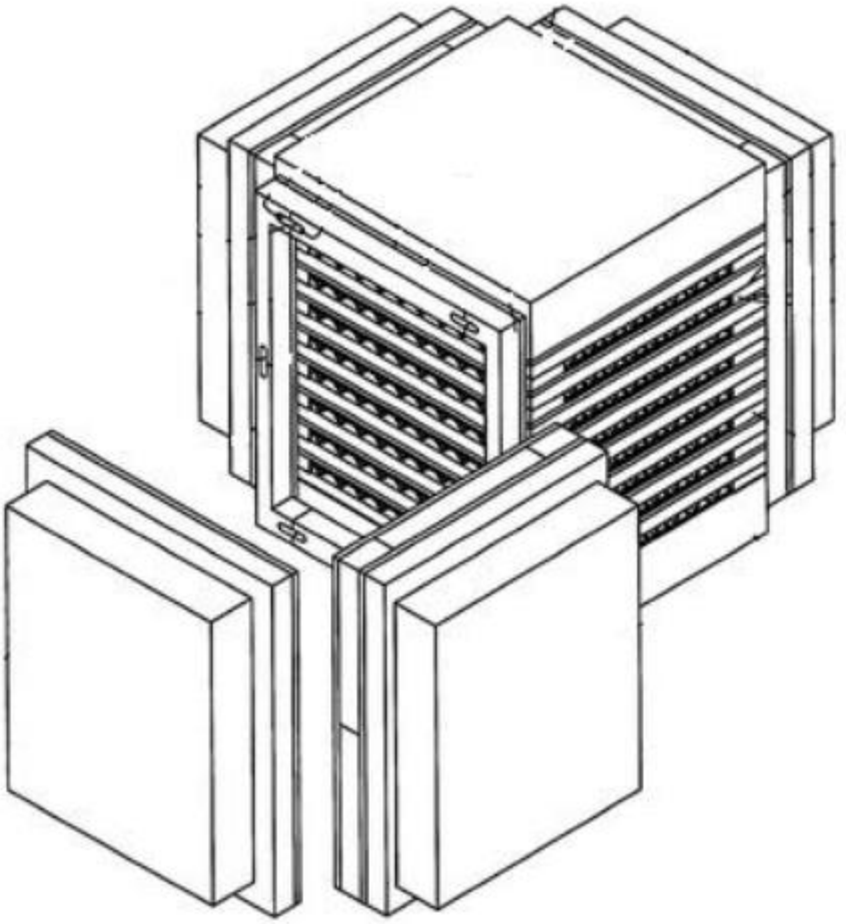


Figure 19: Cell Stack with external manifolds

The formof energy in a fuel cell is difficult to visualize. The inputs are hydrogen and oxygen; the outputs are electricity, heat and water as shown 2.13. The input energy is usually measured as the lower heating value (LHV) of hydrogen, and the output is usually measured as the electric power produced by the cell. Water is a byproduct that could prove useful if properly managed.

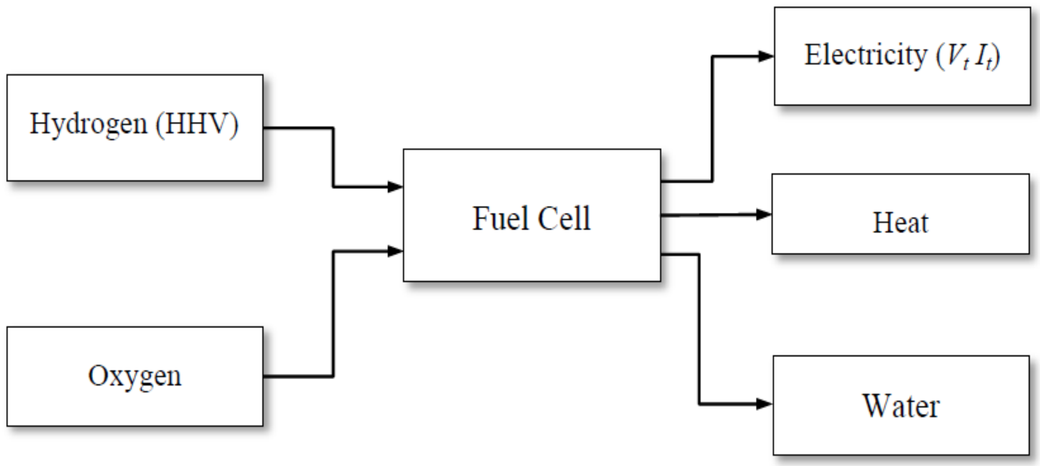


Figure 20: Fuel Cell inputs and outputs

The electrical power and energy are easily calculated using the output terminal voltage and the time of operation. In case of the fuel cells, one should take into consideration the 'Gibbs free energy', G_f, which is the energy available to do external work, i.e. the movement of the electrons round an external circuit, neglecting the work done by changes in pressure and/or volume. This form of energy is similar to the mechanical 'potential energy'. In fact, the point of zero energy is defined by convention at standard temperature and pressure (25°C, 0.1 Mpa). In addition, the change in the Gibbs free energy of formation is equal to the difference between the Gibbs free energy of product and that of its reactants:

$$\Delta G_f = G_f \ of \ products - G_f \ of \ reactants \qquad (2.17)$$

Given the equation for the basic reaction for the hydrogen/ oxygen fuel cell:

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

The product is 1 mole of H_2O and the reactants are 1 mole of H_2 and $\frac{1}{2}$ mole of O_2. The Gibbs free energy of formation is not constant; it varies with temperature and state. If there are no losses in the fuel cell, the process is said 'reversible' and all the Gibbs free energy is converted into electrical energy.

In the Hydrogen fuel cell, two electrons pass round the external circuit for each water molecule produced and each molecule of hydrogen used. Thus for 1 mole, $2N$ electrons pass round the external circuit and the charge flowing is given by the equation:

$$-2Ne = -2F \qquad (2.18)$$

$-e$ is the electron charge equal to 1.602×10^{-19} C

$N = 6.022 \times 10^{23}$ is the Avogadro’s number

$F = Ne$ is Faraday’s constant equals to 96,485 C/mole

The electrical work done for moving this charge is equal to the Gibbs free energy if the cell is lossless:

$$\Delta G_f^O = -2FE_O \quad \text{or} \quad E_O = -\frac{\Delta G_f^O}{2F} \qquad (2.19)$$

This fundamental equation gives the EMF or the Open Circuit Voltage (OCV) of the fuel cell.

Since a fuel cell uses material that are usually burnt to release energy, the most practical way is to compare the electrical energy produced with the heat that would be produced by burning the fuel, or calorific value. This is known more exactly as the ‘enthalpy of formation’ and its symbol is ΔH_f and by convention it is negative, which indicated that energy is released. Thus if W_E is the electric energy produced per mole of fuel, then the efficiency of the fuel cell may be defined as:

$$\eta_{FC} = \frac{W_E}{-\Delta H_f} \qquad (2.20)$$

The efficiency of the fuel cell can be obtained from equation 2.20, as the output electric power (P_E) divided by the energy content of the fuel or enthalpy of formation. It can be put in the following form:

$$\eta_{FC} = \frac{P_E}{-\Delta h_f \dot{m}_{H_2}} \qquad (2.21)$$

Where $\Delta h_f = -286$ kJ/mole is the enthalpy of formation and $\dot{m}_{H_2}$ is the molar flow of hydrogen in mole/s.

However, in practice, not all the fuel can be used, as some fuel crosses through the membrane with no reaction. A *fuel utilisation coefficient* (μ_f) can be defined as:

$$\mu_f = \frac{mass\ of\ fuel\ reacted\ in\ cell}{mass\ of\ fuel\ input\ to\ cell} \qquad (2.22)$$

The fuel cell efficiency is therefore modified as follows:

$$\eta_{FC} = \mu_f \frac{P_E}{-\Delta h_f \dot{m}_{H_2}} 100\% \qquad (2.23)$$

A good estimate for μ_f would be 0.95. This would allow to estimate the fuel cell efficiency by a simple measurement of its terminal voltage and current.

Figure 21 shows the relation H_2 flow (g/s) and the power output (KW) based on the above equations and as taken from [13].

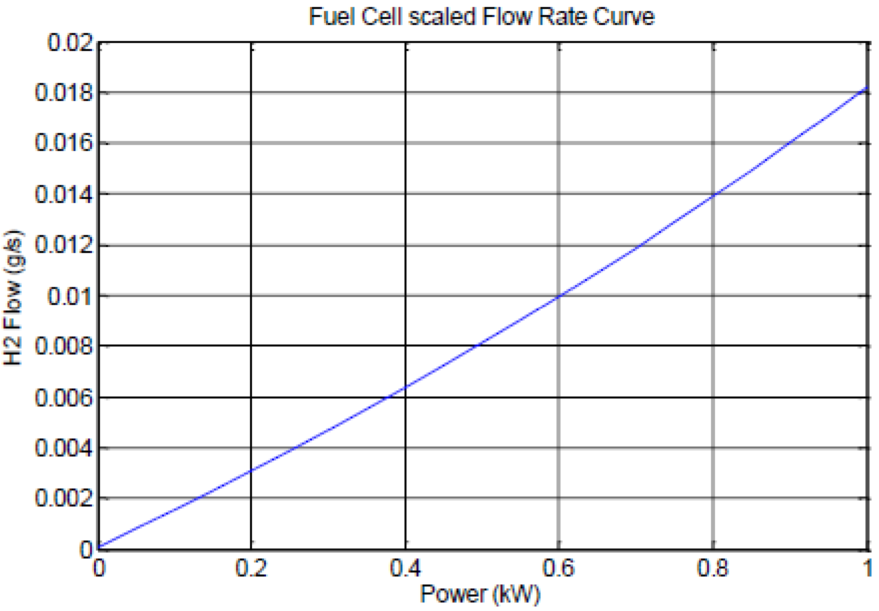
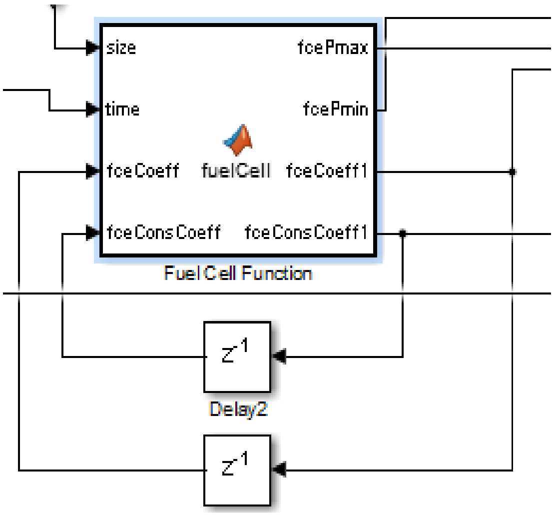


Figure 21: Hydrogen flow curve (g/s) for the Power of the fuel cell

The inputs to the fuel cell block in our simulink program as shown in Figure 22 are the size of the fuel cell in MW, also the initial value of the consumption coefficient and cost coefficient which is calculated at time=0 then it is repeated for every time step. The consumption coefficient is calculated from the curve shown in figure (20) taken from [13], considering a cubic order has a value of [5.921, 0.015, 0, 0]. The output beside the coefficients are the maximum and minimum power. Where the maximum power equals the size determined and the minimum power is 0.05 of the maximum power.

The cost of the fuel cell would be 230$/kW in normal production range and 53$/kW if 500,000 pcs is produced per year as per [18].



```
function [fcePmax,fcePmin,fceCoeff1,fceConsCoeff1]  =
fuelCell(size,time,fceCoeff,fceConsCoeff)

fcePmax=size;
fcePmin=0.05*fcePmax;

if time==0

% Hydrogen loss in mg/s for a 1 kW cell
% Based on data from Bernard's Paper
% Scaled to 10% at rated value as per DOE 2012 Report
fceH2Loss= [ 0  0.3101; 0.1  0.4335; 0.15  0.4704; 0.2  0.4949; 0.4
0.5281; 0.6 0.6026; 0.8  0.9113; 1.0  1.6470 ];
fceH2Loss(:,2)= (fceH2Loss(:,2))* 1e-3;

% Fuel cell stack hydrogen consumption (mg/ s) versus power (kW)
```

```
% Given in ANL Report with peak stack efficiency of 60%
fceH2cons= [ 0  0.0711 ; 0.1  1.422;  0.15  2.104;  0.2  2.782;  0.4
5.767;  0.6 9.040;  0.8 12.647;  1.0 16.529  ];
fceH2cons(:,2)= (fceH2cons(:,2))*1e-3;

% Consumption of H2 by system in g/s
fceH2cons(:,2)= fceH2cons(:,2) + fceH2Loss(:,2);

fcePmax= max(fceH2cons(:,1));
fceCorr= 1.1; % 10% efficiency correction for losses
% fceCorr= 1.0; % No efficiency correction for losses

% Scale curve to one kW for use in different sizes
fceLen= length(fceH2cons);
fceCons=zeros(fceLen,2);
fceCons(1:fceLen,2)= fceH2cons(1:fceLen,2)/ fcePmax* fceCorr;
fceCons(1:fceLen,1)= fceH2cons(1:fceLen,1)/ fcePmax;

fcePmax=size;   % Maximum Fuel Cell power
fcePmin=0.05*fcePmax;  % Minimum Fuel Cell Power

H2cost= 0.003; % $/g of H2

% Fuel cell cost graph specifying hourly cost ($/h) versus power (kW)
fceCons= fceCons* fcePmax;   % Scale up curve to new rating

fceCost= fceCons;
fceCost(:, 2)= fceCost(:, 2)* H2cost* 3600;
[fceCoeff, ~] = CurveFit(fceCost(:, 1),fceCost(:, 2), 'cubic');


fceH2cons= fceH2cons* fcePmax;
[fceConsCoeff, ~] = CurveFit(fceH2cons(:, 1),fceH2cons(:, 2),
'cubic');

fceCoeff1=fceCoeff;
fceConsCoeff1=fceConsCoeff;
else

    fceCoeff1=fceCoeff;
    fceConsCoeff1=fceConsCoeff;

end
```

Figure 22: simulink block for fuel cell and the code used in it

CHAPTER III. METHANOL PRODUCTION SYSTEM

In this chapter we will discuss the other components of the system which represent the reverse osmosis (seawater desalination), the residents, the electrolysis plant, the methanol production plant and the hydrogen storage.

A. **System Description**

Firstly the reverse osmosis for seawter desalination would be described along with the power demand for this process then the residents required to run all the system would be discussed including the water demand and power needed by them.The electrolysis plant method of operation would be then explained and especialy the alkaline electrolysis method that is chosen for our system along with water and power demand for the plant and cost estimate. The hydrogen reservoir model would then be discussed according to the latest known technology for storing hydrogen. Finally the methanol production plant is described including the carbon dioxide capture technique and why green methanol would represent the future of the power industry.

1. ***Seawater desalination (RO)***

Water is an important resource for mankind. It is essential for agricultural and industrial growth, as well as for supporting growing population who require a safe drinking water supply. We find 97% of all water in Oceans, 2% in glaciers and ice caps, and the rest in lakes, rivers and underground. Natural resources cannot satisfy the growing demand for low-salinity water with industrial development, together with the increasing worldwide demand for supplies of safe drinking water. This has forced mankind to search for another source of water. In addition, the rapid reduction of subterranean aquifers and the increasing salinity of these non-renewable sources will continue to exacrebate the international water shortage problems in many areas of the world. Desalination techniques are capable of providing the solution. ‘Desalination’ or ‘Disalinization’ refers to water treatment processes that remove dissolved salts from saline water.

Many methods have been proposed for desalinating saline water, but few were commercially used. The two most popular methods for classifying the well-know desalination processes are as follows:

- Processes in which desalination taking place involve phase change. There are three main methods:
  - Multieffect (ME) distillation
  - Multistage flash (MSF) distillation
  - Vapor-compression (VC) distillation.
- Processes in which desalination takes place without any phase change. These include the following two main methods:
  - Reverse osmosis (RO)
  - Electrodialysis (ED).

Osmosis processes are of current technical interest in two widely separated fields: (1) in the biological science, because of the importance of selective transport through cell membranes to life processes, (2) and in chemical processing, including water and waste water treatment.

One of the great attractions of reserve osmosis is its conceptual simplicity. Basically, we can visualize reserve osmosis as a very fine filtration process using a membrane to filter the salt out of the solution. The only thing that makes it different from ordinary filtration is that there is a minimum driving pressure (osmotic pressure) difference below which the process will not work.

Reverse-osmosis desalination efficiency usually depends on the type of membrane used, its ability for separation and its extent to resist chemical and enviromental effects. Recent developments in membrane technology and construction material made reserve osmosis plant attractive in large desalting capacities.

When we separate pure water and a salt solution through a semipermeable membrane, the pure water diffuses through the membrane and dilutes the salt solution. The membrane blocks most of the dissolved salts, while allowing the water to premeate. This phenomena is know as natural osmosis.

As water passes through the membrane, the pressure on the dilute side drops, and the pressure of the concentrated solution rises. The osmotics flux continues until an equilibrium is reached, where the net water flux through the membrane becomes zero Figure 23b.

At equilibrium, the liquid level in the saline water will be higher than that on the waterside. The amount of water passing in either direction will be equal. The hydrostatic pressure difference achieved is equal to the effective driving force causing flow, called osmotic pressure. This pressure is a strong function of the solute concentration and the temperature, and depends on the type of ionic species present.

Applying a pressure in excess of the osmotic pressure to the saline water section slows down the osmotic flow, and forces the water to flow from the salt solution into the waterside. Therefore the direction of flow is reserved, and that is why this separation process is called reserve osmosis Figure 23c.

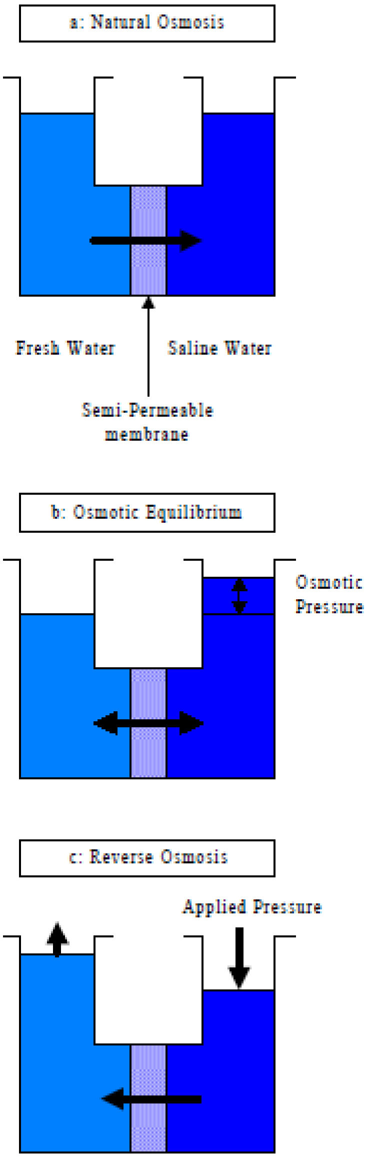
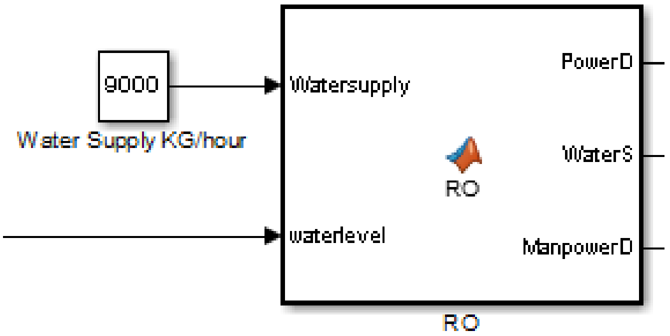


Figure 23: Principle of reserve osmosis

Figure 24 shows that the RO block in our system which has a constant production of 9000kg/h whenever the level of the water inside the water tank goes below 120m3 of water. This system is used for water desalination and feed it to the water tank that gives water to the other blocks (Residents, Methanol plant and electrolysis). The output of this block would be the power demand which is estimated to be 0.003kWh/kg of water. This number is true for temperatue of 25°C and water salinity of 34,000 mg/L. Because salinity is variable around the coasts (and around the rest of the world), the required driving pressure and associated energy needed to produce the same throughput (flux) for different salinities will vary accordingly. A general “rule of thumb” is that the net driving pressure needed to produce an equivalent amount of permeate will increase (or decrease) by about 11 psi (0.76 bar) for each 1000 mg/L incremental change in feed water salinity. [19]. The second output for this block is the amount of manpower required operation and maintainance of the RO system reference [20] give an amount of labourer needed for 9, 12, 15, 20 and 24 Mgd (million gallon per day) by changing the quantity to kg/h we can get the required manpower needed for the system.



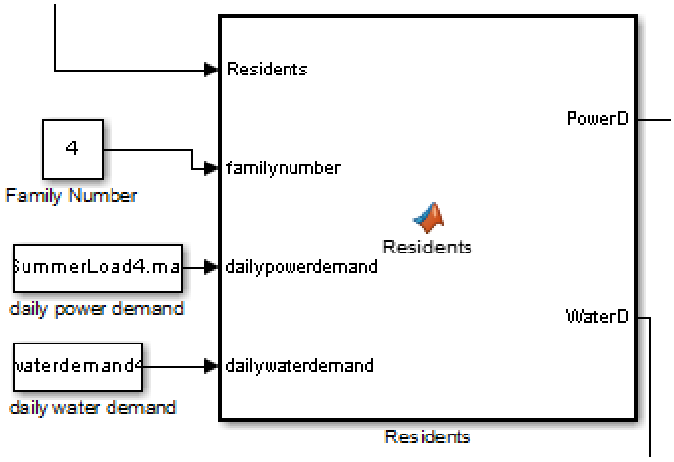
```
function [PowerD,WaterS,ManpowerD] = RO(Watersupply,waterlevel)

WaterS=0;
PowerD=0;
if waterlevel<120000
    WaterS=Watersupply;
    PowerD=WaterS*0.003;
end
if waterlevel>300000
    WaterS=0;
    PowerD=0;
end

% the plant is considered to produce 90,000 Kg of water per day
ManpowerD=round(((90000/3787878.8)+0.188)/0.188);
```

```
end
```

Figure 24: Simulink block of reverse osmosis and code inside it

2. ***Residents***

Figure 25 shows the residents block. The residents would be the total number of labourers required for the power plant, the RO, the methanol and the electrolysis plants. The other input for this block would be the daily power demand and daily water demand per capita. The daily power demand is taken as summer load day from[21] while considering a peak load of 2KW. The daily water demand is taken from [22] based on Figure 26.



```
function [PowerD,WaterD] =
Residents(Residents,familynumber,dailypowerdemand,dailywaterdemand)
%#Calculate the power and the water demand for the residents

PowerD=Residents*familynumber*dailypowerdemand;
WaterD=Residents*familynumber*dailywaterdemand;

end
```

Figure 25: Simulink block for residents and the code inside it

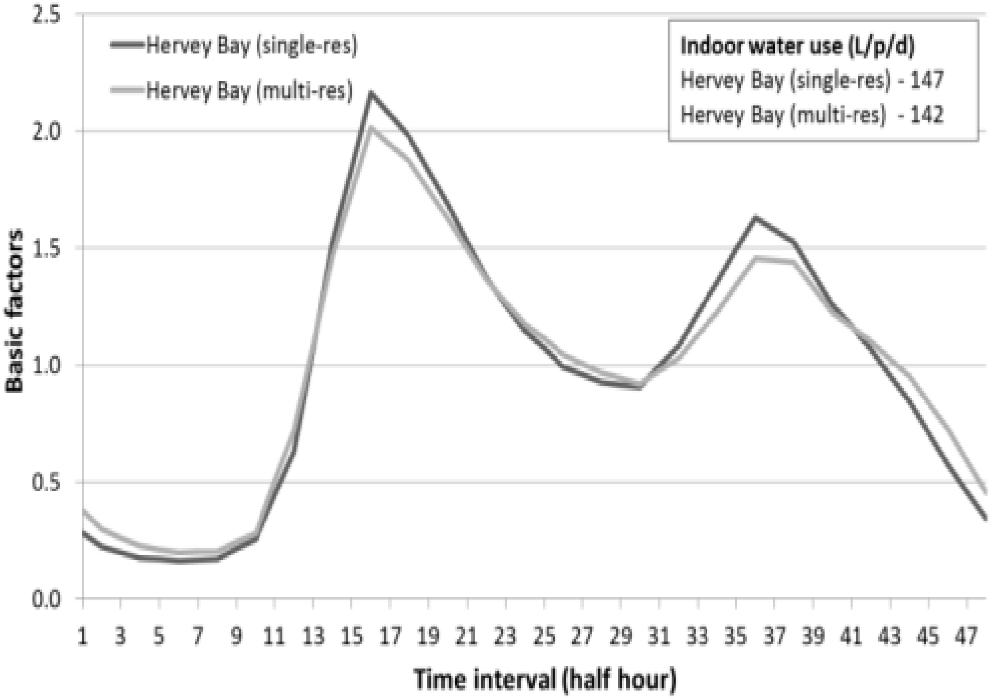


Figure 26: Typical daily water demand variation [22].

The daily power demand is then multilplied by the number of family members which is considered in our case as 4. Similarly for the daily water demand. Thus we get the total power and water demand as an output for this block.

3. *Electrolysis Plant*

Electrolysis : $H_2O \longrightarrow H_2 + \frac{1}{2}O_2$

Electrolyzers use electricity to divide water into hydrogen and oxygen. They are the opposite of fuel cells, and the reactions taking place at the electrodes are the same but in different directions. In practice, the main electrolytes in use are alkaline liquids and solid proton exchange membranes.

For medium-scale users, the advantages of electrolyzers are:

- The product hydrogen is very pure
- It is produced when needed and it is not stored hence it is safer
- Electricity is supplied in easier and safer way than bottled hydrogen
- It is much cheaper than the gas supplies in high pressure cylinders

An electrolytic cell is a device where oxidation-reduction (redox) reactions occur to decompose chemical compounds by electric energy. In the cell, an electrolyte, present in the form of an acid (like HCl), a base (a hydroxide like NaOH) or a salt (like NaCl), reacts with the solvent (usually water) and splits into positive and negative ions (i.e. H^+, Na^+, OH^- or Cl^-). By connecting two electrodes immersed in the electrolytic cell to an outer electric circuit in which an electromotive force is applied, an electron flow is produced through the external circuit and has a corresponding ion flow in the cell internal electrolyte solution. The cathode is the electrode through which the electrons enter the cell and the reduction half-reaction occurs, while the anode is the electrode from which the electrons exit the cell and where the oxidation half-reaction take place.

All chemical species are categorised with respect to their reduction potential (measure in V) that represents its propensity to be reduced or, equivalently, to gain electrons from another chemical species. The higher the reduction potential of a chemical species, the higher its tendency to gain electrons with respect to other species. A chemical species with lower reduction potential will tend to lose electrons to species with higher reduction potential. The reduction potential is measured in standard conditions with respect to a reference standard hydrogen electrode (SHE) with a potential conventionally set at 0 V.

Industrial electrolysers usually consists of more than one electrolytic cell. In order to increase productivity and to evenly distribute the voltage drop, these electrolysers are constructed by several cells connected in series, while the metallic separator between two cells can work as a bipolar plate and function as the anode on one side and the cathode on the other.

The efficiency of electrolysis is calculated as the ratio between the chemical energy contained in the yielded hydrogen and the electric power employed to the process.

Alkaline Electrolysers (AE) take up a large portion of the commercial electrolyser market. They are constructed with materials resistant to the attack of patassium hydroxide (KOH) and are designed in a way to prevent electrolyte leakage. The anode is made of nickel while the cathode consists of nickel coated with platinum. The operating temperature is between 70 – 85 ^oC and the electric current density on the electrodes is around 6 – 10 A/m^2 with an efficiency ratio between 75% - 85%.

An alkaline electrolyser is composed by an electrolytic cell in which two electrodes are immersed in water solution of potassium hydroxide KOH. The OH^- ions are drawn to the anode to be oxidized (i.e. to lose electrons), releasing oxygen molecules, water and electrons which will enter the external electric circuit according to the following reaction:

$$2OH^- \longrightarrow \frac{1}{2} O_2 + H_2O + 2e^- \qquad \text{(anode)}$$

The oxidation potential ΔV_{rid} of this reaction is -0.40 V. At the cathode the released electrons are not absorbed by reduction to the metallic potassium of the K^+ ions contained in the liquid solution, since such reaction, has a very low reduction potential

(ΔV_{rid} = -2.92V). The reaction taking place at the cathode is the reduction of the water itself:

$$2H_2O + 2e^- \xrightarrow{\hspace{2cm}} H_2 + 2OH^- \quad \text{(cathode)}$$

With a rduction potential of -0.83 V, still negative but higher than that of the K^+ ions. Therefore at the cathode the water undergoes reduction (i.e. gains electrons) and releases hydrogen molecules and OH^- ions. The overall energy absorbed by the electrolysis is calculated by this sum:

$$\Delta V_{oss} + \Delta V_{rid} = -0.40V + (-0.83V) = -1.23V \tag{3.1}$$

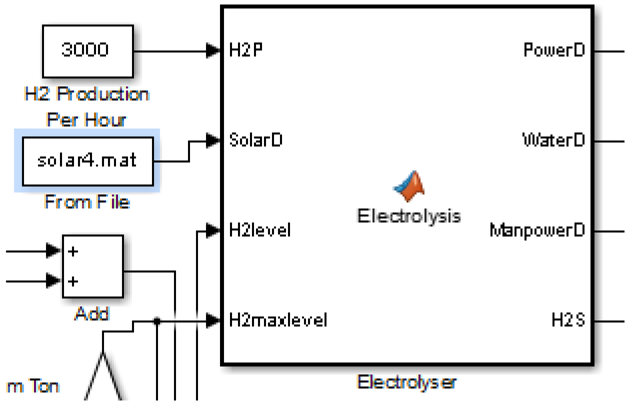
Which equals the electromotive force required to trigger the two non-spontaneous reactions.

A porous diaphragm, permeable to OH^- ions and water but not to H_2 and O_2 gas, allows water and the ionic electric current to pass through while keeping the two gases from mixing with each other, so that the system can store the two gases separately. The overall reaction is expressed as:

$$H_2O \xrightarrow{\hspace{2cm}} H_2 + \tfrac{1}{2} O_2$$

Which gives the inversion of the spontaneous and exothermic combustion reaction of hydrogen and oxygen [26].

Therefore electrical power and water is required to make the electrolysis which will produce the hydrogen gas. Hydrogen is good source of energy, but it can’t be easily transported. Therefore it should be synthesysed to produce methanol. Hydrogen production energy demand is very high 45 kWh/kg of hydrogen based on [23]. The electrolysis plant would check the hydrogen level in the hydrogen tank. As long as the hydrogen tank level is below the maximum level the plant would produce an amount proportional to the solar irradiance where at maximum irradiance it would produce 3000 kg/h.



```
function [PowerD,WaterD,ManpowerD,H2S] =
Electrolysis(H2P,SolarD,H2level,H2maxlevel)
% This Function would give the power output and water demand and
manpower
% needed for the electrolysis process

% Electrolyzer data
SE_elec= 45;     % Specific energy in kWh per kg of H2
SW_elec= 8.95;   % Specific water requirements in kg per kg of H2

H2manpower=0.03;  %H2 production needs around $0.03 manpower for each
KG of Hydrogen

n=1;  % number of production days

%H2 production is done only when solar irradiance is above 100W/m2
if H2level < H2maxlevel-3000
% H2 Supply
    H2S=(SolarD/1000)*H2P;
%Power Needed is 45KWh/KG of H2
    PowerD=H2S* SE_elec;
%Water demand is 8.95KG/KG of H2
    WaterD=H2S* SW_elec;
else
        H2S=0;
        PowerD=0;
        WaterD=0;
end

% Consider 100$ as the salary of labour in one day
 ManpowerD = round(5*H2P*H2manpower/(n*100));

end
```

Figure 27: Simulink block for electrolyser and the code inside it

Figure 27 shows the electrolysis block used in our software where the input to this block is the hydrogen tank level, maximum hydrogen tank level, the solar irradiance and the maximum production rate per hour. The output of the block would be the power demand calculated as 45 kWh/kg of hydrogen produced, the water demand required which is 8.95kg/kg of hydrogen and the hydrogen gas supplied to the hydrogen tank. The manpower required for electrolysis is based on [24] which is \$0.03/kg/day of Hydrogen.

The cost estimation methodology for the H_2 production is based on a plant lifetime of 40 years [12]. The discout rate is taken 6% and the depreciation period of the plant is 7 years, following the Modified Accelerated Cost Recovery System (MACRS). The total capital cost of the plant is calculated as a percentage of the electrolyser system cost \$350/kg of hydrogen produced per day. As we are producing 50 ton of methanol per day, thus 10,000 kg of hydrogen, therefore the capital cost of the electrolyser would be \$3.5 millions. The O_2 derived from the electrolysis unit, is regarded as by-product and will be sold in the healthcare industry at a typical selling price of \$0.1/kg O_2. Since we are producing 10,000 kg of hydrogen gas as described earlier, this amount of hydrogen gas means that we are producing 80,000 kg of oxygen per day, thus 29,200 ton of oxygen per year. This amount of oxygen gas can be sold for \$2.92 million per year. Therefore the net cost of the electrolyser after accounting for the benefits we get from selling the oxygen gas would be \$0.6 million. Thus the electrolysis plant cost is \$35/ton of methanol produced per year [12].

4. ***Hydrogen Tank***

Geologic storage is used extensively in the oil, natural gas, and compressed air energy industries. To understand the scale of this utilization, approximately 800 milion barrels of oil (DOE, 2011) and 100’s of billion cubic feet of natural gas (EIA, 2011) are stored geologically in the United States. The basic drive for geological storage is that the cost per volume-stored is 3 to 5 times less than surface storage. With this relatively inexpensive means to store large volumes, storage can be situated to buffer seasonal demands, provide continuity in case of disruption in the supply chain, and control congestion in the pipeline system.

Geologic cavern storage of hydrogen for industrial use already exists at two locations in Texas. In addition, a hydrogen economy and infrastructure raises similar needs as natural gas and oil infrastructures. Analyses of the hydrogen infrastructure indicate that there may be an important role for geologic storage. This need, similar to fossil energy stocks, is to buffer seasonal demands, provide continuity in case of disruption in the supply chain, and control congestion in the pipeline system.

The Hydrogen Geological Storage Model (H2GSM) is a prototype analytical framework developed to highlight the major components of a ‘gate-to-gate’, large-scale hydrogen storage facility (the analysis focuses on the storage infrastructure only). The analysis includes four storage options, namely salt caverns, depleted oil and gas reservoirs, aquifers, and hard rock carvens. Figure 28 illustrate the overarching assessment methodology and analytical framework.

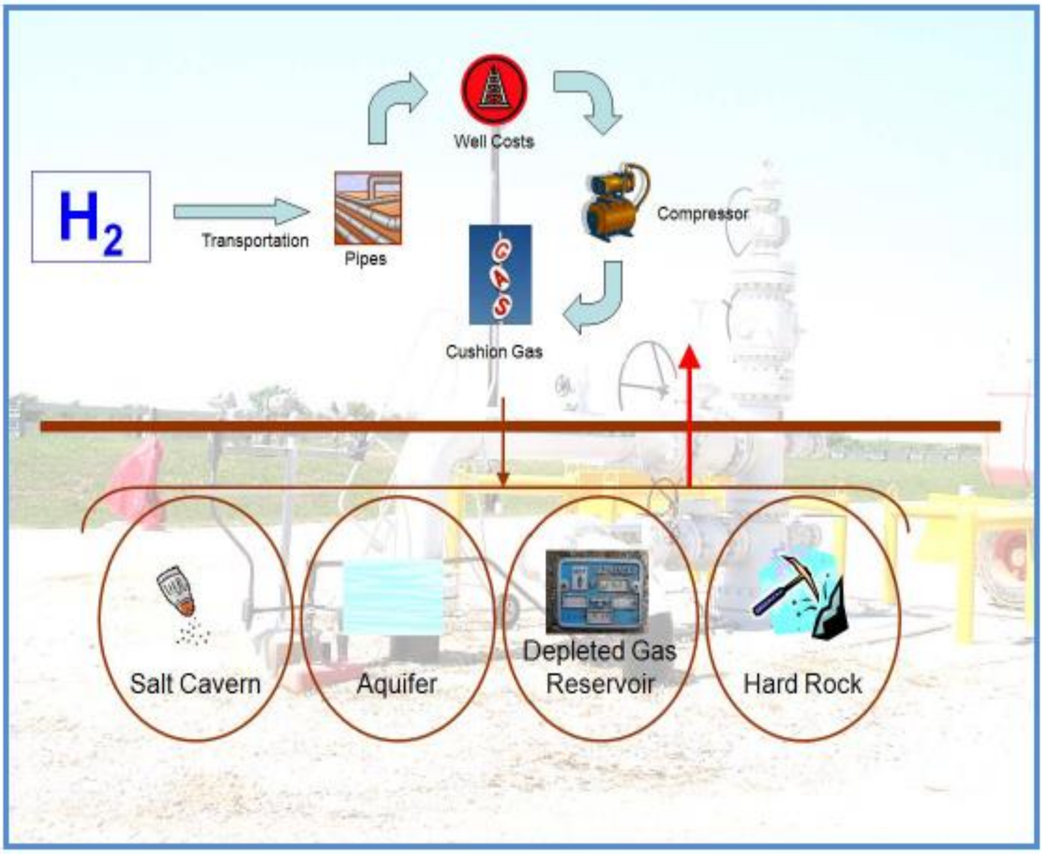


Figure 28: The assessment methodology and model framework

The type of rock formation under consideration to store hydrogen will have profound effects on the physical and economic viability to utilize a particular site. Four types of geological storage options have been examined for this analysis. Currently, depleted gas/oil reservoirs, aquifers, and salt caverns are the three main types of underground storage in use for natural gas today. The other storage options available currently and in the near future, such as lined hard rock caverns, will become more popular as the demand for natural gas storage grows, especially in regions where depleted reservoirs, aquifers, and salt deposits are not available. The storage of hydrogen within the same type of facilities, currently used for natural gas, may add new operational challenges to the existing cavern storage industry, such as the loss of hydrogen through chemical reactions and the occurrence of hydrogen embrittlement. Currently, there are only three locations worldwide, two of which are in the United

States, that store hydrogen. All three sites store hydrogen within salt caverns. However, there have been successful cases of storing both town gas (50 – 60% hydrogen) and helium within aquifers successfully, thus possibly inferring the same media may be suitable for storage of hydrogen gas.

Salt caverns hold substantial promise due to the self-sealing nature of the salt, the ability to customize the size and often shape of the caverns. Depleted oil and gas reservoirs have known production history and thus are proven capable of holding gas. With this information, operators may have a good understanding of the potential rates of injection, with-drawal, and relative storage size of the formation. The reservoirs are easy to develop due to existing infrastructure. However, depleted oil and gas reservoirs may have a higher potential storage option, yet also may represent the option with the least well-understood geology and therefore may require a large number of site surveys to more fully characterize the sites, which would add time and cost to site development. Even with this characterization, the potential for subsurface transport pathways in aquifers may preclude them from becoming an economically-viable storage site due to the high degree of uncertainty, and therefore, financial risk involved with with developing and operating these types of sites. Lastly, hard rock caverns that require mining and impermeable liners represent more fully engineered storage systems that may be developed when other storage options are not available. However, this is a relatively new technology with only one site in the world that is fully operational to store natural gas. Figure 29 below shows the economic analysis developed for providing a cost comparison between the four types of underground storage studied.

Cushion gas to working gas ratios were extracted from a 2004 report by the Federal Energy Regulatory Commission (FERC, 2004). The depleted oil and gas reservoirs and aquifers require higher percentages of cushion gas to keep the formation pressure high enough for successful operations (Beckman et al., 1995; FERC, 2004; NaturalGas.org, 2007). An aquifer system needs cushion gas volumes between 50 and 80% of the total volume depending on the nature of the formation. In Table 1, 50% cushion gas was assumed for the aquifer scenario, where in reality the cushion gas volume could be closer to 80% of the reservoir volume and the capital costs would then be significantly higher.

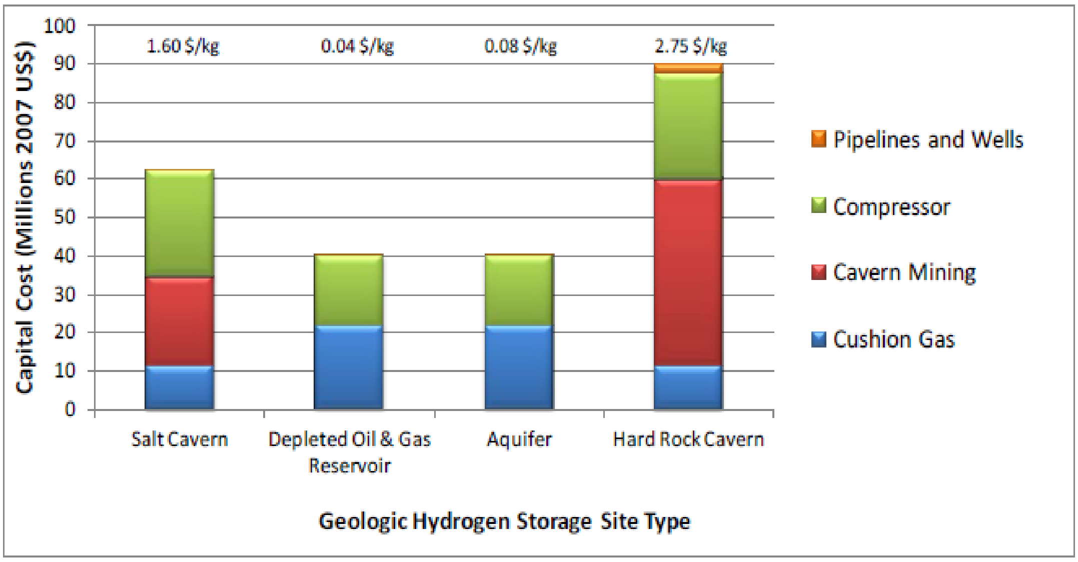


Figure 29: Cost Module (2007 US$)

the hydrogen tank cost that will be used in the simulation is $0.04/Kg of hydrogen for depleted Oil & Gas Reservoir (the lowest value) and $2.75/Kg of Hydrogen for hard rock cavern (the highest value) [27].

5. *Methanol Plant*

Methanol Production : $CO_2 + 3H_2 \longrightarrow CH_3OH + 2H_2OH$

For many decades, inorganic chemistry and the chemistry of aromatics on the basis of coal tar dominated the chemical industry. Methanol (CH_3OH) – also named methyl alcohol, carbinol, or wood alcohol – is the first representative of the homologous series of alcohols that are correctly named by adding the syllable –ol to the corresponding paraffin. Methanol (molar mass 32.0429 g mol^{-1}) is a colourless neutral, but polar liquid. It boils at 64.6°C and freezes at -97.6°C.

With a global annual consumption of 53 million tonnes in 2011, methanol is one of the most important commodities of the chemical industry.

It is, among others, used for the production of plastics and resins, pharmaceuticals, chemical fibers, paint and pesticides. It is also used in the fuel sector for the production of MTBE/TAME (methyl tertiary-butyl ether/ teriary-amylmethylether) is mainly used as an octane booster in gasoline, accounting for 16% of the global annual consumption. However, The share of MTBE has decreased since 2003, when MTBE was replaced by ethanol as an antiknocking agent for fuels due to the contamination of water resources by MTBE from spilled fuels. A large part of the acetic acid, which consumes approximately 9% of global methanol production, is converted into vinyl acetate monomer (VAM).

The remaining 48% of global methanol consumption is divided into production of a large variety of chemical intermediates such as chloromethane, methylamine, methylmethacrylate and methylmercaptane, as well as the use of methanol or methanol derivatives such as dimethyl ether (DME) as a fuel or fuel blend. Overall, aproximately one third of global methanol production is consumed in the fuel sector. The chemicals produced from methanol stayed at approximately the same or slightly decreased levels on a percentage basis between 2009 and 2013 Figure 30. However, the fuel sector (MTBE/TAME/gasoline/DME) was estimated to increase from 30% in 2009 to 40% in 2013 [25].

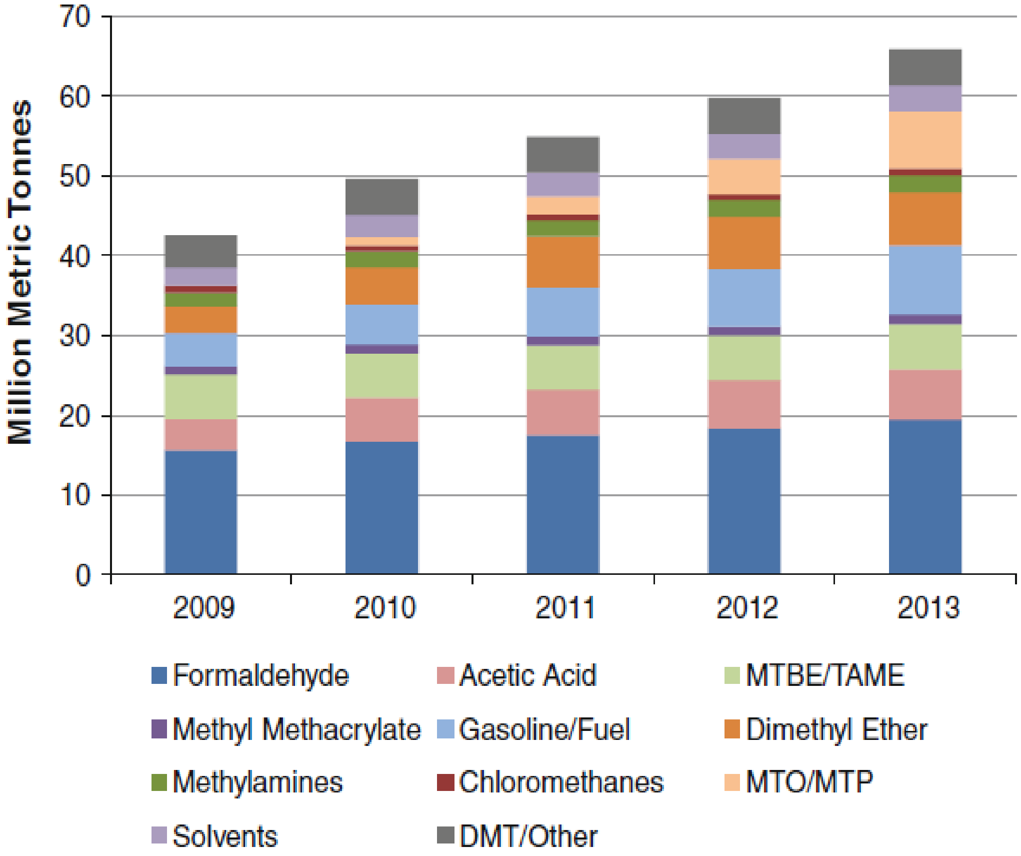
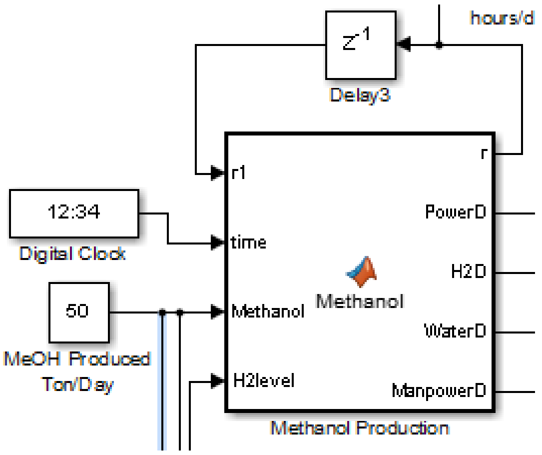


Figure 30: Development of global methanol demand by sector ; MTO (methanol-to-olefins), MTP (methanol-to-propylene)

The production of methanol from hydrogen gas would require to capture CO2 from flue gas of a coal power plant. Among many CO2 capture options, “amine scrubbing (MEA) and oxyfuel technology are considered the most competitive and ready to apply technologies for the first generation of applications in industrial scale. The post combustion chemical absorption technique with amine scrubbing is the most mature technology with higher Technology Readiness Level and has already been tested and implemented in large scale applications. Therefore, the amine scrubbing is selected as the CO2 capture technology for this study. The CO2 chemical absorption from a flue gas is performed bringing a monoethanolamine (MEA) aqueous solvent into contact with CO2 in a column, where the following reaction occurs:

$(CH_2)_2OHNH_2 + H_2O + CO_2 \longleftrightarrow (CH_2)_2OHNH_3^+ + HCO_3^-$

The release of CO2 carried in the solvent occurs in the stripper unit that operates at elevated temperatures, allowing the reverse reaction to take place. The MEA solvent is thus regenerated and reused. The required heat for the solvent regeneration is provided by steam extracted from the steam cycle. The gaseous outlet of the stripper mainly consists of CO2 and steam, and these two components are separated by condensation at ambient temperature.” [11]



```
function [r,PowerD,H2D,WaterD,ManpowerD] =
Methanol(r1,time,Methanol,H2level)
%#Hydrogen needed in Kg/day for MeOH tn/day
H2perton=200; %Methanol production require 200KG of hydrogen per ton
of methanol
PowerDperton=1194; %Methanol needs 1194KW of power per ton of methanol
WaterDperton=685.7; %Methanol produce 685.7KG of water for each ton of
methanol
ManpowerDratio=0.3; % Manpower demand is 0.3 time the amount of
methanol being produced in Ton
r=r1;
if mod((time-1)/24,1)==0
    if H2level > 20000
        r=1;
    else
        r=0;
    end
end

if r==1
    H2D=(Methanol/24)*H2perton;
    PowerD=(Methanol/24)*PowerDperton;
    WaterD=(Methanol/24)*WaterDperton;

else
```

```
    H2D=0;
    PowerD=0;
    WaterD=0;
end
ManpowerD=round(ManpowerDratio*Methanol);

end
```

Figure 31: Simulink block for methanol production and the code inside it

Figure 31 shows the methanol production block used in our software. We would have a constant production of methanol per day (50 ton/day) whenever the hydrogen tank level is above a given threshol level (here taken as 20000 kg of hydrogen), since a one day production of 50 ton of methanol would require 10,000 Kg of hydrogen. Therefore a digital clock is taken as an input for the block and at the beginning of each day the tank level is checked to decide if it is a production day or a rest day. Variable r would be one when there is a production and zero if the level of hydrogen is not enough for one day methanol production. The total amount of production days is cumulated to decide how many days of production we have in a year.

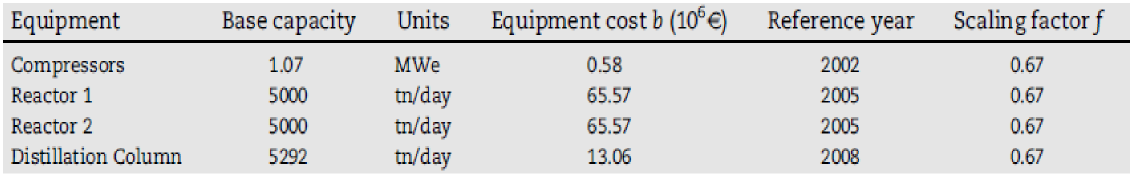
The energy required for methanol production based is about 1194 kWh/ton of methanol [3]. The reaction would give water on the bases of 685.7kg of water per ton of methanol [12]. The manpower demand for operation and maintenance of the plant would be considered as 30% of total cost of the methanol production [12].

In what concerns the techno-economic analysis of the methanol plant, the Total Purchased Equipment Cost (TPEC) is calculated based on similar processes found in literature. According to below equation, based on the cost of an equipment b at a given capacity known, the cost of a similar unit a, with X times the capacity of b, is X^f times the cost of the initial unit.

$$Cost\ of\ equipment\ a = (Cost\ of\ equipment\ b) \times (X^f) \qquad (3.2)$$

Where *f* is the scaling factor depending of the plant is presented in Table 1. With reference to Figure 7, It is assumed that the same reactor found in the syngas synthesis route can be used, since the nature of the reactants is quite similar. The cost of heat exchangers is not taken into account, since it is considered negligible compared to the other components.

Table 1: Methanol plant equipment cost estimation



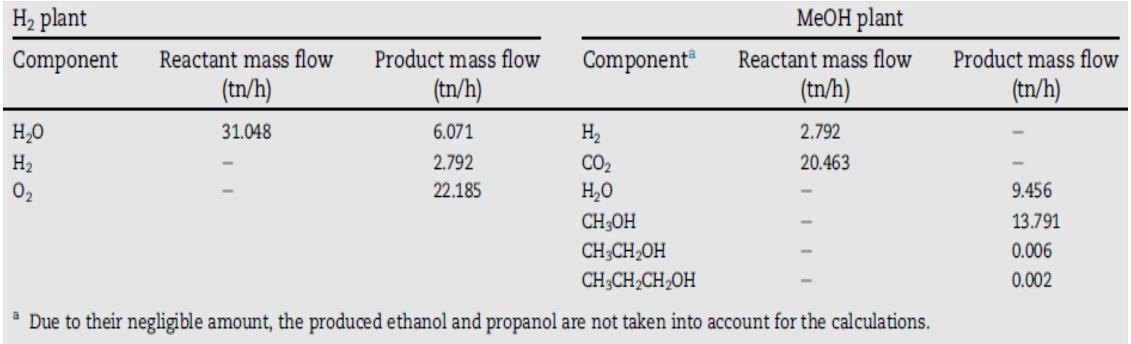
Equipment	Base capacity	Units	Equipment cost *b* (10^6 €)	Reference year	Scaling factor *f*
Compressors	1.07	MWe	0.58	2002	0.67
Reactor 1	5000	tn/day	65.57	2005	0.67
Reactor 2	5000	tn/day	65.57	2005	0.67
Distillation Column	5292	tn/day	13.06	2008	0.67

The equipment cost is calculated based on the quantity of the produced methanol which depends on the mass balance of the scheme. The mass balance is estimated according to the stoichiometric reactions taking place for hydrogen and methanol production in the respective plants and is presented in Table 2.

The Total Capital Investment is calculated from the TPEC based on the methodology presented in Table 3.

The fixed operating costs include the general overhead costs, insurance and taxes, whereas the variable operating costs consist of the feedstock costs, catalyst costs, salaries and maintenance and repair costs. The fixed and variable costs are summarized in Table 4.

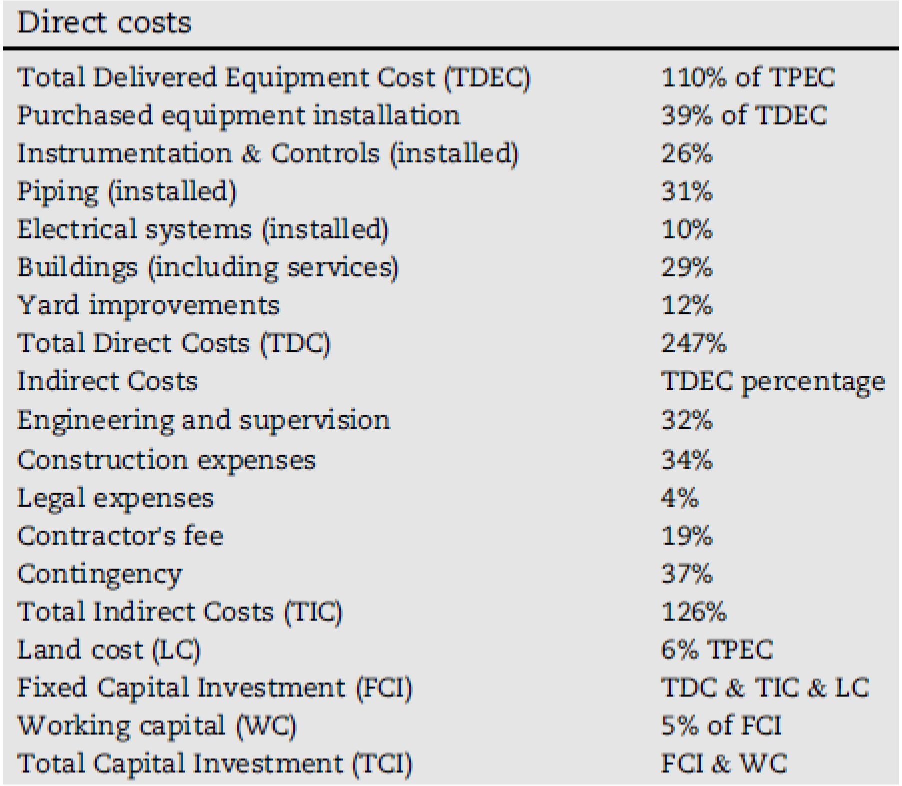
Table 2: Mass balance



H_2 plant			MeOH plant		
Component	Reactant mass flow (tn/h)	Product mass flow (tn/h)	Component[a]	Reactant mass flow (tn/h)	Product mass flow (tn/h)
H_2O	31.048	6.071	H_2	2.792	–
H_2	–	2.792	CO_2	20.463	–
O_2	–	22.185	H_2O	–	9.456
			CH_3OH	–	13.791
			CH_3CH_2OH	–	0.006
			$CH_3CH_2CH_2OH$	–	0.002

[a] Due to their negligible amount, the produced ethanol and propanol are not taken into account for the calculations.

Table 3: Methanol plant total capital investment estimation approach

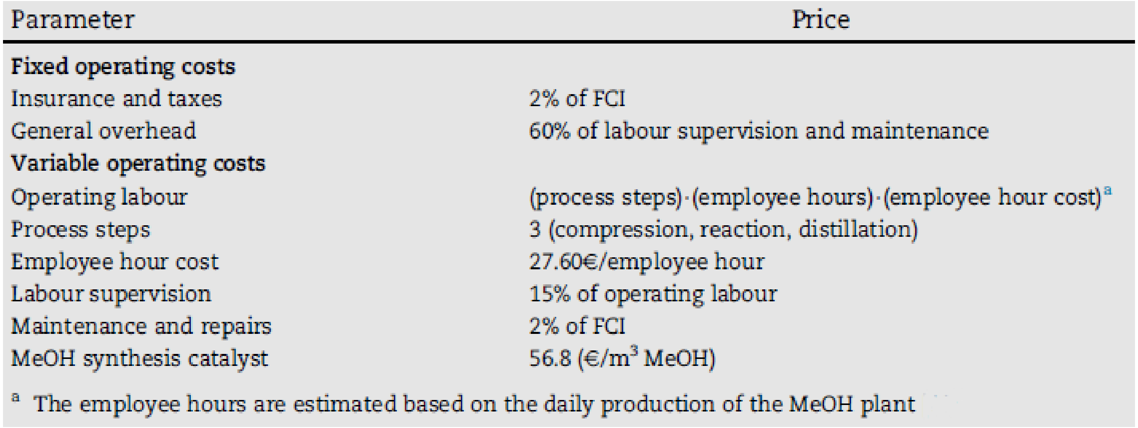


Direct costs	
Total Delivered Equipment Cost (TDEC)	110% of TPEC
Purchased equipment installation	39% of TDEC
Instrumentation & Controls (installed)	26%
Piping (installed)	31%
Electrical systems (installed)	10%
Buildings (including services)	29%
Yard improvements	12%
Total Direct Costs (TDC)	247%
Indirect Costs	TDEC percentage
Engineering and supervision	32%
Construction expenses	34%
Legal expenses	4%
Contractor's fee	19%
Contingency	37%
Total Indirect Costs (TIC)	126%
Land cost (LC)	6% TPEC
Fixed Capital Investment (FCI)	TDC & TIC & LC
Working capital (WC)	5% of FCI
Total Capital Investment (TCI)	FCI & WC

Based on above the cost estimate of the methanol plant is around 105 \$/ton of methanol production and the CO_2 cost 50 \$/ton of methanol produced [12].

To decide the final cost of ton of methanol produced we divide the total cost by the amount of methanol produced in ton.

Table 4: Fixed and variable operating costs.



Parameter	Price
Fixed operating costs	
Insurance and taxes	2% of FCI
General overhead	60% of labour supervision and maintenance
Variable operating costs	
Operating labour	(process steps)·(employee hours)·(employee hour cost)[a]
Process steps	3 (compression, reaction, distillation)
Employee hour cost	27.60€/employee hour
Labour supervision	15% of operating labour
Maintenance and repairs	2% of FCI
MeOH synthesis catalyst	56.8 (€/m^3 MeOH)

[a] The employee hours are estimated based on the daily production of the MeOH plant

CHAPTER IV. SYSTEM INTEGRATION

A. **Description**

This system is represented in the block diagram illustrated in Figure 32. The main items of such a system would be:

- The PV Panels with back up batteries in addition to Hydrogen Fuel Cell as hybrid power source (with the possibility of adding a wind farm in further research).
- The water desalination system that provides the water required for residents and electrolysis.
- Hydrogen gas will be produced and then through synthesis with CO2 gas it will transform into methanol.

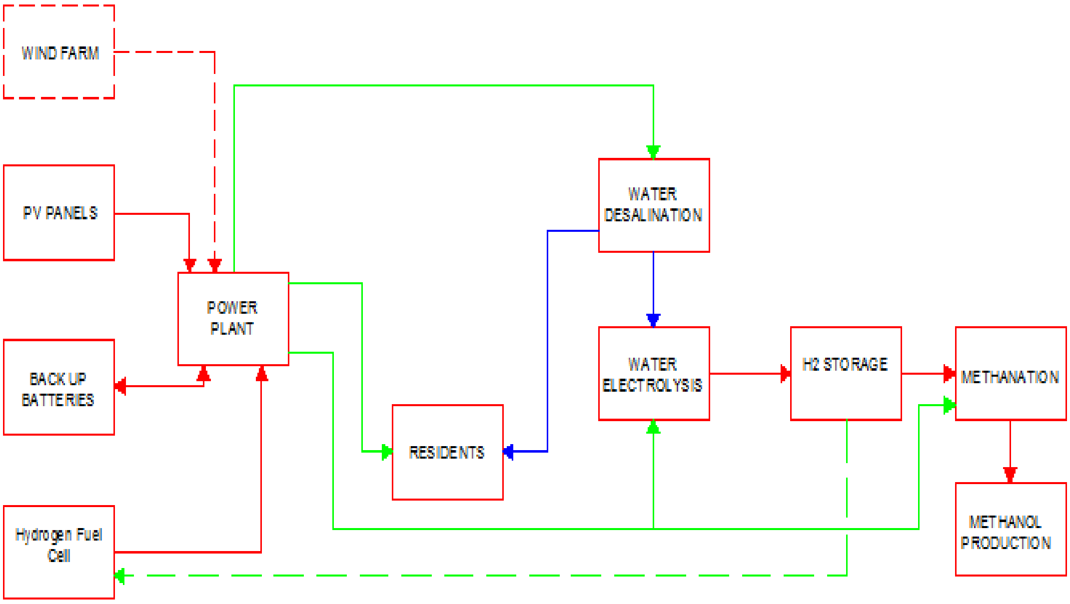
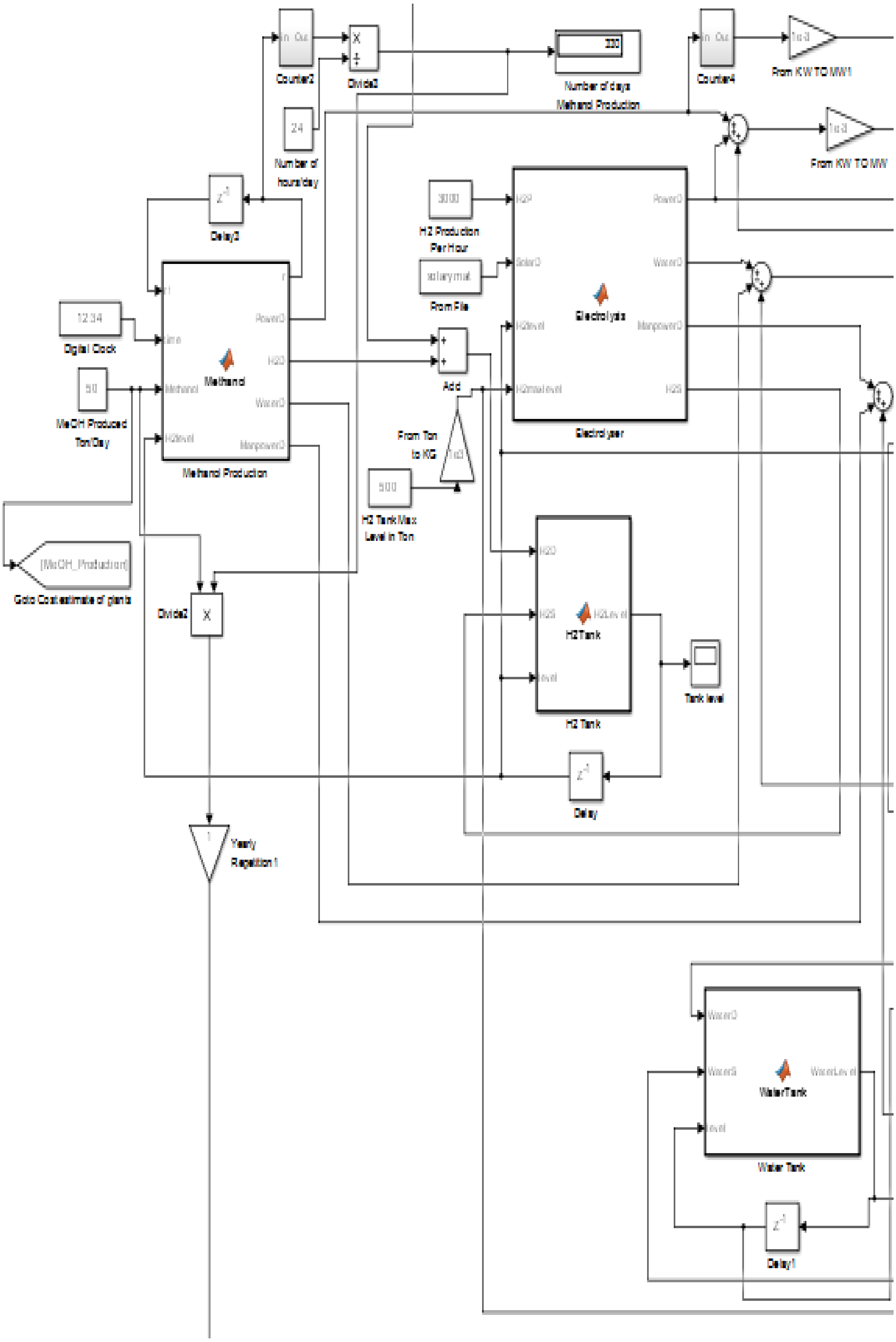


Figure 32: Methanol Production in Desert Area Using Hydrogen Gas

Green line: Power, Blue line: water.


In Out
Counter2
X
÷
Divide3
330
Number of days
Methanol Production
In Out
Counter4
1e-3
From KW TO MW1
1e-3
From KW TO MW
24
Number of
hours/day
z^{-1}
Delay2
3000
H2 Production
Per Hour
H2P
Power0
solary.mat
From File
Solar0
Water0
Electrolysis
H2level
Manpower0
H2maxlevel
H2S
Electrolyser
12:34
Digital Clock
t
time
Power0
Methanol
H2O
50
MeOH Produced
Ton/Day
Methanol
Water0
H2level
Manpower0
Methanol Production
Add
From Ton
to KG
1e3
500
H2 Tank Max
Level in Ton
[MeOH_Production]
Goto Cost estimate of plants
Divide2
X
H2O
H2S
H2Level
H2Tank
level
H2 Tank
Tank level
z^{-1}
Delay
1
Yearly
Repetition1
Water0
WaterS
WaterLevel
WaterTank
level
Water Tank
z^{-1}
Delay1

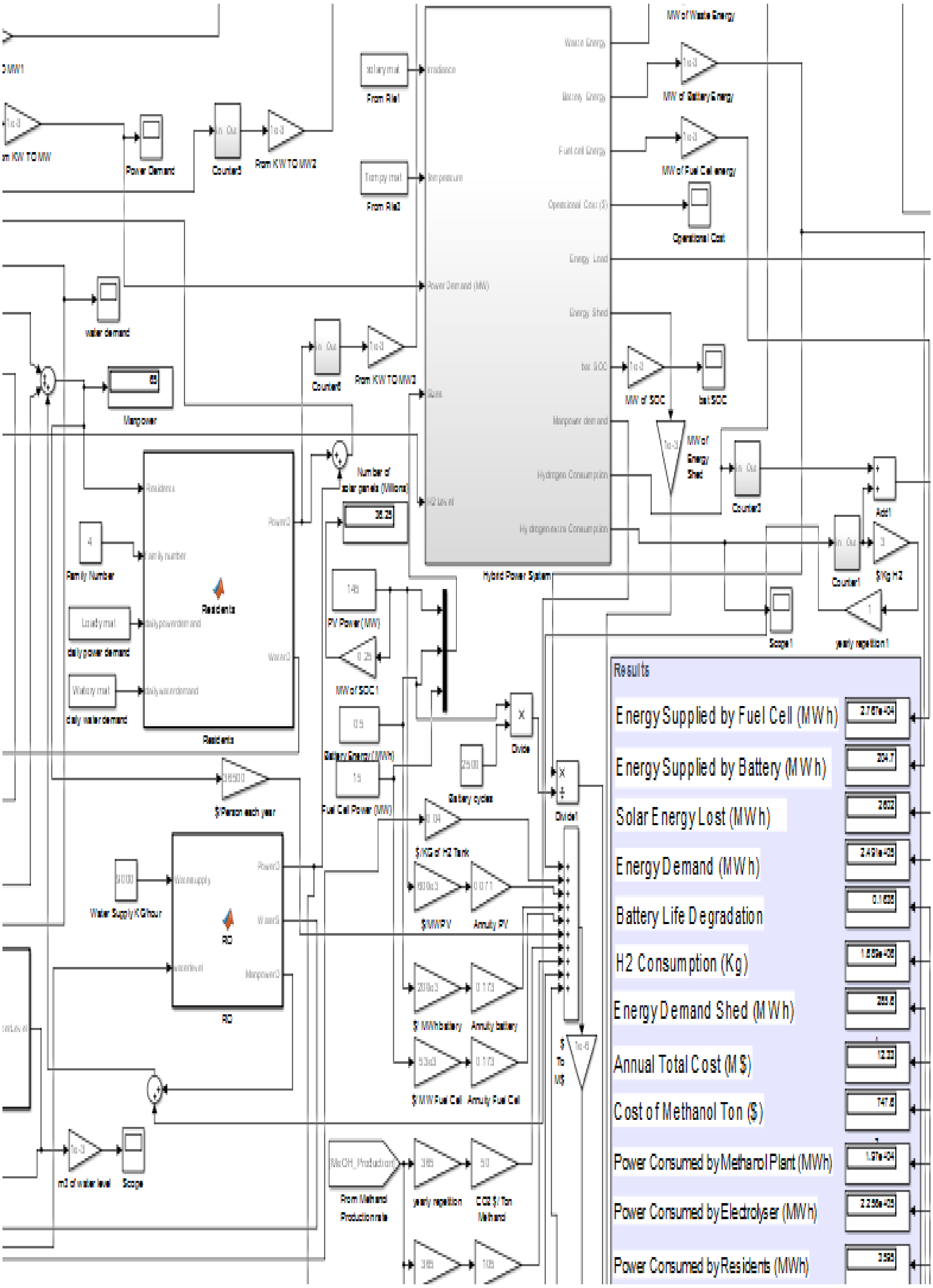


Figure 33: System representation in simulink

1. ***Optimal Operation***

The power plant consists of PV panels, batteries and a hydrogen fuel cell plant, in case the PV panel supply is not enough. The input to this system would be the sum of electric load required by the other blocks (Residents, RO, and methanol production) with the PV power subtracted from it. The other input would be the batteries and the fuel cell data. For the sake of optimizing the operation of the system the only two control variables we have for this case are the fuel cell energy and the battery energy since the solar energy is given and can't be changed. The operation control optimization of the system is done by minimizing the following cost function based on single step optimization method [15]. The cost function for the operation is:

$$\psi = \sum_{K=1}^{N} \left[\phi(G_K) + \frac{\lambda_B \gamma_{avg} B_K (sign(B_K)+1)}{2} \right] \Delta T \qquad (4.1)$$

Where ψ is the cost in \$ of the total operating cost, G_K: is the fuel cell power and $\phi(G_K)$ is the \$/h cost of running the fuel cell at G_K power. This can be deduced from the cost coefficient curve of the fuel cell as shown in chapter 2 for the consumption coefficients of the fuel cell. B_K is the battery power, and λ_B is a battery constant which by varing it would vary the attractivness of the battery to supply the load or to supply the load from the fuel cell. For λ_B less than one the battery would be preferable to supply the load. However if λ_B value is greater than one the fuel cell would be more attractive to supply the load. γ_{avg} is used for optimization as the battery cost valued at an incremental cost in \$/KWh of the fuel cell evaluated at average demand [14].

The above cost function is subject to the following:

$$G_K + B_K + P_K - D_K = 0 \qquad (4.2)$$

Where

$$D_K = M_K + RO_K + RE_K \tag{4.3}$$

G_K is the fuel cell power, B_k is the battery power, P_K is the PV panel power and D_K is the total demand load.

M_K is the Mehtanol & Electrolysis plants power demand, RO_K Reverse Osmosis power demand, and RE_K is the residents power demand.

Other important factors that should be taken in account for optimization:

$$SOC_K - SOC_{K-1} - \phi_B(B_K)\Delta T = 0 \tag{4.4}$$

$$G_{min} < G_K < G_{max} \tag{4.5}$$

$$B_{min} < B_K < B_{max} \tag{4.6}$$

$$SOC_{min} < SOC_K < SOC_{max} \tag{4.7}$$

First We check if the net load is above maximum power of the fuel cell and the maximum battery power. This (extra) laod would be a load shed and will be fed from other source of energy at a cost of 500$/MWh. For the rest of the load we devide the fuel cell power into 81 steps of power, for each step there would be a battery power which when added to the fuel cell power would equal the load. And then the cost function applied with all the constraints to decide the minimum combination of the fuel cell power and battery power to feed the load.

After we get the fuel cell power we can decide the hydrogen demand during this hour which would be taken from the hydrogen tank as long the hydrogen tank level is enough, else the hydrogen will be brought from somewhere else for a cost of 3$/Kg of hydrogen.

2. ***Components Sizing using Ordinal Optimization***

The variables we have in our system are the size of the hydrogen tank, PV peak power, batteries energy, and the fuel cell power. The system is optimized using the ordinal optimization as per the following steps [13]. First we apply different sizes for the variables on a system simulated for only four weeks (one week in winter, one week in spring, one week in summer and one week in autumn) the variables applied are as follows:

Hydrogen tank = [50, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000] the size is in ton of hydrogen.

PV peak power = [100, 125, 140, 145, 150, 155, 160, 175, 200] the size of the PV peak power is in MW.

Batteries energy = [0, 0.5, 1, 3, 5, 10, 20, 40, 60] the size of the batteries energy are in MWh.

Fuel Cell power = [1, 3, 5, 7, 10, 13, 15, 17, 20] the size of the fuel cell power are in MW.

Applying the above variables on the system for 4 weeks we get 8019 results for the per ton cost of methanol and we sort them in ascending order [Step 2]. Plotting the order performance curve OPC we get a flat curve shown in Figure 34 below [Step 3]. We take the first 1% of the result which is g=80 good enough subset (G) and the required alignment level (k=1) [Step 4]. Estimating

$$Z(k,g) = e_1^{Z_1} k^{Z_2} g^{Z_3} + Z_4 \tag{4.8}$$

Where $Z_1 = 8.1378$, $Z_2 = 0.8974$, $Z_3 = -1.2058$ & $Z_4 = 6$ taken from table of regression coefficients for AP=0.95 which correspond to low error bond of 0.5. The value of Z gives the size of the selected subset (S) which is 24 [Step 5]. We select the top 24 values from step 2 (the ones with least cost of ton of methanol and evaluate them using the accurate one-year model [Step 6]. The ordinal optimization method ensures that (S) includes at least one optimum solution with probability AP ≥ 0.95 [Step 7].

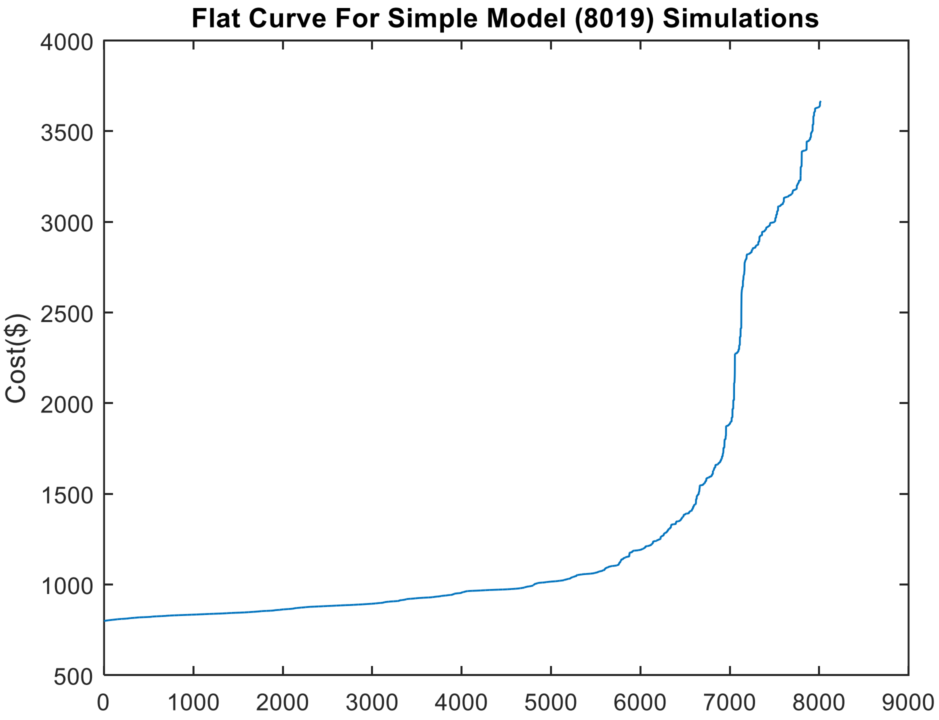


Figure 34: Order Performance Curve

CHAPTER V. RESULTS

In order to produce 50 ton of methanol per day we will buy captured carbon dioxide and make the required electrolysis of the needed hydrogen gas. To provide the water needed for the electrolysis we would make water desalination using a reverse osmosis technology. We need to have manpower to run the methanol, electrolysis and RO plants, these would form the residents of the village adding to them the manpower required to run the power plant. The power needed to run the methanol, electrolysis and reverse osmosis in addition to the power demand of the residents of the village would be provided by the power plant. The power plant includes the PV solar panels with back-up batteries and a hydrogen fuel cell plant. The water demand for the methanol, electrolysis and residents would be provided by the reverse osmosis plant. In order to provide continuity in hydrogen needed for methanol production and for the hydrogen fuel cell plant, a hydrogen underground tank is proposed. The production of hydrogen in the electrolysis plant is proportional to the solar irradiance such that at full irradiance of 1000W/m^2 there would a production 3000kg/hour of hydrogen gas, on the same side if there is 0W/m^2 irradiance there would not be any hydrogen gas production. According to [28] if the electrolyser is operated in a cycling on-off mode, this would damage the electrolyser in very short time, therefore a battery is needed to provide short term energy storage keeping the electrodes of the electrolyser energized while off. The cost of this battery would be negligible compared to the total system investment.

Applying the steps mentioned in Chapter 4 with the different sizes mentioned for the hydrogen tank, the solar PV peak power, the battery energy, and the fuel cell power to get the methanol cost per ton. Here it is noted again that the cost of fuel cell is taken as \$53/kW [18], the cost of hydrogen storage is … In the Ordinal Optimization

(OO) process, we first run the simple model, having a period of four weeks for all the different sizes; the results for some of the best 24 designs are shown in Table 5, which shows that the best solar power is chosen at 145 MW peak, the battery energy size chosen is in the low values ranging from 0 to 3 MWh, while the fuel cell power chosen is either 15 or 17 MW, and finally, due to the low cost of the hydrogen tank a wider variety of sizes was obtained. In the second step of OO an accurate model is run with a one year simulation period, and the best designs are as shown in Table 6. In this table we notice that the first six values agree on having 145 MW peak solar power and 15MW of fuel cell power. Also, the battery energy size is generally low, with the best result being zero MWh, or no battery. Finally the hydrogen tank best result is the 700 ton of hydrogen, with the rest of the results have a tendency towards the high values. During the simulation, the hydrogen reservoir was considered to be a depleted oil and gas reservoir with a cost of 0.04$/kg of hydrogen.

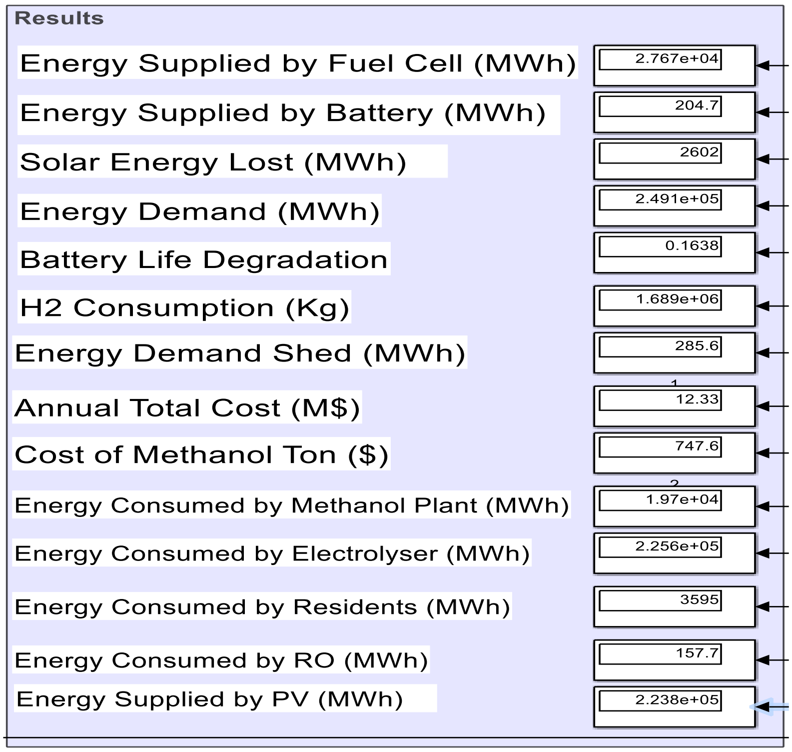
Table 5: Some of The first 24 results of the simulation for four weeks only for the different sizes considered

Cost of Ton of Methanol ($)	H2 Tank Size (Ton)	PV Power (MW)	Batteries Energy (MWh)	Fuel Cell Power (MW)
800.16	700	145	0	15
800.25	400	145	3	17
800.41	800	145	0	15
800.42	400	145	0.5	15
800.67	500	145	0.5	15
800.67	900	145	0	15

Table 6: The first 6 of the best 24 results after doing the simulation for one year

Cost of Ton of Methanol ($)	H2 Tank Size (Ton)	PV Power (MW)	Batteries Energy (MWh)	Fuel Cell Power (MW)
747.66	500	145	0.5	15
748.99	500	145	0	15
749.23	600	145	0	15
749.47	700	145	0	15
749.72	800	145	0	15
749.96	900	145	0	15

The figures for the results, hydrogen tank and power demand and other results belong to the optimum solution and are shown in Figure 35 below. The results shown below indicate that the optimum solution would have a 0.5 MWh back-up battery, this is in compliance with the fact that the ramp restriction of the fuel cell would require a small amount of battery back-up. Also it is shown that the battery life degradation is 0.16 per year, therefore the battery life is expected to be 6.25 years, and this is close to the estimated life of the battery when calculating the annual cost of the batteries (which is considered to be 7 years).



Results

Energy Supplied by Fuel Cell (MWh)	2.767e+04
Energy Supplied by Battery (MWh)	204.7
Solar Energy Lost (MWh)	2602
Energy Demand (MWh)	2.491e+05
Battery Life Degradation	0.1638
H2 Consumption (Kg)	1.689e+06
Energy Demand Shed (MWh)	285.6
Annual Total Cost (M$)	12.33
Cost of Methanol Ton ($)	747.6
Energy Consumed by Methanol Plant (MWh)	1.97e+04
Energy Consumed by Electrolyser (MWh)	2.256e+05
Energy Consumed by Residents (MWh)	3595
Energy Consumed by RO (MWh)	157.7
Energy Supplied by PV (MWh)	2.238e+05

Figure 35: Results of the simulation in Simulink

It can be noticed from Figure 35 that the total energy demand is 249 GWh/year. The energy consumed by the methanol plant is 20 GWh/year, while the energy consumed by the Electrolyser is 226 GWh/year, also the energy demand of the Residents in the village is estimated to be 4 GWh/ year, and finally the RO plant requires 0.2 GWh/year energy to provide the needed water.

Figure 36 shows the hydrogen level in the hydrogen tank all over the year. It is very clear that during the winter time the level of hydrogen in the tank is at low level. However, during summer time the level of the hydrogen in the tank raise up and fill the tank to the maximum level.

Figure 37 represents one week in winter hydrogen tank level, which as can be shown stay at low level around 20 ton of Hydrogen in the tank. While Figure 38 shows the level in the hydrogen tank during one week in the summer. Which confirm that the level stays at high level of around 500 ton of hydrogen (the maximum tank level).

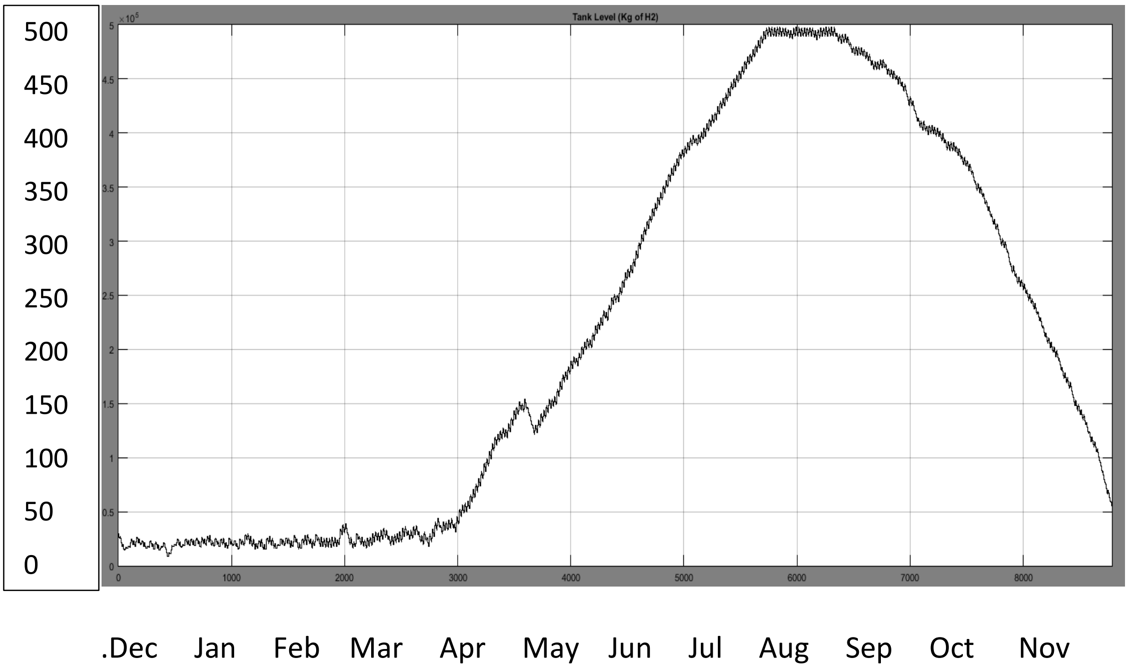


Figure 36: Hydrogen Tank level in one year (Ton of Hydrogen)

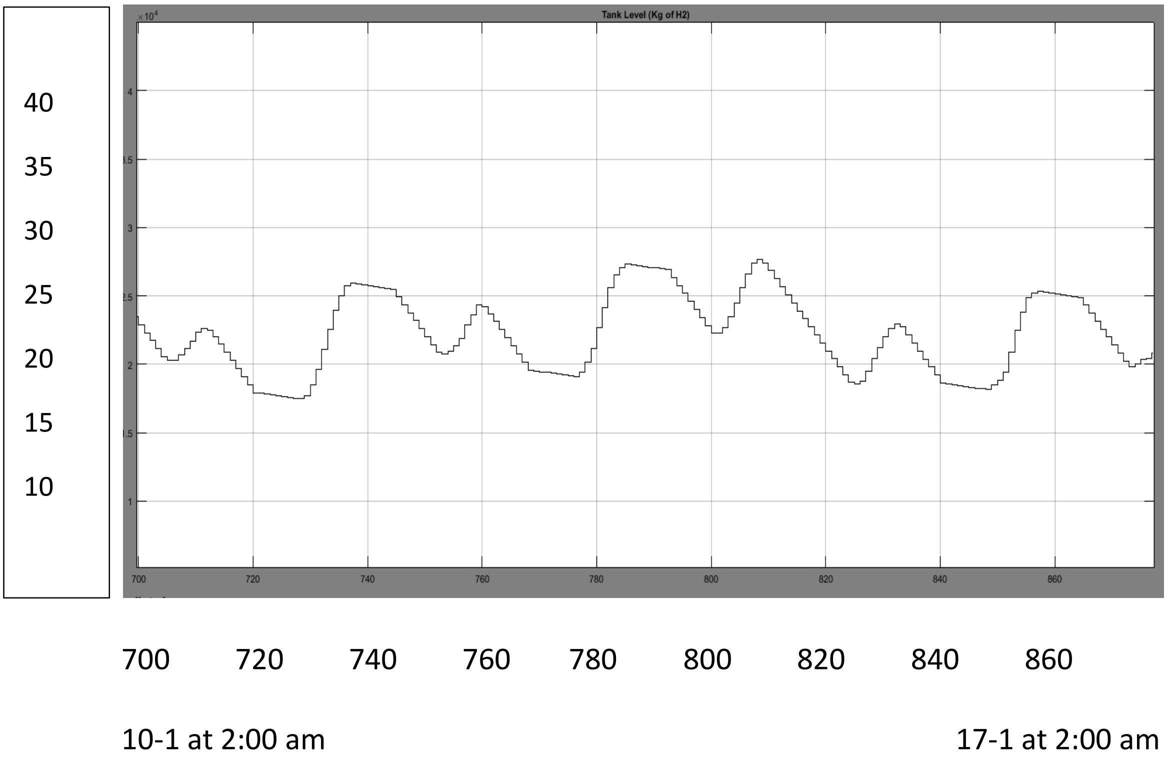


Figure 37: Hydrogen tank for one week in winter (Ton of Hydrogen)

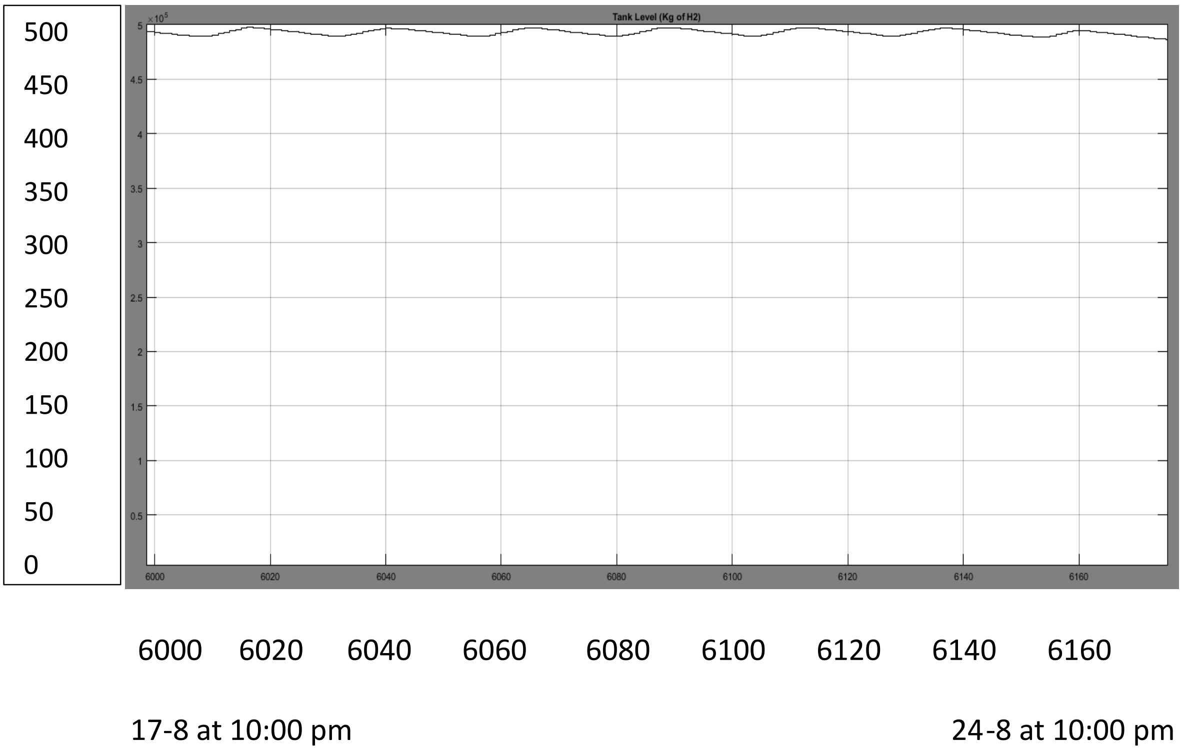


Figure 38: Hydrogen Tank for one week in summer (Ton of Hydrogen)

Figure 39 shows the total power demand all over the year, which as expected has a similar shape to the irradiance level. Since the electrolyser consume the greatest amount of energy, and the production of hydrogen by the electrolyser is done in proportion to the irradiance level, thus the shape of the energy demand by the village is similar to the solar irradiance during the year.

Figure 40 shows the energy demand during one week in the winter. The energy is low due to the fact that there is low solar irradiance during this time of the year. However Figure 41 represents the energy demand during one week in the summer. It is clear that the energy demand during this period of the year is higher than the winter time as there is a higher hydrogen production.

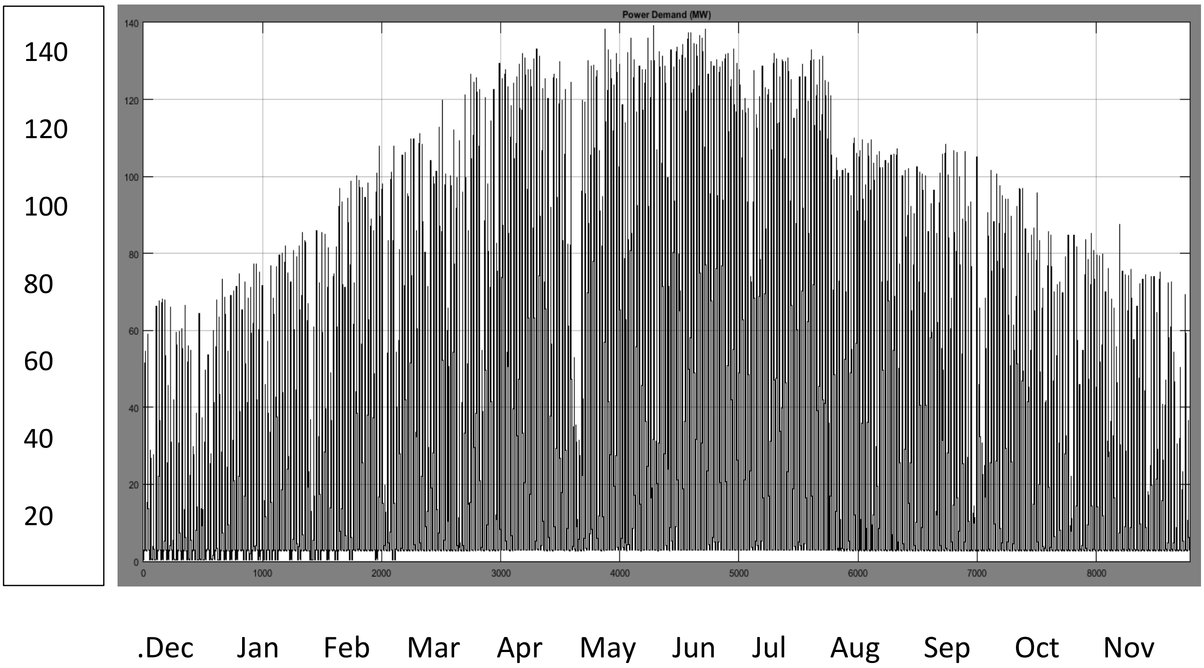


Figure 39: Power demand (MW)

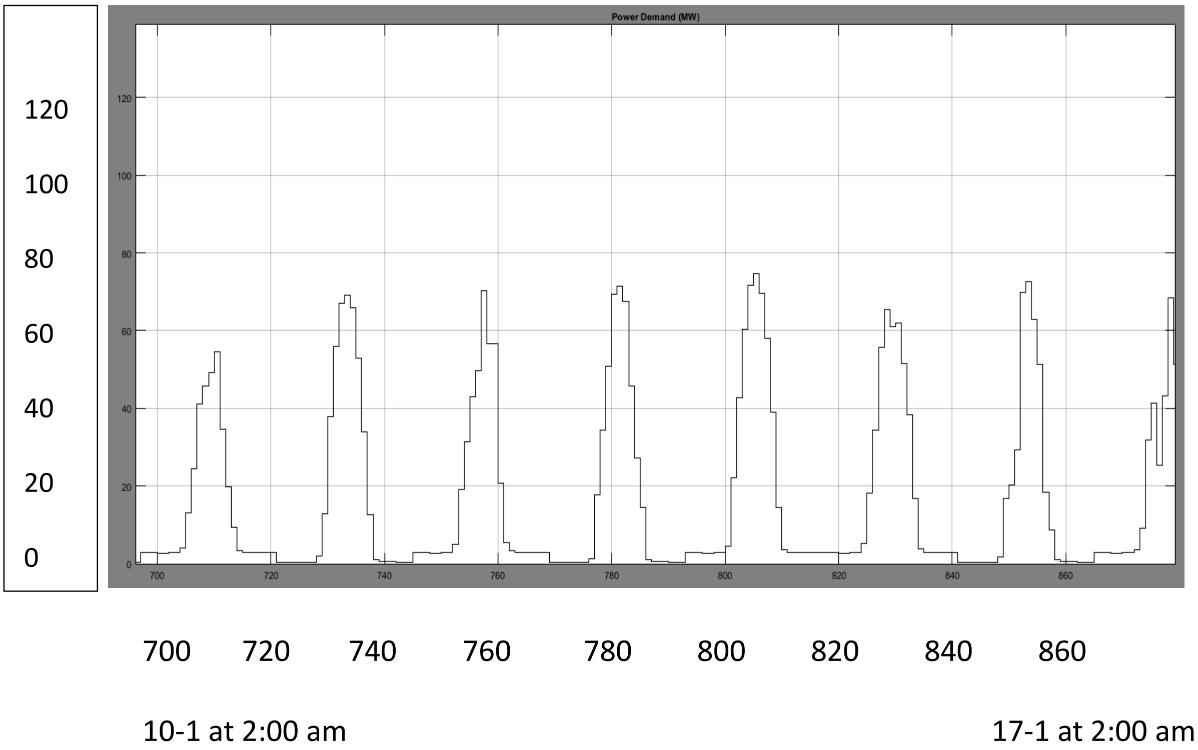


Figure 40: Power demand one week in winter (MW)

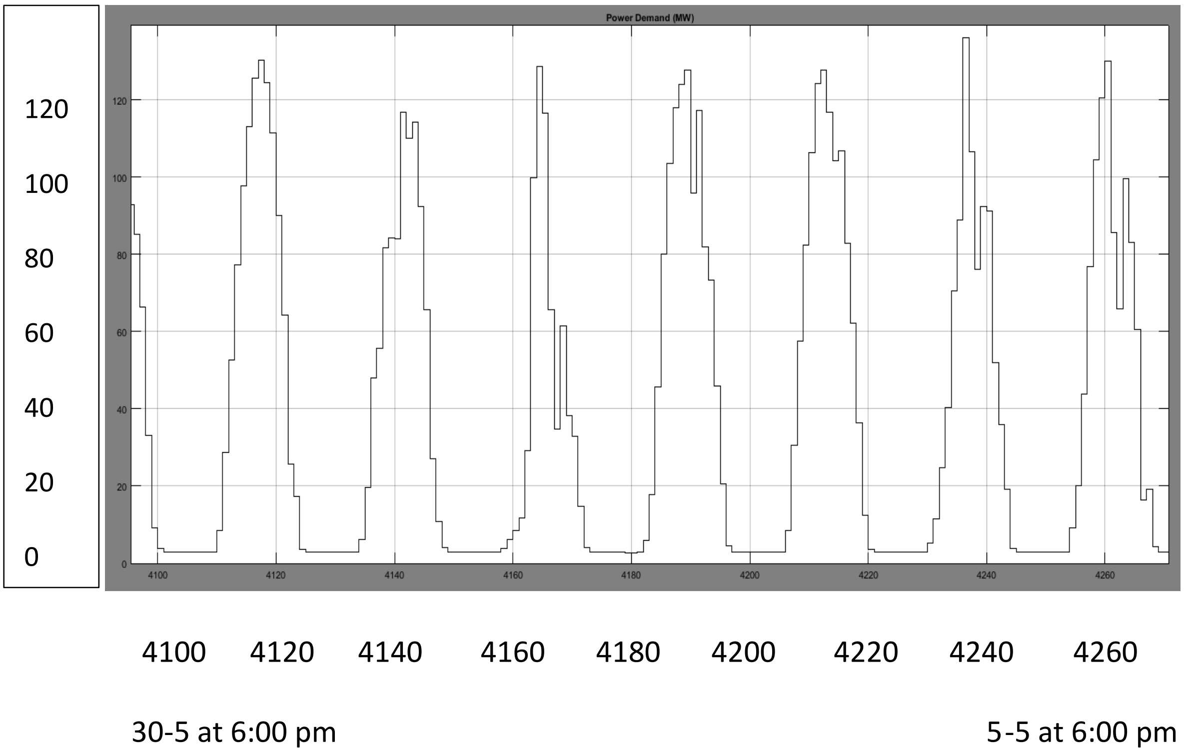


Figure 41: Power Demand one week in summer (MW)

Further to the results shown above, as the optimum size of the hydrogen tank is 500 ton of hydrogen, it is expected to have a size according to [27] of 33.8 million m^3 of depleted oil and gas reservoir at pressure of 2,000 psi and temperature of 315.1 K.

If we consider hard rock cavern for the hydrogen tank, which has the highest cost among all the other underground hydrogen tanks at $2.75/kg of hydrogen, and by applying the same ordinal optimization method, we would get the results shown in Table 7.

Table 7: The first 5 of the best results after doing the simulation for one year

Cost of Ton of Methanol ($)	H2 Tank Size (Ton)	PV Power (MW)	Batteries Energy (MWh)	Fuel Cell Power (MW)
818.44	400	150	0	10

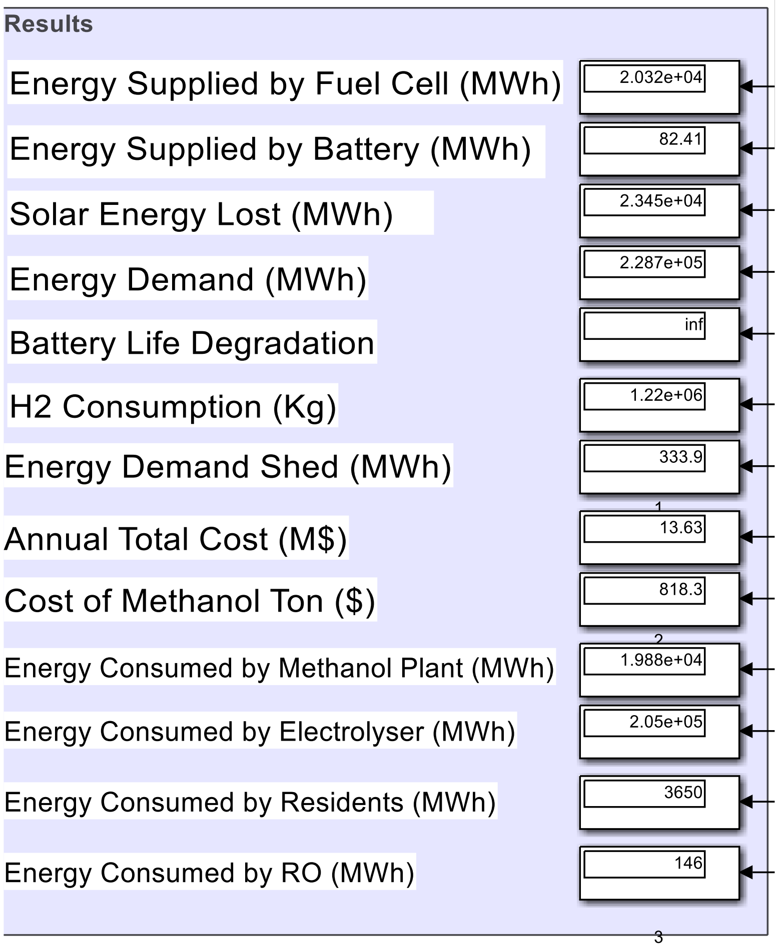
818.66	400	150	0	13
818.88	300	150	0	10
819.33	400	150	0.5	10
819.41	300	150	0.5	10

Thus it is shown in Table 7 that as the cost of the hydrogen tank increases the best result would tend to decrease the size of the hydrogen tank and the total cost of methanol ton is increased to $818.44. To illustrate this result further Figure 42 shows the output of the simulation using Simulink.

It is noticed in Figure 42 that the battery life degradation give an infinite value due to the selection of zero battery energy as an optimized result. However, there should be a small value of batteries energy in order to compensate for the fuel cell ramping rate.

However if we consider a fuel cell cost of $230/kW, the optimum solution would be 400 ton of hydrogen tank, 150MW of solar power and 10MW of fuel cell power. The battery energy was zero which means that it is required only in small value. This result is similar to the simulation done with the hard rock cavern hydrogen tank.

Therefore the best cost we have is $747.6 / ton of green methanol. Although the price of methanol is $500/ton, further research can lead to reduce this amount by adding farming to produce methanol from biomass. Also adding wind power sources may add valuable source of energy to reduce the cost or by increasing the amount of methanol to be produced.



Energy Supplied by Fuel Cell (MWh)	2.032e+04
Energy Supplied by Battery (MWh)	82.41
Solar Energy Lost (MWh)	2.345e+04
Energy Demand (MWh)	2.287e+05
Battery Life Degradation	inf
H2 Consumption (Kg)	1.22e+06
Energy Demand Shed (MWh)	333.9
Annual Total Cost (M$)	13.63
Cost of Methanol Ton ($)	818.3
Energy Consumed by Methanol Plant (MWh)	1.988e+04
Energy Consumed by Electrolyser (MWh)	2.05e+05
Energy Consumed by Residents (MWh)	3650
Energy Consumed by RO (MWh)	146

Figure 42: Results of the simulation in Simulink using hard rock cavern hydrogen tank

The optimum cost of a methanol ton is $747.6. This is for a production during 330 days/year, thus the total amount of methanol produced per one year (knowing that we are producing 50 ton/day) is 16500 ton/year. This is considered as a medium production plant. The cost of the production per one year is $12.33 Million. The main items that form this cost are:

- The annual cost of the methanol plant. Which is $1.92Million. Which present 15.6% of the total annual cost.
- The annual cost of the electrolysis plant after reducing the oxygen selling is $0.64Million. Which is 5.2% of the total annual cost.

- The annual cost of buying the captured CO_2 gas is $0.91Million. Which represent 7.4% of the total annual cost.
- The optimum solution require 65 laborers to run all the plants, considering a yearly salary of $36,500 per person per year (which is $100 per day) would result in a total of $2.4 Million salaries per year. Thus it forms 19.3% of the total annual cost.
- For the fuel cell plant for the optimum solution having a power of 15 MW its annual cost is $0.14Million. Which represent 1.1% of the total annual cost.
- The optimum solution gave a 0.5 MWh of battery energy thus the battery annual cost is $0.02Million and represent 0.1% of the total annual cost.
- The optimum solar plant size is 145 MW peak power. Which has annual cost of $6.18Million. Thus consist of 50.1% of the total annual cost. The solar plant is producing 224GWh per year where 2.6GWh of them is lost.
- One of the items that represent part of the cost is the hydrogen storage which is considered to be a depleted oil and gas reservoir which has a cost of $0.04/Kg of hydrogen. The optimum solution is to use 500 ton storage of hydrogen which have an annual cost of $0.02Million. This represents 0.1% of the total annual cost.
- The last item is the energy shed which is about 285.6MWh. For that item we considered a price of $500/MWh. The cost was taken high intentionally to reduce the amount of energy shed to the maximum. This item annual cost is $0.14Million and thus it stands for 1.1% of the total annual cost.

Further to the points mentioned above the initial investment cost consist of the followings:

- The PV panels of 145 MW power with $0.6 per watt has an initial cost of $8.7 million.
- The batteries of 0.5 MWh energy with $200 per kW gives an initial cost for the batteries of $0.1 million.
- The fuel cell of 15 MW with $53 per kW has an initial cost of $0.8 million.
- The methanol plant has an annual cost of $1.92 million, thus the initial cost of the plant considering 20 years age would be $34.4 million.
- The electrolyser to produce 3000 kg per hour has power of 7MW and an annual cost of $0.64 million, thus the initial investment cost of the electrolyser would be $13 million.
- The hydrogen tank would have an initial investment cost of $0.02 million and is considered as negligible compared to the other costs.

Thus the total initial investment cost of the project would be $57 million.

CHAPTER VI. CONCLUSION

The project studied the operation and design of decentralized self-sufficient solar-based power system in the desert to produce a valuable energy product, green methanol.

The plant is manned by a community that have access to water and energy as by-products of the plant operation. The income of the community is from the sale of the highly valuable energy product which is essentially carbon neutral. Methanol production is fixed at 50 ton/day from hydrogen available in a high pressure storage tank.

The proposed system will provide water and electricity to places of need in North Africa or elsewhere first before considering the idea of providing Europe with power. It will help to create work opportunities in these areas for people living there. Thus, solving the migration problem by reducing the high level of migration from Africa and Middle East to Europe. The project investigated the technical and economic viability of a self-sufficient community where the manpower are provided with electricity, water and salaries to get their family life requirement. They also produced a prime energy product and reduced CO_2 emissions all over the world. Transform the solar energy in these areas into a source of energy that can be sold and easily transferred to all over the world. The study focused on producing hydrogen by electrolysis, then stored in underground reservoirs and finally transformed into methanol by synthesis. It has been proven that such system can be done on a relatively small scale and based on an independent investment, and therefore would not be affected by the political relation between countries. Also the study showed that the idea itself can be built in different places and countries among North Africa, Western Sahara, Yemen and the Middle East, which would create a competitive market among the energy producers. Therefore, this would lead to reduced prices of energy and a continuous development and improvement of the system to be more profitable. It is expected that further research on the topic for having “clean energy wells” spread all over the deserts will increase the energy security in the world by having another sustainable and distributed sources of energy available for use.

According to the results shown in Chapter 5, the main item that play an important role in the cost of the production of methanol is the solar power demand which is mainly used for the electrolysis activity.

The total energy demand for one year is 249 GWh. Taking into consideration the annual cost of the energy supply for the PV panels and the Fuel cell, which is $6.18Million and $0.14Million respectively, which adds up to $6.32Million as the total cost of energy. Thus the price of electricity is about $25.4/MWh. If we can reach an electricity price of $10/MWh, this would require to reduce the annual cost by 3.83M$. This would give a final price of methanol of $500/ton which is a reasonable price.

Canada is set to impose a national carbon price in 2018. The initial price will be a minimum of $10 (Canadian) per metric ton of CO2, and it will increase annually by $10/tonne to reach $50 in 2022 according to Carbon Tax Center Electricity production in the United States would produce carbon dioxide around 0.5 ton/MWh from different fossil fuel sources according to EIA. . Therefore, if we consider a carbon credit of $40/ton of carbon dioxide emissions the price of electricity would be below the edge price of $10/MWh, thus we would have an economic viable solution for green methanol production. Based on that and without CO_2 emissions the price of the electricity produced reducing carbon dioxide emissions would be 25.4 – 20 = 5.4 $/MWh.

Therefore, we can expect to have an economic viable solution by including an increase on the carbon dioxide emission tax to above $40/ton. Further research to reduce the price of the PV panels and to include wind energy should lead to a better price. Including a farm that produce a biomass which through synthesis can produce methanol also should provide a better solution and lower price of the ton of methanol produced.

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