Modelling and Optimal Design of a *Fuel Cell Energy Storage System* using rejected energy by Wind Parks in isolated Electric Grids

A dissertation for the licentiate
of Electronic Engineer

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ABSTRACT

In this dissertation a methodology for modeling and optimal sizing of an Energy Storage System using Hydrogen (H_2) as an energy carrier is presented. The Fuel Cell Energy Storage System (FCESS) consists of an Electrolyzer's Array to produce Hydrogen using electricity, a reservoir to store the fuel, a Fuel Cell's Array to produce electricity from stored Hydrogen and Power Electronics for conversion and dispatch of the energy between the components of the system.

The FCESS is charged using rejected energy produced by wind parks connected to the power network, and aims to supply a predefined and constant amount of power to the electric grid during peak load-demand hours, so as the wind energy penetration from the network is maximized. Two charging scenarios are considered: an autonomous system using energy only from rejected part of the wind park, and an interconnected system that imports energy from the electric grid at low-demand hours to maintain the guaranteed power supply at periods with no rejected energy.

Modeling of the FCESS has been made using the MATLAB/*Simulink* and the model parameters have been derived from manufacturer's performance data-sheets or measurements obtained from literature. The simulation has been made on an annually basis with simulation step of one hour and the optimal designs in each case have been found using the Genetic Algorithms optimization method.

Finally, economic analysis has been applied to optimal designs and the economic viability of the system has been estimated based on the investment *Discounted Payback Period* – DPP and *Internal Rate of Return* – IRR determination. The results show that the Hydrogen market is not yet commercially mature for a Fuel Cell Energy Storage System to be economically viable.

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ABREVIATIONS

AFC	Alkaline Fuel Cell
BESS	Battery Energy Storage System
BM	Boundary Mutation
DAFC	Direct Alcohol Fuel Cell
DCFC	Direct Carbonate Fuel Cell
DMFC	Direct Methanol Fuel Cell
DPP	Discounted Payback Period
ESS	Energy Storage System
FC	Fuel Cell
FCESS	Fuel Cell Energy Storage System
fitFunc	Fitness Function
GA	Genetic Algorithms
IRR	Internal Rate of Return
MCFC	Molten Carbonate Fuel Cell
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
NUM	Non-Uniform Mutation
objFunc	Objective Function
PAFC	Phosphoric Acid Fuel Cell
PE	Power Electronics
PEMFC or PEFC	Proton Exchange Membrane Fuel Cell or Polymer Electrolyte Fuel Cell
SAC	Simple Arithmetic Crossover
SC	Simple Crossover
SOFC	Solid Oxide Fuel Cell
STP	Standard Temperature Pressure
UM	Uniform Mutation
WAC	Whole Arithmetic Crossover

1. INTRODUCTION

1.1 Motivation

The conventional fossil fuel energy sources such as petroleum, natural gas and coal which meet the world's energy demand today are being depleted rapidly. It is estimated that there are 250 years of economically recoverable reserves of coal at today's rate of usage and according to most of the forecasts for oil reserves the production is going to peak soon and then start declining [1]. Moreover the combustion products are causing pollution and amplify the green house effect. Many countries have start taking measures to reduce these impacts; Japan is required to reduce CO2 emissions by 14% (172 million tons) on average during the period between 2008 and 2012 [2].

Alternative ways of producing energy other than fossil fuel sources are nuclear and renewable sources. Issues that surround nuclear waste disposal persist and no nuclear plants have been built in the United States of America in the last 30 years [3]. So renewable energy sources such as solar, wind, tidal, geothermal etc. are attracting more attention; wind energy is a very promising option because of high efficiency and electricity production in areas with significant wind potential. Thus, wind generation is substantially increasing its share in the electricity generation portfolio in many countries. In the case of Spain, it is planned to reach a 20 GW level till 2010 [4].

As far as Greece is concerned and especially in some islands of the Aegean Sea, wind generation is one favorable option because of their significant wind potential and the high electricity generation costs via the conventional thermal power stations. Most of these electric grids are not connected to the mainland electric network of Greece and thus use small, autonomous thermal power stations usually powered by diesel engines. The resulting electricity generation cost is 0,1 to 0,7 €/kWh. On the other hand, the high wind potential (average wind speed 6-15 m/s at 40 m) in these islands leads to a wind electricity production cost lower than 0.078 €/kWh [6].

However, there are obstacles that limit the wind-energy penetration in such isolated electric grids; the stochastic variation of the wind speed leads to mismatch between energy generation and demand, the technical minima of the electric grid thermal energy-generation units and the transmission line instability problems [5]. A very attractive option for the wind energy penetration to be increased is an Energy Storage System. Such a system improves the electric energy power

quality and the power system reliability through frequency control and voltage regulation methods. The energy storage capability can be achieved using various means such as pumped hydro storage, batteries and fuel cell arrays. In this study the fuel cell arrays energy storage system is investigated and compared with other alternative options.

1.2 Brief report on the FCESS and its design

The fuel cells are characterized by many attractive features such as efficiency, fast load-response, modular production, fuel flexibility and have the main advantage over batteries regarding the capability to produce electricity for unlimited time a long as the required amount of Hydrogen has been stored.

The proposed system consists of the electrolyzer's array that produce pure Hydrogen compressed at certain value of pressure, the fuel tank (reservoir) where Hydrogen is stored and fuel cell array that consumes Hydrogen and produces electricity. There are also power electronics for conversion and dispatch of the energy between the components of the system. The block diagram is depicted in **Fig. 1.1.**

As previously mentioned, the main purpose of the FCESS is the increase of the wind energy penetration in isolated electric grids. Therefore, the system under investigation aims to provide a **predefined – guaranteed constant** amount of power during the peak load demand hours (i.e. 11:00 to 15:00) on a daily basis for a whole year. The charging process is made using wind-generating energy surplus which is rejected by the grid and ,in case of the interconnected system, energy bought from the network during low demand hours (i.e. from 00:00 to 08:00) in a cheap price.

To estimate the FCESS' s economic viability an economic analysis has also taken place. The resulting economic benefit is calculated according to the system's components total capital, maintenance and service costs, the cost of purchasing the complementary energy required and total revenues achieved from sales during the system operational time period. Using these calculations an optimum solution is found for a number of different scenarios using optimization method based on Genetic Algorithms. Its economic viability is investigated via modern economic analysis methods of discounted payback period and internal rate of return.

1.3 Outline of the dissertation

Chapter 1 presents an introduction to the main problem of wind energy generation and indicates the need of energy storage. In **Chapter 2** different energy storage systems are introduced and a brief comparison to the FCESS is made; then a detailed description of the individual FCESS components follows in **Chapter 3**. Modeling and simulation of these components is presented in **Chapter 4** and **Chapter 5** respectively. Moreover, in **Chapter 6** the optimization method which took place based on Genetic Algorithms is introduced and the economic analysis made using the previous results is reported in **Chapter 7**. Finally, in **Chapter 8** results and discussion is made. References can be found in **Chapter 9** and Appendixes **A** and **B** at the end.

2. STATE OF THE ART ON ENERGY STORAGE SYSTEMS

2.1 Definition

Energy Storage System (ESS) is defined as the system that stores-deposits energy. This definition is almost being used when referred to electric energy storage. The means that store electric energy to all intents, convert-reform it to a different form in which the storage is permissible; this procedure is always reversible so the energy can be extracted back when needed. There are a lot of different ESS with different concepts of operation and topologies; among them I will focus on the three more promising nowadays: pumped hydro storage systems, battery energy systems and fuel cell arrays storage systems.

2.2 Pumped Hydro Storage System

A technical and economic analysis of a pumped hydro storage system is presented in [7]**.** The proposal focuses on a pumped storage system that consumes rejected electric energy from a wind park and converts it to potential energy, as water is pumped from a low-level reservoir to a high level. At this form, energy can be converted back to electricity via a water turbine which operates utilizing the water flow from the high-level reservoir to the low-level when the need occurs. Controlling the water flow and the water turbine's rounds per minute, very good quality and reliable generation of electricity can be achieved. This system in [7] aims also at a constant and guaranteed amount of power on a daily basis every day of the year, so that extra energy from the electric grid is occasionally imported. The main characteristics of this approach are: **long lifetime period** (approximately 30 years) and **high installation cost** due to construction of the water reservoirs and the hydroelectric turbines; also a big number of limitations relatively increase the landscape and water reserves of the area. The pumped hydro storage system has moreover the following disadvantages: a quite **long implementation time interval**, negative **influences on environmental topology** of the installation area, and **no flexibility** at future possible changes on the local network. Especially in the case of remote islands of the Aegean Sea, there are usually significant ground morphology limitations and lack of natural resources such as water. Also a possible scenario of interconnection with the bigger and more stable electric grid of the mainland of Greece should not be ignored; in that case an energy storage system would lose its main advantages and would be transferred to another remote island which is not possible. This is an unfavorable scenario, particularly if the great installation/implementation cost and the long payback horizon are considered.

2.3 Battery Energy Storage System

Another approach to the same problem of wind energy penetration is presented in [5] describing a Battery Energy Storage System (BESS). Accordingly, [5] the BESS consists of battery bank and multiple bidirectional DC/AC power converters connected to a common DC-Bus. That is rejected wind energy is imported to the system, converted from AC to DC and charging of the battery bank is made. In this case, electric energy is reformed to chemical form and stored to batteries as reversible chemical reactions take place. Power electronics control the energy flow between the components and reliable electricity generation is accomplished. The main characteristics of such a system are synopsized to a much **lesser lifetime period**, and a much **lesser installation and maintenance costs**. The BESS has neither need of a special ground morphology nor explanates in a large area; a small warehouse with air conditioning is just enough. Moreover, **flexibility** is undeniably one of its major advantages as it consists of small and easy-to-transfer components, so neither the installation is a time-consuming process nor the possible future reallocation of the BESS is a cost prohibitive prospect. In terms of environmental influences, the BESS has no gas emissions or other pollutive products, but the batteries contain materials such as sodium sulfur and phosphorus that should not be exposed. There is the **need of a methodical recycle process** to say that BESS is an environmentally friendly way to store energy.

2.4 Fuel Cell Energy Storage System

This study, above all, emphasizes on FCESS. The main idea is to store energy in the form of Hydrogen. Independent components exist so that each one serves a very specific role in the energy storage process; the electrolyzer is the one that produces Hydrogen from water consuming electricity. It is an environmentally friendly process as Hydrogen, Oxygen and heat are the only products of the reaction. The Hydrogen produced is then stored compressed in a special gas tank where there are no losses greater than 1.5-2 % per year. From that reservoir, Hydrogen heads to the fuel cell array where it is consumed and electricity is produced. This electrochemical reaction is also environmentally friendly as it takes Hydrogen and Oxygen from ambient air and electricity, heat and water are produced (PEM FC used). In this storage system the Hydrogen serves the role of energy carrier, so its amount equals to the stored energy. This is the main common feature with the pumped hydro storage, meaning the rate of energy storage, the rate of energy return and the total amount of energy which may be stored are independent with each other. Such a system can be

adapted to the very specific needs of the studding scenario, having for example a small electrolyzer system if there is no need of a high Hydrogen production rate (assuming lots of hours of operation for balancing), a fuel tank proportional to the low-energy availability periods and fuel cells as many as the power output requirements are satisfied. This is a great difference between FCESS and BESS in which these features are not completely independent. Theoretically the overall storage system's efficiency may achieve the 50% level, but practically, obstacles reduce this value in the range of 30% to 40%. In particular this work, modeling of the components with existing commercial products and taking into account a lot of parameters shows efficiency close to 34%.

Regarding the practical differences between the above two storage systems, the FCESS has the following characteristics: **medium lifetime period** (15 years for most expensive components), **high initial cost** due to expensive capital investment, very **little maintenance**, and **medium flexibility** in future changes on electric grids' conditions. In more details, fuel cells can be found with more than 20,000 hours of operation life time which means approximately 15 years for 4 hours of operation daily. Also, the electrolyzers mostly have a rated life time period of 10-15 years and the fuel tank can be used theoretically for an unlimited number of times if appropriate examination takes place every 10 years for the first 30 years (USA' s check method). Regarding the initial cost of the components, as noticed before, the global market proves itself not mature enough yet commercially and these costs are quite high to compete effectively the previous storage systems. However, the FCESS shares the similarity with the BESS of a small installation area with no specific requirements except a building and appropriate air conditioning. FCESS consists of separate components connected with wires or pipes, so a possible reallocation is not forbidden but not as easy as in the BESS system. In regards to the environmental influences, the Fuel Cell Energy Storage System has no harmful emissions at all and provides no pollution to the environment. Even in the case of a leak and the unfortunate event of a fire, the low luminosity of the flame restricts the emission of thermal radiation to less than **one tenth** of that of hydrocarbon flames. Furthermore, the low density and high diffusivity of Hydrogen results in the very rapid dispersal of liquid Hydrogen after spillage, so that the risk of fire persists for a much shorter period than that with other liquid fuels [1].

2.4 Conclusions

The Energy Storage System is a very important component on Renewable Resources due to the

variability of energy production and technical minima of the electric grid. Among them, the pumped hydro storage system is intended for great scale storage with a long lifetime period, but high initial cost and lots of limitations relatively to the area to be installed; the BESS is more suitable for storage at lesser scale, with medium initial cost, short lifetime period and flexibility relatively to the installation area and reallocation possibilities. The focus of this study is the FCESS which combines advantages and disadvantages from the two previous systems: high installation cost, medium lifetime period and flexibility.

3. DESCRIPTION OF FCESS COMPONENTS

3.1 Introduction to H_2 as an energy carrier

Hydrogen is one of the most promising alternative fuels of the future because of two main characteristics: (i) it has the capability to store energy of high quality (highest energy per unit mass of **all** fuels – HHV=141,9 MJ/kg and LHV=119,9 MJ/kg – three times more energy than gasoline for the same mass quantity) and (ii) it can be generated via electrolysis and infinite amounts can be produced given the required electric energy. Hydrogen has been visualized to become the cornerstone of future energy systems based on renewable energy sources, therefore many scientists study the concept of using Hydrogen as an energy carrier in storage and transport of energy. The same concept shares a great number of companies and industries manufacturing and promoting products for production, storage and consuming Hydrogen. The National Renewable Energy Laboratory (NREL) of USA has specified certain goals at certain schedule till 2017 of reducing Hydrogen production cost generated by wind energy and officially introduce the Hydrogen generation by renewable sources [8].

As demonstrated before, Hydrogen can be produced from water via electrolysis. The basic well-known chemical reaction of splitting water in Hydrogen and Oxygen is:

$$H_2O \xrightarrow{\text{electricity}} H_2 + \frac{1}{2} O_2$$

Via an electrolyzer, electricity separates the molecules of H_2O water and molecules of Hydrogen (H_2) and Oxygen (O_2) are produced along with heat. It is very important to notice that this reaction is reversible and H_2 reacting with O_2 can produce water and energy, thou there is not only one version of this procedure. According to the concept of combustion, if a certain amount of thermal energy is given Hydrogen and Oxygen react brashly and water along with energy from the explosion is produced. Another electrochemical procedure that uses H_2 and O_2 but produces electricity and heat instead of explosion, is the concept of fuel cell operation and is the one that I will focus on. The thing that is worthy of notice, is that if Hydrogen is produced via electrolysis and is consumed via the above electrochemical reaction, an excellent environmentally benign energy cycle is achieved.

A typical Fuel Cell Energy Storage System consists of a hydrogen producing unit (electrolyzer), a

hydrogen storing unit (Fuel Tank), and a hydrogen utilizing unit (PEM Fuel Cell). At each stage of the storage-return procedure Hydrogen and water remain in a closed circle, Oxygen is released and absorbed from the atmosphere and only electricity and heat are imports/exports of this closed system. **Fig. 3.1** shows this cycle:

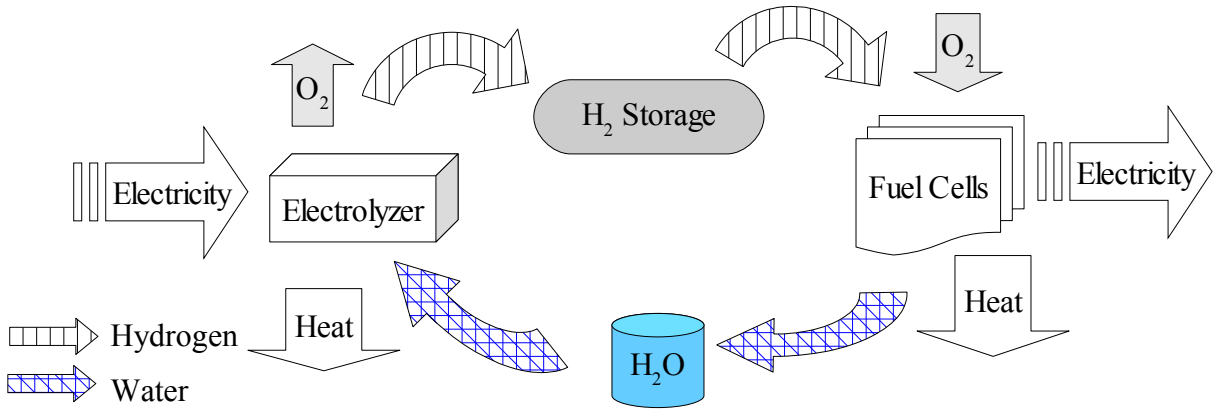


Fig. 3.1: The hydrogen cycle on a FCESS

3.2 Fuel Cell

The electrochemical reaction in which Hydrogen and Oxygen react to form Water and electricity, takes place on the fuel cell (FC). The main advantage of FC among other methods of consuming H_2, is the higher overall conversion efficiency (not subject to Carnot cycle's limitation) and no emissions at all in case pure Hydrogen is supplied.

3.2.1 History

In [9] a summary of the historical development of fuel cell technology is presented. The fuel cell principle was discovered by Englishman William Robert Grove in 1839. The technical development of fuel cells started shortly after World War II when Francis T. Bacon of Cambridge, England, successfully developed a high pressure fuel cell. Subsequently, alkaline fuel cells (AFC) and proton exchange membrane fuel cells (PEMFC) were developed for space programs (Gemini, Apollo, Space-lab). In the early 1970s, the development of phosphoric acid fuel cells (PAFC), high temperature molten carbonate (MCFC), and solid oxide fuel cells (SOFC) started. PEMFC was not significantly investigated before the late 1970s. These intensified activities, mainly by Ballard, Siemens, H Power, International Fuel Cells and several US Universities and research centers, resulted in considerably improved Membrane Electrode Assemblies (MEA). Therefore, weight and cost of the PEMFC could not be reduced drastically and their performance increased dramatically. The first commercial power plant for the PEMFC began operating in 1992 with the 200 kW

PC25™. With the formation of a partnership of the New Generation of Vehicles by Chrysler, Ford, General Motors and the US government in 1993, a new focus was set on transportation applications of fuel cells. Their aims are lower amounts of resources for longer distances with fewer emissions.

3.2.2 FC main features

As noticed in [9], the fuel cell is important for terrestrial applications of the hydrogen technology, because it combines a relatively **high efficiency** with very **low emissions**. In addition, it operates at a **constant temperature**, and the heat from the electrochemical reaction is available for **co-generation** applications. Fuel Cell power plants can be configured to use a **wide variety of fuels** and produce a **wide range of electrical outputs**. Also, these plants by operating on Hydrogen and Oxygen mostly offer **high power density**. Thus, a fuel cell is a preferred power generator in remote applications where system's weight and volume are important parameters. Other advantages are pointed below:

***Advantages**:*

- Direct conversion of chemical to electrical energy / no intermediate stages
- Excellent behavior, even with partial loading
- Wide variety of operating temperature
- Fuel Flexibility
- Zero or very low noise and environmental emissions
- Quick response to load changing

***Disadvantages**:*

- Relatively high costs compared to conventional power sources
- Life time limitations (no much confirmed knowledge about real life time exist)
- Decreasing electrical efficiency as function of the operating lifetime
- Special treatment of fuel is necessary
- Noble materials are mostly needed for membranes, electrodes, electrolytes

3.2.3 FC Types

Fuel Cells are classified as power generators because they can operate continuously, or for as long as fuel and oxidant is supplied. The application of fuel cells largely depends on the operation conditions, such as the values of the typical operation temperature and efficiency, and the fuel type

supplied. So a large number of different fuel cells technologies that have been developed are analyzed at [10] :

- Polymer Electrolyte Fuel Cell (PEMFC or PEFC)
- Alkaline Fuel Cells (AFC)
- Phosphoric Acid Fuel Cell (PAFC)
- Molten Carbonate Fuel Cell (MCFC)
- Solid Oxide Fuel Cell (SOFC)

This separation is based on the electrolyte used. Another classification can be made based on the fuel consumed:

- Direct Alcohol Fuel Cell (DAFC) or Direct Methanol Fuel Cell (DMFC). Fuel Cells which use directly alcohol such as methanol without any process made before. Usually PEMFC.
- Direct Carbonate Fuel Cell (DCFC). Fuel Cells using directly carbon as a fuel without an intermediate stage of volatilization. Usually SOFC, MCFC or AFC.

3.2.3.1 Polymer Electrolyte Fuel Cell (PEMFC / PEFC)

At this fuel cell type the electrolyte is a polymer membrane which is a good proton conductor. The electrodes, both anode and cathode, are manufactured by carbon in combination with electro-catalyst platinum (Pt) so small areas exist on them for the reaction. Water as product of the reaction is the only liquid existing on the cell, so corrosion is very limited. On the other hand, the water management is an important parameter. Evaporation rate must equal the production rate so the membrane is kept wet, otherwise the reaction will not take place properly and a great danger of membrane cracking and permanent damage exists. The operating temperature is always sub-100 °C and usually in the range of 60 °C to 80 °C. Fuel supplied is gas of high Hydrogen conciseness with minor quantities of carbon monoxide (CO) because of its destructing property for Pt catalyst. Moreover, sulfur and halogen remains must be removed anyhow.

PEMFC are the most common fuel cells used in vehicles, power generation stations and mobile devices. Main advantages/drawbacks are shown below:

➢ *Advantages*

- The solid electrolyte provides good separation between the fuel and the oxidant.
- Low operation temperature - lots of benefits with quick start-up among them.
- Not so expensive manufacturing materials compared with others.
- High power density (2 Watt/cm^2 maximum) which means high power generation at small area and little weight.
- High efficiency when fuel is pure Hydrogen

➢*Disadvantages*

- Low temperature means no thermal energy co-production for a hybrid system is allowed.
- Water management is not such an easy problem. Flooding and cracking must be avoided at any causes.
- Pure Hydrogen must be supplied (concentration above 99,9 %), otherwise life time will be reduced dramatically.

The PEMFC is the focus of this study because is the most appropriate FC for pure Hydrogen consumption (not just Hydrogen-containing fuels). High efficiency and low temperature are favorable at an ESS.

3.2.3.2 Alkaline Fuel Cell (AFC)

Hydroxide of potassium (KOH) is the electrolyte at this Fuel Cell type. Operating temperature varies from 120 °C to 250 °C in proportion to KOH concentration. A big variety of different materials can be used as electro-catalysts such as nickel (Ni), silver (Ag), metal oxides and noble metals. The preferable fuel for AFC is pure Hydrogen too; as in PEMFC, CO poisons the catalyst and even a small quantity of CO2 may react with the KOH and alters the electrolyte's quality. However, there are some variations of AFC that consume solid carbon as a fuel (DCFC).

➢*Advantages*

- High efficiency for pure Hydrogen as a fuel and O_2 as an oxidant
- Big variety of electro-catalyst materials.

➢*Disadvantages*

- Great sensitivity to CO and CO_2, so only pure Hydrogen must be supplied.
- Cause of CO_2 sensitivity, Oxygen cannot be used directly from the atmosphere as an oxidant and a certain procedure of CO2 removal must be performed before.

The last mentioned drawback of AFC proves them inappropriate for a FCESS. Our aim is Oxygen production from the Electrolyzer (released to ambient air) and then consumed from the Fuel Cell (absorbed from the ambient air), so that a recycle of Oxygen is accomplished.

3.2.3.3 Phosphoric Acid Fuel Cell (PAFC)

At PAFC, phosphoric acid is the electrolyte. Operating temperatures vary from 150 to 220 °C because at lower temperatures the ability of phosphoric acid to conduct ions is reduced. Moreover, as Pt is used as an electro-catalyst, there is a danger of poisoning from CO at low temperatures. No water management is required because the phosphoric acid's concentration is 100% and the water vapors' pressure is properly reduced.

➢*Advantages*

- PAFC are less sensitive to CO presence compared to AFC and PEMFC. Tolerance approximately to 1%.
- Temperature levels are low enough so no special heat-tolerant materials are used to rest of the system as in SOFC and MCFC
- Temperature levels are high enough so thermal energy co-production can take place.

➢*Disadvantages*

- The Oxygen decrement happens at low rates, so Pt is used also in cathode.
- Complex fuel process if not-pure Hydrogen is supplied (in PEMFC and AFC this process is more complex and inexpedient)
- Phosphoric Acid is a corrosive essence, so expensive materials are used at specific parts of

the fuel cell.

3.2.3.4 Molten Carbonate Fuel Cell (MCFC)

Alkaline carbonate salts are used as electrolyte to MCFC. Operating temperature's levels are 600-700 °C and the electrolyte is molten. At anode nickel is used and nickel oxides to cathode. There is no need of expensive noble metals usage and the fuel can be also hydrocarbons as internal reforming happens.

➢*Advantages*

- Cheap electro-catalysts cause of high operation temperature.
- The internal reforming procedure that takes place let most of hydrocarbons and even CO to be used.
- High efficiency when thermal energy co-production is used.

➢*Disadvantages*

- Corrosive-tolerant materials are needed.
- Limited lifetime cause of high operating temperature.
- There is a need of CO_2 supply at cathode, which means complex separation procedures of CO_2 from the rest of the fuel.
- High resistance values of the cells, so power density is limited to 100-200 mWatt/cm^2 range.

3.2.3.5 Solid Oxide Fuel Cell (SOFC)

At solid oxide type of FC the electrolyte is a solid, not porosity metal oxide. Operating temperature is from 600 °C to 1000 °C and the transferred ions are Oxygen ions. At the beginning, the limited conductivity led to operating temperature level of 1000 °C; lately thinner electrolytes manufactured and operation was possible at the 650-850 °C range.

➢*Advantages*

- Cause of the solid state of the electrolyte, the cell can take various shapes.
- Not corrosive problems exist.
- CO can be used as fuel at SOFC.
- In contrast to MCFC, there is no need of CO_2 supplement to the cathode.
- High power densities may be achieved similar to PEMFC.
- Very high efficiency when heat is also utilized as in MCFC.

➢*Disadvantages*

- Manufacturing and service of the system's materials problems arise from the very high operating temperatures.
- Limited life time period.

3.2.4 Fuel Cell Description and Operation

In [10] an overall brief demonstration of the FC operation is made. The simplest form of the ideal Fuel Cell is shown in **Fig. 3.2:**

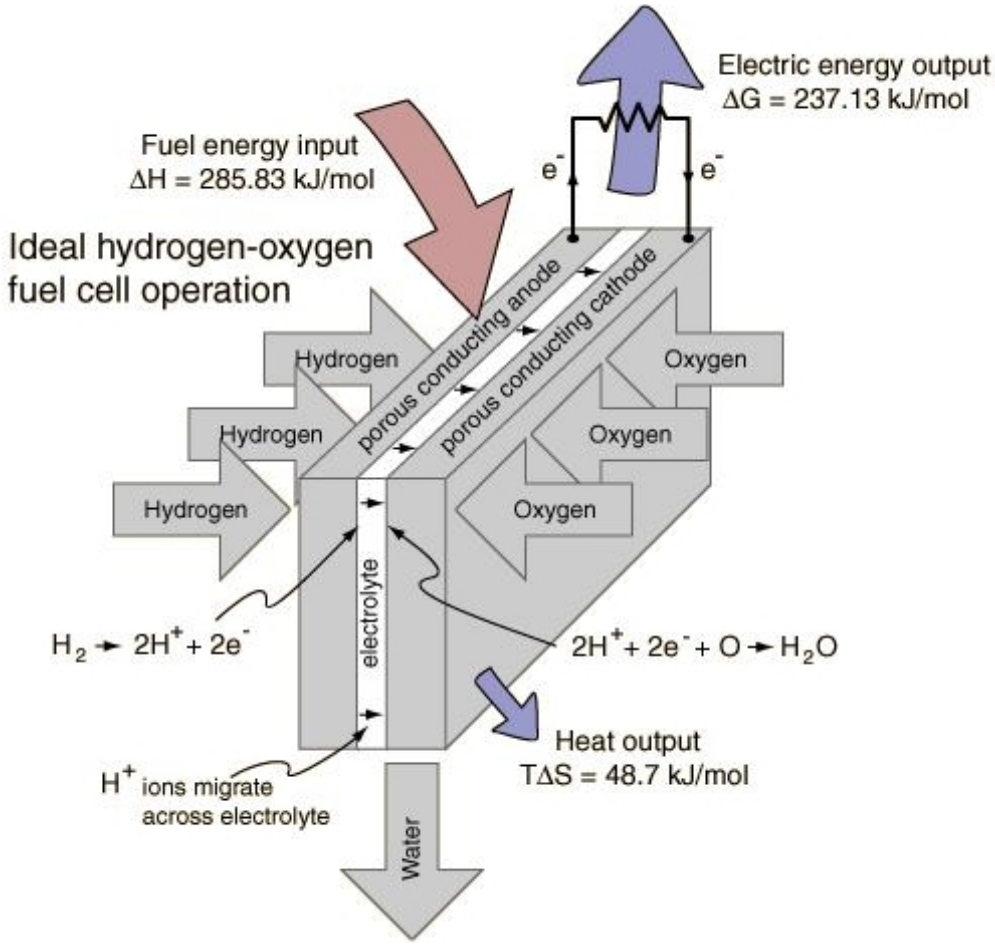


Fig. 3.2: Basic Fuel Cell Operation

The main parts of a FC are the *electrolyte* which allows ions to transpierce and the *electrodes* of anode and cathode that are made of porous conductive materials and aim to spread the fuel and oxidant as well as to conduct electrons. More analytically, the *electrolyte*'s function is to ease the electrochemical reaction and to allow ions to transpierce through it; also it is a natural obstacle for fuel and oxidant direct mixture avoidance. Regarding the *electrodes,* their main functions are to provide the area at which the electrochemical reaction takes place, to provide electrical connection with the load, to separate the reactants uniformly and to lead the reaction products to cells output; that is why they are always made of porous and conductive materials.

During FC operation, fuel is continuously being supplied to anode, in the simplest case Hydrogen, and oxidant to the cathode, usually Oxygen. The electrochemical reaction takes place between *electrode* and *electrolyte*, so it is important that a big number of small areas exists, at which reacting substance contacts both of them. The number of these areas is a key factor for FC efficiency. At liquid electrolyte FC types a part of the electrode must contact the electrolyte, allowing reactants' transfer at the same time; overlapping of the electrode may lead to lower efficiency. On the other hand, at solid electrolyte FC types a large number of areas, at which reactants contact to the electrode and electrolyte simultaneously, must exist.

In the simple case of the Hydrogen/Oxygen PEM Fuel Cell the cell reactions are the below:

Anodic half reaction: $H_2 \rightarrow 2\,H^+ + 2\,e^-$

Cathodic half reaction: $\frac{1}{2}O_2 + 2\,H^+ + 2\,e^- \rightarrow H_2O$

The overall reaction: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$

Hydrogen is oxidized on the anode and oxygen is reduced on the cathode. Protons are transferred from the anode to the cathode through a PEM and electrons are carried to the cathode over an external circuit (load). On the cathode, oxygen reacts with protons and electrons forming water and producing heat. Both the anode and the cathode contain catalyst to speed up the electrochemical processes. The overall $\mathbf{2H_2 + O_2 \rightarrow 2H_2O}$ reaction produces 48,7 kJ/mol of heat and 237,13 kJ/mol electric energy.

3.3 Electrolyzer

Hydrogen can be prepared in several different ways, but economically the most important processes involve removal of hydrogen from hydrocarbons. Commercial bulk hydrogen is usually produced by the steam reforming of natural gas [11]. However, the procedure of electrolysis is the focus of this study mainly because of the reversibility of the process as discussed at 3.1. The electrolyzer is the machine that converts electricity into chemical energy which produces Hydrogen. The procedure of electrolysis may be done by several ways such as alkaline, acidic and solar photo production; today the first two methods are commercially available.

3.3.1 Electrolyzer types description

As presented in [9], the most economically appropriate for an ESS are the **Alkaline Water Electrolyzers**. The electrolyte used in an alkaline water electrolyzer is aqueous potassium hydroxide (KOH) mostly with concentrations of 20-30 wt.%. The typical operating temperatures and pressures of this electrolyzer are 70-100 °C and 1-30 bar respectively. Usually, an electrolyzer consists of several electrolytic cells connected in parallel; two distinct cell designs exist: mono-polar and bipolar. In mono-polar cells the electrodes are either negative or positive while bipolar cells have electrodes that are negative on the one side and positive on the other side separated by an electrical insulator as shown in **Fig. 3.3**.

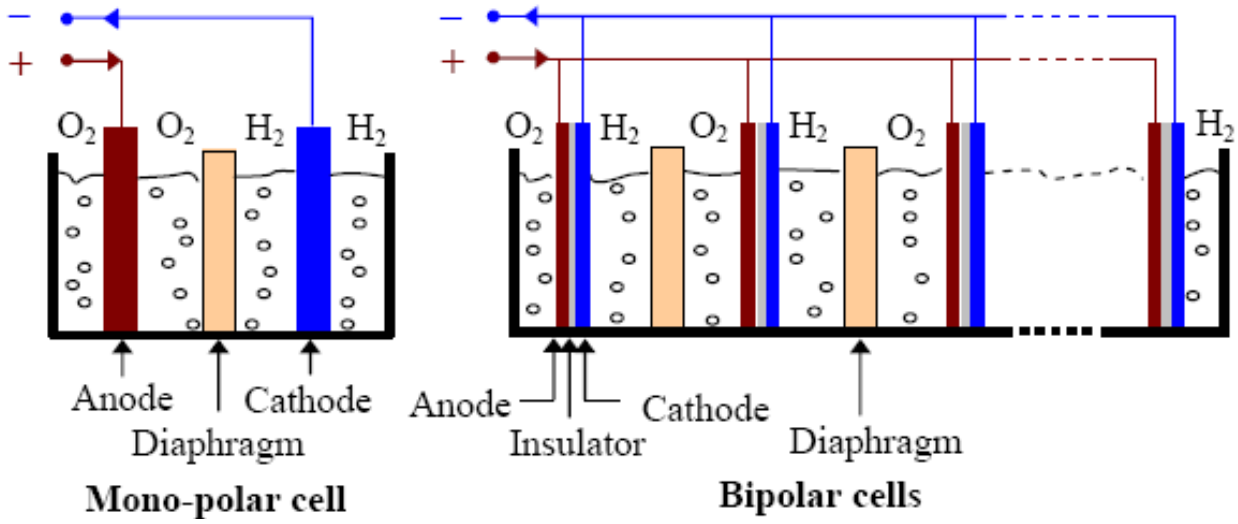


Fig. 3.3 Mono-polar and bipolar electrolytic cell designs

The bipolar electrolyzer stack is more compact and operates at higher pressures (up to 30 bar) in contrast to mono-polar cells that operate at atmospheric pressure. Compactness of the first leads to

shorter current paths in the electrical wires and electrodes, which means reduced losses due to internal ohmic resistance of the electrolyte and thus increase of the overall efficiency. In addition, the fact that it operates at high pressures is most favorable at an ESS in which Hydrogen storage in compressed form is the next stage after production; that is no external compress machine is needed (higher efficiency of the overall ESS). However, a drawback of the bipolar cells is that a single cell failure leads to malfunctioning of the whole stack; this does not happen in the mono-polar cell case, in which they are connected individually and disconnection of a single one is not such a problematic procedure. Moreover, the relatively sophisticated and complex system design of the bipolar cells leads to higher cost compared to the other option. Nevertheless, the previous advantages have prevailed and bipolar cells are used mostly at electrolyzer's industry today as at this study also.

3.3.2 Alkaline Water Electrolyzer Operation

The decomposition of water into Hydrogen and Oxygen can be achieved by passing a DC electricity current between two electrodes separated by a KOH electrolyte with good ionic conductivity. Water is a very ionic conductor and for this reason a conductive electrolyte must be used, so that the reaction can proceed at a technically acceptable cell voltage. The reactions are synopsized below:

Anodic half reaction: $2\,OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2\,e^-$

Cathodic half reaction: $2\,H_2O + 2\,e^- \rightarrow H_2 + 2\,OH^-$

The overall reaction: $H_2O \rightarrow H_2 + \frac{1}{2}O_2$

As presented in [9], a representative plot of the theoretical and actual voltages for an alkaline water electrolyzer versus the current density at high and low operating temperatures is shown in **Fig. 3.4**:

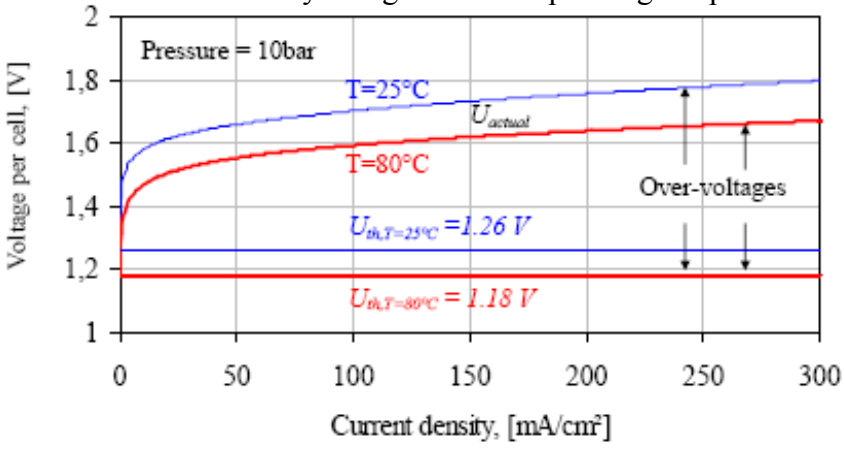


Fig. 3.4 I-U curves for an electrolyzer cell at high and low temperatures

3.4 Fuel Tank

Hydrogen is the simplest and most abundant element of the universe; it is clean and pollution free. It has a lot of interesting characteristics that prove it appropriate as an energy carrier: it is the lightest of all elements (molecular weight: 2.016 g / mol), its density is about to14 times less than air (0.08376 kg / m^3 at standard conditions) and it has a very high diffusion rate. It is liquid at temperatures below 20,3 K at atmospheric pressure and the density in that case is about to 70,8 kg / m^3. It contains the highest energy per unit mass of all fuels and because of its small molecular size leaks more easily through porous materials than other common gases at equivalent pressures (at the same holes or joints, it leaks 1,26 to 2,8 times faster than natural gas). It is generally non-corrosive and non-reactive with typical container materials, as well as non-toxic and non-poisonous. As a result of the above characteristics Hydrogen seems to be a promising energy carrier but with storage difficulties on the other hand.

3.4.1 Compressed gaseous Hydrogen storage

The most common and widely used method to store Hydrogen is in compressed form. Special pressure tanks exist for this cause usually made of steel or aluminum; their shell is properly manufactured to be thick enough, so that few holes for Hydrogen leakage exist. However, another approach of compressed Hydrogen storage is in aboveground earth caves; utilizing such cavities, great amounts of Hydrogen may be stored at various pressures proportionally to geologic shape. The main advantage of the cave-storage is that the leak is almost zero, but there are a lot of parameters that have to be taken in so that storage can be possible. Among all storage technologies, the compressed gaseous Hydrogen has the longest history and cheapest price. It is suitable for Electrolyzers also, as most of them (bipolar cells) produce Hydrogen at high pressures and no extra mechanism is needed so storage procedure to be completed. On the other hand it is the most dangerous storage way of all.

3.4.2 Liquid Hydrogen storage

Hydrogen is liquid at -253 °C (at atmospheric pressure), so an effective and energy efficient way of liquid Hydrogen storage requires complicated insulation techniques. At this natural state it has a volumetric energy density value of about 2760 kWh/m^3 and that's why is has been used as a fuel in space technology for several years [9]. The main advantage of this method is the reduced risks

compared to compressed gas, a great amount of energy (approximately 20-30 % of the Hydrogen's energy content) has to be used to accomplish liquefaction though. So it seems that it is not a cost-efficient approach for an ESS.

3.4.3 Metal Hydrides storage

This method is based on Hydrogen chemical binding by some metal hydrides, metals or alloys that react with Hydrogen producing heat. The reversible reaction may be done if the appropriate amount of thermal energy is supplied, so the metal hydride and Hydrogen are produced back again. The main characteristics of this procedure are the exothermic reaction that takes place at storage and the endothermic one when Hydrogen is released. That means that certain heat management problems arise at storage process and extra energy has to be expended at the second stage. However, heat supply may be not such a problem if thermal energy utilization of another component of the overall system is made; that is for the FCESS, if a small amount of energy is given initially and the fuel cells start operating, the heat co-production may provide the continuous flow of Hydrogen without extra energy expended. This way of storage is still not favorable for a FCESS mainly because of the high costs and limited lifetime (much lower than compressed gas tanks).

3.5 Power Electronics (PE)

Power conversion and energy dispatch at FCESS is a very important issue to consider. Power electronics are used so energy is converted and dispatched from the one component of the system to the other, as well as prevent the expensive electrochemical devices from damage. Specifically, at this study the AC coupled system topology is chosen as it is shown at **Fig. B.1,** so rectifiers are needed to electrolyzer system to transform the AC to DC and inverters to fuel cell array to accomplish the opposite. Also the voltage output of fuel cells array varies significantly in proportion to Hydrogen supply rate and pressure, so DC-DC converters are needed to stabilize the output and to equalize it with the inverters' input. In any case PE are an important parameter for the reliable operation of the system, while at the same time extra energy consumption takes place, therefore reducing the overall system's efficiency.

3.5.1 Inverter

The inverter is a high-power electronic oscillator that converts direct current (DC) to alternating

current (AC). The resulting AC can be at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits. The name “inverter” came from the early mechanical AC to DC converters which were made to work in reverse. Static inverters have no moving parts and are used in a wide range of applications, from small switch power supplies in computers, to large electric utility high-voltage direct current applications that transport bulk power. Inverters are commonly used to supply AC power from DC sources such as solar panels, batteries or fuel cells [11].

At the FCESS (**Fig. B.1**), an array of inverters connected in parallel between the electric grid and the Conv-DC bus coverts the direct current to alternating so it can be exported to the network.

3.5.2 Rectifier

A rectifier is an electrical device that converts alternating current (AC) to direct current (DC), the opposite operation to inverter. Rectifiers have many uses including as components of power supplies and as detectors of radio signals. Rectifiers may be made of solid state diodes, vacuum tube diodes, mercury arc valves and other components [11].

At the FCESS, rectifiers are used to electrolyzers to convert the AC injected from the electric grid to DC supplied to the electrolyzer cells. It is worthy of notice that in this work commercial products are used, modeled and simulated, so the electrolyzer component commercially available always has enclosed its Power Electronics which are mainly rectifiers. That is no extra rectifier component is required naturally, but it is modeled for the losses to be accurate.

3.5.3 DC to DC Converter

In electronic engineering, a DC to DC converter is an electrical circuit which converts a source of DC from one voltage level to another. It is used in a great number of applications for this voltage leveling up or down and for electrical protection from overvoltages and other power anomalies. There is a big variety of implementations such as linear regulators, switched mode conversion, magnetic, capacitive and electrochemical [11].

The voltage regulation is the main aim of the converters array connected between the FC-DC-bus and Conv-DC-bus (**Fig. B.1**) as the voltage output of the fuel cells varies significantly according to the amount and pressure of Hydrogen supply.

No detailed description of the above power devices is made because of the great number of dissertations in literature.

3.6 Conclusion

This chapter reviews all components of a FCESS. A few things are worth to be mentioned: *the overall efficiency of the system depends on each component individually*. That is, if a costly electrolyzer is chosen for good operating behavior or the latest manufactured fuel cells with great performances are selected, a similar DC-DC converter or inverter has to be chosen; the overall efficiency is greatly depended on PE as on every component of the system. *Bipolar technology is chosen for electrolyzers* because of the better operating behavior (compared to mono-polar technique) and the Hydrogen output flow which is pressurized and is led directly to fuel tank. This choice is perfectly combined with the *Pressured Hydrogen Storage* which is selected because of the cheapest price and longest life time period. Finally, as mentioned, *AC-couple topology* is used; this is because I wanted the FCESS to consist of available commercial products. That is, electrolyzers of high power scale that produce pressurized Hydrogen have mostly 3-phase AC input, because they are mainly intended to be used in some indoor application at an interconnected with the local grid area. So no common DC bus was able to exist with Fuel Cells. This last DC-coupled topology is usually preferable for fewer PE devices to exist.

4. MODELING OF FCESS

Modeling is the basis of estimation of a system's operation and approximation of all the important to consider characteristics. It basically consists of mathematical models, formulas and equations which describe the system's operation and predict the values of all the important parameters. This models and formulas are translated to computer language and so a simulation can be made. The whole procedure is of major significance, because an accurate estimation of FCESS' s operation leads to knowledge of the compatibility and appropriateness of the system components.

The modelling and simulation was made with the toolkit MATLAB/*Simulink*. All model-parameters have been derived from manufacturer's performance data-sheets or measurements obtained form literature and have been simulated for model validation. The individual component's theoretical analysis, mathematical model and computer model in Simulink are presented below:

4.1 PEM Fuel Cell modelling

4.1.1 Fuel Cell Voltage

4.1.1.1 *Theoretical Cell Voltage*

The theoretical voltage of PEM fuel cell is:

$$U_{theo} = 1{,}2297 + (T - 298{,}15)\frac{\Delta S_0}{nF} + \frac{RT}{nF}\ln\left(\frac{p_{H_2} p_{O_2}^{1/2}}{p_0^{3/2}}\right) \quad \textbf{(4.1.1)}$$

,where:

- **T** is the operating temperature
- **ΔS_0** is the change of entropy at STP equal to: -0,1634 kJ /(K mol)
- **n** are the number per electrons per mole. i.e. n=2
- **F** is Faraday's Constant and is equal to 96485,309 C/mol
- **R** is the Universal Gas Constant and equals to 8.31451 J/(K mol)
- **P_{H2}** is the Hydrogen supply pressure
- **P_{O2}** is the Oxygen supply pressure. If air is used 100 kPa pressure may be assumed
- **P_o** is the reference pressure that is 100 kPa

As expected, theoretical voltage of a PEMFC is affected by the ambient temperature and the supply pressure of reactants. Detailed description on the above formula and the modeling in *Simulink* may be found at **Appendix A**.

4.1.1.2 *Losses and overvoltages*

The above operation of the fuel cell is the ideal one regarding to a PEMFC with Hydrogen as a fuel and Oxygen as an oxidant. To estimate the real behavior we have to consider the losses and operating conditions' influence. The ambient temperature and reactants' pressure effects are shown above:

➢***Temperature influence,*** as already modeled in (**4.1.1)**, the temperature increase leads to ideal voltage decrement of about to 0.84 mV / °C so U_{theo} takes values lower than the ideal 1.2297 V. It is also an important factor for other losses that are described below.

➢***Pressure influence***, pressure increment may boost cell's efficiency. However, this fluctuation is not always possible as the Hydrogen pressure is proportional to the current amount stored at the reservoir.

Beside the operating condition influences, losses that lead to much lower voltage are presented below [10]:

➢***Activation Losses***. The reaction activation energy at the electrodes is the cause of this type of losses. The reaction activation energy is defined as the threshold that the supplied energy has to surpass for the start-up. This kind of losses mainly depends on the reaction itself, the electrolyte, the reactants concentration and slightly on the current density.

➢***Ohmic Losses***. Are caused mainly by ionic resistance of the electrolyte and the electrodes and the electrode's ohmic resistance. Ohmic losses are proportional to current density and significantly depend on the materials, the cell's shape and temperature.

➢***Concentration losses***. The limited mass transfer of the reactants at the cell's interior is the reason concentration losses are caused. They are greatly influenced by current density and electrodes' structure. The physical explanation is that molecules are not uniformly interfused at the cell's interior and some of them do not come in contact with the electro-catalyst and the membrane simultaneously.

All these types of losses are modeled and the detailed description may be found at **Appendix A.** Since the theoretical voltage and main losses have been modeled, the overall cell voltage is the sum:

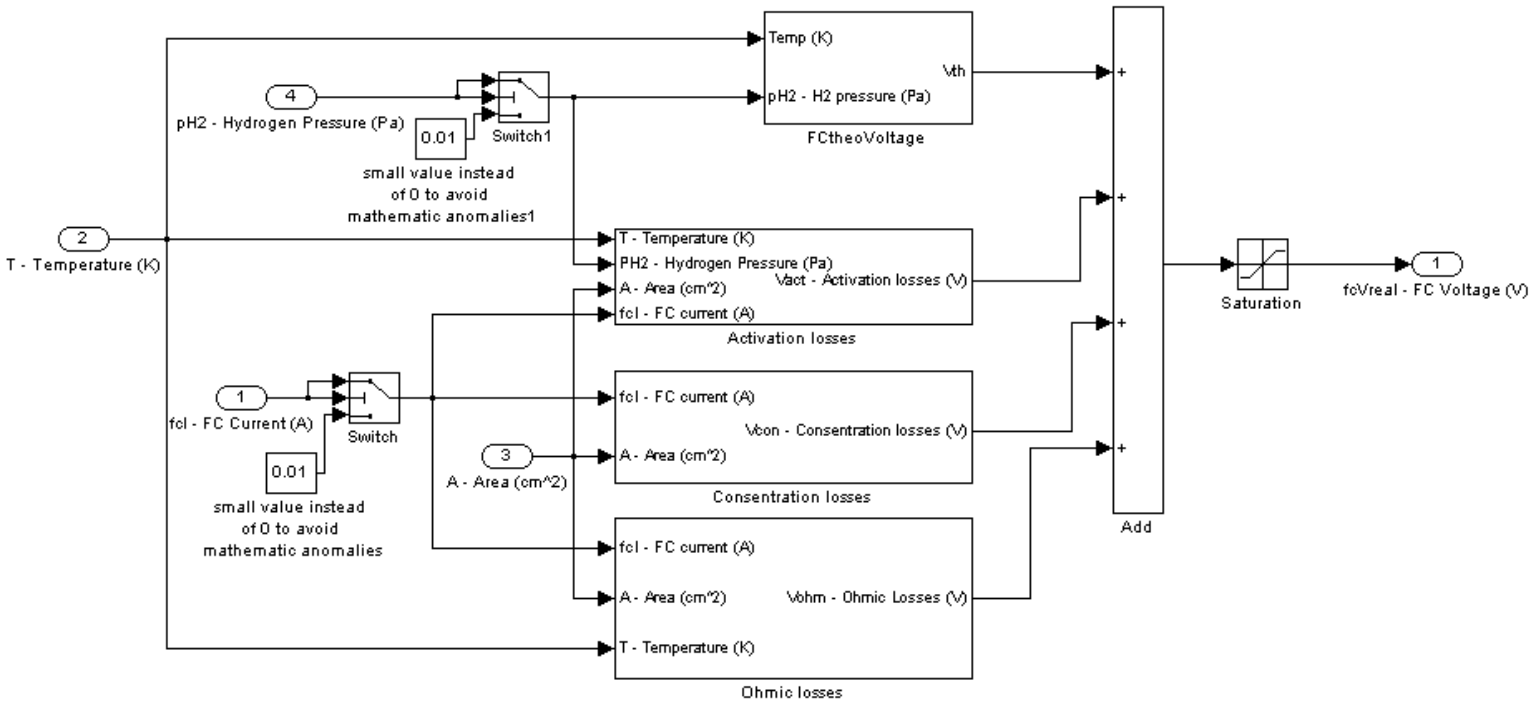


Fig. 4.1 The actual cell voltage V_{real}

Some elements, such as switches and saturation circuits, are used for smooth execution of the retroactive calculation of the operational point of the cell.

The U-I curves resulted from the simulation for **T=353 K, A=43,5 cm^2, P=1480305 Pa** are depicted at **Fig. 4.2** and **Fig. 4.3.** Prospectively, the actual voltage is much lower than the ideal 1,2297 V; the activation over-potential as it seems is "approximately" constant (little influence of current density), the ohmic losses increase proportionally to the current density as expected, and concentration over-voltage is very little at low and medium current ranges but grows exponentially at high current densities.

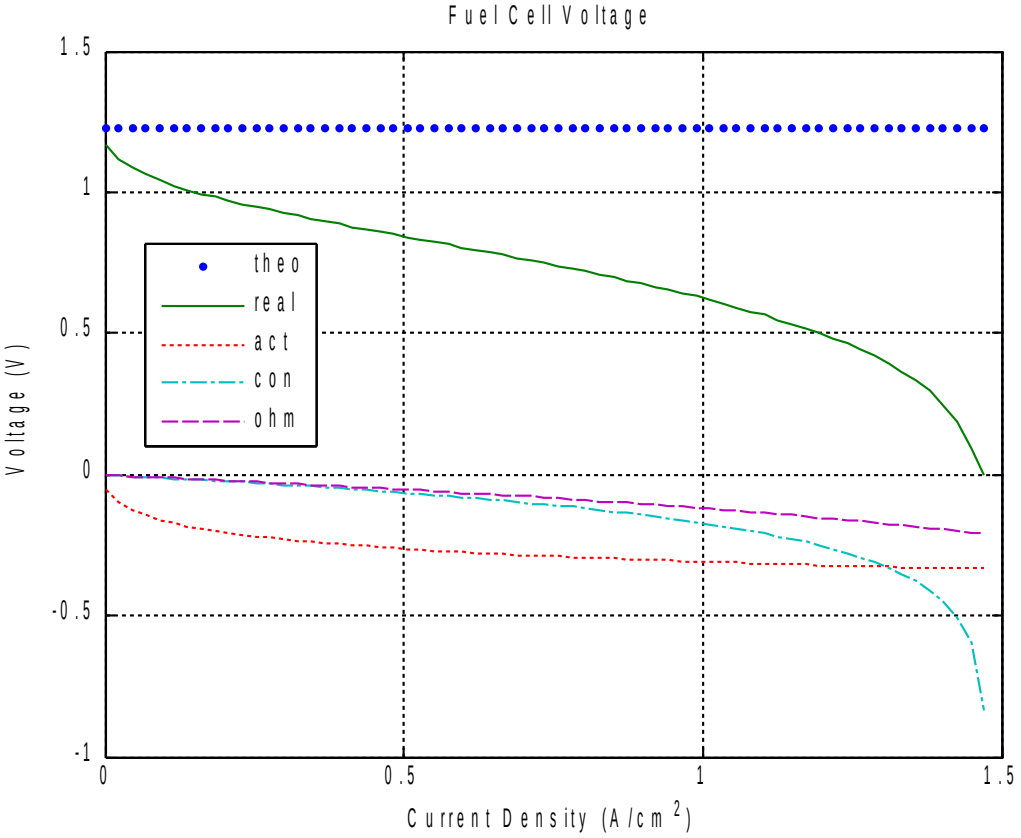


Fig. 4.2 The theoretical, actual and over- voltages of the fuel cell

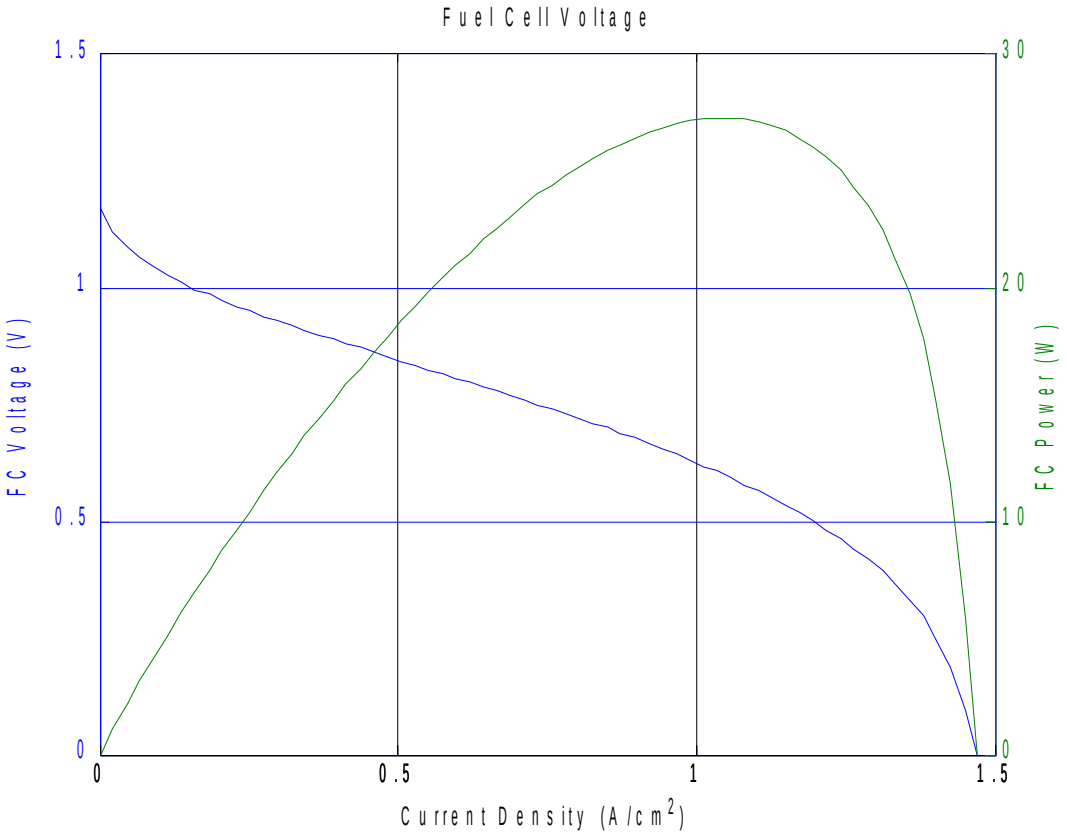


Fig. 4.3 The actual voltage and power versus Current Density

4.1.2 Hydrogen fuel cell consumption

The consumption of Hydrogen supplied to a fuel cell is directly proportional to the rate of electrons transfer at the electrodes, meaning the output current to the external circuit. For several cells connected in series the formula of Hydrogen Consumption (mol / sec) is [9]:

$$\dot{m}_{H_2} = \frac{Ns \cdot I_{fc}}{n \cdot F \cdot \eta_F} \quad \textbf{(4.1.2)}$$, where:

- **Ns** is the number of cells connected in series
- $\mathbf{I_{fc}}$ is the fuel cell current (A)
- **n** is the number of electrons per mole, i.e. 2
- **F** Faraday's Constant and equivalent to 96485,309 C/mol
- $\boldsymbol{\eta_F}$ is the Faraday's efficiency (detailed description is given in **Appendix A**)

The model in *Simulink* is depicted at **Fig. 4.4**:

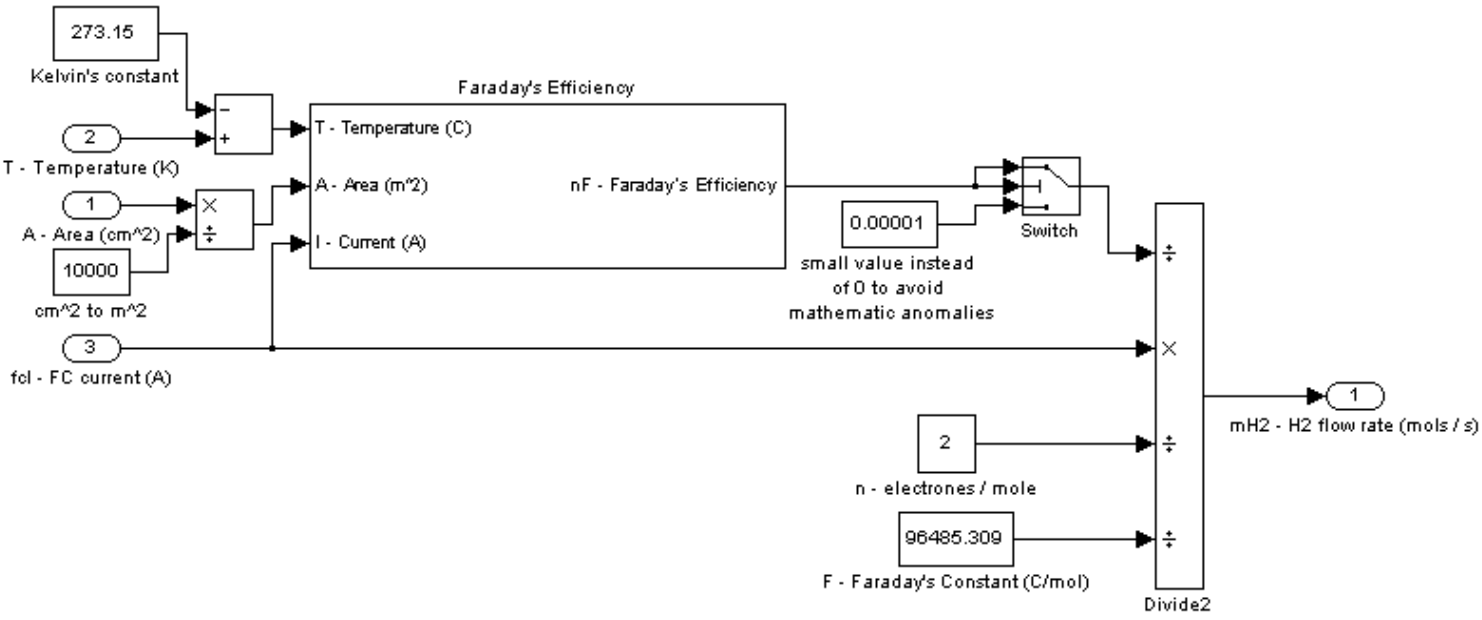


Fig. 4.4: The model of Hydrogen Consumption based on **(4.1.2)**

4.1.3 PEMFC Efficiency

The cell efficiency is defined as the ratio between the utilized energy and the energy the fuel contains. However a more convenient formula is: $\eta_{fc} = \frac{\Delta G}{\Delta H}$, where ΔG is the change in Gibbs free

energy (electricity produced) and ΔH is the reaction enthalpy change which represents the heat generation. At the ideal PEMFC where reactants are pure Hydrogen and Oxygen and at **STP**, ΔH_0 = -286 kJ/mol and ΔG_0 = -237,3 kJ/mol. So the maximum theoretical fuel cell efficiency is:

$$\eta_{fc} = \frac{-237,3}{-286} \simeq 0,83$$

To estimate the efficiency of an actual PEMFC we have to consider the losses, so the final form of the fuel cell efficiency is given by:

$$\eta_{fc} = 0.83 \frac{V_{real}}{V_{theo}} = \frac{0.83}{1.2297} V_{real} = 0.675 \cdot Vreal \quad \textbf{(4.1.3)}$$, where Vreal is the actual voltage of the cell.

4.2 Electrolyzer Cell modeling

4.2.1 Electrolyzer Cell Voltage

The model of electrolyzer that is approached is based on steady-state electrochemical operation at which it can be assumed that its function is opposite as that of a fuel cell when reactants are Hydrogen and Oxygen. Specifically, the reactions that take part at the electrolyzer cell are:

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

Cathodic half reaction: $2\ H_2O + 2\ e^- \rightarrow H_2 + 2\ OH^-$

The overall reaction: $H_2O \rightarrow H_2 + \frac{1}{2} O_2$

During the above procedures a certain amount of electric energy is required.

The formulas below take into account an alkaline electrolyzer (typically aqueous potassium hydroxide KOH) and the modelling is cell-based; for the whole stack's characteristics simply multiply by the number of the cells. The voltage representation is described in [13]:

$$elV = V_{rev} + \frac{r_1 + r_2 T}{A} I_{el} + s \cdot \log\left(\frac{t_1 + t_2/T + t_3/T^2}{A} I_{el} + 1 \right) \quad \textbf{(4.2.1)}$$, where:

- $\mathbf{V_{rev}}$ = 1.2297 V the reversible ideal potential
- **T** the operating temperature (K)
- $\mathbf{I_{el}}$ is the current of the cell (A)
- $\mathbf{r_1}$ is an empirical ohmic parameter equal to 8,05 x 10^{-5} Ω m^2
- $\mathbf{r_2}$ is also an empirical ohmic parameter equal to -2,5 x 10^{-7} (Ω m^2)/ °C
- $\mathbf{t_1}$ is an over-voltage coefficient: -0.1002 m^2/A
- $\mathbf{t_2}$ is an other over-voltage coefficient: 8,424 (m^2 °C)/A
- $\mathbf{t_3}$ is the third over-voltage coefficient: 247,3 (m^2 $°C^2$)/A
- **s** is coefficient of the electrode over-voltage: 0,185 V

The **(4.2.1)** contains all the losses at the electrolyzer cell occurring caused by the current density and temperature. As already shown at **Fig. 3.4** as the temperature decreases, the voltage takes higher values, so temperature levels have to be kept at high levels. However, seldom are electrolyzers manufactured to operate at temperatures above 100 °C continuously for technical reasons. In addition, the current density causes losses that give the below form of V-I curve (**Fig. 4.5**).

The above formula has been modeled in *Simulink* (**Fig. 4.6**) and simulated for model verification at **25 °C** and with **25 dm^2** electrode area.

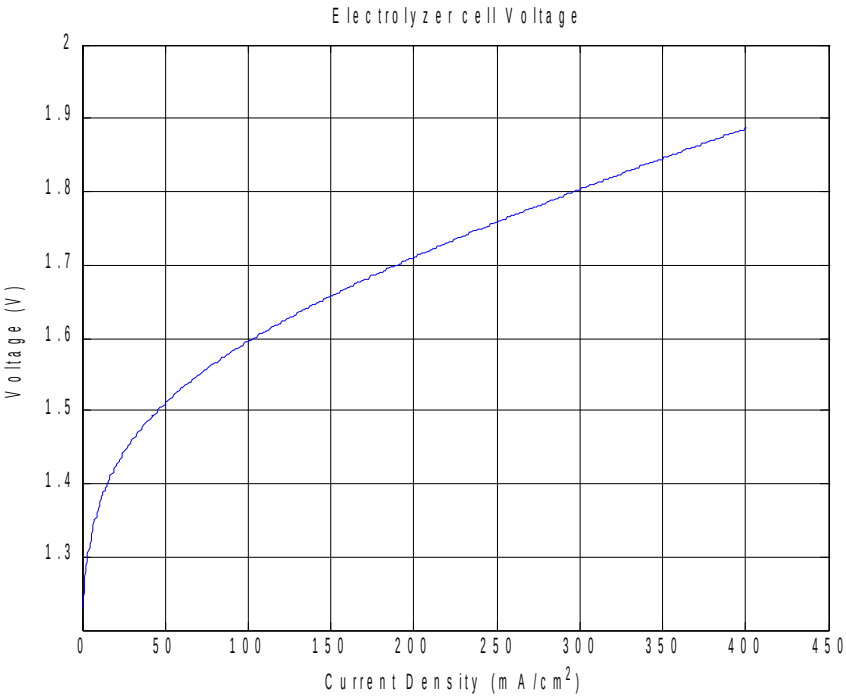


Fig. 4.5 The voltage versus current density for an electrolyzer

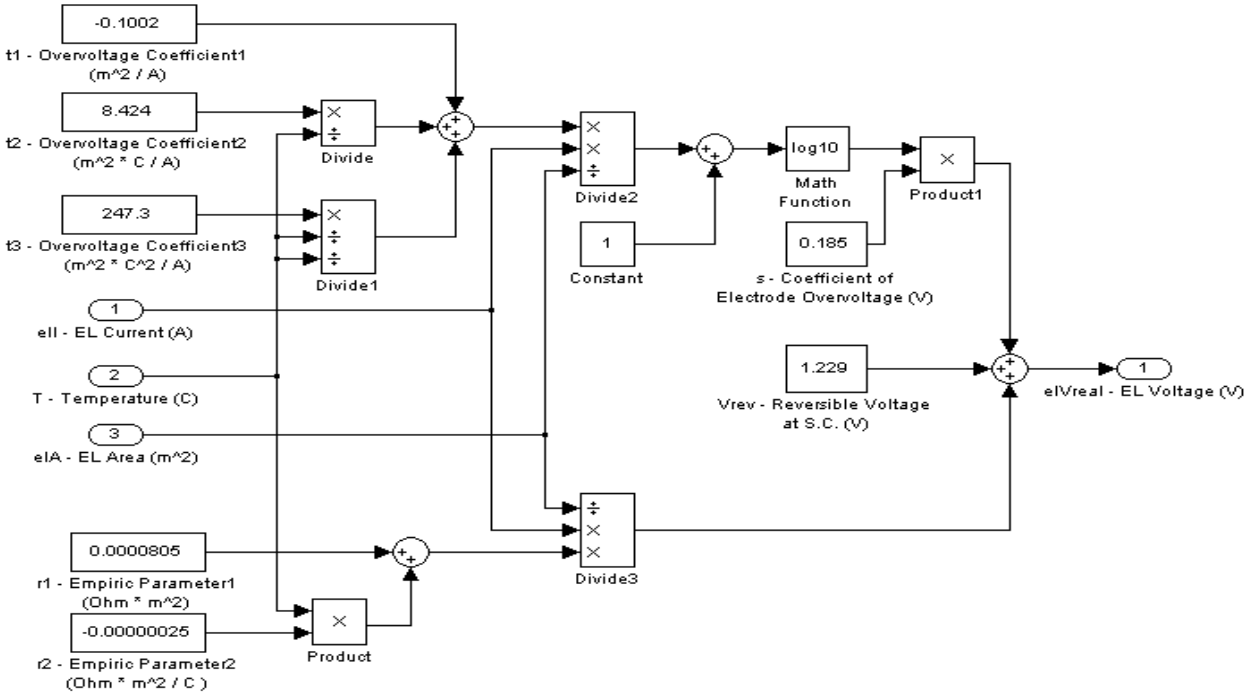


Fig. 4.6 The *Simulink* model of electrolyzer's voltage based on **(4.2.1)**

4.2.2 Electrolyzer Hydrogen Production

According to Faraday's law, the production of Hydrogen is directly proportional to the rate of transfer electrons to the electrodes that is the current. Thus, the mathematical model that describes the Hydrogen production is similar to **(4.1.2),** except that the Faraday's efficiency factor is at numerator position instead of denominator:

$$m^{\circ}_{H_2} = 2\, m^{\circ}_{O_2} = m^{\circ}_{H_{2O}} = \eta_F \frac{Ns \cdot I_{el}}{n \cdot F} \quad \textbf{(4.2.2)}$$, where:

- **Ns** is the number of cells connected in series
- $\mathbf{I_{fc}}$ is the electrolyzer cell current (A)
- **n** is the number of electrons per mole, i.e. 2
- **F** Faraday's Constant and equivalent to 96485,309 C/mol
- $\boldsymbol{\eta_F}$ is the Faraday's efficiency (detailed description is given in **Appendix A**)

The model in *Simulink* is depicted at **Fig. 4.7**:

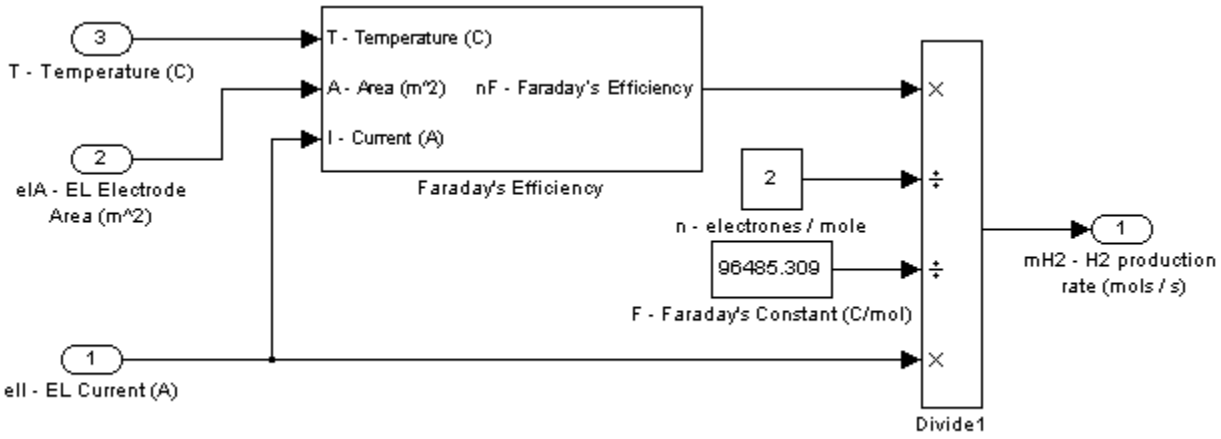


Fig. 4.7 The Hydrogen production model based on **(4.2.2)**

4.3 Fuel Tank modelling

As discussed at 3.4, there are various forms of Hydrogen Storage, but the compressed gaseous form has prevailed for reasons already analyzed. So, to model the Hydrogen behavior at a fuel tank in compressed form it is considered as obedience to the *Ideal Gas Law* and the well-known formula is given by [11]:

$$P\,V = n\,R\,T \quad \text{, where:}$$

- **P** is the Hydrogen pressure (Pa)
- **V** is the volume of the tank (m^3)
- **T** is the temperature (K)
- **n** is the number of moles stored (mol)
- **R** is the Universal Gas Constant and equals to 8.31451 J/(K mol)

The current approach of the Hydrogen storage is based on the below methodology:

✓ *Calculate how much Hydrogen is produced by the electrolyzer at this time step (moles / hour) OR how much Hydrogen is needed to be consumed by the fuel cells*

✓ *Calculate how much gas is currently stored at the tank and if there is space for the newly produced quantity OR if the requested amount to be consumed exists*

✓ *The free space is determined by the pressures of Hydrogen supply and fuel stored*

The model in *Simulink* is shown below:

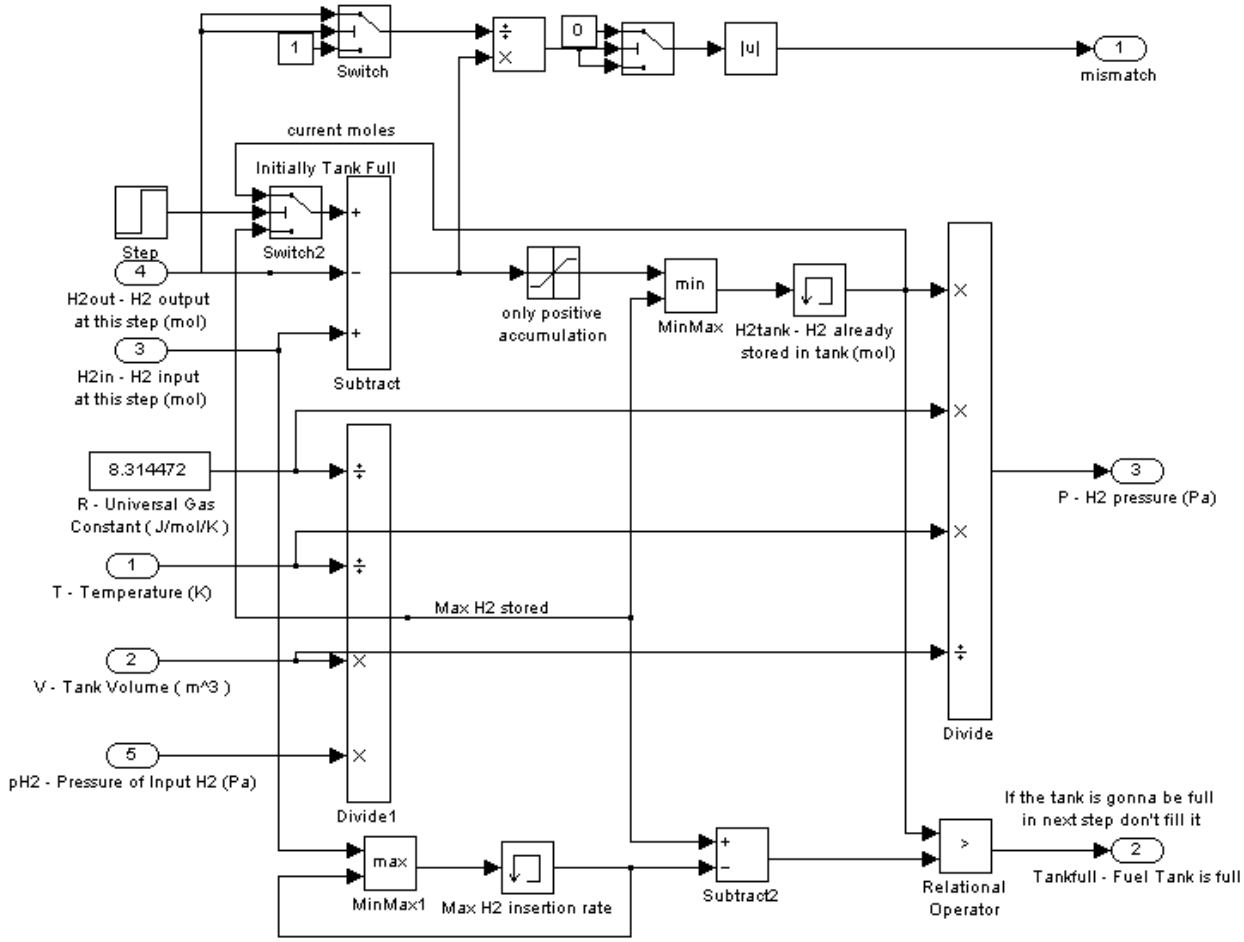


Fig. 4.8 The Fuel Tank model in *Simulink*

The Hydrogen input (production) and output (consumption) of the tank are all inputs to the model because they are already calculated at electrolyzer and fuel cell components respectively. The Pressure of supplied Hydrogen is the #2 output and is needed for the fuel cell voltage to be determined accurately **(4.1.1)**. #1 output **mismatch** is worthy of notice, as is the signal that figures out if Hydrogen available for the fuel cells exist; also #3 output **tank_full** determines if the tank is full so electrolyzers stop working.

4.4 Power Electronics modeling

As shown in 3.5, PE are needed for the reliable operation of the FCESS. The model that is approached focuses on energy losses at PE and does not investigate the complicated electronic phenomenon. This simplified approach was chosen, because for a FCESS, PE are just components that convert and dispatch energy with an efficiency decrement cost; nothing more nothing less. So,

if the voltage of the fuel cells can be accepted by the DC-DC Converters, transformed to the appropriate levels for the inverters and then converted to 3-phase AC for export to the grid, then one needs to just calculate the losses to decrease the overall efficiency; there is no need for realistic representation of the 3-phase AC voltage and current to determine the correct operation and power losses. Thus, the **[9]** presents a linear power conditioning unit model:

$P_{out}=\eta_{rated}\cdot(P_i-P_{standby})$ and $P_{standby}=0.01\cdot P_{rated}$, where:

- $\mathbf{P_{out}}$ is the Power output of the component
- $\mathbf{P_i}$ is the Power input
- $\mathbf{P_{standby}}$ is the continual power losses even it does not operating (is just ON)
- $\mathbf{P_{rated}}$ is the maximum power delivered by the PE component and is determined by the manufacturer
- $\boldsymbol{\eta_{rated}}$ is the rated efficiency

For $\mathbf{P_i < P_{standby}}$, the model efficiency is assumed to be zero. When $\mathbf{P_i}$ approaches the rated power $\mathbf{P_{rated}}$, the standby power consumption is negligible in comparison to the model input power and consequently the model operates at its rated efficiency.

The DC-DC Converter model is presented below:

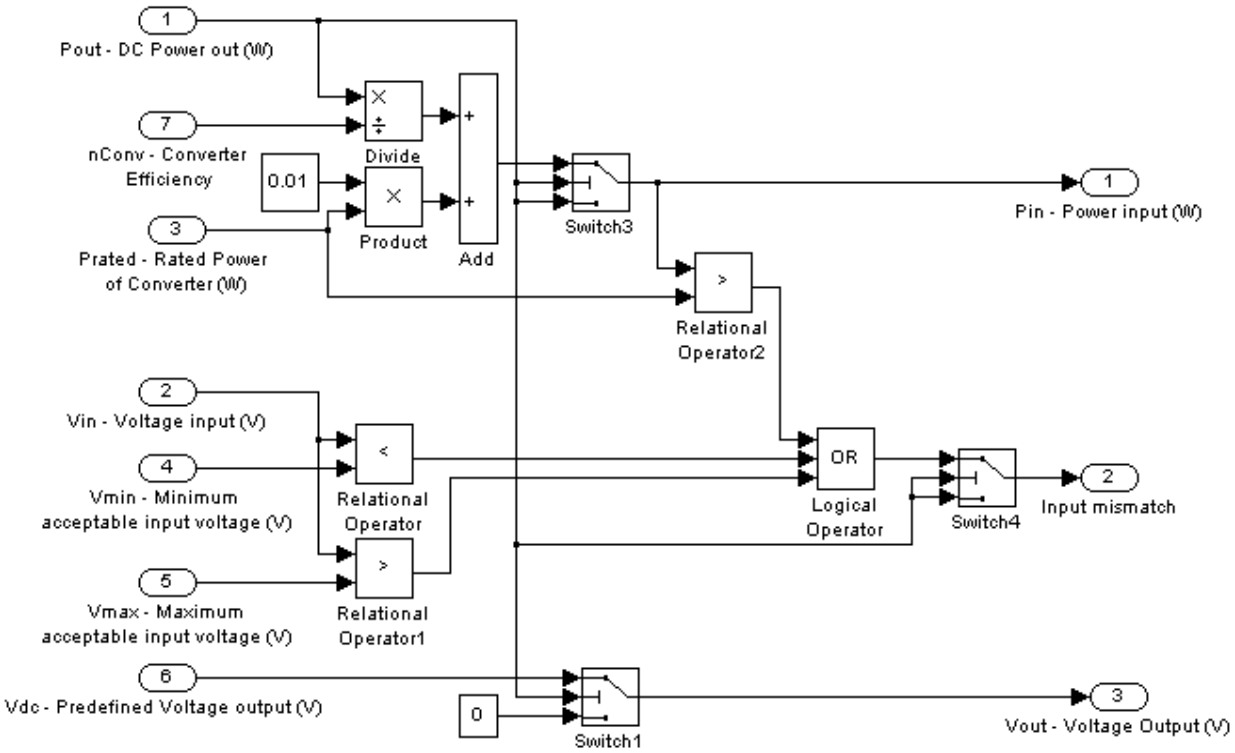


Fig. 4.9 The DC to DC Converter model in *Simulink*

As discussed above, the input appropriateness is investigated at voltage and power levels; that is, check if the voltage value is in the input voltage range and examine if power in is lower than the maximum P_{rated}. For this model and the model of the inverter, it is worthy of notice that the component's power input (energy from the fuel cells) is a model's output (#1) and the component's power output (stabilized DC voltage) is a model's input (#1). This modeling was made because at the simulation the calculation process is reverse: the goal to be achieved is a certain constant value of power to the grid, so the output of the inverter is known (and so for the DC-DC converter) and the input power value needs to be calculated. The next step is to know how much energy the fuel cells are required to produce and so the Hydrogen consumption rate is determined.

A much similar model for the inverter is depicted at **Fig. 4.10**:

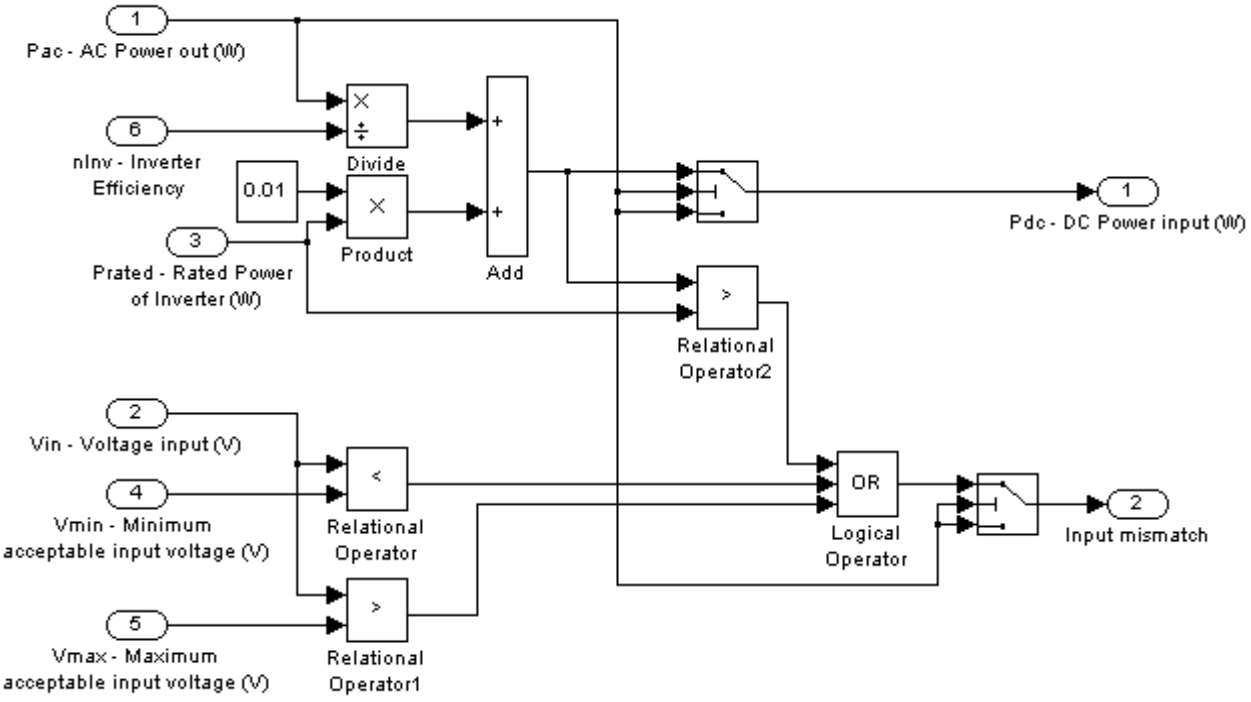


Fig. 4.10: Inverter model in *Simulink*

4.5 Conclusion

In this chapter a detailed description of the mathematical formulas and models of the FCESS' s basic components is presented. All these models have been derived from literature and values of the parameters have been obtained from manufacturer's data sheets. In some cases, small scale adjustments was made so the model to describe accurately the commercial available product, but in general the above formulas provide a very satisfying estimation of components' operation according

to measurements found in literature. Thus, these models are complex and detailed enough to a very good approximation of the FCESS' s operation to be accomplished, but are also simple enough so that a whole year's simulation can finish in few seconds. The overall FCESS modeled in *Simulink* has multilevel structure and many peripherals that complete the systems modeling; the detailed connection and that of the described components and the overall overview of the FCESS may be found at **Appendix B**.

5. SIMULATION PROCEDURE

5.1 The methodology

The simulation of the FCESS is the main aim of this study. The modeling that has been made intends to estimate and approximate the behavior of the system for one whole year, so results on the appropriateness and performance are extracted. These conclusions will lead to a reliable and economically optimum system via Genetic Algorithms. So, the goal of the simulation step is to to determine if the upon investigation system fulfills the requirements for a steady and reliable operation for one whole year; that is a constant-guaranteed amount of power is exported to the electric grid four hours a day (from 11:00 to 15:00), 365 days a year. The simulation step is one hour during which a steady state operation is assumed, so for a FCESS simulation 8760 hourly steps are required; almost 2.7 to 3.3 seconds is the real runtime period.

The overall simulation steps may be shown briefly at the flowchart in **Fig. 5.1**. The process is completed in 8760 hourly steps at which various operations such as Hydrogen production/storage and consumption take place. The FCESS operation may be separated in two stages; the charge and the retrieving process. The retrieving process is the Hydrogen consumption via FC and energy production delivered to the electric grid; this happens at 11:00 to 15:00 each day to achieve the guaranty of standard exported power required. The charge procedure is Electrolyzers operation utilizing rejected energy from wind parks or purchased energy from the power network and storage of Hydrogen at the reservoir; it takes place when rejected energy is available or at hours from 00:00 to 08:00 daily if purchased energy is decided to be imported.

As it may be seen at **Fig. 5.1,** at each step a series of calculations is made. According to the guaranteed amount of power, the type and number of Inverters and DC-DC Converters may be determined as well as the operational point of the Fuel Cells; so, the consumed quantity of Hydrogen is known at the end of each energy retrieving step and the Tank status (pressure, quantity) is updated properly. Respectively, at the charge steps Hydrogen is added to the tank if there is space and if energy available exist for the Electrolyzers operation. According to the available amount of power offered to Electrolyzers, the operational point is calculated and the how much Hydrogen is produced is determined; at the end of this step the tank status is updated with the new values of Hydrogen quantity and pressure.

It is important to notice that at each simulation step procedure a detailed control on the reliable operation is made; if a mismatch is acknowledged either from incompatibility of some components or from not satisfying the requirements, then the simulation ends at a Failed Operation status and the solution is rejected.

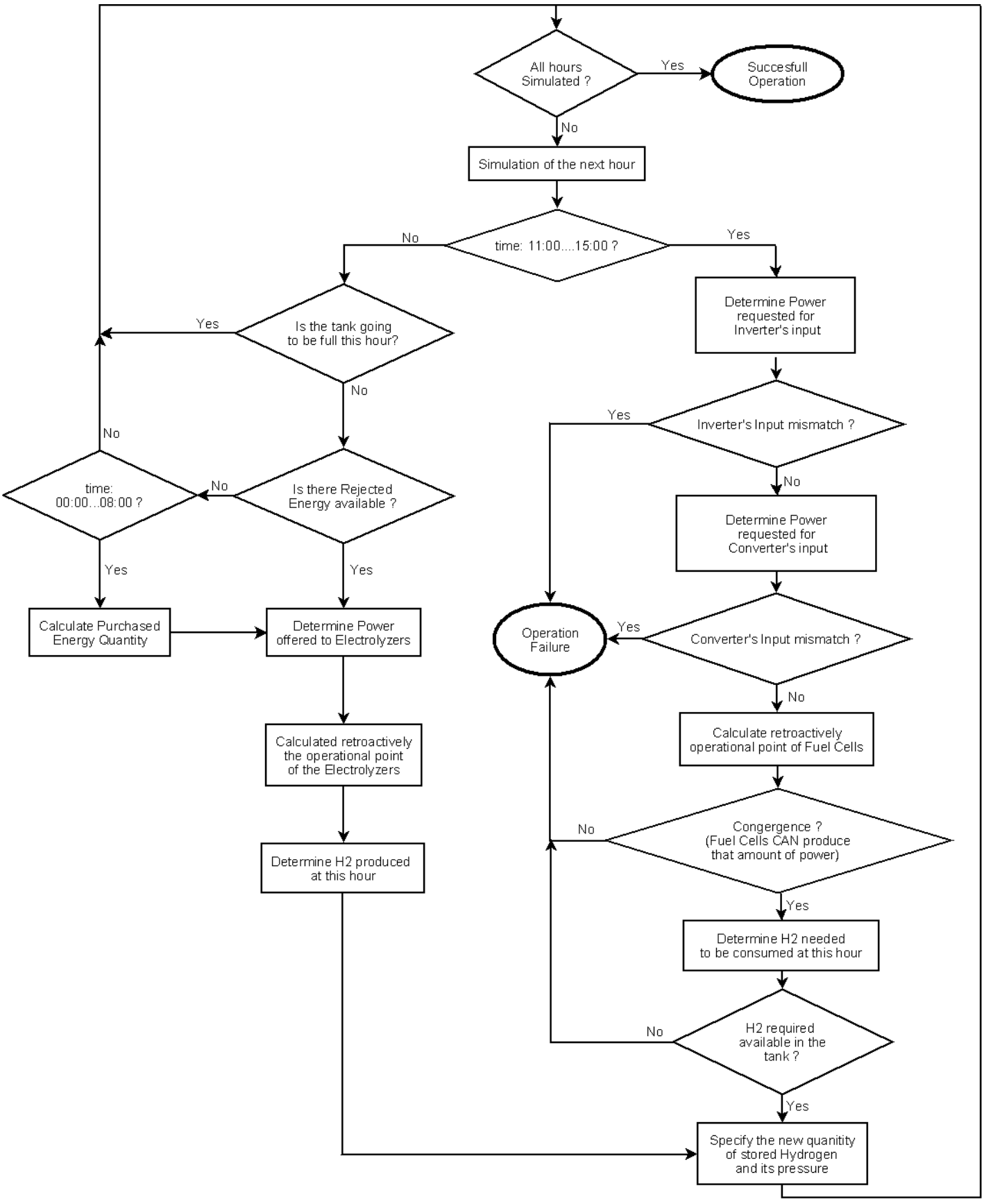


Fig. 5.1: The Simulation flowchart

5.2 Simulation Parameters

The energy rejected from the wind park is shown at **Fig. 5.2**:

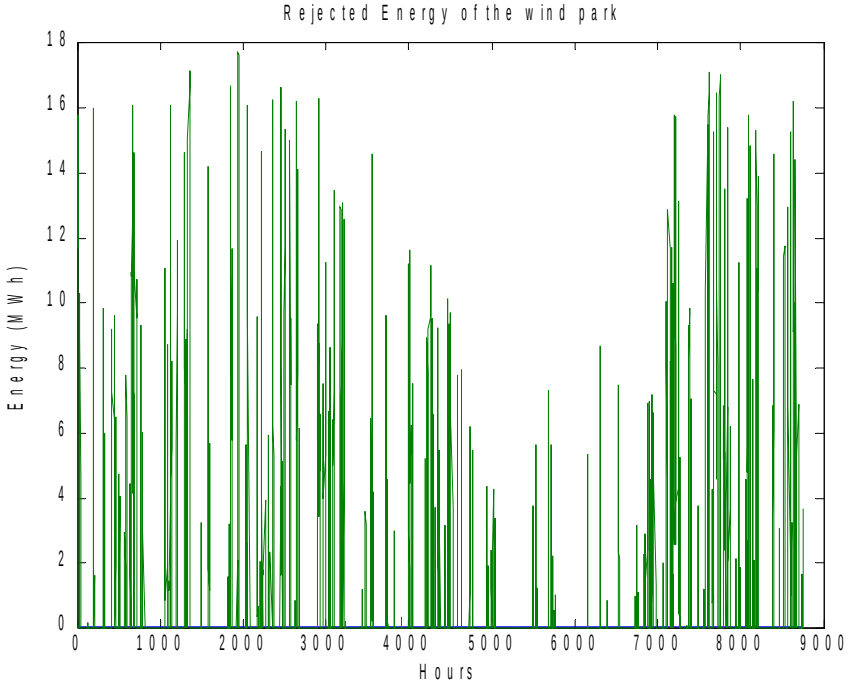


Fig. 5.2: The rejected energy of the wind park

As can be seen, energy is rejected in just 18% of the year and this rejection is in the form of thin "spikes". That means that an ESS will not benefit from all the rejected energy, but it will reject some constrainedly.

A simulation of a successful operation of a FCESS and specifically, the fuel tank state is depicted below for a general idea to be obtained:

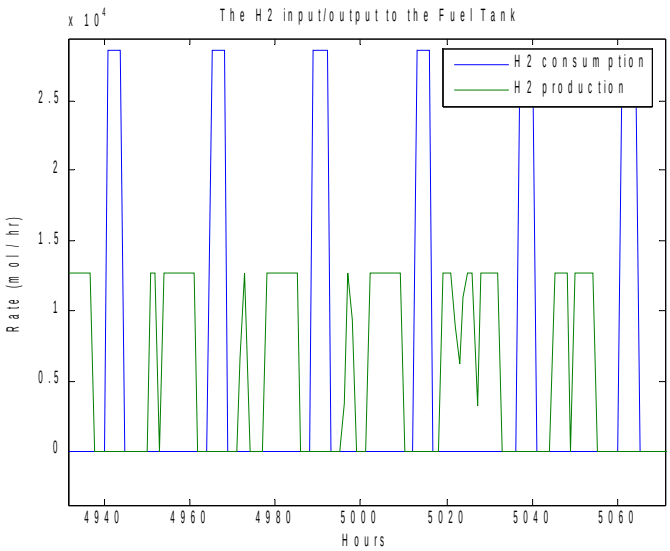


Fig. 5.3: H_2 in and out of the fuel tank for a typical period of the year

At **Fig. 5.3,** H_2 import and export are figured for a typical period of the year for a random FCESS. As can be seen, the *consumption rate* is a periodic signal with a constant value as amplitude; the reason is obvious, as the power production from the FC is periodical with a standard value (4 hour a day, 365 days a year). The reliability of the system and the fulfillment of the main requirement are to produce that amount of power periodically and a minor mismatch would lead to Failed Operation status.

On the other hand, the H_2 *import/production* depends on the available wind energy; so, when rejected energy is offered the electrolyzers operate at that value of power (so H_2 production varies), and when no rejected energy is available there is energy purchase from the electric grid (which is possible only between 00:00 and 08:00).

At **Fig. 5.4** the pressure status is depicted for the whole annual period:

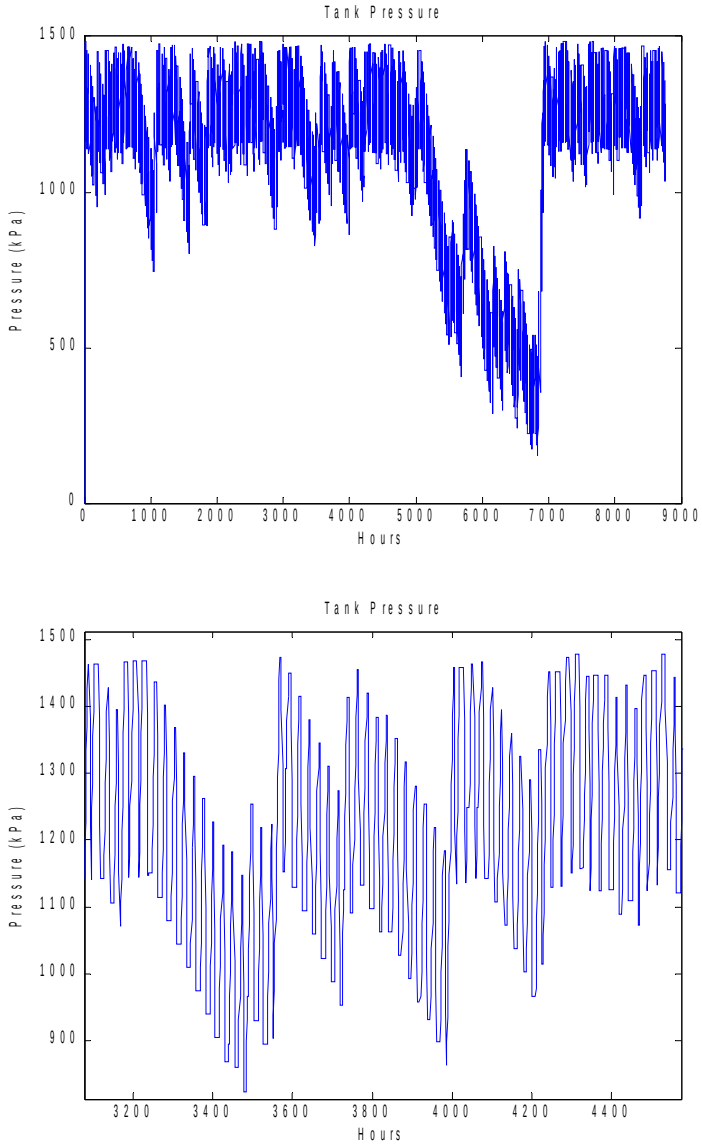


Fig. 5.4: The pressure levels of the fuel tank

The pressure value is proportional to the Hydrogen stored quantity (*Ideal Gas Law*) and it is obvious that it continuously changes. An important observation is that the pressure levels mainly depend on the rejected wind-energy; so when rejected energy is offered to the system the tank tends to be full, but at periods that wind energy is not available, such as from 5000 to 7000 hours, the tank tends to empty.

6. OPTIMIZATION PROCEDURE USING GENETIC ALGORITHMS

6.1 History

In the 50's and 60's many computer scientists investigated evolution systems believing that genetic evolution could be used as an optimization method for technical problems. The main idea of those systems was the development of a possible solution population for a certain technical scenario, using calculations inspired by natural genetic mutation and selection.

Genetic Algorithms (GA) were invented by John Holland at 60's and developed by himself and his students in the 60's and 70's. The initial goal of Holland was not to make algorithms to solve certain problems, but to study the phenomenon of orientation as it takes place in nature and to develop methods with which these mechanisms could be implanted to computers.

The Genetic Algorithms of Holland is a method with which an initial population of chromosomes is formed and an offspring is created using a type of natural selection and the genetic operators of mutation and crossover. Each chromosome consists of several genes, and each gene has a specific number of different versions. The selection operator determines which of them will be combined and will make descendants; it is based on the chromosome adaptability. The crossover procedure is a genes swap between two chromosomes and the mutation operator randomly chooses a version for a gene [14].

6.2 Basic principles

The GA do not try to solve a problem via mathematical methods but using biological evolutionary procedures, something that proves them flexible. They converge to the optimum solution independently if the scenario describe-functions are linear or non-linear, discrete or continuous time, of few or many minima/maxima, NP or non-NP complete.

In such an optimization problem, each candidate solution is named as *chromosome* and the whole set of solutions as *population*. Each chromosome has several *genes* each of them representing one of the parameters of the problem-function. The method aim is to evolve the chromosomes at subsequent steps so finally all of them converge to a certain solution-set of parameters that is the

global optimum. The population at each step during this procedure is called *generation*, and it continually changes, despite maintaining the chromosomes number constant.

The four main characteristics of the GA that prove them suitable for global optimum calculation are **flexibility**, **selection**, **mutation** and **crossover**. The steps of a typical GA method are shown below:

1) Random initialization of the population – this is 1st generation
2) Iterative process:
   (a) Fitness Function calculation
   (b) Selection of parents-chromosomes
   (c) Crossover operator
   (d) Mutation operator
   (e) Constraints Evaluation and chromosome repair
3) End process when solution found is satisfying enough or a maximum number of steps is reached

That is, at each step the offspring is created selecting the "best" chromosomes of the current population and rejecting the "worst"; those chromosomes selected are combined via the crossover method and changed via the mutation technique, so a significantly different population is created based on the most-promising solutions of previous generations while maintaining the diversity and premature convergence is avoided [14].

6.3 Parameters representation

The way the problem parameters are coded in the chromosomes as genes is a very important issue. A very popular method is coding at binary form; each gene is represented by a sequence of 0 or 1 and stands for a certain value of the gene-parameter. The main disadvantage of this coding is visible when parameters take values from large ranges; the number of sequence bits is constrainedly big, which means that the search space of the solution is grown larger. In addition, very often the scenario parameters are real numbers and not just integers; in this case, more complex and time-consuming genetic operator methods need to be developed.

For the above obstacles to be overcome, a different coding of the genes as real numbers (floating point numbers) is chosen. At such a representation the chromosome form is $[g_1\ g_2\ g_3\ \ldots.\ g_n]$, where g_i is a floating point number for the gene. All the genetic operators are adjusted for this kind of representation.

Specifically for the FCESS, the genes are four: the number of Electrolyzer units, of Fuel Tanks, of Fuel Cell Stack units and the guaranteed amount of power. There is no need of PE number calculation as it comes up from the constant power. There are also three parameters for the FCESS modeling: the Electrolyzer, Fuel Tank, and FC types which are the complete commercial solutions with all the technical characteristics. These parameters need to be specified for the fitness function calculation and mainly for constraints evaluation (which requires the system simulation) during the GA execution and cannot participate in the GA optimization process; so an iterative procedure takes place and all product combinations are checked.

6.4 Fitness Function

The objective function of an optimization problem is defined as the representation of a certain characteristic of the scenario which needs to be optimized. This may be economic cost, time cost, quantity or size of an object etc and it may take positive or negative values. Fitness Function is the function that comes from the Objective Function via a one-way correspondence and it is used at GA. The reason the Fitness Function is used as an intermediate stage of the chromosomes appropriateness calculation, is that for the selection to be made the parameter that will determine appropriateness must have two characteristics:

- *the higher the value is, the better the solution is*. That means that if the investigated problem is a maximization one that's OK, but if it is a minimization one the function values must be turned to opposite.
- *non-negative values*. This is important for the selection procedure as described at 6.5.

So, the Fitness Function uses Objective Function but maybe at the opposite form and maybe with some constant number added so values are positive.

At the current optimization of the FCESS, the objective function is the incomings minus expenses of the system for a certain number of years (details in **chapter 7**). So, the fitness function is the objective function as it is (not opposite), except for a constant number added in some cases to avoid negative values. This constant is not predefined and it is not added at each generation, as it is not easy to estimate the global objective function's minimum and add it at absolute form for every possible solution. Alternatively, at each generation the minimum value of objective function for all current population's chromosomes is calculated and this is added at absolute form.

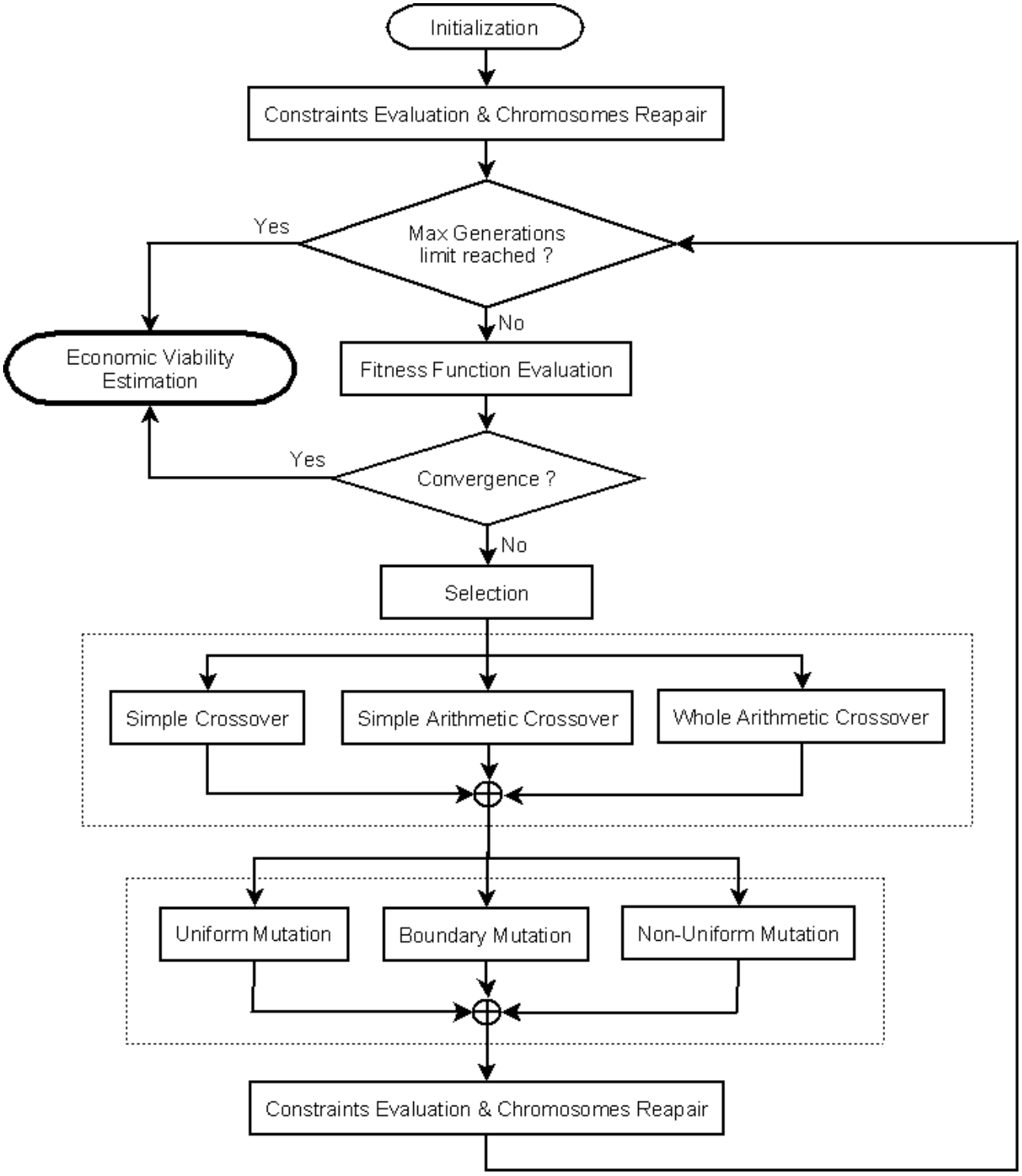


Fig. 6.1: The GA flowchart

6.5 Selection

The selection is obviously the procedure that selects the most promising chromosomes of the population of the current generation and applies crossover and mutation; that is, the offspring will consist of these selected chromosomes with some of them changed via the genetic operators. The appropriateness of the chromosomes is estimated using the Fitness Function. In [14] the most popular selection techniques are numerated:

- Elitist Selection: The best solutions are always selected.
- Fitness-proportionate Selection: The most suitable chromosomes is more possible to be selected
- Scaling Selection: The selection strictness is increased as generations pass by. That is, the best solutions are selected for certain as closing to the end.
- Tournament Selection: Discrete sets of the population are created and a comparison between the chromosomes of each set is made; only one will survive from each set.
- Rank Selection: a sorting based on the appropriateness of the chromosomes is made. The selection is made using the rank in that list and not the absolute values; that contributes to avoiding very good solutions to prevail too early.
- Generational Selection: the offspring completely replaces the chromosomes of the current generation, even the parents.
- Steady-state Selection: the offspring replaces a number of less suitable solutions of the current generation.
- Hierarchical Selection: several smaller selection procedures take place, loose and simple at the beginning but strict and complex as closing to the end; time-consuming efficiency is achieved.

At this study, a mechanism known as roulette's wheel with a small addition is used. The roulette's wheel method is based on the principle that each chromosome is selected with a probability proportionate to the fitness. So, assume $\mathbf{f_i}$ the fitness function for i chromosome, $\mathbf{p_i}$ the probability this solution to be selected and **N** the population number. Its value is given by:

$$p_i = \frac{f_i}{\sum_{i=1}^{N} f_i}$$

The exact procedure is:

- Calculate f_i for all chromosomes
- Compute the p_i for all chromosomes

- The cumulative possibility is calculated as determined by: $sp_i = p_{i-1} + p_i$, with $p_0=0$
- N random numbers are generated at (0,1) range
- For each random number *r*, determine *k* at which $sp_{k-1} < r \leq sp_k$. This is the index of selected chromosome.

A small addition was made to the above typical roulette's wheel method. 10% of the selected chromosomes is based on the *Elitist Selection* method and the rest 90% on the roulette's wheel; that is if N=30, the selected chromosomes consist of 3 that are the best of the current generation and of 27 that are determined via the above methodology. This was made to maintain the elitist in the population regardless, in order to provide both diversity and strictness.

6.6 Crossover

Crossover is the swap of genes between two chromosomes. There are some versions at which several chromosomes participate in this procedure and not just two, but at this study the popular way was chosen. For the crossover operation to be performed a number from the already chosen chromosomes is selected; each chromosome has a predefined probability to participate in crossover and so random number generation is needed. The chromosomes are separated in pairs and crossover takes place at each pair; if the total number is odd another chromosome is selected randomly. There are three different crossover operations that take place:

1)Simple Crossover (SC)

At the simple crossover, a random point (gene) at the chromosomes is determined randomly. All genes from this point till the end are swapped between the two parents. Probability chosen: 10%

2)Simple Arithmetic Crossover (SAC)

A random point for crossover is also determined. The difference is that the genes are not just swapped but a balanced mean of their values replaces them. Specifically, a random number **r** is generated at the range [0,1]; then assuming chromosomes **a** and **b**: $a_i = r\,a_i + (1-r)\,b_i$ and $b_i = r\,b_i + (1-r)\,a_i$ for each **i** gene from the crossover point till the end. Probability chosen: 10%

3)Whole Arithmetic Crossover (WAC)

This crossover version is much similar to SAC but it takes place in all the genes of the

chromosomes, meaning no certain point is determined as all genes are replaced by a balanced mean as shown above. Probability chosen: 10%

These three crossover operations possibly take place, but only one per chromosome pair. The order in which they occur is the order presented above and if one chromosome participates in one of them no other crossover will happen to it.

6.7 Mutation

Mutation is the random change of the value of one gene and it mainly contributes to solutions diversity and evolution. For each chromosome there is a certain possibility to be mutated. Three types of mutation are used at this work and are presented in the order they take place; if one of them occurs to a chromosome, it cannot participate in others.

1) Uniform Mutation (UM)

At uniform mutation a random gene of the chromosome is selected and its value is replaced randomly from the available range. Probability chosen: 10%

2) Boundary Mutation (BM)

As in UM but the randomly selected gene takes the maximum or minimum (toss-up) available value. The probability is much smaller: 3%

3) Non-Uniform Mutation (NUM)

This procedure's operation is not constant as generations are passing by, but it changes following the algorithms progress. The GA usually find difficult to detect the optimum at a small area, meaning local search. Fine local tuning is the capability to find the exact optimum and not just the area which contains it, so this is what NUM does. The gene that is going to be replaced does not take uniformly random value from the available range, but a random value from a much smaller are close to the current value in the available range. This area starts large enough at the early generations and shrinks as it approaches towards the end. So for **g** as the gene to be mutated, its new value **g'** is given by: $g' = \begin{Bmatrix} g + ro(\bar{g} - g) \\ g - ro(g - \underline{g}) \end{Bmatrix}$, where $ro = r\left(1 - \frac{n}{N}\right)^B$ and:

- **r** is a random number in [0,1]
- **n** is the number of current generation
- **N** is the number of maximum generations
- **B** is a constant in range [2,5] and chosen as 3,5.

The NUM probability chosen is 35%

6.8 Constraints Evaluation & Chromosome Repair

At initialization and after each genetic operation, the solutions may not fulfill the requirements they should. That happens because the genes are related complicatedly and it is possible a small change to one of them to lead to inappropriateness of the whole chromosome. We cannot predict this undesired event, but we can check the chromosomes and if unsuitability is found to "repair" them.

The main constraint that the upon investigation FCESS has to fulfill, is the steady and continual operation for one whole year at which it provides the guaranteed amount of energy the certain four hours a day for every day of the year. So, for the constraint fulfillment examination a simulation of the system is needed for one year. During this year if a single minor mismatch between the components happens, either for technical reasons (such as FC voltage out of DC-DC Converter's input range) or because little Hydrogen was stored, the system fails to fulfill the constraints. All these possible disturbances are modeled to signal *mismatch* as described in **Appendix B**.

So, to check if a chromosome is OK from the constraints point of view, a simulation has to be done; besides, that is the reason all this study on FCESS components operation and modeling is made. However, something that is very important to point out is the time-consuming property of this process; the simulation real time ranges from 2, 7 to 3, 3 seconds which is too much. A lot of effort was made for this time to be reduced, but not better improvement can be made because of the complexity of the models and some complicated processes as the retroactive operational point calculations of the Electrolyzer and FC.

To counterbalance this problem lots of code optimizations were made and two of them are the most important ; the *constraints evaluation & chromosome repair* takes place only in chromosomes with such a possible problem, that is, only chromosomes that have been mutated or have participated in

crossover go through this process. That is achieved simply by keeping the indexes of altered chromosomes and running the simulation only for those, as the others are just selected from the previous generation at which all of them were OK.

The other more complicated addition for time efficiency was the shrinking of the search space. The four genes of the chromosome (noEL, noTank, noFC and Pload) are related to each other; so, for a certain value of Pload the number of FC ranges in specific bounds, as:

✓ there is a minimum number at which the Fuel Cells operate at 100% and below that number there will not be feasible to provide the guaranteed power

✓ it is not profitable the FC to operate at very low power point (as it may be seen at **Fig. 4.3** below the 70% of power rated, the power-current relation is almost linear, that means standard efficiency below that point), because no significant efficiency gain is achieved. So a maximum limit for the FC number can be estimated below which the optimum number certainly is.

Same assumptions were made for the numbers of the Electrolyzers and Tanks too. These empirical limitations are a very rough estimation of the components relation; the accurate one is the simulation. It is a kind of pre-estimation of constraints evaluation and makes the optimization process much shorter as search space shrinks and fewer generations are needed for the convergence.

The chromosome repair is the second part of this procedure. If an inappropriate chromosome is found, it is not smart to be rejected and a new random one to replace it; the suitable thing is to repair it, that means change the parameters that way that it fulfills the constraints. In the FCESS case, the following policy is considered: if the mismatch is caused by technical problematic component's cooperation then other component's type combination is investigated (next iteration at the iterative process – **Fig. 6.1**). If mismatch is caused by failure to provide the constant amount of Power that means Hydrogen unavailability; for a specific power value, the FC number is surely enough to provide it as it belongs to the range previously discussed. However, for the Electrolyzers and Fuel Tank number there is not certainty that the system will always have Hydrogen stored. So, these numbers have to be increased; maybe one of them or both. For this to be determined, a rough estimation of the most possible “problematic” number of the two is made. That number is increased slightly and then the constraints evaluation takes place again. If again mismatch is acknowledged, the same steps are made iteratively till a suitable solution is determined.

6.9 GA Convergence

Theoretically, convergence is achieved when all the chromosomes are exactly the same. For this to be achieved it sometimes is a very time-consuming process; so usually the convergence criterion is the solutions to diverge slightly; this diverge-quantity is determined in proportion to the problem. In the FCESS case, the following policy is considered:

- the mean value of the Fitness Function of all the chromosomes is computed
- it is numerated how many of them diverge no more than 1% of the mean value from that mean value
- if half of the chromosomes are found to be close enough, then convergence is acknowledged.

It is worthy of notice that this technique is very accurate to determine the small area of the optimum; the diversity of the population is achieved via the previously described techniques, so it is an unlikely scenario that the mean value (which always is a number between the chromosome's fitness function values) is too close to the fitness function values but this area is not that of the global optimum solution. In such a scenario the population has converged in a local optimum and the reason is the diversity maintenance which obviously was not achieved. So, with that convergence criterion a small area where there is optimum solution is defined surely.

However, since absolute convergence was not chosen, the best chromosome of this population may differ slightly to the global optimum; this is affected by the diverge percentage (1% chosen) , as the smaller it is the more unlikely is this scenario to happen. This number was chosen to be small enough so global optimum is found (or a solution very close to it) and high enough to avoid more calculation time; at significantly most cases when convergence is acknowledged, the optimum solution is one member of the population indeed and it is found as the best of the current population; this way the values swing is avoided till all of the chromosomes are identically the same and lot of time is saved (the diversity maintenance should always be considered – it is an obstacle at the convergence part of the algorithm).

To confirm that the algorithm will have an end, as theoretically it may never converge, a time limit is considered; this is a maximum number of generations assumed as 10,000. After that limit, the procedure will certainly end and the best solution will be assumed as the global optimum. This happens for obvious reasons.

7. ECONOMIC ANALYSIS

The optimization procedure that takes place, aims to determine the economically optimum configuration of the FCESS based on real economic elements. This economic appropriateness of a certain FCESS is calculated computing the total expenses and incomings for a number of years; this process is based on popular economic methods of viability estimation. So, this economic analysis takes place for the fitness function to be evaluated for each chromosome at each generation, but the economic viability is examined only for the optimum solution found. This analysis uses a number of economic parameters described below, but taxation has not been considered since these expenses depend on the investor tax rate, the State taxing system and the Renewable Energy promotion policies which vary significant worldwide.

7.1 Fitness Function

The fitness function returns a value that determines the chromosome appropriateness and depends on the total money spent and money earned for a certain number of years. So, first the Objective Function is defined:

$$objFunc(noEL, noTank, noFC, Pload) = I_n - IC_n - SC_n - EP_n \text{, where:}$$

- **objFunc** is the objective function
- **noEL** is the number of Electrolyzers units
- **noTank** is the number of Fuel Tank units
- **noFC** is the number of Fuel Cells Arrays units
- **Pload** is the standard power exported to the grid from 11:00 to 15:00 daily
- $\mathbf{I_n}$ is the total Incomings from the investment for **n** years
- $\mathbf{IC_n}$ is the Initial Cost invented for the overall system purchase
- $\mathbf{SC_n}$ is the Service Cost and Replacement Cost of the components for **n** years
- $\mathbf{EP_n}$ is the Energy Purchased cost for **n** years; for the autonomous case equals to zero

With the above definition the problem is a maximization one, so the only constraint is the Fitness Function to take non-negative values. Therefore:

$fitFunc(noEL, noTank, noFC, Pload) = objFunc(noEL, noTank, noFC, Pload) + C_{max}$, where:

- **fitFunc** is the Fitness Function
- $\mathbf{C_{max}}$ is a constant always greater than the Objective Function values
$(C_{max} > ObjFunc, \forall noEL, noTank, noFc, Pload)$

Theoretically C_{max} equals to the absolute of the minimum value of the objFunc for all input combinations. However this calculation is not an obvious one but a complex process which also depends on the component's type and to a lot of other conditions; so an alternative way is found, that is C_{max} calculation is made at each generation and is the absolute of the minimum objFunc of the current population chromosomes. Besides, the fitFunc is needed for convergence criterion and selection process and its aim is to compare the chromosomes of the current generation between each other, therefore this relevant fitFunc determinations is a very satisfying option.

7.1.2 Initial Cost

As referred on [5], the the total investment capital cost for equipment purchase is based on the initial expenses, the State subsidization and the discount rate:

$$IC_n = (1 - subsid) \cdot IC_0 \cdot (1 + i)^n$$, where:

- **subsid** is the subsidization ratio
- **i** is the the discount rate which increases the initial cost as years passing buy; here assumed 8 %
- **n** is the investment operation horizon
- $\mathbf{IC_0}$ is the Initial Cost of the purchase at the time of the investment and is given by:

$$IC_0 = noEL \cdot C_{EL} + noTank \cdot C_{Tank} + noFC \cdot C_{FC} + noConv \cdot C_{Conv} + noInv \cdot C_{Inv}$$, where:

- $\mathbf{C_k}$ is the cost of the k component

These initial costs for **medium scale system** roughly range:

✓ *Alkaline Electrolyzer with pressure output* > 2,000 € / kW

✓ *Pressure Fuel Tank* > 600 € / 100 SL of Hydrogen

✓ *Fuel Cell Array* > 6,000 € / kW at most cases

✓ *Inverter* > 25 € / kW

✓ *DC-DC Converter* > 200 € / kW

7.1.3 Service Cost

The service cost is defined as the maintenance, replacement and repair costs of the components. For FC arrays, Electrolyzers and Fuel Tank no actual maintenance is needed except occasional supervision so only replacement cost is considered. For PE, lifetime is assumed as the guaranteed years of operation by the manufacturer; so in that case no maintenance costs are considered. also So, for the replacement costs:

$$SC_n = scEL_n + scTank_n + scFC_n + scConv_n + scInv_n \text{ , where:}$$

- $scEL_n = noEL \cdot C_{EL} \cdot \sum_{k=1}^{\left[\frac{n-1}{life}\right]} \frac{(1+infl)^{k \cdot life}}{(1+i)^{k \cdot life}} \cdot (1+i)^n$
- $scTank_n = 0$ (life > 30 years)
- $scFC_n = noFC \cdot C_{FC} \cdot \sum_{k=1}^{\left[\frac{n-1}{life}\right]} \frac{(1+infl)^{k \cdot life}}{(1+i)^{k \cdot life}} \cdot (1+i)^n$
- $scConv_n = noConv \cdot C_{Conv} \cdot \sum_{k=1}^{\left[\frac{n-1}{life}\right]} \frac{(1+infl)^{k \cdot life}}{(1+i)^{k \cdot life}} \cdot (1+i)^n$
- $scInv_n = noInv \cdot C_{Inv} \cdot \sum_{k=1}^{\left[\frac{n-1}{life}\right]} \frac{(1+infl)^{k \cdot life}}{(1+i)^{k \cdot life}} \cdot (1+i)^n$, where:

➢ **infl** is the inflation ratio assumed as 3 %

➢ **life** is the component life in years; it is determined by operation hours and manufactures statements

7.1.4 Incomings

The Incomings come up from the energy sales. This energy is the power exported for 4 hours a day, 365 days a year and for **n** years and is given by [5]:

$$I_n = I_0 \cdot (1+ovrprc) \cdot (1+i)^n \frac{1-\left(\frac{1+ovrprc}{1+i}\right)^n}{i-ovrprc} \text{ and } I_0 = 365 \cdot 4 \cdot Pload \cdot sprice \text{, where:}$$

- **I_0** are the incomings for the first year
- **ovrprc** is the energy overprice ratio assumed as 2 %
- **sprice** is the price the kWh sold

7.1.5 Energy Purchase

For the interconnected case energy is purchased from the grid at low demand hours (i.e. 00:00 to 08:00) sometimes when the tank is not full and there is not rejected energy available. This purchase contributes to increased reliability to the system as that way it will be more sustainable to no-rejected-energy periods. So the total cost of imported energy from the electric grid is given by:

$$EP_n = EP_0 \cdot (1+ovrprc) \cdot (1+i)^n \frac{1-\left(\frac{1+ovrprc}{1+i}\right)^n}{i-ovrprc} \text{ and } EP_0 = pEnergy \cdot pprice \text{, where:}$$

- **EP_0** is the purchased energy cost the first year
- **pEnergy** is the total energy purchased for one year; for autonomous system is zero
- **pprice** is the purchase price

7.2 Economic Viability

The economic viability of the FCESS is estimated only for the optimum solutions as those are the focus. It is based to two popular modern ways, the *Discounted Payback Period* (DPP) and the *Internal Rate of Return* (IRR).

The DPP is defined as the time **n** in years that sets the system Net Present Value (NPV) to zero [5]:

$$NPV = objFunc \frac{(noEL, noTank, noFC, Pload)}{(1+i)^n} = 0$$

That is, the discounted rate **i** is assumed 8 % as normal and the number of years that the objFunc

nullifies is considered as the DPP. This value must be lower than the investment horizon for the economic viability to be acknowledged.

The IRR is defined as the discounted rate value that sets the NPV to zero [5]:

$$NPV = objFunc\frac{(noEL, noTank, noFC, Pload)}{(1+i)^n} = 0$$

That is, the investment horizon **n** is standard as normal but the value of **i** that NPV nullifies is considered as the Internal Rate of Return. A system is estimated as economic viable if IRR is more than 6% for 7 years of investment horizon, 12% for 15 and 16% for 30 years.

8. RESULTS & DISCUSSION

8.1 The parameterization of the optimization procedure

At this study the case of Crete's autonomous-isolated electric grid is investigated; according to data provided by the Greek Public Power Corporation the technical minimum of electric network thermal power stations is 151 MW, while at Spring 2008 the minimum load power demand was 175 MW. The rejected energy is derived from three wind parks of 25 MW rated power and with a total of 9774 MWh rejected energy during 2005 [5]. So, the optimization procedure considers FCESS with Pload in range [100 kW, 25 MW] with a step of 10 kW.

The number of chromosomes that take place are 30 so diversity is maintained through generations and each chromosome has the form [noEL,noTank,noFC,Pload] as described in **6.3**.

For the solution appropriateness estimation and economic viability determination the below local market conditions are considered:

✔Discount Rate: i = 8%

✔Inflation Rate: inf = 3%

✔Electricity annual price escalation rate: ovrprc = 2%

✔IRR minimum: 6% for 7 years, 12% for 15 years and 15% for 30 years

Four condition parameters play significant role at this process; the number of investment horizon years **n** , the selling price **sprice**, the state subsidization ratio **subsid** and the rate of sold over purchased energy price **sale_buy_ratio**. The investment horizon **n** is investigated for 7, 15 and 30 years because the FC have expected lifetime of 7-8 or 15 years proportionally to the model, the electrolyzers have life time of 50.000 hours which is more than 15 years for most cases and Fuel Tanks expected life time overcomes the 30 years. The current selling price is 0,13 € / kWh and subsidization 0% as no relevant assistance programs are running at the time. The **sale_buy_ratio** is considered as 10%.

8.2 Results

The results of the optimization procedure and economic analysis confirm the first estimations for non economic viability even in most favorable conditions; this is mainly due to very expensive components costs (Electrolyzer,Fuel Cells and Fuel Tanks) and the low overall efficiency ≈ 30-45%. At this chapter various economic scenarios are studied and results are extracted for the **interconnected** FCESS and it is shown that the market is not economically mature enough for such a system to be economic viable. For the autonomous system the results are far worse, as there is not an option of energy purchase at periods with not rejected energy available, so there is no need of reference.

8.2.1 Real market conditions – 7 years

Real market conditions assumed: **sprice = 0.13 € / kWh , subsidization = 0%** and **sale_buy_ratio = 0,1.** A very rough approximation of the objective function landscape is shown at **Fig. 8.1**:

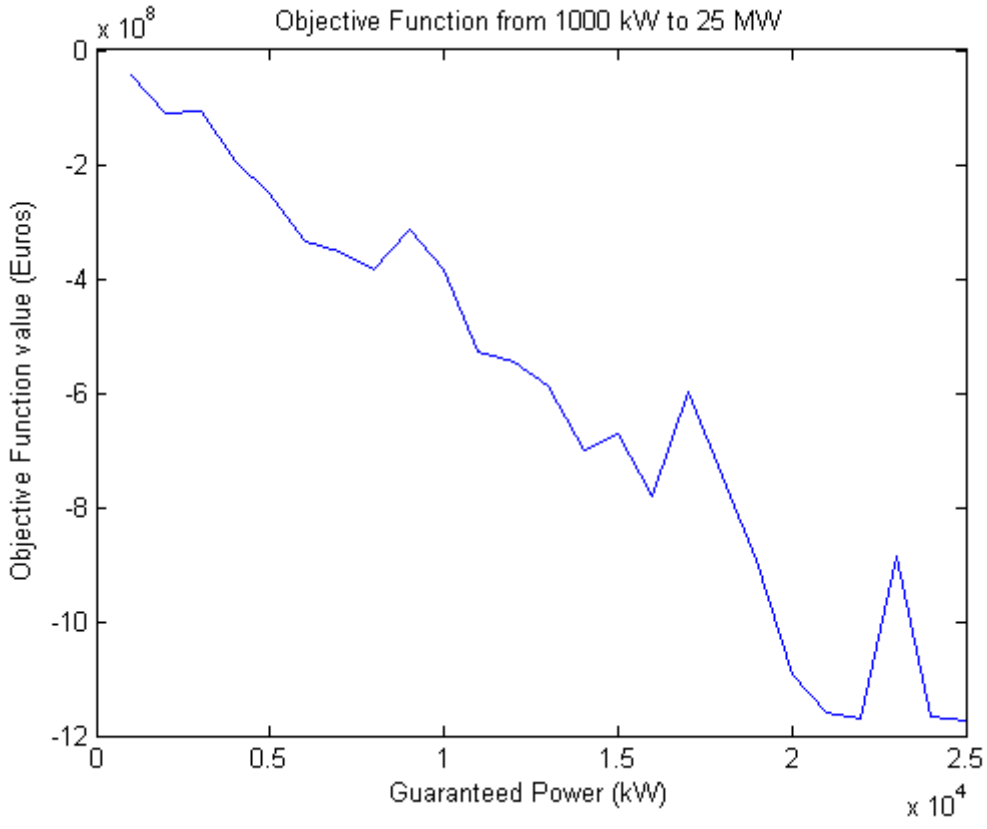


Fig. 8.1: Objective Function landscape for real market conditions and 7 years

As it may be seen, for bigger scale systems the losses are significant more at the grade of hundreds of millions Euros. So, the optimum solution acknowledged via the G.A. is the one with the minimum power value; specifically:

✔1 unit of Electrolyzer (HySTAT 60)

✔382 units of Fuel Tanks (900 SL)

✔11 units of Fuel Cell Arrays (HyPM HD12)

✔141 units of DC-DC Converters (SD-1000L-24)

✔200 units of Inverters (CAU600W-24)

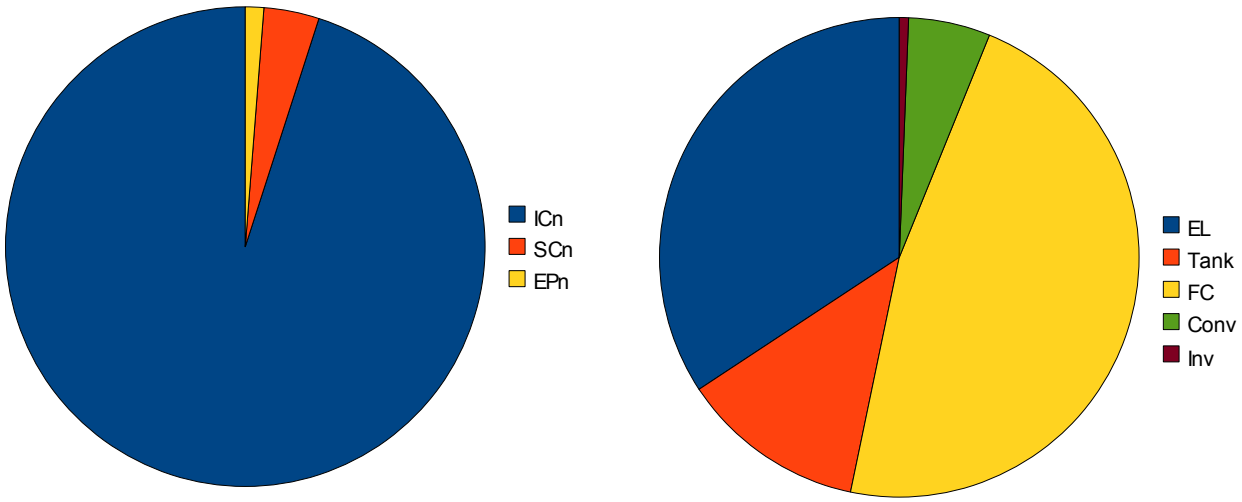
✔100 kW delivered to the grid

Economic Analysis:

➢Total Expenses: 3 037 903 Euros.

➢Total Incomings: 182 348 Euros, which is 6.00 % of total expenses

➢Economic Benefit: - 2 855 555 Euros



Distribution of total expenses *Distribution of Initial & Service Costs*

Fig. 8.2: Distribution of expenses at real market conditions and for 7 years

Technical Analysis:

✔Consumed totally 476.962 MWh and produced 146,000 MWh of Energy - **30.61 % overall efficiency**

✔Purchased totally 303.840 MWh of Energy from Local Network - **63.70 % of total energy consumed**

✔Utilized 173.122 MWh of total 9774 MWh Rejected Energy of Wind Park - **1.7711 % utilization**

✔Power Electronics efficiency of EL: 89.10 %

✔EL efficiency: 90.77 %

✔FC efficiency: 48.71 %

✔Power Electronics efficiency of FC: 77.53 %

✔**The overall system efficiency is: 30.61 %!**

8.2.2 Real market conditions – 15 years

The same market conditions, but with investment horizon of 15 years:

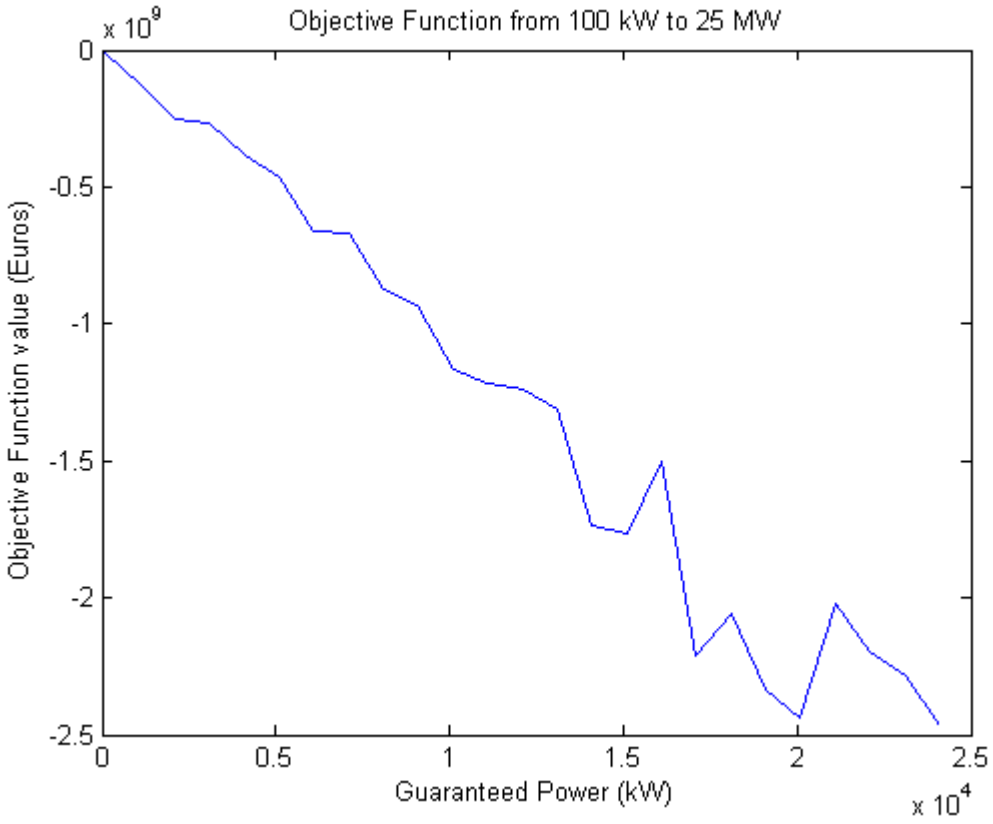


Fig. 8.3: Objective Function landscape for real market conditions and 15 years

As it may be seen, the FCESS is not profitable at all and the bigger it is the greater the losses are. So, the optimal solution decided from the optimization is the one with the minimum expenses:

✔1 unit of Electrolyzer (HySTAT 60)

✔381 units of Fuel Tanks (900 SL)

✔68 units of Fuel Cell Arrays (s2000)

✔141 units of DC-DC Converters (SD-1000L-24)

✔200 units of Inverters (CAU600W-24)

✔100 kW delivered to the grid

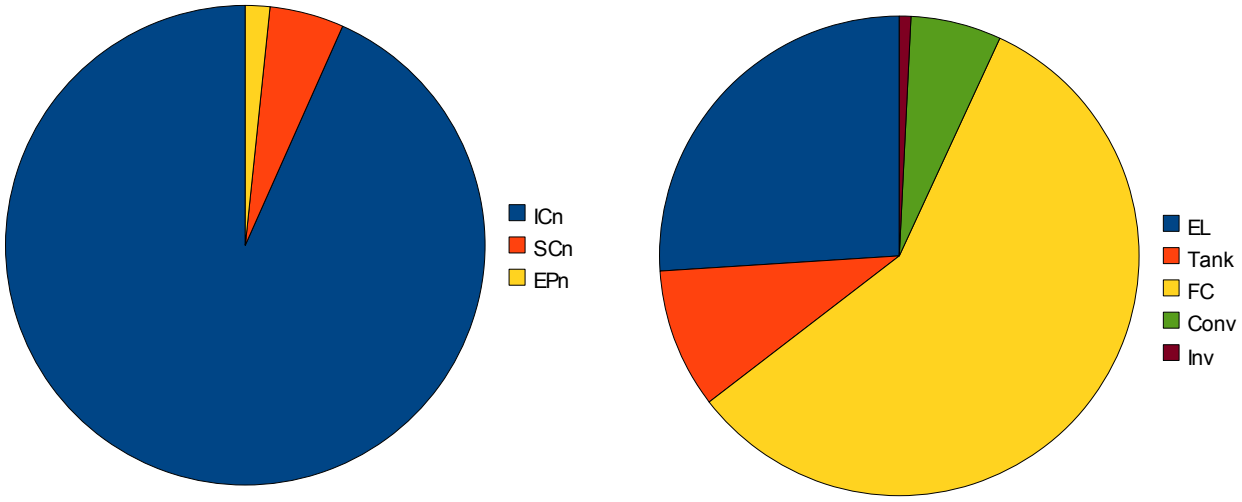
The above solution is very similar to the one of 7 years except the FC unit; at this case it is selected a model with more expected lifetime that is more profitable.

Economic Analysis:

➢Total Expenses: 7 441 532 Euros.

➢Total Incomings: 589 274 Euros, which is 7.92 % of total expenses

➢Economic Benefit: - 6 852 258 Euros



Distribution of total expenses *Distribution of Initial & Service Costs*

Fig. 8.4: Distribution of expenses at real market conditions and for 15 years

Technical Analysis:

✔Consumed totally 475.684 MWh and produced 146,000 MWh of Energy - **30.69 % overall efficiency**

✔Purchased totally 304.416 MWh of Energy from Local Network – **64.00 % of total energy consumed**

✔Utilized 171.268 MWh of total 9774 MWh Rejected Energy of Wind Park - **1.7521 % utilization**

✔Power Electronics efficiency of EL: 89.10 %

✔EL efficiency: 90.77 %

✔FC efficiency: 48.84 %

✔Power Electronics efficiency of FC: 77.53 %

✔**The overall system efficiency is: 30.69 %!**

8.2.3 Real market conditions – 30 years

As shown above the current market conditions do not allow for a FCESS to be economically profitable; this is true also for 30 years investment horizon:

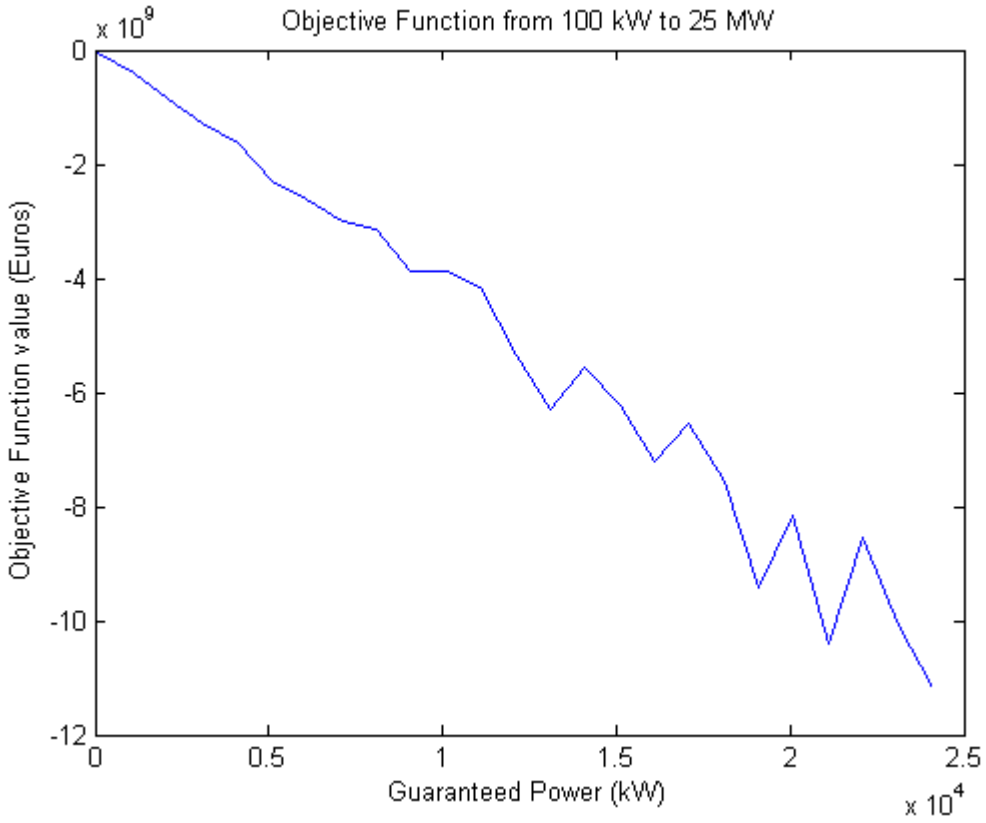


Fig. 8.5: Objective Function landscape for real market conditions and 30 years

The same conclusions can be made for this case too. The fewer losses offer a small system:

✔1 units of Electrolyzer (HySTAT 60)

✔381 units of Fuel Tanks (900 SL)

✔68 units of Fuel Cell Arrays (s2000)

✔141 units of DC-DC Converters (SD-1000L-24)

✔200 units of Inverters (CAU600W-24)

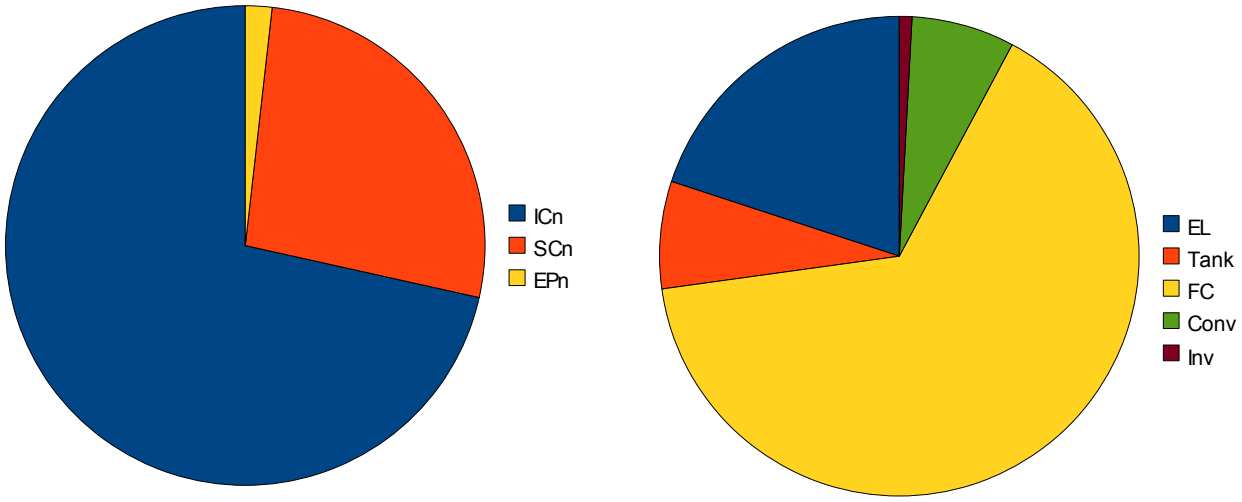
✔100 kW delivered to the grid

Economic Analysis:

➢Total Expenses: 30 807 522 Euros.

➢Total Incomings: 2 662 363 Euros, which is 8.64 % of total expenses

➢Economic Benefit: - 28 145 159 Euros



Distribution of total expenses *Distribution of Initial & Service Costs*

Fig. 8.6: Distribution of expenses at real market conditions and for 30 years

It is worth of notice that the FC cost at this case prevails among the others. That is because the model with the longest life time is chosen which is approximately to 15 years, so there is a need of FC replacement at the middle of the investment horizon and thus the Service Cost – SC is significantly increased.

Technical Analysis:

✔Consumed totally 475.684 MWh and produced 146,000 MWh of Energy - **30.69 % overall efficiency**

✔Purchased totally 304.416 MWh of Energy from Local Network – **64.00 % of total energy consumed**

✔Utilized 171.268 MWh of total 9774 MWh Rejected Energy of Wind Park - **1.7521 % utilization**

✔Power Electronics efficiency of EL: 89.10 %

✔EL efficiency: 90.77 %

✔FC efficiency: 48.84 %

✔Power Electronics efficiency of FC: 77.53 %

✔**The overall system efficiency is: 30.69 %!**

8.2.4 Subsidization 100% – 7 years

Lots of different subsidization scenarios were investigated, but even in the case of 99% NO economic viability was achieved for **sprice=0,13 €/kWh** and **rc=0.1**. So, assuming 100% subsidization of the initial cost:

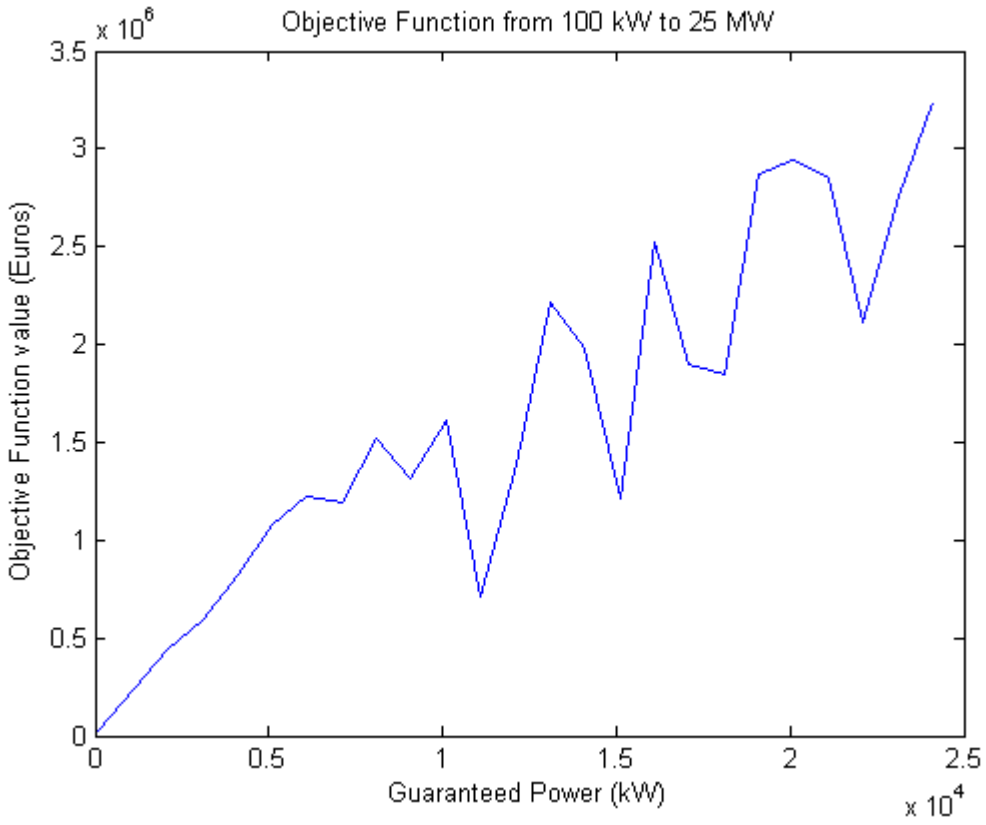


Fig. 8.7: Objective Function landscape for 100% subsidization and 7 years

A very rough approximation of the objective function landscape is depicted above; as it seems positive Net Present Value is achieved. At this case the optimum solution is obvious again but this time it corresponds to maximum Power delivered:

✔155 units of Electrolyzer (HySTAT 60)

✔469 014 units of Fuel Tanks (900 SL)

✔18 452 units of Fuel Cell Arrays (HyPM HD12)

✔35 098 units of DC-DC Converters (SD-1000L-24)

✔50 000 units of Inverters (CAU600W-24)

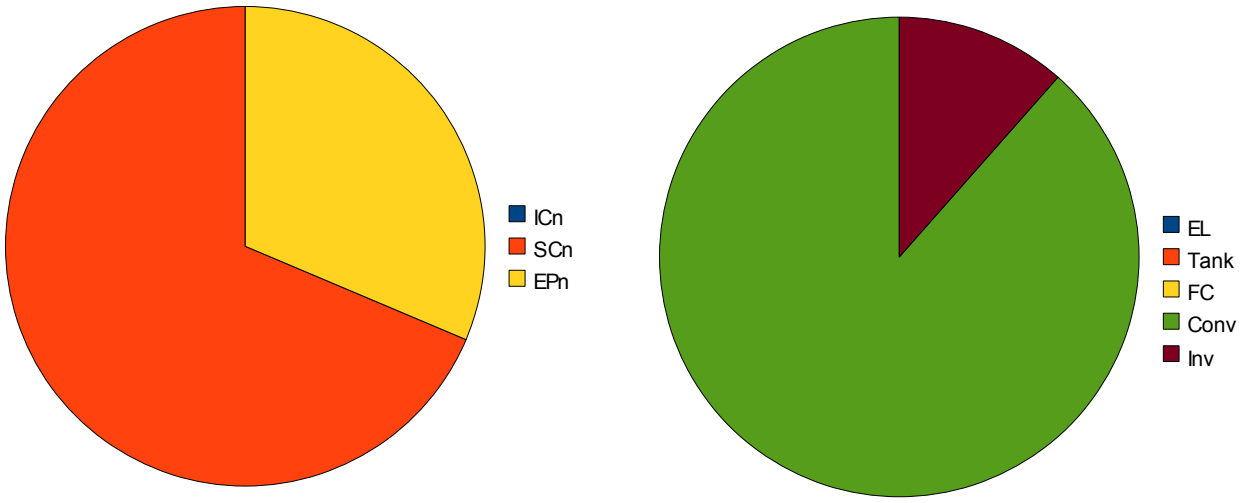
✔25 MW delivered to the grid

Economic Analysis:

➢Total Expenses: 41 165 252 Euros.

➢Total Incomings: 45 586 905 Euros, which is 110.74 % of total expenses

➢Economic Benefit: 4 421 653 Euros



Distribution of total expenses *Distribution of Initial & Service Costs*

Fig. 8.8: Distribution of expenses at real 100% subsidization and for 7 years

It is important to notice that the Initial Cost is zero as it is subsidized completely, and the Service Cost is free of Electrolyzer/Tank/FC as their lifetime is longest than 7 years. So, the only expenses are the energy purchase and the PE replacement. This solution is economically viable with DPP = 0 years and IRR = ∞ ; the incomings are always more than expenses from the first year, so the IRR is theoretically infinite.

Technical Analysis:

✔Consumed totally 84 441.05 MWh and produced 36 500 MWh of Energy - **43.23 % overall efficiency**

✔Purchased totally 75 530.88 MWh of Energy from Local Network – **89.45 % of total energy consumed**

✔Utilized 8 910.17 MWh of total 9774 MWh Rejected Energy of Wind Park - **91.1531 % utilization**

✔Power Electronics efficiency of EL: 88.56 %

✔EL efficiency: 91.37 %

✔FC efficiency: 68.70 %

✔Power Electronics efficiency of FC: 77.53 %

✔**The overall system efficiency is: 43.23 %!**

As it may be seen, a very satisfying penetration of rejected energy from wind parks is achieved ≈ 91%; on the other hand far more energy had to be purchased from the network as there was not enough to charge this ESS. Also, at this perfectly matched solution a very good overall efficiency is accomplished above 43%.

8.2.5 Subsidization 100% – 15 years

The same scenario of completely subsidization of the initial costs for 15 years of investment horizon is considered as lower percentages (even 99%) showed non-economic viability. The landscape of the NPV is shown below:

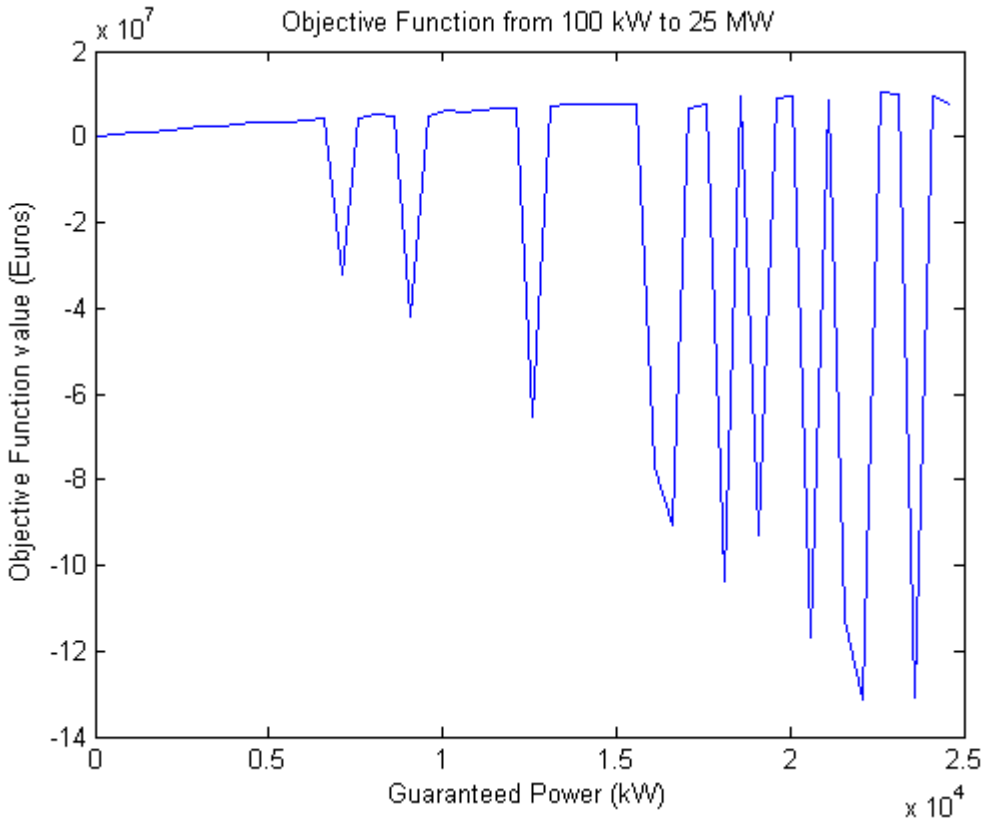


Fig. 8.9: Objective Function landscape for 100% subsidization and 15 years

The strange thing at this graph is an ascending line with deep spikes; this happens because this rough simulation considers semi-random solutions for each Pload. Specifically, the Electrolyzer components is the reason of this spikes; the expected lifetime is about to 50 000 hours, so this varies

significantly depending on the operation. If few Electrolyzers are chosen, they have to operate for more and they will malfunction sooner.

Despite the above observation, the optimum solution found is:

✔179 units of Electrolyzer (HySTAT 60)

✔271 814 units of Fuel Tanks (900 SL)

✔18 452 units of Fuel Cell Arrays (s2000)

✔35 098 units of DC-DC Converters (SD-1000L-24)

✔50 000 units of Inverters (CAU600W-24)

✔25 MW delivered to the grid

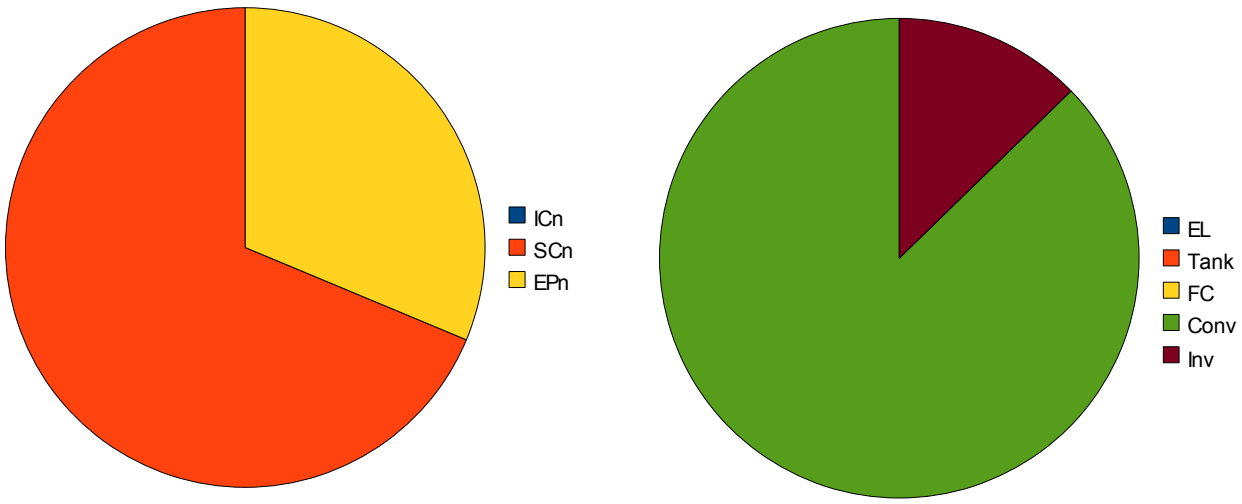
It may be noticed that compared to the 7-years solution, this one has more electrolyzers and fewer reservoirs; the reason is the previously discussed: that way the electrolyzer system operates for 15 years exactly and then malfunctions, and since Hydrogen is produced at higher rates there is no need for so large storage volume.

Economic Analysis:

➢Total Expenses: 135 189 785 Euros.

➢Total Incomings: 147 318 552 Euros, which is 108.97 % of total expenses

➢Economic Benefit: 12 128 767 Euros



Distribution of total expenses *Distribution of Initial & Service Costs*

Fig. 8.10: Distribution of expenses at real 100% subsidization and for 15 years

The same notices with the 7 years solution can be made: no expensive component replacement and economic viability accomplished with DPP = 0 years and IRR = ∞.

Technical Analysis:

✔Consumed totally 113 916.796 MWh and produced 36 500 MWh of Energy - **32.04 % overall efficiency**

✔Purchased totally 104 805.216 MWh of Energy from Local Network – **92.00 % of total energy consumed**

✔Utilized 9 111.58 MWh of total 9774 MWh Rejected Energy of Wind Park - **93.2136 % utilization**

✔Power Electronics efficiency of EL: 88.61 %

✔EL efficiency: 91.20 %

✔FC efficiency: 50.97 %

✔Power Electronics efficiency of FC: 77.53 %

✔**The overall system efficiency is: 32.04 %!**

8.2.6 Subsidization 100% – 30 years

At this case the scenario is much more different compared to 7 and 15 years. As shown below, the FCESS for 30 years investment horizon has always losses due to replacements costs:

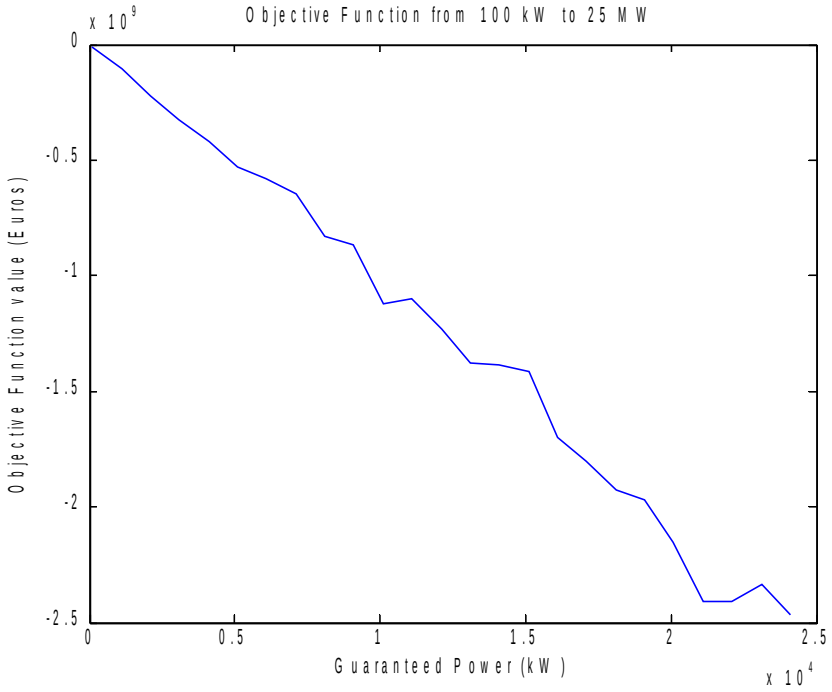


Fig. 8.11: Objective Function landscape for 100% subsidization and 30 years

So, the optimum solution is the cheapest one with the lesser losses:

✔1 units of Electrolyzer (HySTAT 60)

✔381 units of Fuel Tanks (900 SL)

✔68 units of Fuel Cell Arrays (s2000)

✔141 units of DC-DC Converters (SD-1000L-24)

✔200 units of Inverters (CAU600W-24)

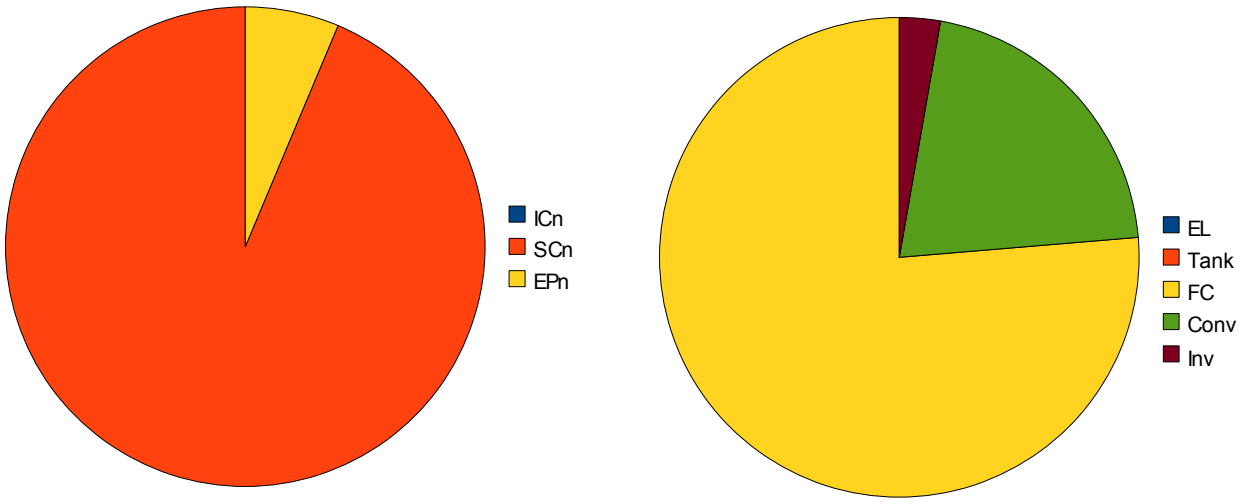
✔100 kW delivered to the grid

Economic Analysis:

➢Total Expenses: 8 774 570 Euros.

➢Total Incomings: 2 662 363 Euros, which is 30.34 % of total expenses

➢Economic Benefit: - 6 112 207 Euros



Distribution of total expenses *Distribution of Initial & Service Costs*

Fig. 8.12: Distribution of expenses for 100% subsidization and for 30 years

No Initial Costs at all and no replacement costs for Electrolyzer/Tank are the main characteristics of the above figures. The limited lifetime of the FC (approximately to 15 years for s2000 model) is the reason that this solution is not economically viable.

Technical Analysis:

✔Consumed totally 475.684 MWh and produced 146,000 MWh of Energy - **30.69 % overall**

efficiency

✔Purchased totally 304.416 MWh of Energy from Local Network – **64.00 % of total energy consumed**

✔Utilized 171.268 MWh of total 9774 MWh Rejected Energy of Wind Park - **1.7521 % utilization**

✔Power Electronics efficiency of EL: 89.10 %

✔EL efficiency: 90.77 %

✔FC efficiency: 48.84 %

✔Power Electronics efficiency of FC: 77.53 %

✔**The overall system efficiency is: 30.69 %!**

8.2.7 High selling price = 3,40 €/kWh – 7 years

At no subsidization case, a very high selling price **sprice** is assumed so the NPV is positive. For **n=7** years, there was found a solution with positive objective function and payback period lesser than the investment horizon at the 3.4 €/kWh:

✔37 units of Electrolyzer (HySTAT 60)

✔66 580 units of Fuel Tanks (900 SL)

✔827 units of Fuel Cell Arrays (HyPM XD12)

✔9 828 units of DC-DC Converters (SD-1000L-24)

✔14 000 units of Inverters (CAU600W-24)

✔7 000 kW delivered to the grid

Economic Analysis:

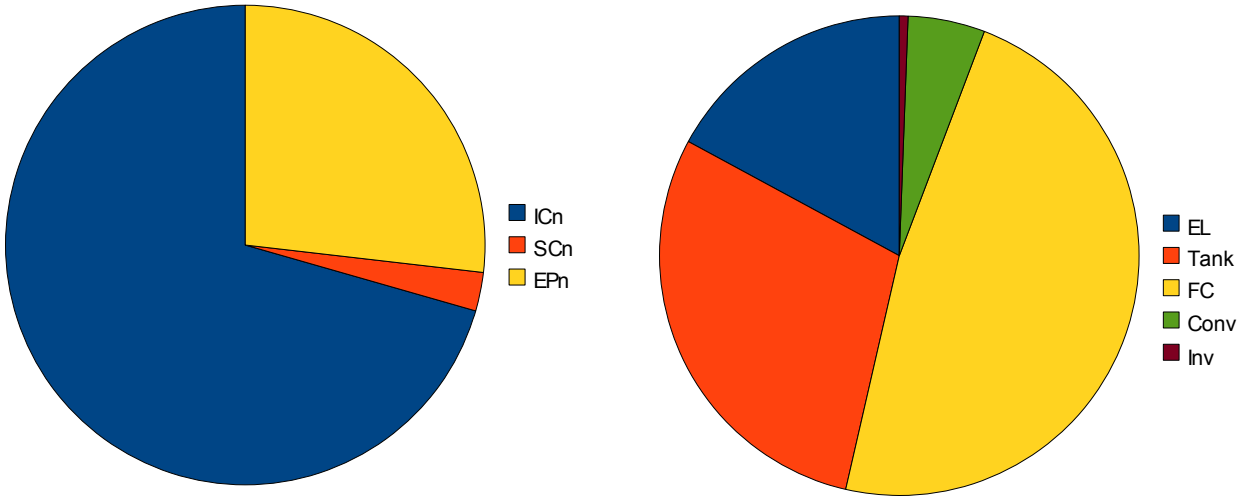
➢Total Expenses: 303 847 528 Euros.

➢Total Incomings: 333 836 414 Euros, which is 109.87 % of total expenses

➢Economic Benefit: - 29 988 886 Euros

At **Fig. 8.13** the distribution of expenses is depicted. It is worth noticing that at these conditions, the Energy Purchase cost is not negligible at all; that happens because of the high selling price and the standard **sale_buy_ratio=0,1** assumed. The DPP equals to 5,89 years < 7 years and IRR equals to 11,86% < 12% . As pointed at economic analysis chapter, for an economic viability

acknowledgment both NPV > 0 and DPP < 7 and IRR > 6%, so this is an economic viable solution .



Distribution of total expenses *Distribution of Initial & Service Costs*

Fig. 8.13: Distribution of expenses for sprice=3,4 €/kWh and for 7 years

Technical Analysis:

✔Consumed totally 31 997.342 MWh and produced 10 220.000 MWh of Energy - **31.94 % overall efficiency**

✔Purchased totally 24 956.352 MWh of Energy from Local Network – **78.00 % of total energy consumed**

✔Utilized 7 040.990 MWh of total 9 774 MWh Rejected Energy of Wind Park - **72.0310 % utilization**

✔Power Electronics efficiency of EL: 88.94 %

✔EL efficiency: 91.16 %

✔FC efficiency: 50.62 %

✔Power Electronics efficiency of FC: 77.53 %

✔**The overall system efficiency is: 31.94 %!**

8.2.8 High selling price = 2,65 €/kWh – 15 years

For 15 years investment horizon and **sprice= 2,65 €/kWh:**

✔43 units of Electrolyzer (HySTAT 60)

✔82 638 units of Fuel Tanks (900 SL)

✔6 147 units of Fuel Cell Arrays (s2000)

✔11 232 units of DC-DC Converters (SD-1000L-24)

✔16 000 units of Inverters (CAU600W-24)

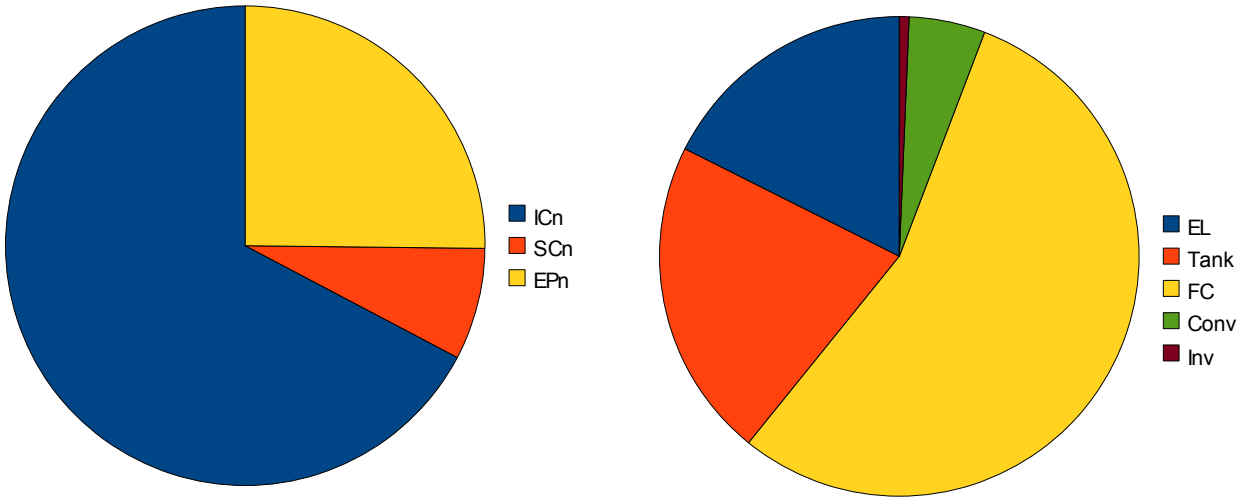
✔8 000 kW delivered to the grid

Economic Analysis:

➢Total Expenses: 926 809 890 Euros.

➢Total Incomings: 960 970 247 Euros, which is 103.69 % of total expenses

➢Economic Benefit: 34 160 358 Euros



Distribution of total expenses *Distribution of Initial & Service Costs*

Fig. 8.14: Distribution of expenses for sprice= 2,65 €/kWh and for 15 years

As expected Service/Replacement Cost is not a major factor as no replacement is needed for the main and expensive components for 15 years. The estimated DPP: 12.65 years < 15 years and IRR: 8.80 % < 12 %; thus it is not economically viable solution.

Technical Analysis:

✔Consumed totally 35 695.216 MWh and produced 11 680.000 MWh of Energy - **32.72 % overall efficiency**

✔Purchased totally 28 359.360 MWh of Energy from Local Network – **79.45 % of total energy consumed**

✔Utilized 7 335.856 MWh of total 9 774 MWh Rejected Energy of Wind Park - **75.0475 %**

utilization

✔Power Electronics efficiency of EL: 88.92 %

✔EL efficiency: 91.21 %

✔FC efficiency: 51.85 %

✔Power Electronics efficiency of FC: 77.53 %

✔**The overall system efficiency is: 32.72 %**

8.2.9 High selling price = 2,47 €/kWh – 30 years

For 30 years investment horizon and **sprice= 2,47 €/kWh:**

✔36 units of Electrolyzer (HySTAT 60)

✔79 176 units of Fuel Tanks (900 SL)

✔5 167 units of Fuel Cell Arrays (s2000)

✔9 828 units of DC-DC Converters (SD-1000L-24)

✔14 000 units of Inverters (CAU600W-24)

✔7 000 kW delivered to the grid

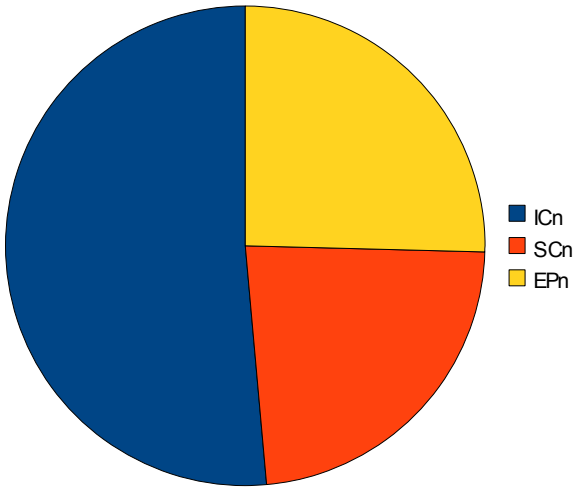
At **Fig. 8.15** the distribution of expenses is shown:

Economic Analysis:

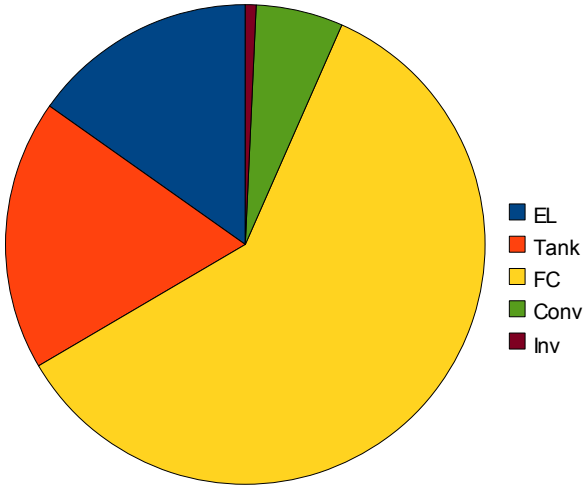
➢Total Expenses: 3 342 079 926 Euros.

➢Total Incomings: 3 540 942 714 Euros, which is 105.95 % of total expenses

➢Economic Benefit: 198 862 788 Euros



Distribution of total expenses



Distribution of Initial & Service Costs

Fig. 8.15: Distribution of expenses for sprice= 2,47 €/kWh and for 30 years

The DPP estimated: 13,9 years < 30 years but IRR: 9.03% < 15%, so this is not an economic viable solution.

Technical Analysis:

✔Consumed totally 31 778.796 MWh and produced 10 220.000 MWh of Energy - **32.16 % overall efficiency**

✔Purchased totally 24 509.952 MWh of Energy from Local Network – **77.13 % of total energy consumed**

✔Utilized 7 268.844 MWh of total 9 774 MWh Rejected Energy of Wind Park - **74.3620 % utilization**

✔Power Electronics efficiency of EL: 88.94 %

✔EL efficiency: 91.17 %

✔FC efficiency: 50.97 %

✔Power Electronics efficiency of FC: 77.53 %

✔**The overall system efficiency is: 32.16 %**

8.3 Conclusions & Discussion

The main disadvantage of renewable energy sources is the stochastic energy production and the

significant variation on the energy output delivered to the electric grid; that leads to mismatches between production and demand which means rejected energy. A very effective way to increase the energy penetration to the grid is via an Energy Storage System.

At this study, the case of the autonomous electric grid of Crete is investigated and specifically the case of three wind parks of 25 MW total power rated; the ESS used to utilize the rejected energy uses Hydrogen as energy carrier. Among other Energy Storage Systems, the FCESS combines compact size, reallocation flexibility (such as batteries) and exact adjustment to the very specific needs of the studied case (such as pumped hydro storage). It has no emissions and all of its materials are recyclable, so it is an environmental friendly way of store energy.

The individual components of the FCESS are studied carefully, modeled and a one year simulation is made for operation estimation. Then, an optimization process takes place and the economically optimum combination of component types and quantities is calculated. For different scenarios, the economic viability is estimated and it is determined if it is in one's interest.

At previous parts of this chapter, it is shown that the FCESS is not economically viable solution at current real market conditions. There are two main reasons that cause that: the very high prices of the individual components and the low overall efficiency of the system. The prices as described at **7.1.2** lead to overall cost above 20 000 €/kW which is tremendously high for economic viability to be achieved.

A lot of effort is being made nowadays to that direction though; cheapest Fuel Cells may be achieved if the required catalyst (precious noble metals) quantity is reduced or is replaced with other common and inexpensive materials. Also, the FC efficiency can be increased via various methods of creating those certain areas where the reactions take place. In addition, the operation of the fuel cell could be optimized; the losses control would contribute to higher efficiency, but at an ideal scenario at which an almost constant value of voltage is produced. there would be no need of the DC-DC Converter component (increased overall efficiency and decreased costs).

For the Electrolyzer component, a lot of research is being made also for different types other than the traditional Alkaline one. The PEM Electrolyzers have introduced themselves at the market lately with lots of promising characteristics. As far as the alkaline electrolyzer is concerned, the mono-polar technology leads to cheapest prices but Hydrogen produced is unpressurized. So, in

combination with an other way of Hydrogen storage, such as in liquid form or in metal hydrides, maybe a different solution with some advantages is achieved.

Moreover, a very interesting prospect is the reversible operation of a single unit which will be used both as an electrolyzer and a fuel cell. Researches to this way have not returned remarkable results yet, as such created components have low efficiency for both Hydrogen production and consumption processes and no long life time period.

In either case, experience on the components manufacture ,which is added nowadays rapidly, may lead to better products, more reliable and resistant with longer life time periods. On the other hand, some approaches consider the FCESS as an Hydrogen production center too; that is, Hydrogen is produced via the Electrolyzers and then it is either stored at the tank or sold mainly for mobile usage. Such an approach may prove itself profitable especially at the future when Hydrogen will be used at mobile applications.

Finally, the state's role is very important for favorable conditions formation; generous subsidizations and high selling prices would boost significantly such efforts. It is worth of notice that the energy produced from an FCESS is of excellent quality; the storage and retrieve are environmentally friendly procedures and the constant-guaranteed amount of power delivered at peak load demand hours is of significant importance. This last guaranty may be proved valuable at isolated grids, such as at islands of the Aegean, as fewer thermal power stations would be needed. So, both the inventor and the state will benefit from these economic assistances.

8.4 Recommendations for future work

Future work relatively to the FCESS may be done at various directions. First of all, a more complex hybrid system could be investigated combining other ways of short-term and long-term energy storage; possible options are hyper-capacitors, batteries, pumped hydro storage system e.t.c. This way a system which combines advantages and disadvantages of all the others will be achieved and maybe it is found a Hybrid Energy Storage System which will be flexible and adjustable at the very specific needs of the occasion.

In addition, at this study some assumptions on the FCESS are made as far its structure and configuration is concerned that would be interested to question. As discussed above, the bipolar

Alkaline Electrolyzer was chosen because produces pressurized Hydrogen and it is the most old and tested electrolyzer than the PEM one. It would be interested to investigate the case of a PEM electrolyzer and maybe in combination with another type of Hydrogen storage as described at **3.4**. Also, at the FC operation Air is the oxidant and not pure Oxygen which leads to lesser efficiency; a case of Oxygen storage could be investigated too, at which there will be an Oxygen reservoir as for Hydrogen and it will be filled up from the electrolyzer or from the air via a purification system.

As far as model accuracy is concerned, the mathematical formulas and models used at this study are all tested and lead to a very satisfying component operation. However, if execution time does not matters, more complex and accurate models exist with many empirical parameters that adjust the component function very close to the real one. For more realistic approach, lots of individual smaller components except those already considered should be investigated such as pipes and valves for Hydrogen and water dispatch, the electronics that control the main components and other items that are practically needed. Also, neither the building that will house the stuff has been taken into account nor the place that the system will be installed. These parameters ,as well as state taxation, are important details that are difficult to model so were ignored.

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APPENDIX A: PEMFC MODEL

A:1 Voltages

A:1:1 Theoretical Voltage

Focusing on PEMFC with Hydrogen as a fuel and Oxygen as an oxidant the follow reactions take place:

Anodic half reaction: $H_2 \rightarrow 2\,H^+ + 2\,e^-$

Cathodic half reaction: $\frac{1}{2}O_2 + 2\,H^+ + 2\,e^- \rightarrow H_2O$

The overall reaction: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$

In **[10]** the fuel cell's model is presented analytically:
The maximum energy produced by a fuel cell depends on *Gibbs free energy* of the overall reaction, that is: $W = \Delta G = -n\,F\,E$ **(A.1)**

- **n** is the number of electrons take part in the reaction, that is: 2
- **F** is Faraday's Constant and is equal to 96485,309 C/mol
- **E** is the ideal voltage of the cell

Gibbs free energy may also be calculated from: $\Delta G = \Delta H - T\Delta S$ **(A.2)**

- **ΔH** is the reaction's enthalpy
- **ΔS** is the reaction's entropy

The total thermal energy of the reaction is the enthalpy **ΔH**. The *Gibbs free energy* results if **TΔS** is subtracted which vanish from non-reversible entropy changes. **TΔS** equals the heat produced at fuel cell's operation. **ΔS** take negative values at this case that the Hydrogen oxidation is an exothermic reaction.

If Standard Conditions (STP) are assumed, that is 1 atm pressure and 298 K temperature, the **(A.1)** equation forms as: $\Delta \mathring{G} = -n\,F\,\mathring{E}$. From laboratory measurements and experiments $\mathring{E}$ has been calculated and is equal to $\mathring{E} = U^{\circ}_{theo} = 1.2297\,V$. For the model's accuracy, this value has to be corrected for the corresponding conditions of the fuel cell's operation. So, for the general form of

the reaction: $\alpha A+\beta B\rightarrow\gamma\Gamma+\delta\Delta$ the *Gibbs free energy* for various temperatures equals to:

$$\Delta G=\Delta\mathring{G}+R\,T\ln\left(\frac{f_{\Gamma}^{\gamma}f_{\Delta}^{\delta}}{f_{A}^{\alpha}f_{B}^{\beta}}\right)\quad(\boldsymbol{A.3})$$

- **R** is the Universal Gas Constant and equals to 8.31451 J/(K mol)
- **T** is the temperature
- **f** is fugacity or otherwise named as activity. In terms of pressure $f=\frac{p_i}{p_0}$,where p_i is defined as the partial pressure of species i and p_0 is a reference pressure (usually the atmospheric pressure: 1 atm or 100 kPa).

From **(A.1)** and **(A.3)** the below equation is obvious:

$$U_{theo}=U_{theo}^{\circ}-\frac{R\,T}{n\,F}\ln\left(\frac{f_{\Gamma}^{\gamma}f_{\Delta}^{\delta}}{f_{A}^{\alpha}f_{B}^{\beta}}\right)\quad(\boldsymbol{A.4})$$

The above formula is known as *Nerst Equation* and provides the open circuit voltage for a reaction of the general form as discussed. So for the current overall reaction of a PEM fuel cell:

$$U_{theo}=U_{theo}^{\circ}-\frac{R\,T}{n\,F}\ln\left(\frac{f_{H_2O}}{f_{H_2}\sqrt{f_{O_2}}}\right)\quad(\boldsymbol{A.5})$$

or

$$U_{theo}=1{,}2297+\frac{R\,T}{n\,F}\ln\left(\frac{p_{H_2}p_{O_2}^{1/2}}{p_0^{3/2}}\right)\quad(\boldsymbol{A.6})$$

,where:

- $\mathbf{P_{H2}}$ is the Hydrogen supply pressure
- $\mathbf{P_{O2}}$ is the Oxygen supply pressure. If air is used pressure 100 kPa may be assumed
- $\mathbf{P_o}$ is the reference pressure, 100 kPa

For this relationship, once the cell voltage at STP is known, the cell voltage can be determined at other pressures too. The theoretical equilibrium cell voltage can be expressed also as a change in *Gibbs free energy* for the reaction of Hydrogen and Oxygen **[10]**. Therefore, this voltage at conditions different from the STP is given by:

$$U_{theo}=1{,}2297+(T-298{,}15)\frac{\Delta S_0}{n\,F}+\frac{R\,T}{n\,F}\ln\left(\frac{p_{H_2}p_{O_2}^{1/2}}{p_0^{3/2}}\right)\quad(\boldsymbol{A.7})$$

,where:

- **T** is the operating temperature
- $\mathbf{\Delta S_0}$ is the change of entropy at STP equal to: -0,1634 kJ /(K mol)
- **n** are the number per electrons per mole. i.e. n=2
- **F** is Faraday's Constant and is equal to 96485,309 C/mol
- **R** is the Universal Gas Constant and equals to 8.31451 J/(K mol)

- $\mathbf{P_{H2}}$ is the Hydrogen supply pressure
- $\mathbf{P_{O2}}$ is the Oxygen supply pressure. If air is used 100 kPa pressure may be assumed
- $\mathbf{P_o}$ is the reference pressure, that is 100 kPa

The above relationship that gives the **theoretical cell voltage** is modeled also is *Simulink* and is depicted at **Fig. A.1**.

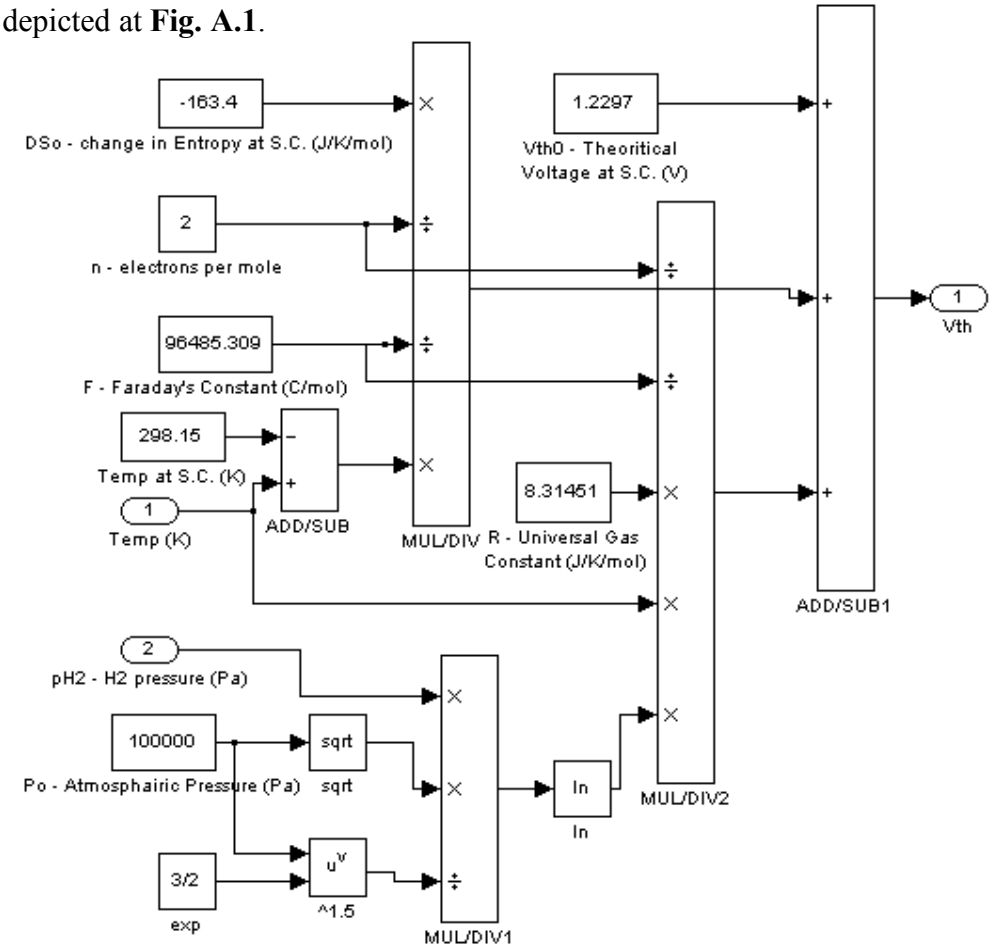

Fig. A.1: Theoretical Fuel Cell Voltage based on **(A.7)**

A:1:2 Activation losses

Activation over-potential is related to the slowness of the reactions that take place on the surfaces of the electrodes. A portion of the voltage generated is lost in driving the chemical reaction at the electrodes; that is why it is called activation. [12] provides a detailed formula:

$V_{act} = -[\xi_1 + \xi_2 T + \xi_3 T \ln(C_{O_2}) + \xi_4 T \ln(I_{fc})]$ $(\boldsymbol{A.8})$,where $\xi_1 - \xi_4$ are parametric coefficients:

- $\xi_1 = -0{,}948$
- $\xi_2 = 0{,}00286 + 0{,}0002 \ln(A_{fc}) + 4{,}3\text{x}10^{-5} \ln(C_{H2})$
- $\xi_3 = 7{,}6 \text{ x } 10^{-5}$
- $\xi 4 = \mathbf{-1{,}93} \text{ x } 10^{-4}$, and

$C_{O_2} = P_{O_2} \cdot 1{,}97 \cdot 10^{-7} \cdot \exp\left(\frac{498}{T}\right)$, $C_{H_2} = P_{H_2} \cdot 9{,}174 \cdot 10^{-7} \cdot \exp\left(\frac{-77}{T}\right)$ are the concentrations of Oxygen and Hydrogen at the catalytic interface of the electrodes and P_{O2} and P_{H2} are the partial pressures respectively.

At **Fig. A.2** the *Simulink* modeling is depicted:

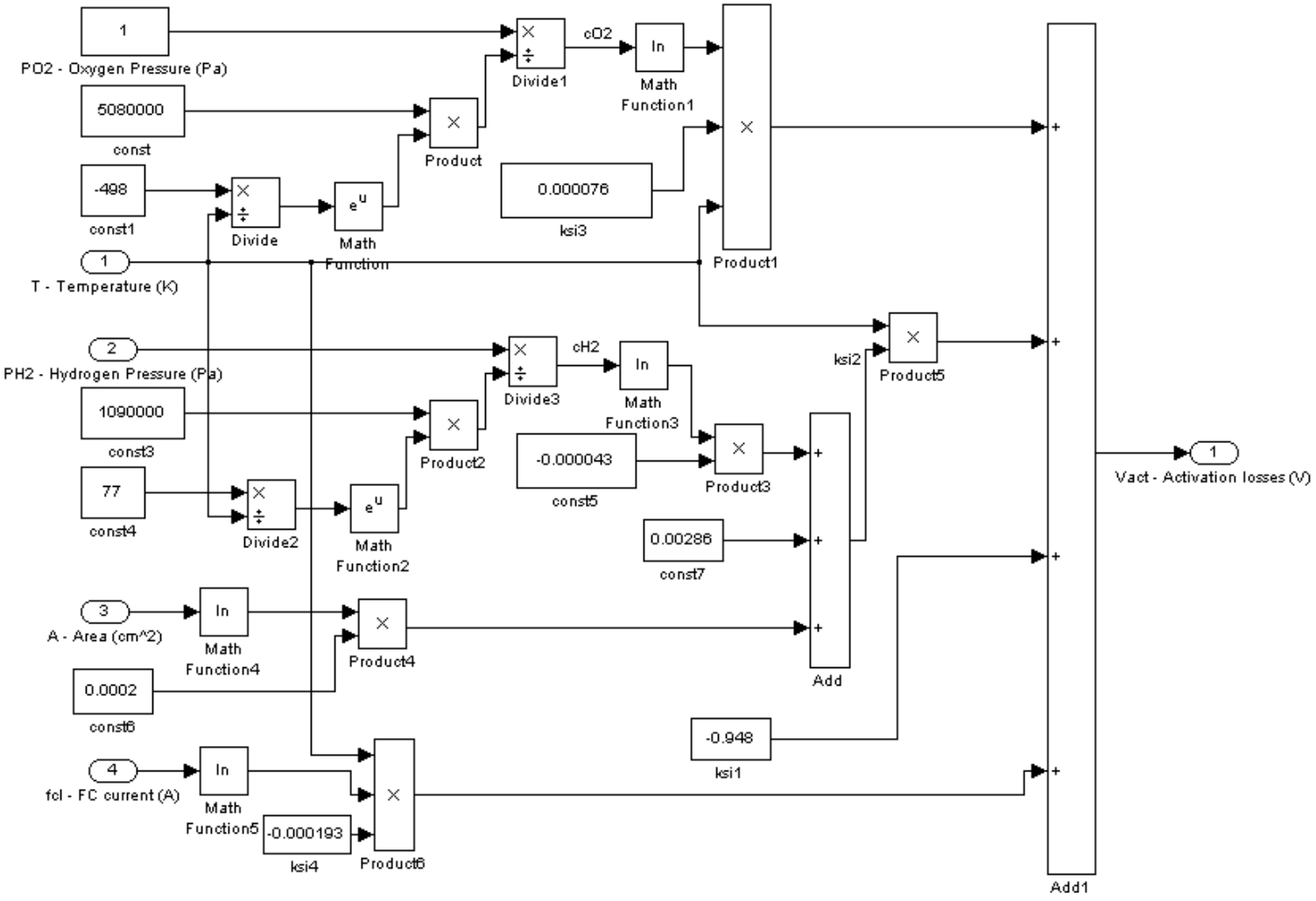

Fig. A.2: The Activation over-potential based on **(A.8)**

A:1:3 Ohmic losses

Ohmic over-voltage occurs due to resistance to the flow of ions (protons) in the electrolyte membrane and resistance to the flow of electrons through the electrodes' substrates and the two

catalyst layers. The detailed mathematical model is presented in [12] :

$V_{ohm} = I_{fc}(R_M + R_C)$ $(A.9)$, where R_M is the membrane's resistance and R_C represents the resistance to the transfer of protons through the membrane and is considered constant and equivalent to 0,0003 Ω. Relatively to R_M:

$R_M = \frac{\rho_M \cdot l}{A}$, where l is thickness of the membrane (cm^2), A is the cell active area (cm^2) and ρ_M is the specific resistivity of the membrane for the electron flow (Ω.cm) given by:

$$\rho_M = \frac{181.6 \cdot [1 + 0.03 \cdot \left(\frac{I_{fc}}{A}\right) + 0.062 \cdot \left(\frac{T}{303}\right)^2 \cdot \left(\frac{I_{fc}}{A}\right)^{2.5}]}{\left[\psi - 0.634 - 3 \cdot \left(\frac{I_{fc}}{A}\right)\right] \cdot \exp\left(4.18 \frac{T - 303}{T}\right)}$$, where:

- $\mathbf{I_{fc}}$ is the fuel cell current (A)
- **A** is the active cell area (cm^2)
- **T** is the temperature (K)
- **ψ** is an adjustable parameter with value 23. The model in *Simulink* is shown at **Fig. A.3:**

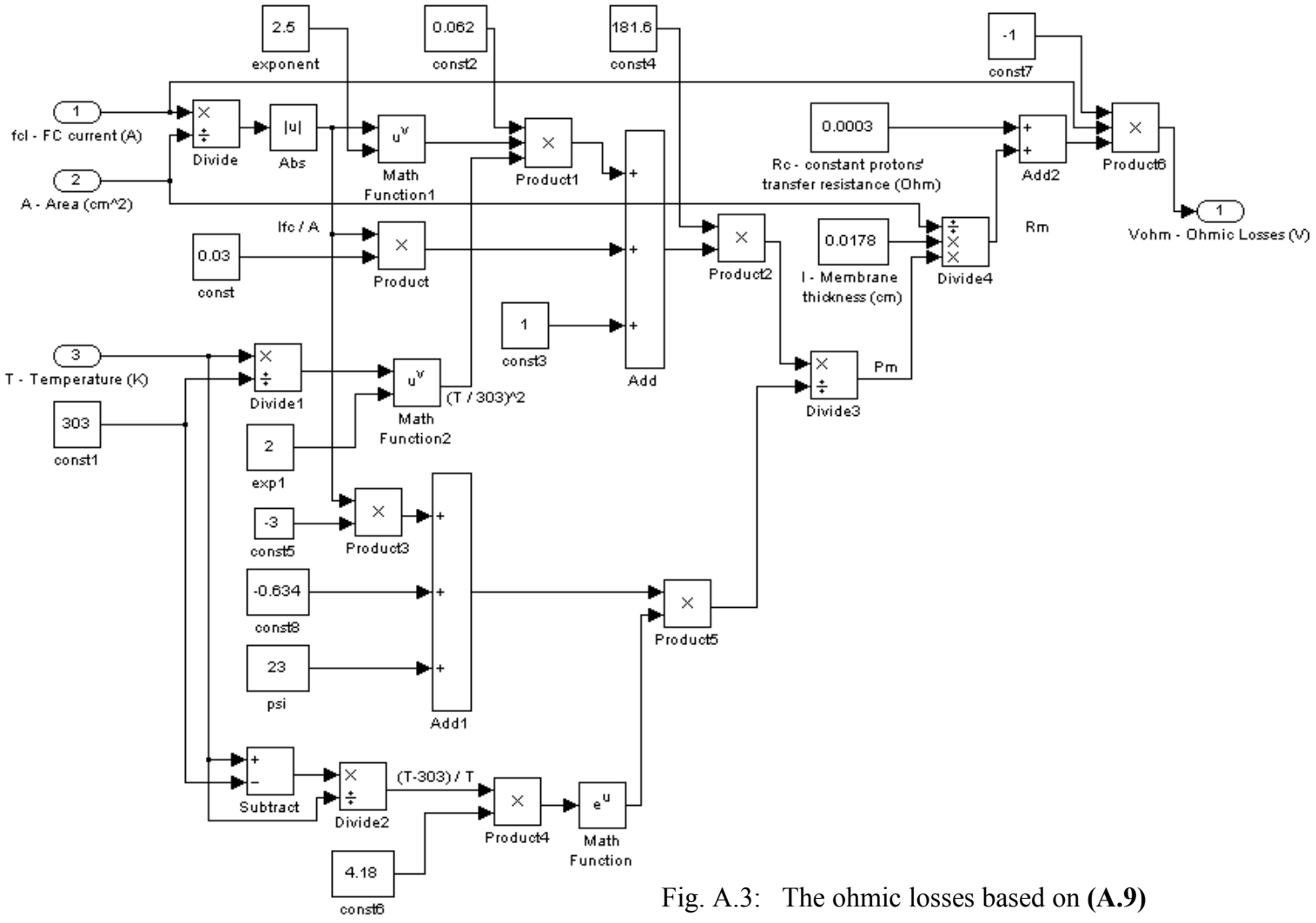

Fig. A.3: The ohmic losses based on **(A.9)**

A:1:4 Concentration losses

Concentration over-potential is caused due to the limited mass transfer of the reactants at the interior of the cell. This, by its turn, causes a decrease in the partial pressures of these gases. Reduction in the pressures of oxygen and hydrogen depends on the electrical current and on the physical characteristics of the system. To determine an equation for this voltage drop, a maximum current density, *Jmax*, is defined under which the fuel is being used at the same rate of the maximum supply speed. The current density cannot surpass this limit because the fuel cannot be supplied at a larger rate. Typical values for *Jmax* are in the range of 500 to 1500 mA/cm2
The empiric model has been derived from [12]**:**

$$V_{con} = -B \cdot \ln\left(1 - \frac{J}{J_{max}}\right) \quad (\boldsymbol{A.10}) \text{ , where:}$$

- **B** is a parametric coefficient, that depends on the cell and its operation state. Equals to 0.15 V
- **J** represents the actual current density of the cell (A/cm2).
- $\mathbf{J_{max}}$ is the current density limit with a value of 1500 mA/cm2 assumed

This formula is modeled to *Simulink* as:

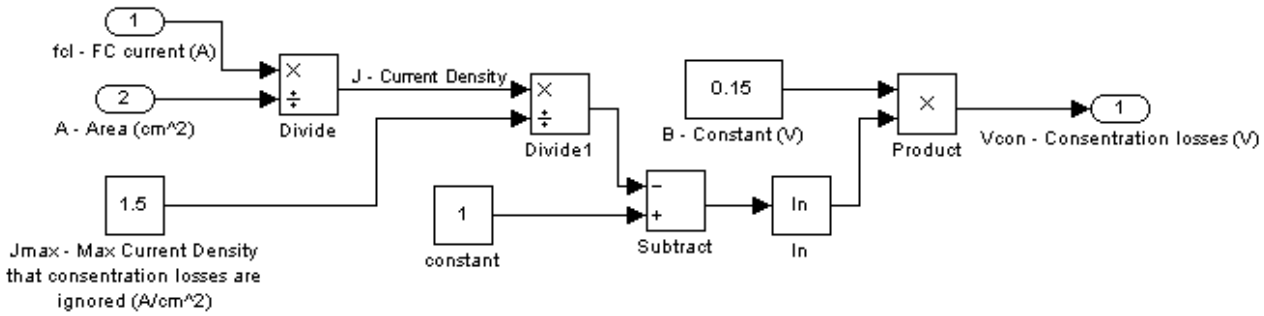

Fig. A.4: The concentration losses based on **(A.10)**

A:2 Fuel Consumption

According to Faraday's law, the consumption of Hydrogen is given by:

$$\dot{m}_{H_2} = \frac{Ns \cdot I_{fc}}{n \cdot F \cdot \eta_F} \quad (\boldsymbol{A.11}) \text{ , where:}$$

- **Ns** is the number of cells connected in series
- $\mathbf{I_{fc}}$ is the fuel cell current (A)
- **n** is the number of electrons per mole, i.e. 2

- **F** Faraday's Constant and equivalent to 96485,309 C/mol
- η_F is the Faraday's efficiency

The Faraday's efficiency decreases as temperature increases and lower resistance, as well as more current losses eventuate. At [13] an empirical formula is considered:

$$\eta_F = \frac{\left(\frac{I_{fc}}{A}\right)^2}{f_1 + \left(\frac{I_{fc}}{A}\right)^2} f_2 \quad (\boldsymbol{A.12}) \text{, where:}$$

- $\mathbf{I_{fc}}$ is the fuel cell current (A)
- **A** is the active area (m^2)
- $\mathbf{f_1}$ = 2.5 T + 50
- $\mathbf{f_2}$ = -0.00075 T +1

The model in *Simulink* and the simulation graph follow:

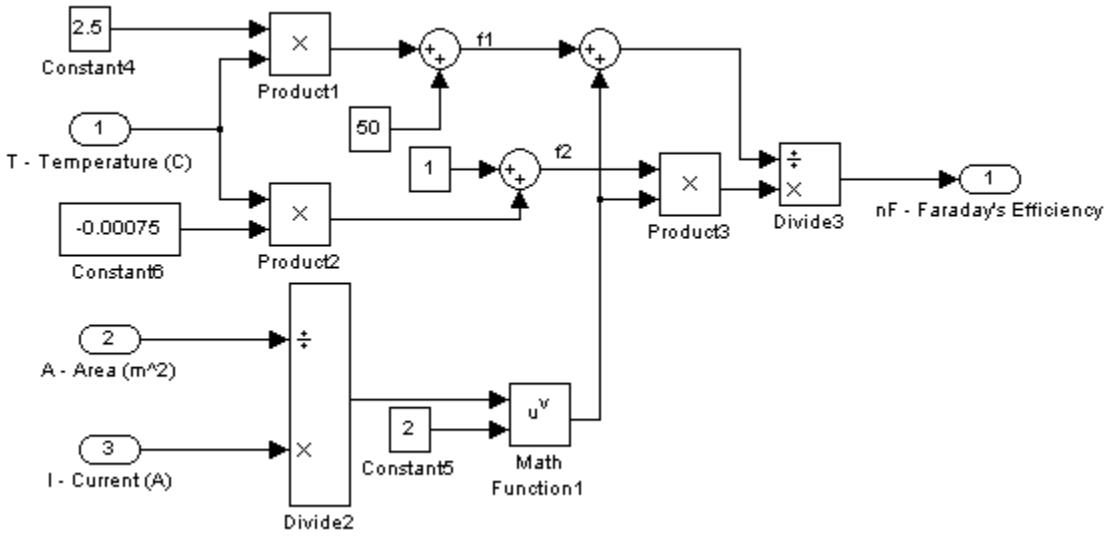

Fig. A.5: The Faraday's Efficiency model based on **(A.12)**

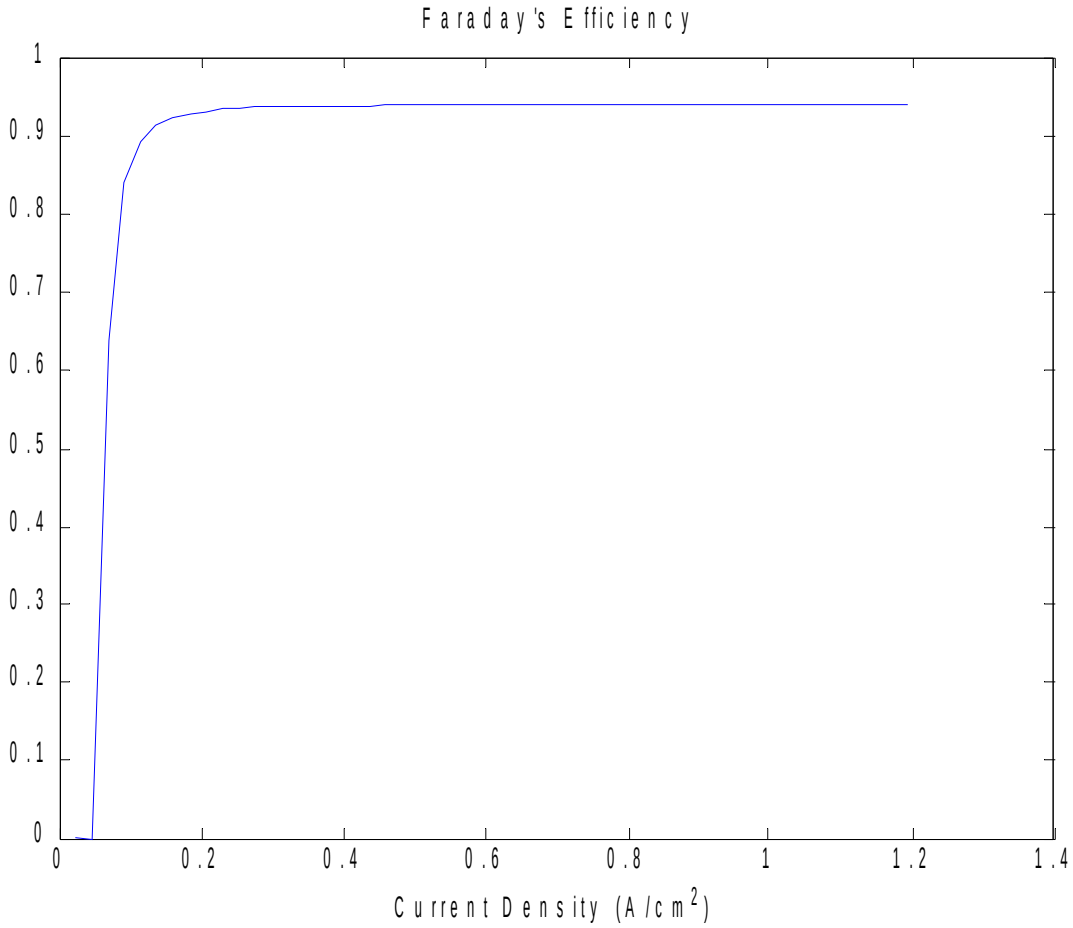

Fig. A.6 The Faraday's Efficiency versus current density for **80 °C** and **43.5 cm^2**

APPENDIX B: FCESS configuration

B.1 The overview

As discussed at chapter 3 the main components of a FCESS are the electrolyzer, the fuel cells, the fuel tank and power electronics. To model a FCESS responsive to real market conditions, it is important to model each of the above components as a stack of smaller units. In **Fig. B.1** the overall FCESS block diagram is depicted:

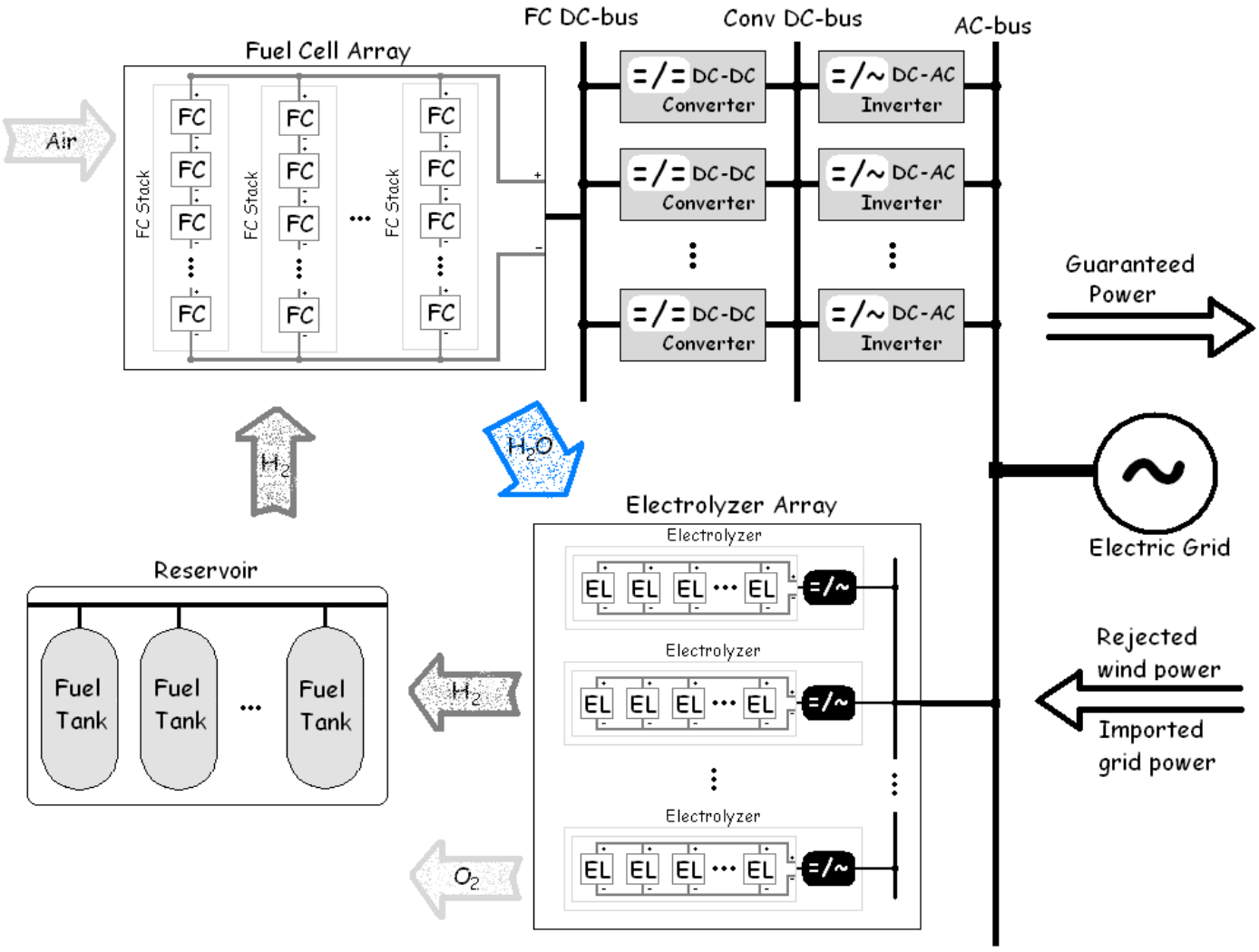

Fig. B.1 The FCESS block diagram

As can be seen, all of the components consist of smaller ones and some of them consist of smaller ones too. Specifically:

➢ The **Fuel Cell Array**, consists of several **Fuel Cell Stacks** connected in parallel. The commercial product is the **Fuel Cell Stack** and for the needed power supply to be accomplished a certain number of them have to be connected in parallel. The **Fuel Cell Stack** is comprised by several fuel cells **(FC)** connected in series, so a certain value of voltage is achieved (usually at ranges 12...72 V)

➢ The **DC-DC Converter's Array** consists of several **DC-DC Converters** connected in parallel between the *FC DC-bus* and the *Conv DC-bus*. This choice is made for two reasons: it may not exist the certain power rating DC-DC Converter unit as a commercial product, and if there is a solo converter failure the system continues operating without disturbances until the repair/replacement is done (consider an 20% Converter surplus for this occasions) .

➢The **DC-AC Inverter's Array** is comprised of several **DC-AC Inverters** and the reasons are the same as above.

➢The **Electrolyzer's Array** consists of several **Electrolyzer** units connected in parallel. Each of the **Electrolyzers** as existing commercial product is comprised of Electrolyzer cells (**EL)** connected in parallel and a rectifier that converters input AC to DC at suitable levels.

➢The **Reservoir** consists of several commercially available **Fuel Tanks** so the desired volume is achieved.

The overview of the model in *Simulink* is depicted in **Fig. B.2**. As it is shown, the basic components have been modeled and lots of signals perform the communication so a correct simulation is done.

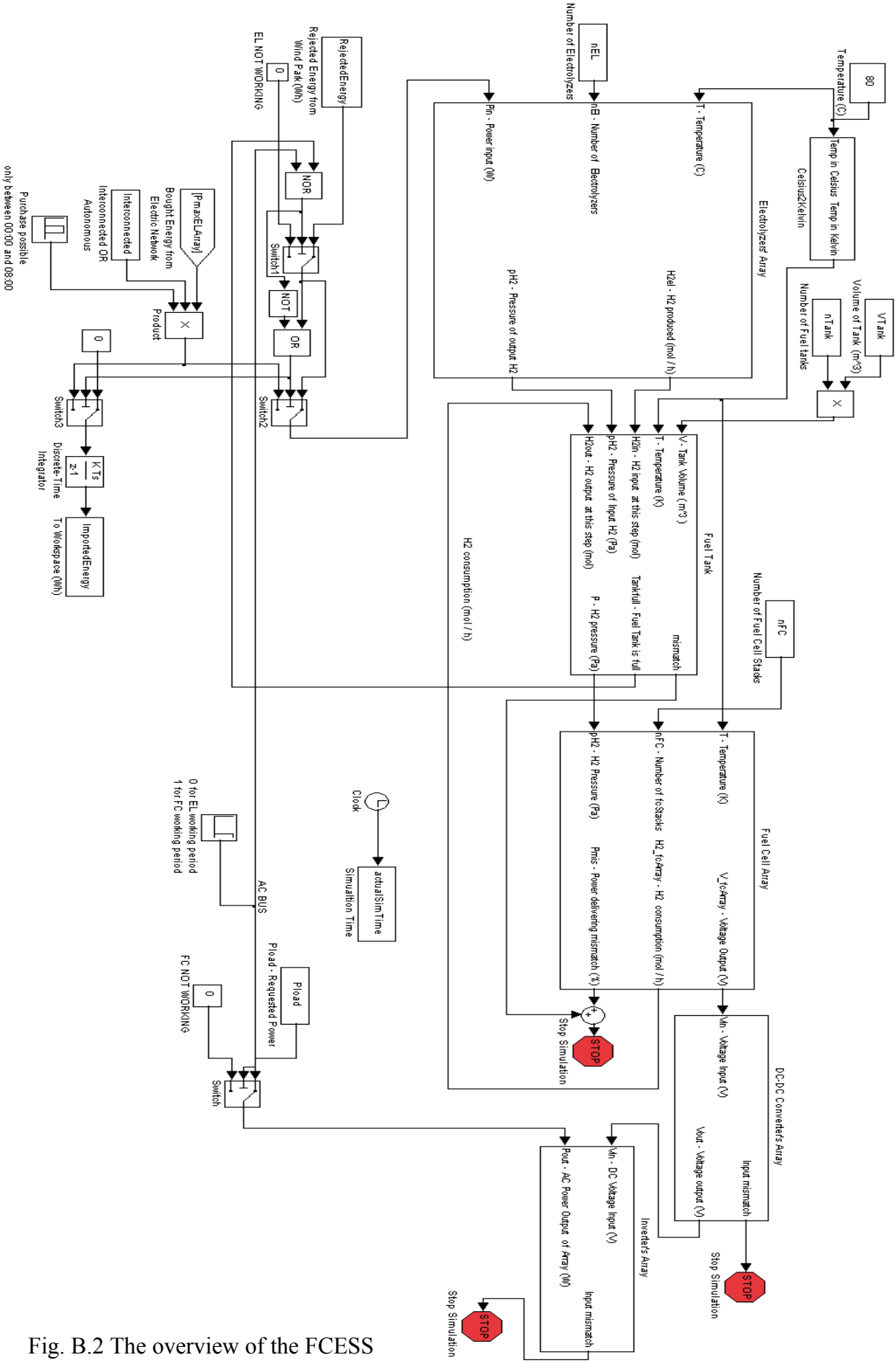

Fig. B.2 The overview of the FCESS

B.2 The Fuel Cell Array

The Fuel Cell Array consists of several Fuel Cell Stacks connected in parallel. The model is shown below:

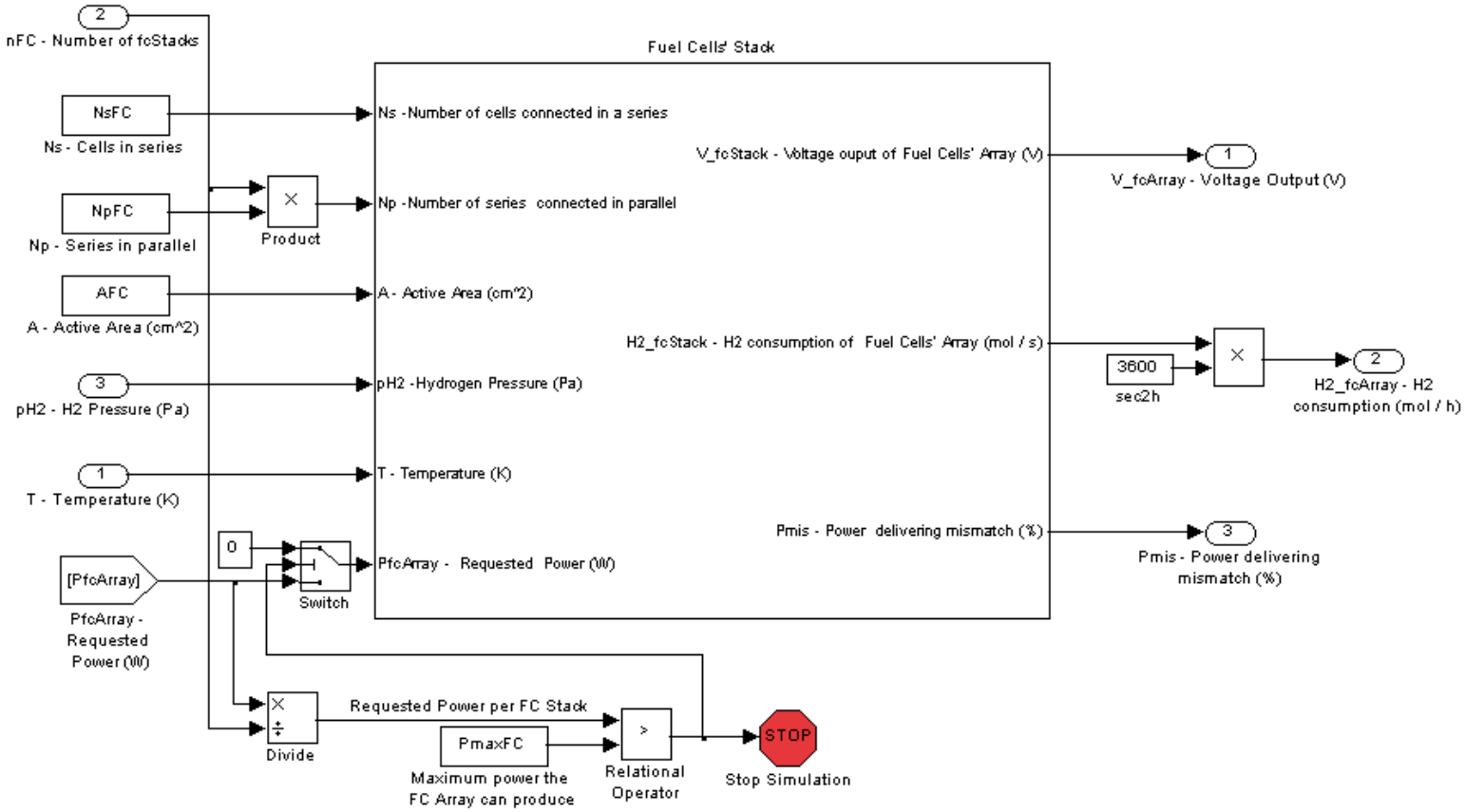

Fig. B.3 The Fuel Cell Array model in *Simulink*

Characteristics of each stack (No of cells in parallel and in series, the active area), the total number of stacks and the operating conditions (Temperature and Pressure) are all inputs; The **PfcArray** is worth noticing as it determines the power the Fuel Cell Array is required to produce. It is calculated from the guaranteed amount after Converter and Inverter losses are considered, and is used for the determination of the operational point of the Fuel Cell Stacks. If this retroactive procedure does not converge (that means that too much power is required to be produced), it is recognized and simulation ends as Failure. Obvious outputs of the Fuel Cell Array are the voltage and the H_2 consumption rate, that is how much H_2 is needed to be retrieved from the fuel tank so the required operation is achieved.

B.3 The Fuel Cell Stack

The Fuel Cell Stack consists of several Fuel Cell connected in series. The *Simulink* model is shown below:

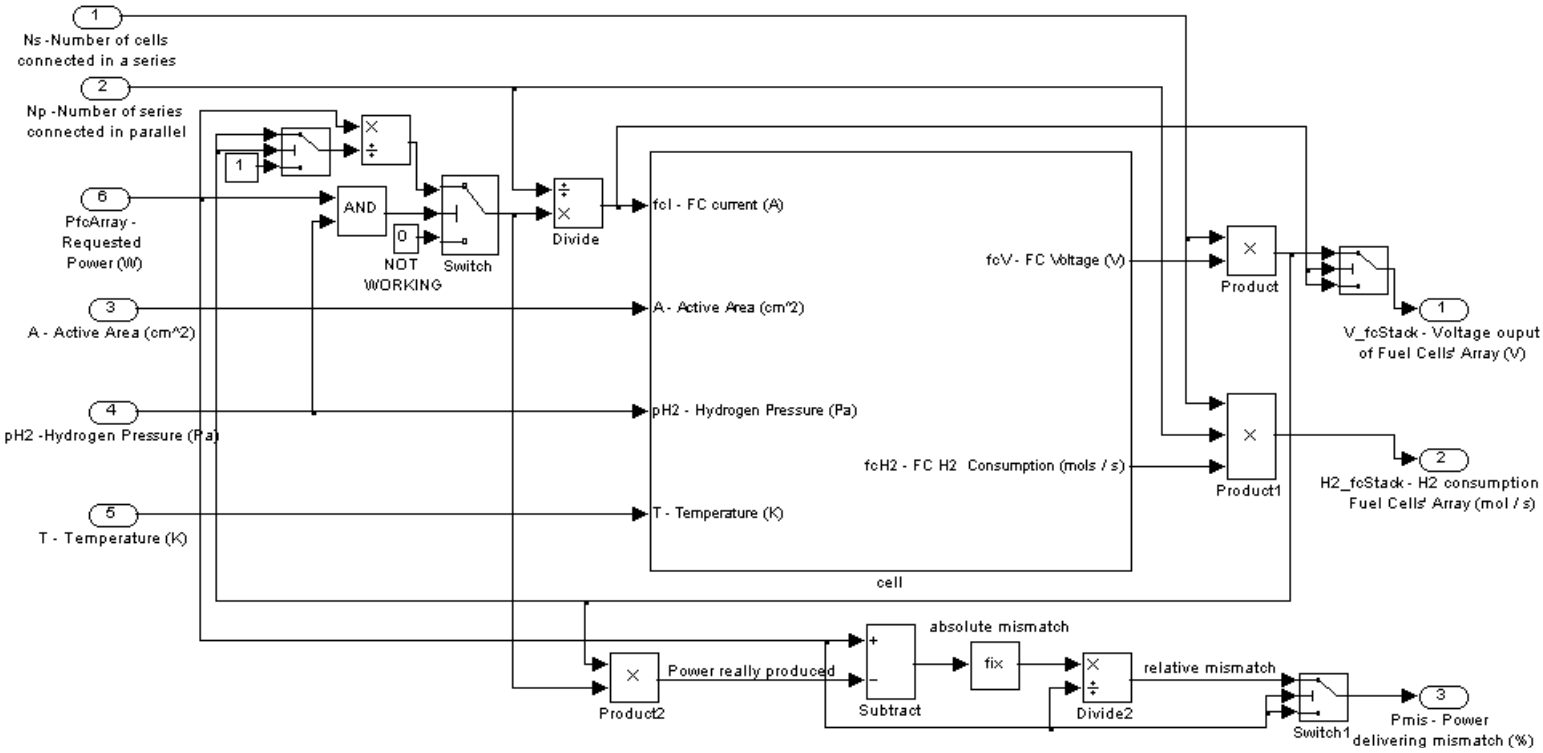

Fig. B.4: The Fuel Cell Stack model in *Simulink*

The thing that is worth noting at this model is the retroactively operational point calculation. This is implemented with algebraic loop between the Voltage and the Current of the stack. Specifically, when the fuel cells are not operating (there is not requested power to produce), then the signal *Pfcarray* has zero value, so the output of *Switch* is an initial zero value for the current and an initial zero value for voltage is determined from the cell. When power is required to be produced by the fuel cells, then the value of the current – input of the cell- is calculated as the ratio of Power over Voltage. This new current value determines a new voltage level which specifies a new current value and so on. This procedure stops when there is a convergence, meaning there is a current value which determines a voltage value and when the power is divided by this voltage the same current is calculated. These two values of current and voltage is the operational point of the stack. It is important to point out that this retroactive process does not take simulation time, meaning no simulation step is made if the convergence is not achieved. So, this way a reliable and accurate way of operational point calculation and therefore H_2 consumption determination is achieved.

B.4 The Electrolyzer Array

The Electrolyzer Array consists of several Electrolyzers – commercial products – connected in parallel. At **Fig. B.5** the model in *Simulink* is depicted; main technical parameters and operating conditions are inputs to the model and the H_2 production rate as its pressure value also, are outputs. The power offered to the system is the signal Pin, and it is filtered in the case that its value is more than the nominal (case of rejected wind energy).

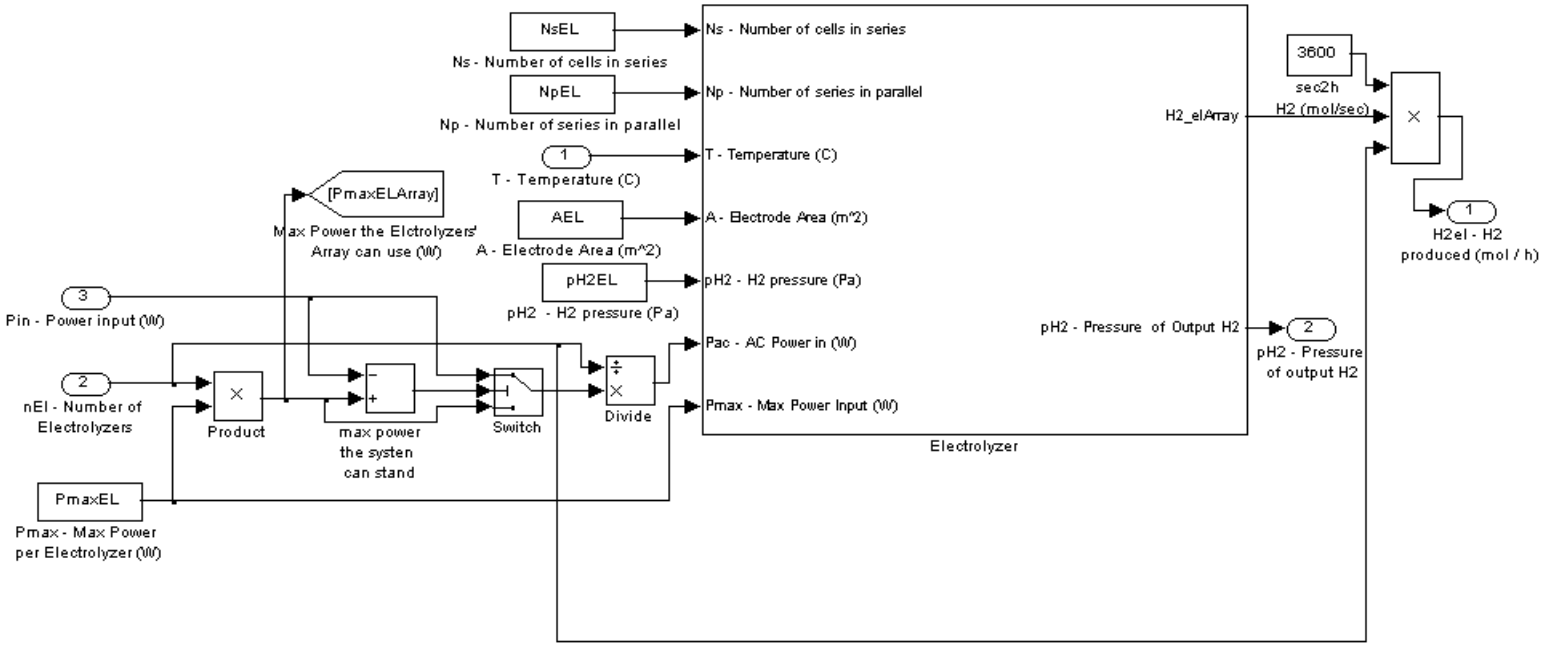

Fig. B.5: The Electrolyzers Array model in *Simulink*

B.5 The Electrolyzer unit

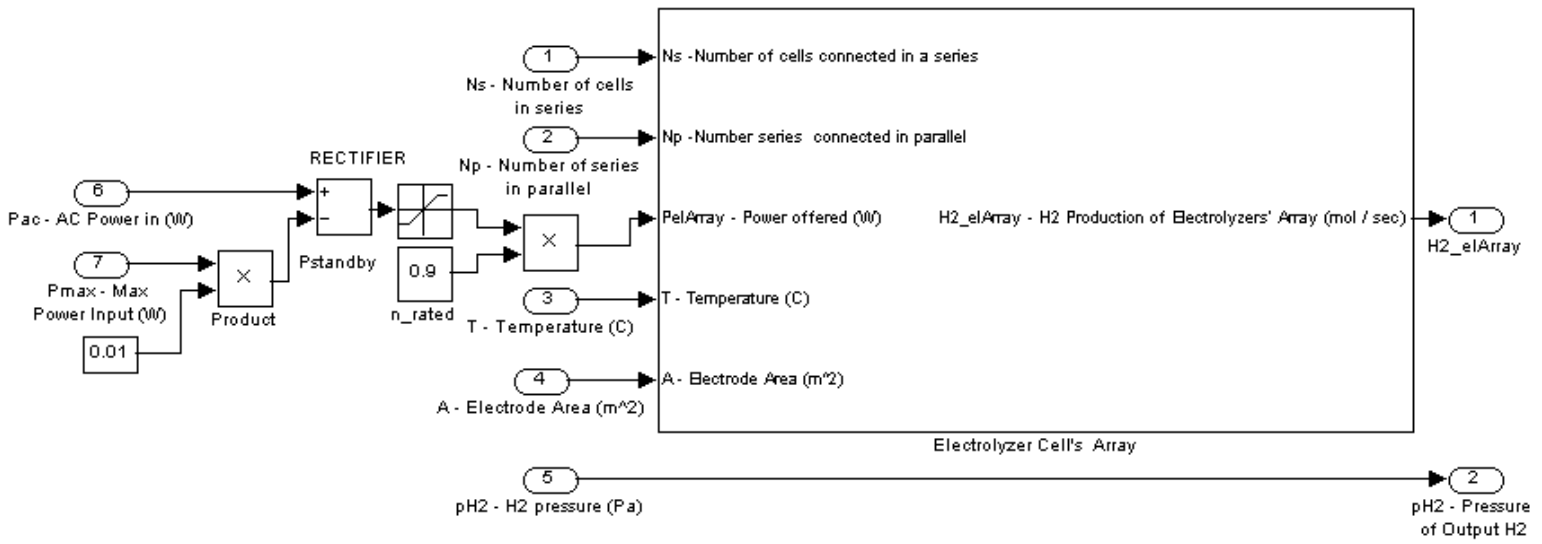

Fig. B.6: The Electrolyzer Unit modeled in *Simulink*

The Electrolyzer is comprised of several cell-arrays connected in parallel and its power electronics to convert AC to DC and appropriate voltage levels; this last PE is modeled as a rectifier which just contributes to the losses. All important characteristics and parameters are inputs to the model.

B.6 The Electrolyzer Cell Array

The Electrolyzer-cell Array consists of several cells connected in parallel (and maybe in series); their number is input to the model. The thing that is worthy of notice is the retroactive operational point calculation that takes place. Correspondingly to the Fuel Cells, the current is initialized and when electrolyzers are operating, an iterative process of re-determination of current and voltage values takes place. This procedure always converges because the power input is already filtered and an operational point always exist.

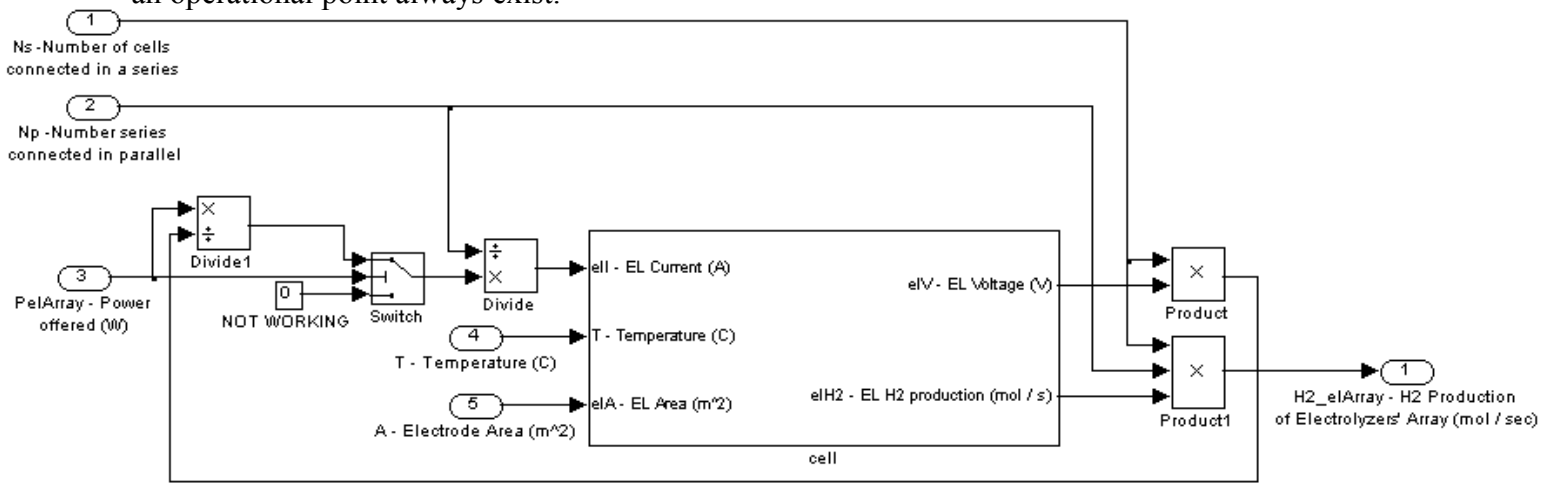

Fig. B.7: The array of Electrolyzer cells in *Simulink*

B.7 The DC-DC Converters Array

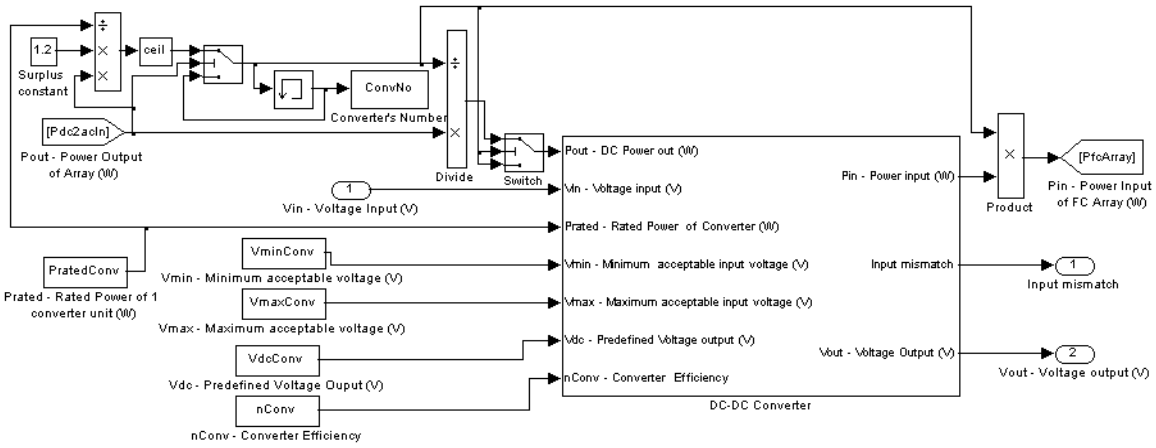

Fig. B.8: The Array of DC-DC Converters modeled in *Simulink*

The Converters Array consists of several Converters connected in parallel; their technical parameters are inputs to the model and the power in of the converter (= the power produced by the fuel cells) is a model's output. Moreover, the *mismatch* signal that indicates input mismatch, either from voltage levels or from power value, is also an output and is used to end precociously the simulation in such a case.

Another thing that should be noted, is the converters number calculation. This number can be determined by the constant and predefined value of power out; the exact amount of power needed to be converted is specified and, according to rated power of the converter, the total number is estimated. A 20% units surplus is considered for increased reliability as pointed at **B.1**.

B.8 The Inverters Array

A very similar structure is chosen for the Inverters Array as the Converters Array. The modeling is shown in **Fig. B.9.**

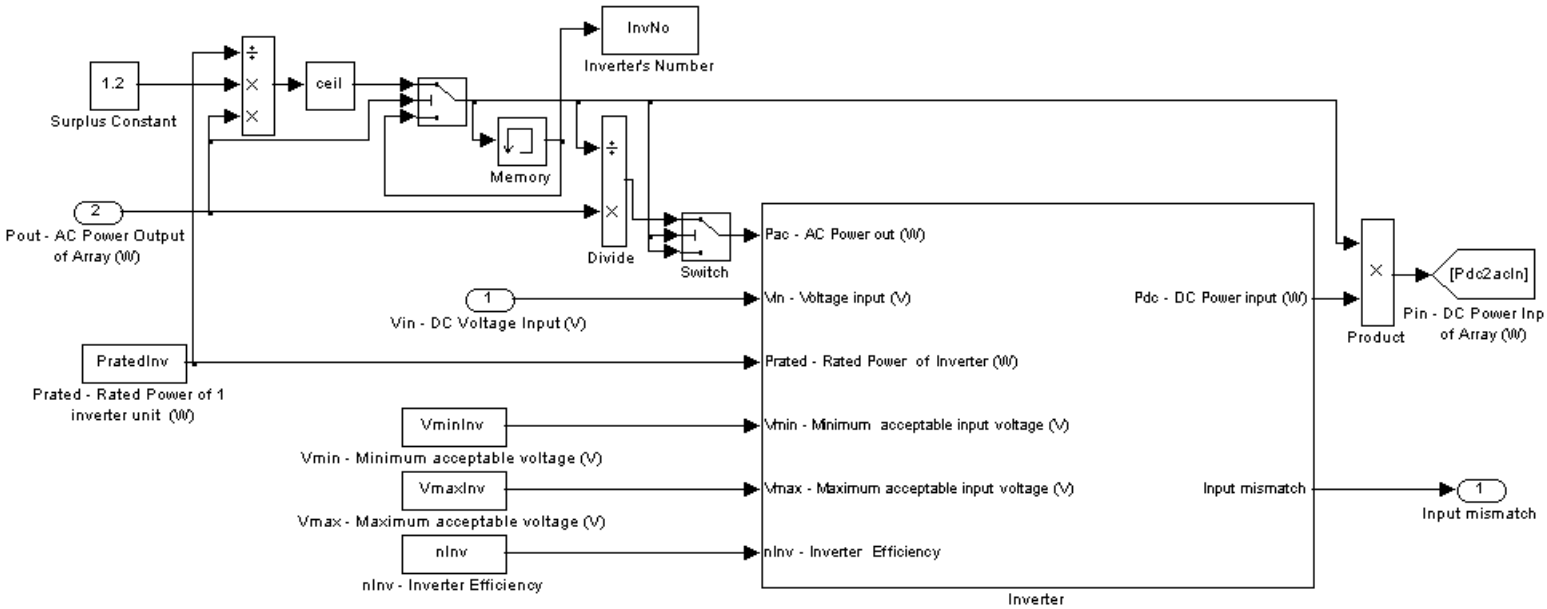

Fig. B.9: The Inverters Array in *Simulink*