Department of Mechanical and Aerospace Engineering

Feasibility of Wind-H_2 Systems in Spain within the current RES Framework (Royal Decree-law 9/2013)

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Signed: NOEL GANCEDO FEITO Date: 06/09/2013

Abstract

The threat of an imminent climate change caused by rising green house gas emission coupled with fossil fuel depletion warnings have encouraged governments, especially in develop countries, to stimulate the development of electrical sectors towards a model more dependent on renewable energy resources. In this context, wind energy has played an important role in the aforementioned development. Focusing in the case of Spain, during the last decade wind energy has experienced a tremendous growth, fostered by high government economic aids for wind power generation. Nevertheless, the economical crisis that Spain is suffering has leaded to a conservative electrical system reform regulated by the *Royal Decree-law 9/2013 of 12th July 2013* that abolishes any economic aid for renewable energy generation. The above coupled with the instability nature of wind power generation as consequence of the stochastic behaviour of wind may prevent a higher penetration of wind power in the Spanish electrical sector. In this context, energy storage arises as a possible solution for solving the aforementioned constraints.

Therefore, the present dissertation aims to study the economical feasibility of a wind farm integrated with hydrogen storage (as most of the experimental projects are working in this line nowadays) regarding the current Spanish framework for RES. This study covers different energy management strategies and wind farm sizes in order to compare them from a economical point of view. For doing so, a model of a hypothetic Wind-H_2 system and the Spanish economical framework has been designed for been applied to any wind farm affected by the above framework. The model has been applied to a specific case study and integrated with HOMER software for obtaining technical results. Moreover, an economical feasibility study has been undertaken based on the technical results obtained coupled with economical inputs of the model. In light of the results obtained, a wind farm integrated with hydrogen storage that sells all hydrogen produced arises as the only alternative that guarantees the economical feasibility of wind farms in Spain nowadays. With regards, the rest of management strategies, important technical and economical constraints (assessed in the present dissertation) need to be overcome for becoming cost-effective options in the future.

Acknowledgements

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Table of Contents

List of figures

List of tables

List of Graphs

1 INTRODUCTION

1.1 Motivation

Fossil fuel depletion and green house gas emissions have encouraged electrical sector to develop towards an energy model more dependent on renewable energy resources. In this context, wind energy has achieved high penetration levels in developed countries. Especially in Spain, wind energy is the major contributor among the renewable energy resources depicting the 14.5% of the renewable energy generation in 2011, even higher than hydro-energy contribution (13.1%) (Red Electrica de España (REE), 2000; Ministerio de Industria, Energía y Turismo, 2012).

However, as other renewable energy technologies wind energy systems depends on a stochastic and unpredictable energy source, leading to frequent mismatches between power demand and supply as well as favouring electrical instabilities in the grid. This important constraint prevents wind farms to be a stable and trustful generation system. Therefore, the solution that seems to be most suitable for solving the aforementioned constraint is energy storage. With regards energy storage, during the last decade´s hydrogen as an energy vector has become a real alternative to fossil fuels due to the following advantages (Vezirolu and Barbir, 1992; Rosa, 2003; Pino, 2010):

- Hydrogen has a high energy density per unit volume. However, hydrogen is always combined with other substances and its reformation requires more energy than its energy storage capacity.
- It can be produced by a large variety of energy sources and used in a wide range of applications and equipment.
- Electricity and hydrogen are interchangeable energy vectors, due to hydrogen can be converted into electricity with acceptable efficiency, much higher than any fossil fuel.
- Hydrogen is reformed from water and its combustion or electrochemical reaction releases liquid or water vapour.
- It can be stored as liquid, gas or solid state.
- It can be transported long distances through pipes, tanks, tracks, etc.

Therefore, using hydrogen as energy storage system in wind farms would allow wind energy to be more manageable, having the following benefits (Pino, 2010):

- Reduction of power deviations incurred by wind farms caused by errors between the estimated and their real power generation. What is more, this would curtail the penalties associated with those deviations and ensure a stable power generation.
- Enhance the energy management of wind system in order to achieve the technical and economical optimum by storing energy during low-price periods (off-peak hours) and selling electricity during high-price periods (peak hours).
- Ensure the electrical quality as the energy management would prevent electrical instability of the grid coupled with higher penetration of wind energy in the energy sector.

Consequently, a growing interest in evaluating the technical and economical feasibility of integrated renewable energy systems with hydrogen storage has arisen. For example, Shiroudi and Hosseini (2011), Rosa (2003) and Zoulias and Lymberopoulos (2007) have assessed a hydrogen storage system integrated with solar arrays from a technical and economical point of view. Others studies integrate hydrogen storage systems with large combination of renewable energy systems such as the work of Ipsakis, et al. (2008) and Sudol (2009) that undertakes a technical study of different control strategies for a hydrogen system integrated with PV-wind system (the latter is based on a existing system at Totara Valley). For larger combinations of renewable energy systems, Dufo-López, et al. (2006) carried out an optimization of control strategies for stand-alone renewable energy-hydrogen system composed by a PV array, wind farm, hydropower station and backup batteries. Furthermore, other studies such Aguado, et al. (2009) relates more with hydrogen storage integration into wind farms, tacking an economic assessment of a generic Wind-H_2 system aided by a simulation model that determines the most profitable control strategy. This model is based on an internal combustion engine and a predicted wind speed which is assumed to be real wind data with a fixed forecast error. Other studies focus more on optimizing the control strategy so as to obtain the largest revenues by selling electricity during peak periods and storing it during off-peak periods, within the previous Spanish framework (*Royal Decree 661/2007*) (Bernal and Dufo, 2008). Moreover, this analysis is based on different hypothetic scenarios related with technical development of equipment, as well as capital and O&M costs. In connection with the equipment capital cost and its possible variations in fuel cells technologies, Sanghai (2013) studied its impact on the total annualized cost for individual applications such power reserve and load shifting. With regards a new concept that relies on wind farms operating at the same time as hydrogen station for transport (Wind-H_2 stations), Korpas and Greiner (2007) undertook a technical analysis of a Wind-H_2 station integrated in weak grids. Others have focused more in estimating the hydrogen production cost of a Wind-H_2 system composed by one turbine as well as evaluating the equipment size that accomplishes the economical optimum, based on the previous Spanish framework (Royal Decree 661/2007) (Mengibar, 2011). Furthermore, Charles, et al. (2009) carried out a techno-economic analysis of a Wind-H_2 system regarding two different energy management strategies. The first one consist of supplying the demand by the system in a weak grid meanwhile the latter relies on providing a constant power for a fix amount of time by integrating the electrolyser in a well connected grid in Scotland.

Nevertheless, there is a lack of research in economical analysis of large wind farm integrated with hydrogen storage and based on PEMFC technologies, especially within the current Spanish framework regulated by the *Royal Decree-law 9/2013 12th July*. Even more, when comparing different energy management strategies such combining both electricity and hydrogen trade in different levels.

1.2 Purpose

Given the above paragraph, the aims of the present dissertation are as follows:

- ✓ Develop a model for undertaking a technical and economic analysis of a Wind-H_2 system with different energy management strategies based on the current Spanish economical framework for renewable energy generation.
- ✓ Study the economical feasibility of wind farms in Spain, regarding the *Royal Decree-law 9/2013 12th July* that regulates the electrical production from renewable energy resources.
- ✓ Analyze the technical and economical feasibility of different Wind-H_2 systems sizes based on PEMFC technology regarding the aforementioned framework for three different energy management strategies:

- Load following
- Load following coupled with hydrogen trade
- Only hydrogen trade (Selling all hydrogen produced)

✓ Evaluate the necessary equipment cost reduction and technological development in order to guarantee the economical feasibility of Wind-H_2 system in Spain.

1.3 Objectives

In order to achieve the aforementioned aims of the present dissertation, the steps that have been undertaken during the whole project are the followings:

1. A literature review was carried out for understanding the Spanish energy market and the new economical framework applied to renewable energy systems. Moreover, it was reviewed the operation of Wind-H_2 system, different hydrogen equipment and its most important features for designing the model.
2. Real and predicted wind speed for a specific area of Spain was collected.
3. A simulation model was designed based on the wind data, equipment selected, system control strategy and Spanish framework.
4. A simulation of each case study aforementioned using HOMER has been undertaken, providing technical results.
5. An economical analysis for each case has been performed based on the technical results obtained.
6. Final conclusions have been drawn from the results obtained in the dissertation.

A schematic explanation of the steps described above can be seen in the following picture:

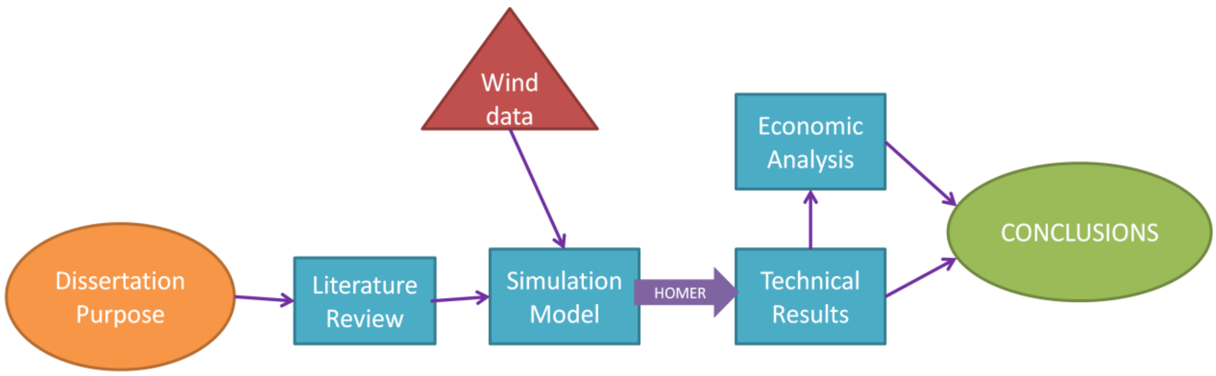


Figure 1. Dissertation methodology

2 LITERATURE REVIEW

2.1 Spanish Energy Policy

During the last decades, the European Energy Policy has been influenced by the increasing evolution of oil prices as well as its heterogeneous geographical distribution which lead to high energy dependence. Furthermore, the recent environmental concerns within the governments and population, the intense economic development pursued by governments and the energy market liberalization have also characterised the framework of the European Energy Policy.

With regards the Spanish Energy Policy, apart from being in line with the European Energy Policy it has been directed to solve the main challenges that had undermined the Spanish energy sector for the last 30 years, which are:

- High energy intensity, greater than the average energy intensity within the EU.
- Strong energy dependence on fossil fuels, due to the shortage of oil and gas deposits as well as high extraction cost of coal.
- High green house gas emissions caused by the increasing energy demand and transport.

Accordingly, the Spanish Energy Policy has targeted to ensure electrical supply meanwhile reducing the external energy dependence, improve the competitiveness of Spanish economy with special attention to the energy intensity, and promote sustainable development of economic, social and environmental aspects. Therefore, the framework of this energy policy has been characterised by the following core guidelines:

- Promoting the development of renewable energy, especially solar and wind energy due to its high potential across the Spanish peninsula. With this regards, the government has established the “Renewable Energy Promotion Plan 2000-2010”, “Renewable Energy Plan 2005-2010” and the current “Renewable Energy Plan 2011-2020” which aims to accomplish 20% of electrical generation coming from renewable energy in terms of primary energy and 10% of energy consumption in the transport sector.
- Boost improvements in energy efficiency and savings in both supply and demand side through the Savings and Energy Efficiency Strategy 2004-2012.

This aimed to reduce energy intensity to EU levels, coupled with the construction of combine cycle power plants although it has been constrained by the economical crisis.

- Both electrical and gas interconnection with France, Portugal and Argelia as well as improvements in electrical transmission infrastructures and gas transport facilities.
- Liberalization of the Spanish electrical and gas supply, accordingly with the European Directives in terms of electrical market liberalization (Mengíbar, 2011; Folgado, 2003).

2.2 Economic Regime of Renewable Energy in Spain

As other economical activity, wind farm management aims to maximize revenues and optimize the operating cost maintaining high availability of wind turbines and ensuring long lifetime of equipment. Revenue maximization is derived from the sales of the electricity generated by the wind turbines.

In Spain, wind energy sales is regulated by the *RDL 9/2013 12th July*, that repeals the *RD 661/2007*, *RD 1578/2008* and article 4 of *RDL 6/2009* and also modifies the *Law 54/1997, 27th November*, establishing a new legal and economic regime for the production of electrical energy in Spain based on the following principles:

- The repeal of the *RD 661/2007* eliminates the "Special Regime" for renewable energy system which is based on a specific Feed-In Tariff for the different types of renewable energy systems and its priority access to the grid. As a consequence, renewable energy systems shall compete with the rest of technologies in the Energy Market regulated by the *Law/54/1997* (Electrical Sector Law).
- In order to compensate the revenue reduction of renewable energy operators derived from the abolition of the Feed-In Tariff, a specific remuneration will be paid to the operator company in order to equate them to the rest of technologies, regulated by the "Ordinary Regime", allowing them to compete on equal conditions and obtain a "reasonable profit". This additional remuneration will be calculated for the lifetime of the wind farm, considering the revenue associated

with the electricity sales in the energy market, average operating cost of the wind farm, its power rated and the initial investment associated only with the energy production. Moreover, renewable energy operators will only be entitled to this remuneration in case of being an "efficient and well managed company" and registered in the Registry of Remuneration Regime managed by the Ministry of Industry, Energy and Tourism (Boletín Oficial del Estado, 2013)

2.2.1 Remuneration mechanism for electrical energy produced by renewable energy systems in Spain.

Regarding the legislation aforementioned, renewable energy shall compete with the rest of technologies in the Daily Energy Market organized by a private entity called Electrical Market Operator (OMEL). In this way, the hourly price of the electricity coming from renewable is that resulted from the energy auctions between electrical sellers and purchasers for each hour of the day, known as Daily Market Price (PMD, "Precio del Mercado Diario"). These 24 auctions are carried out the day before the electricity is generated. Apart from this market, in Spain there are Long Term and Intra-daily Markets. However, the present case study considers that the electrical production of the wind farm is trade only in the Daily Energy Market (Energía y Sociedad, n.d.) (www.omelholding.es, n.d.). For more information about energy markets in Spain and auction process between sellers and purchaser visit:

http://www.energiaysociedad.es/detalle_material_didactico.asp?id=18&secc=5
http://www.omelholding.es/omel-holding/

Furthermore, the *Royal Decree 436/2004* requires wind farm operators to submit power generation estimation to the market operator (OMEL), in order to improve the energy traded in the Daily Market and optimize its management enhancing the matching with the energy demand. It should be noticed that apart from the prediction of the wind speed for the wind farm site, other commercial factors are involved in the trade process which are not considered in this project due to its confidential and complex nature.

These wind speed predictions rely on complex statistic and physical models that take into account past and current weather conditions, altitude, temperature, orography, etc. Moreover, there are different types of wind speed modelling whose explanation is out of the scope of this project. Once the wind speed prediction is obtained, estimation of the power generated by the wind farm is worked out through the power curve of the turbine facilitated by the manufacturer, considering also the unavailability of wind turbines due to maintenance works, equipment fails, etc.

Nevertheless, the stochastic nature of the wind speed causes deviations between the real power generated and predicted by the wind farm. What is more, as the wind power generated by the turbine is proportional to wind speed to the third power, small deviations of the wind speed lead to big deviations in the power output of the wind turbine. These excess or deficit of electricity is accommodate by the Spanish grid operator *Red Electrica de España (REE)* by reducing or rising as required power production of other generators, using reverse energy systems such as hydro-pumped storage power plants, etc. As a result, the grid operator incurs a cost derived from the sell and purchase of electricity at a different price respect the PMD established for that time. This cost is known as Deviation Cost which can be "up" or "down" depending on the type of deviation (excess or deficit respectively). This Deviation Cost is proportional to PMD and it is derived from a complex calculation whose description is out of the scope of this project. Further information about the calculation process of Deviation Cost can be review in the work of Matres (2006).

The wind farm operator is responsible of assuming this deviation cost if the deviation exceeds 5% of the predicted power. Otherwise, it is assumed by the energy demand side as reduction of the remuneration derived from deviations. This penalization of energy deviations is resulted by multiplying the energy deviation (that can be "up" or "down" when there is excess or deficit of power generation respectively) and its cost in absolute value. In addition to this, the aforementioned penalization also depends on the energy balance of the system leading to two possible scenarios:

- Power deviation settlement is favourable for the system: the power deviation of the wind farm matches the direction of the energy balance needed by the system. In other words, if the wind farm has a "settlement deviation up" and the system requires increasing electrical production or if the wind farm has a "settlement deviation down" and the system requires reducing electrical generation. In this case, the Deviation Cost is cero.

- Power deviation settlement is against the system: the power deviation of the wind farm is contrary to the direction of the energy balance needed by the system. In other words, if the wind farm has a "settlement deviation up" and the system requires reducing electrical production or vice versa. In this case, the Deviation Cost is higher than cero and depends on the PMD for that time as explained above.

Moreover, the Deviation Cost settlement can be carried out in two ways: consolidated Deviation Cost settlement by settlement subject, which depends on the total deviation of the program units or settlement of each program unit. The economic analysis undertaken in this project will be based on the latter.

The final remuneration that wind farm operator receive, results from the balance of the settlements associated to OMEL (for the power contracted), REE (for the deviation penalizations) and National Energy Commission (CNE) (Matres, 2006; Moreno, 2009).

2.3 Wind Energy Contribution to the Spanish Energy Sector

Energy policies designed by the government to foster the development of renewable energy production in Spain have lead to successful results. Therefore, the renewable energy installed in Spain has grown from 3518 MW in 2000 to 46486 MW in 2012, becoming the predominant energy resource with a 29.7% of annual electrical contribution. What is more, this increment has been driven mainly by the wind and solar energy, depicting 14.5% and 3.1% of the renewable energy generation in 2011 (Red Eléctrica de España, 2000; Ministerio de Industria, Energía y Turismo, 2012).

Focusing in wind energy, the following chart shows the annual increment of wind power capacity installed in Spain over the period 1998-2012, covering the 17.41% of energy demand just below nuclear (22.21%) and coal (19.78%) power stations (see Figure 2). What is more, in March 2011 wind power reached the first position in power supply with a 21% of the energy demand (Red Eléctrica de España, 2011; idea.es, 2013; Mengíbar, 2011).

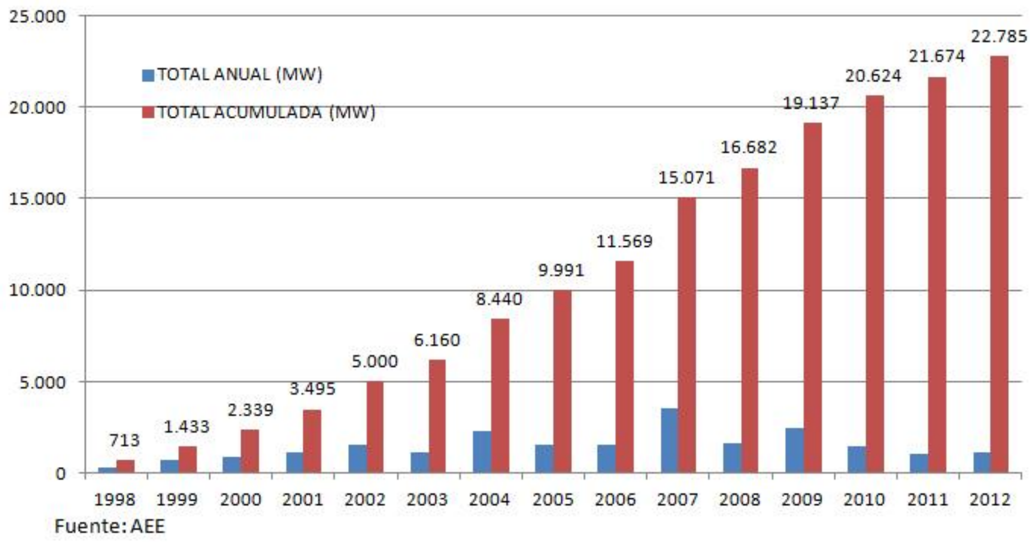


Figure 2: Annual and cumulative evolution of wind power capacity 1998-2012 (Agenciaandaluzadelaenergia.es. 2012)

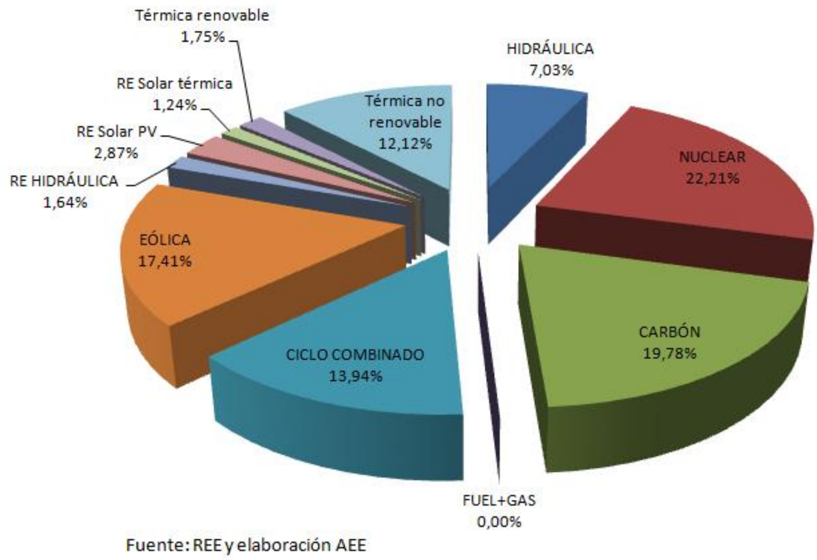


Figure 3: Coverage of electrical energy demand in 2012

A parameter for representing the utilization of the power capacity related to energy systems is the load factor, defined as the relation between the power generation of the energy system during a specific period of time and the power generation working at rated power during the same period. With regards Spanish wind farms, their average load factor was 24% in 2012, being a poor value if compared with other technologies as nuclear or coal power stations (Mengíbar, 2011).

The following table shows the typical values of load factor associated with different power technologies.

Typical Load Factors	
Wind farm	20-40%
Photovoltaic	10-15%
Hydropower station	60%
Nuclear power station	60-98%
Coal power station	70-90%
Combined gas cycle power stations	60%

Table 1: Typical load factor values associated with energy systems (Mengíbar, 2011)

This poor load factor associated with wind farms is mainly due to:

- The randomness of renewable energy generation induces electrical grid instability and electrical quality deterioration. Therefore, the renewable energy generation is controlled by grid operator as required in order to avoid these problems.
- Traditional power stations, which are working near the lower technical limit and cannot be disconnected from the grid (e.g. nuclear power stations) has priority for injecting power to the grid.
- The randomness and unpredictability nature of the wind. This issue makes the supply and demand matching with wind energy very difficult to achieve. For example, there are periods with higher power generation than grid energy demand, especially at night, when the grid operator must disconnect turbines to avoid stability problems in the grid. On the other hand, other times the power output of wind farms is lower than required by the grid, needing an energy backup for offsetting that energy deficit.

Nowadays, the most suitable solution for increasing the load factor of wind farms seems to be the integration of energy storage in wind farms (Mengíbar, 2011).

2.4 Energy Storage for Wind Farms

The use of energy storage systems (ESS) in wind farms would result in a more reliable electrical supply and more flexible power plants, with energy shifting from peak to off peak demand periods. This would prevent the necessity of an energy backup and reduce the energy dissipation due to grid constraints, being this limit equivalent to 5% of power excess respect the short-circuit power at the point of common coupling, in the case of Spain (Aguado, et al., 2009).

In addition to this, ESS has other benefits related to electrical quality as follows (Díaz, et al., 2011; Sanghai, 2013; Korpaas, 2005):

- To control voltage and frequency variations at the connection point of the wind power plant, preventing the wind farm disconnection from the grid.
- To protect the dc-link of the converter from over-voltage.
- To mitigate power oscillations of the system, caused by the system disturbances as a result of high penetration levels of wind power to the grid, through the control of the active and reactive power.
- To operate as spinning reserve, if power plants are required to regulate their active power for up to 30 minutes in order to control system frequency.

With regards the energy storage technologies that are currently in commercial or developing state are shown below (Díaz, et al., 2011):

- Pumped hydro storage (PHS)
- Compressed Air Energy Storage (CAES)
- Battery Energy Storage System (BESS)
- Flow Battery Energy Storage System (FBESS)
- Hydrogen-based Energy Storage System (HESS)
- Flywheel Energy Storage System (FESS)
- Superconducting Magnetic Energy Storage (SMES)
- Supercapacitor Energy Storage System

This study will focus on energy storage systems based on hydrogen, mainly due to its flexibility as it can supply electricity through a fuel cell or being used directly in many applications such as chemical processes, transportation, synthetic generation of methane, etc. Moreover, this technology can storage big amount of energy during long terms because of the high energy density of hydrogen and the available hydrogen storage technologies.

2.5 Hydrogen as an Energy Vector

Due to hydrogen is not an energy source by itself but a primary energy carrier, it is considered as “energy vector”. In the mid-eighties, the concept of a “Hydrogen Economy” has arisen, based on an energy model in which hydrogen would constitute the link between primary energy sources and consumers.

Nowadays, the transition to the “Hydrogen Economy” has already started, since US and EU have established guidelines that includes the state-of-art of hydrogen technology and challenges to overcome in order to reach the hydrogen energy vector target by 2050. Moreover, the *Joint Technology Initiative (JTI)* has been set up in order to promote and support hydrogen projects in EU.

The EU guidelines expect a large scale hydrogen production from renewable energy by 2020, and thus the current hydrogen projects are mostly oriented to integrate wind farms with hydrogen storage in order to develop a technical and economical feasible wind-hydrogen technology (Pino, 2010). Therefore, listed below are the some of the most important Wind-H_2 projects along the world that seek to prove the feasibility of hydrogen as energy storage in wind farms and develop new control strategies that favours a higher wind energy penetration in the energy sector (Pino, 2010).

- Hidrólica (Spain): its construction started in 2007 in Tarifa (Cádiz) and it is currently in operation. The project aims to analyse the equipment behaviour being connected to the grid. That is why the hydrogen equipment is not well dimensioned for the wind farm size. The project comprises a wind farm of 80 MW, PEM electrolyser of 60kW, a two compressed hydrogen storage tanks of 82.5 Nm^3 at 15 and 10 Nm^3 at 200 bar respectively, and also a PEMFC of 12 kW.
- Sotavento Project (Spain): it is in operation since 2008 in Galicia, and aims to match energy supply and demand aided by hydrogen storage. The system is

composed by a wind farm of 17.56 MW, a 288 kW alkaline electrolyser of 10 bar, a compressed hydrogen storage tank of 1960 Nm^3 at 200 bar and internal combustion engine connected to a electrical generator of 55 kW.

- ITHER Project (Spain): the Technological Infrastructure for Hydrogen and Renewable Energy project (ITHER) set up in 2005, study the construction and operation of a hydrogen storage integrated with a range of renewable energy systems (PV and wind energy). The project comprises 100 kW of PV arrays, three wind turbines (80, 225 and 330 kW), an alkaline electrolyser of 63 kW and other PEM electrolyser of 7kW, a metal hydride storage at 350 bar and a 1.2 kW fuel cell.
- RES2H2 (Spain-Greece): known as "Cluster Pilor Project for the Integration of RES into European energy sectors" and funded by the V European Union Framework program. The project comprises two Wind-H_2 systems, one in Canarias Islands (Spain) set up in 2005 and the other in Lavrion (Greece) operating since 2007. The main purpose of the project is to optimize the integration of wind farms coupled with hydrogen storage in weak grids and prove the economical feasibility of hydrogen production from wind energy.
- HARI Project (United Kingdom): it was base in the West Beacon Wind Farm (Loughborough) and was in operation between 2001 and 2006. Its objective was to produce hydrogen by water electrolysis aided by the electrical surplus of the West Beacon, White Hill Wind Farm and an experimental PV array. The project comprised two wind turbines of 25 kW, a 13 kW PV array, two micro hydro-turbines of 3kW, a 34 kW alkaline electrolyser at 25 bar, a compressed hydrogen storage tank of 2856 Nm^3 and two PEMFC of 2 kW (with heat recovery) and 5 kW.
- UTSIRA Project (Norway): located in the Utsira Island, it was operating between 2004 and 2006. Its target was to achieve the match between energy supply of a wind farm and demand of the total Island aided by hydrogen storage. The system consisted of two wind turbines of 600 kW, a 50 kW electrolyser, a compressed hydrogen storage of 2400 Nm^3 at 200 bar, a PEMFC of 10 kW and internal combustion engine of 10 kW adapted to hydrogen.
- Prince Edward Island Project (Canada): it consists of an experimental hydrogen storage system that processes the electrical supply of the North Cape Wind Farm

situated in the island. The hydrogen produce will supply two electric buses based on a PEMFC. The project is currently in development phase that will comprise an alkaline electrolyser of 66 Nm^3/h at 17 bar, two compressed hydrogen storage tank (4000 Nm^3 at 17 bar and 112 Nm^3 at 430 bar) and a internal combustion engine combined with a electric generator of 120 kW.

- Wind2H2 (United States): the project is undertaken by the National Renewable Energy Laboratory and aims to evaluate the electrolyser behaviour when connected with wind turbines, develop control strategies that optimize hydrogen production and identify issues for curtailing costs and improving efficiency. The system is composed by two wind turbines (100 kW and 10 kW), a PV array of 10 kW, two electrolysers (PEM of 7 kW and alkaline of 40 kW), compressed hydrogen storage of 1000 Nm^3 at 250 bar, a 5 kW PEMFC and internal combustion engine suitable for hydrogen with 40 kW of rate power.

It should be mentioned that the promoters of these projects are reluctant to publish the data and results gathered during the lifetime of the project.

2.6 Wind-H_2 System Components

Apart from provide a more accurate adjustment of the wind power generation to the energy demand, integrated wind farms with h_2 storage systems increase its flexibility in terms of energy consumption. Therefore, the energy output of the wind farm can be both electricity and h_2, suitable for a wider range of applications than a conventional wind farm. However, it should be keep in mind that the main objective of a Wind-H_2 system is generating electricity directly from the wind turbines, unless the power output exceeds the power contracted by the wind farm operator and overcome the safe operating limit of the grid.

With regards its components, a Wind-H_2 energy system consists of the following equipment:

- Wind Turbine: it transforms the primary energy (wind kinetic energy) into electricity. The electrical output of the turbine depends on the wind speed, defined by its power curve. For economical and safety reasons, this power curve presents a cut-in and cut-off point, marking the minimum and maximum operation conditions of the turbine respectively.

Moreover, this transformation has efficiency, known as *power coefficient (Cp)* defined as the energy fraction contained in the wind that is converted into electricity. What is more, this power coefficient depends on the available wind power and rotor design (diameter and pitch angle), and it is usually represented by a graph as follows:

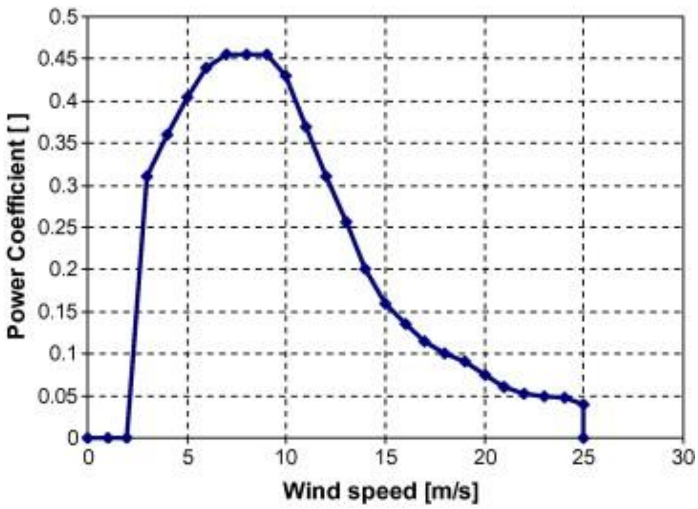


Table 2: Cp vs wind speed (Basbous, et al., 2012)

As can be seen in the graph, the highest energy conversion efficiency of a typical wind turbine is 45% approximately at 9 m/s, coinciding with the range of most frequent wind speeds. Furthermore, at low wind speeds efficiency is not so important due to the poor energy content of the wind. In the same way, the turbine efficiency at high wind speeds decrease dramatically in order to waste any excess of energy above the design turbine conditions in order to prevent unsafe turbine operation.

It should be noticed that the aim of a wind farm is extract kilowatt hours of the wind at the lowest cost during the next 20 years, rather than having a high technical efficiency of a the wind turbine, due to the fuel in this case is free. Thus, the optimal wind turbine does not have to coincide with the highest energy output per year. However, as each metre square of the rotor costs money, it is desirable to collect the greatest amount of energy as long as the kilowatt hour cost is maintained down (Angel, 2012).

- Hydrogen electrolyser: it carries out the water decomposition into its components, hydrogen and oxygen, through the electrical current (electrical surplus generated by the turbine) between two electrodes in presence of an electrolyte. This chemical reaction known as electrolysis is defined by the following equation (Pino, 2010):

$$H_2O\ (l) + \text{Electricity} \longrightarrow H_2\ (g) + \frac{1}{2} O_2\ (g)$$

This global reaction can be conducted through different sub-reactions leading to three types of electrolyser: alkaline, proton exchange membrane or solid oxide electrolyser. The following picture shows a schematic explanation of the reaction process carried out by the two commercial electrolysers currently available:

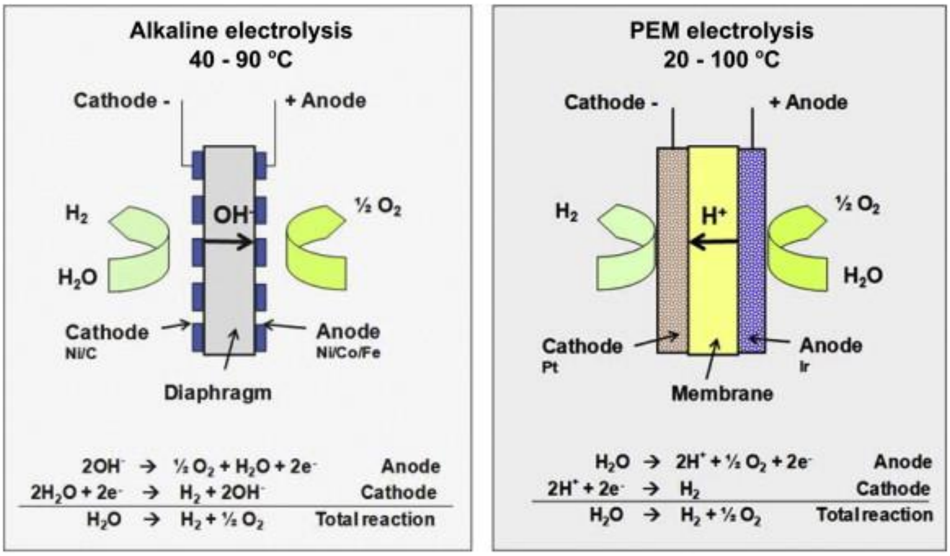


Figure 4. Schematic of the operating principle of an alkaline and PEM water electrolysis cell (Carmo, M; Fritz, D; Mergel, J et al.; 2013)

Furthermore, the oxygen and hydrogen production of the electrolyser is a function of time and it is expressed by the Faraday Law as follows (Sandoval, 2006):

$$m = \frac{It}{nF}$$

where,

m: moles of hydrogen/oxygen produced per unit of time (mol/s)

I: current [A]

t: time [s]

n: number of electrons

F: Faraday´s Constant [96485 C/mol]

Moreover, combining this equation with the Ideal Gas Equation results in the following equation that defines the volumetric production of hydrogen as a function of the electrical load:

$$V = \frac{IRT}{nPF}$$

where,

V: is the volume of hydrogen/oxygen produced per unit of time (m^3/s)

R: Universal Gas Constant [0.08205 atm L/K mol]

T: temperature [K]

P: pressure [atm]

Regarding these equations, there is a lineal dependence between the hydrogen production and power consumption of the electrolyser as can be seen in the following graph:

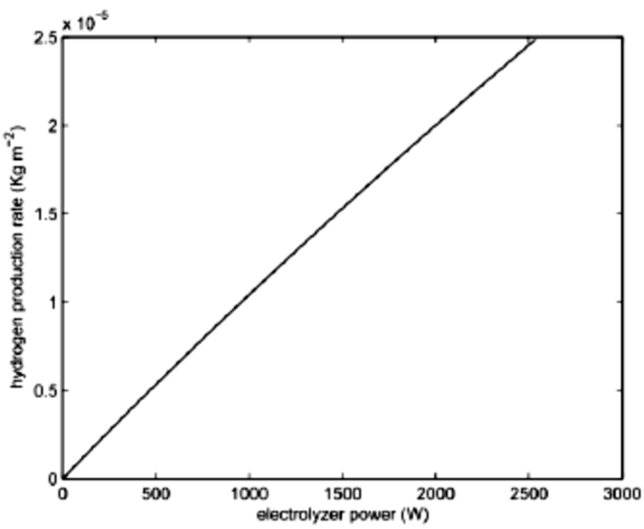


Figure 5: Relation between hydrogen production and power consumption of the electrolyser (Mengíbar, 2011)

Frequent starts and stops of the electrolyser affect negatively to its performance and lifetime which depends on the type of electrolyser. Therefore, an adequate control strategy is necessary to prevent these operating conditions (Korpaas, Greiner & Holen, 2005). With regards its efficiency, calculated as the relation between the energy required for undertaking the electrolysis reaction (high heating value of hydrogen) and the real amount of energy used by the electrolyser to do so, which varies between 60-90% depending on the electrolyser type (Mazloomi, et al., 2012; Tsiplakides, 2011; Anon, 2011; Charles, et al., 2009).

Another operational constraint is the minimum power load required for the start up of the electrolyser which is approximately 15% of its rate power output (Mengíbar, 2011).

Furthermore, there are two main types of commercial electrolysers, alkaline or PEM electrolyser with power capacities between 20 kW-160 MW (Godula, Jehle and Wellnitz, 2012) and 5-50 kW (Priego, 2009) respectively. Regardless the type of electrolyser, the main components that comprises a range of stacks are the followings:

- Two electrodes, one cathode and one anode where the electrical power is applied.
- An electrolyte that determines the type of electrolyser. This can be acid (based on a proton exchange membrane) or alkaline electrolyte. The benefits of the PEM electrolyser are associated with its solid nature in contrast with the liquid nature of the alkaline electrolyte. These benefits are more safety and reliability, good response to fluctuating electrical inputs, it achieves high pure hydrogen (up to 50 bar) and it requires lower operating voltages of the stack due to the reduction of ohmic losses in the membrane. However, PEM electrolyser has lower capacities than alkaline electrolysers (between 0.1-10 Nm^3/h), is more susceptible to corrosion and electrode deactivation, resulting in high maintenance cost and small life time of 6000 hours approximately. On the other hand, alkaline electrolysers are the most mature and cheapest technology, with

high capacities (up to 800 Nm^3/h) and long lifetime up to 10 years. Nevertheless, its liquid nature increases its susceptibility to leakages and undermines its response to fluctuating electrical inputs, increasing energy wastage when integrated with renewable energy systems. What is more, the gas products can contain traces of electrolyte and its operation pressure is limited to 30 bar requiring auxiliary depuration and compression equipment. (Swalla, D; Sink C.; Bates, M. et al., 2008; Reissner, 2010, Charles, et al., 2009)

- A diaphragm or membrane, depending on the electrolyser type, that prevents the substance mixture between the anode and cathode sides.

Another consideration should be taken in the election of the stack type. The electrolyser stack can be unipolar or bipolar. Unipolar stacks are cheaper due to its easy construction, operation, maintenance and low energy consumption of the water pump (because of its operation at low pressure). On the other hand, bipolar stacks can be pressurized avoiding the installation of low-medium hydrogen compressors and hence increasing the efficiency of the system. Moreover, its stack connexion is easier than unipolar stacks, the water pump consumption is higher (as consequence of the higher operating pressure) and it presents greater parasite currents which force to install stronger electrical protections (Pino, 2010).

A comparison between the electrolyser options commercially available regarding their key characteristics is displayed in Table 3:

			Capital and O&M cost	Power Capacity	Lifetime	Good response to fluctuations	Efficiency	Safety	H_2 purity
Electrolyser	Electrolyte	ALKALINE	+++	+++	+++	+	++	+	++
		PEM	+	+	+	+++	++	+++	+++
	Stack	Unipolar	+++				+	+++	
		Bipolar	+				+++	+	

Table 3. Electrolyser technologies comparison

- Hydrogen storage: the types of H_2 storage mostly used in renewable energy applications are:
  - *Pressurised hydrogen storage*: hydrogen can be stored at either medium or high pressure, in vessels, tanks or underground. However, the most common storage system is pressurized tanks at 200 bar.
  - *Liquid hydrogen storage*: this technology is suitable for storing large quantities of hydrogen. For obtaining hydrogen at liquid state, the storage temperature must be maintained at -253 ºC, which requires a cooling and compressing process, very energy intensive, as well as insulated and reinforced materials to keep cryogenic temperatures and under-pressure conditions. Thus, the highly inefficiency of these processes coupled with expensive tanks required, make this technology the least cost effective.
  - *Metal hydride storage*: specific combinations of metallic alloys storage hydrogen and release it when required at constant pressure in safe way due to the low storage pressure (2 bar approximately). Moreover, the charging reaction is mildly exothermic meanwhile the absorption process requires some cooling. The life time of a metal hydride is conditioned by the hydrogen impurities, which fills the spaces in the metal that were occupied by hydrogen. However, this prevents fuel cell to be damage due to impurities. Another advantage of this technology is the low volumetric storage capacity compared with the rest of methods (Larminie et al., 2003; Tsiplakides, 2011)

- Fuel cell: it combines hydrogen and oxygen to produce water generating an electrical current between electrodes through the reverse electrolysis reaction carried out by the electrolyser. In this way, the anode in presence of a catalyst undertakes the separation of hydrogen into protons and electrons. The latter flows through an external circuit to the cathode whereas positive ions travel to the cathode side through the electrolyte. In this process, thermal energy is generated which is susceptible of being used, increasing its global efficiency. The main types of fuel cells regarding its electrolyte are:

- *Polymer Electrolyte Membrane (PEM):* its components are those of the PEM electrolyser. This type of electrolyte allows operating temperatures between 85-105 ºC favouring high current and power density in the system, which benefits a compact design, lightweight and quick start-up time compared with other fuel cells. Moreover, the solid nature of the electrolyte is less prone to corrosion than liquid electrolyte resulting in economical maintenance cost and longer lifetime (Sanghai, 2013). Typical stack sizes available are between 1-100 kW (National technology laboratory, 2004).
- *Alkaline (AFC):* it is based on a liquid electrolyte (potassium hydroxide) with low operating temperatures (90-100ºC). It has the greatest electrical efficiency among fuel cells but it can work only with pure gases and requires carbon dioxide concentrations in the feed. For this reasons, it is considered too expensive for commercial applications (Sanghai, 2013). Typical stack sizes available range from 10 kW to 100 kW (National technology laboratory, 2004).
- *Phosphoric Acid (PAFC):* it consists on a liquid electrolyte with high concentrations of phosphoric acid and low operating temperate in the range of 150-200 ºC. It is the most advanced fuel cell, reliable and mostly used in applications of about 1 MW, especially in stationary power plants (Sanghai, 2013).
- *Molten Carbonate (MCFC):* it operates at high temperature in the range of 600-700 ºC in order to achieve acceptable conductivities and improvements in the oxidation-reduction processes. Nevertheless, this high operating temperature favours the cell corrosion, diminishing the life span of fuel cell components (Sanghai, 2013). Typical stack sizes available are between 300 kW-3 MW (National Technology Laboratory, 2004).
- *Solid Oxide (SOFT):* it is the latest high temperature fuel cell technology developed, operating in a range about 1000ºC and presenting high power densities as well as long start up time which makes it only suitable for stationary operation regimes. Its electrolyte comprises two-phase gas-solid system, preventing corrosion of components and eliminating the need of a water management system which is the main advantage against other fuel cell technology. However, this extreme operating temperature requires construction with costly ceramic materials, being the key for becoming

commercially feasible option (Sanghai, 2013). Typical stack size available varies from 1 kW to 2 MW (National Technology Laboratory, 2004).

Figure 6 and Table 4 show the operating principle and main features of the fuel cell technologies described above:

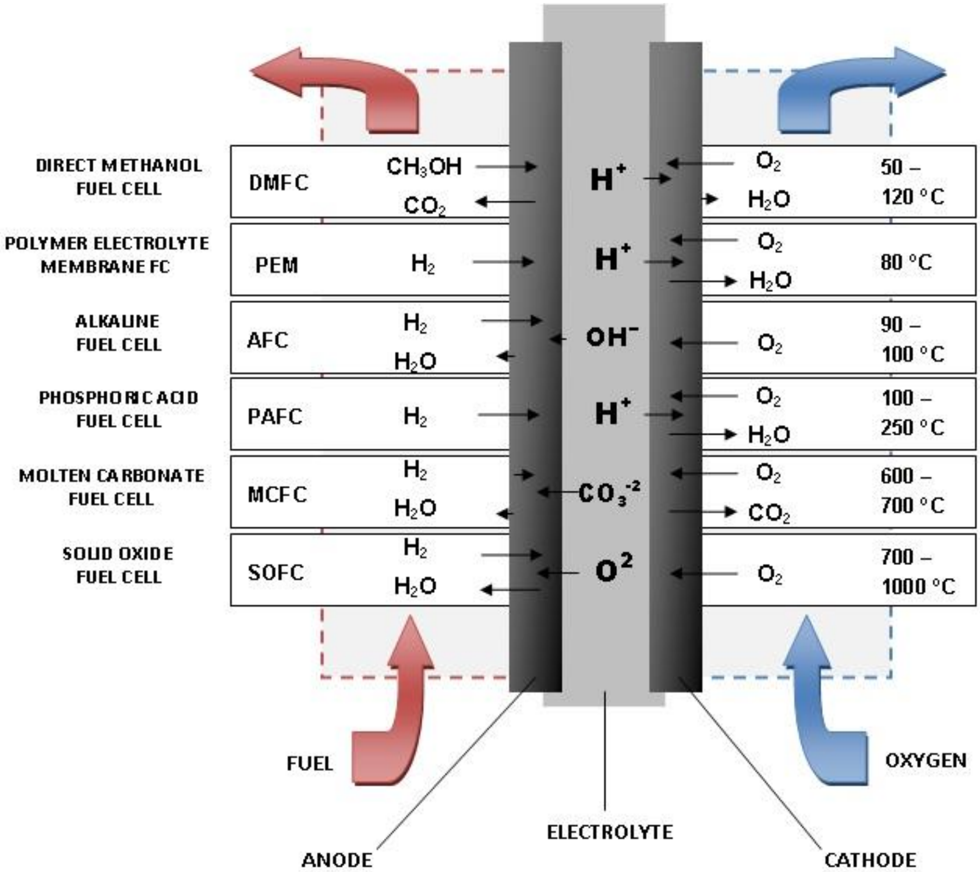


Figure 6. Operating principle of the different types of fuel cell (Fuelcells.org, 2013)

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Efficiency	Applications	Advantages	Disadvantages
Polymer Electrolyte Membrane (PEM)	Perfluoro sulfonic acid	50-100°C 122-212° typically 80°C	<1kW-100kW	60% transportation 35% stationary	• Backup power • Portable power • Distributed generation • Transporation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up	• Expensive catalysts • Sensitive to fuel impurities • Low temperature waste heat
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90-100°C 194-212°F	10-100 kW	60%	• Military • Space	• Cathode reaction faster in alkaline electrolyte, leads to high performance • Low cost components	• Sensitive to CO_2 in fuel and air • Electrolyte management
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a matrix	150-200°C 302-392°F	400 kW 100 kW module	40%	• Distributed generation	• Higher temperature enables CHP • Increased tolerance to fuel impurities	• Pt catalyst • Long start up time • Low current and power
Molten Carbonate (MCFC)	Solution of lithium, sodium, and/ or potassium carbonates, soaked in a matrix	600-700°C 1112-1292°F	300 kW-3 MW 300 kW module	45-50%	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP	• High temperature corrosion and breakdown of cell components • Long start up time • Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	700-1000°C 1202-1832°F	1 kW-2 MW	60%	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte • Suitable for CHP & CHHP • Hybrid/GT cycle	• High temperature corrosion and breakdown of cell components • High temperature operation requires long start up time and limits

Table 4: Comparison of Fuel Cell Technologies (U.S. Department of Energy, 2011)

A comparison between the fuel cell types commercially available regarding their key characteristics is displayed in Table 5:

		Capital cost	O&M cost	Power Capacity	Lifetime	Intermitent operation	Efficiency
FUEL CELL	PEMFC	+	+++	+	+++	+++	+++
	ALKALINE	+++	+	+			+++
	PAFC	++	+++	++		+	+
	MCFC	+	+	+++	+	+	++
	SOFC	+	+++	+++		+	+++

Table 5. Fuel cell technologies comparison

In addition to this, Wind-H_2 System comprises a control system that carries out the energy management based on the control strategy implemented. As electrolysers and fuel cells work with DC current, an AC/DC rectifier and DC/AC inverter are required to adjust voltages and intensity between wind turbines, hydrogen system and grid side. Furthermore, as the output voltage of a fuel cell stack depends on the load current which is very variable renewable energy systems, it requires a DC-DC converter that regulates these voltage variations, maintaining an output voltage of 400V equivalent to 120/240V AC (National Energy Technology Laboratory, 2004). Besides this, a compressor is required for storing hydrogen in a pressurized tank as well as a water pump for supplying water to the electrolyser (Sanghai, 2013).

The following picture shows a diagram of a typical Wind-H_2 energy system:

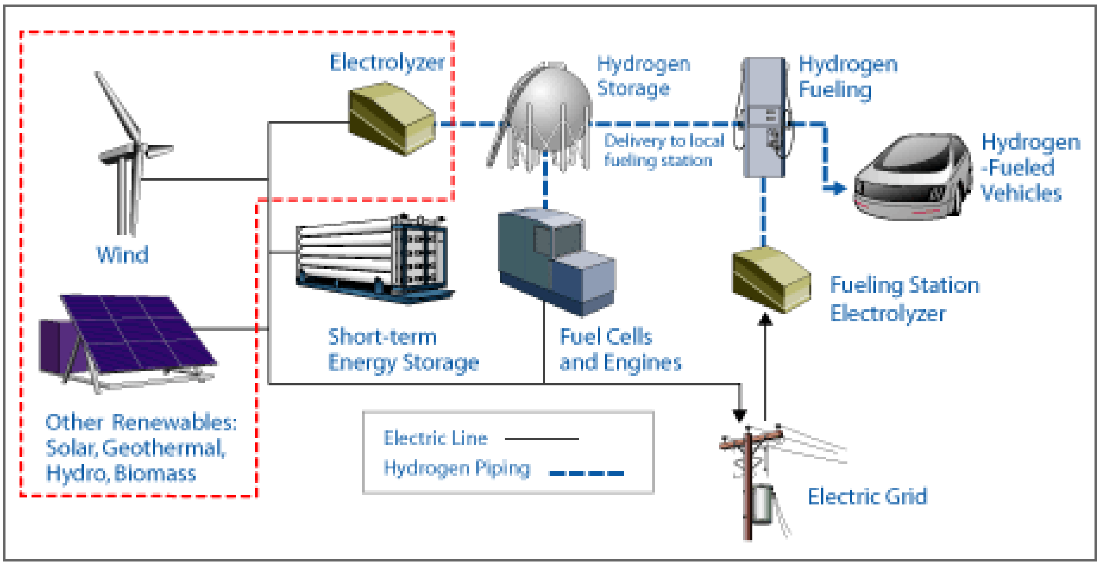


Figure 7: Configuration of a Wind-H2 energy system (Www1.eere.energy.gov, 2011)

2.7 Operating principle of a Wind-H_2 System

The integration of a wind farm with hydrogen technology aims to enhance the matching between the primary energy source (wind energy) and energy demand (either electrical or hydrogen demand) through the use of hydrogen as an energy storage medium. As a result, the wind farm operator carries out a different energy management strategy depending if the operator aims to reduce power deviations or optimize the revenue. Therefore, there are two main types of operating modes:

- *Load following mode*: it aims to reduce the penalization associated with the power deviation incurred by the wind farm respect the power contracted in the Energy Market.

  In this way, when the power production of the wind farm exceeds the power contracted for a specific period of time, the electrolyser absorbs that electricity surplus generating hydrogen which is stored. On the other hand, when the power production of the wind farm is lower that the power contracted, a fuel cell or internal combustion engine process the hydrogen storage, generating electricity that is injected into the grid. If there is a hydrogen load, other a combined Electrical-H2 load following mode can be undertaken, diverting part of the hydrogen for being sold. As this option avoids the energy losses associated with the fuel cell/internal combustion engine efficiency and the fact that hydrogen can be sold at a higher price than electricity, this project is going to study its profitability respect the electrical load following. However, it should be noticed that the hydrogen load following is conducted at the expense of the power deviations incurring in higher penalizations than electrical load following mode.

- *Maximization of revenue mode*: it consists of diverting electrical production of the turbine during low electricity price periods (off-peak hours) to the production of hydrogen. Thus, this hydrogen can be sold directly or being transformed into electricity when electricity price is high (peak hours) (Pino, 2010).

2.8 Modelling tools for studying Wind-H_2 systems

The modelling tools listed below are based on mathematical models that allow to analyse the performance and economics of wind farms integrated with hydrogen storage (Pino, 2010):

- HOMER (Hybrid Optimization Model for Electric Renewables): it was developed by the National Renewable Energy Laboratory (NREL) owned by the Energy Department of United States. It can perform thermodynamic and economic calculations of integrated renewable energy systems for different combination sizes. The calculation process consists of the defined system energy and evaluation of its demand meeting for each combination. Then, it works out the installation and operating cost of the system during its lifetime. The results are listed regarding its economical feasibility although in can be organized by its demand meeting by ignoring the economical inputs required by the software (Pino, 2010; Mengíbar, 2011).
- WindHyGen: developed by CENER (Centro Nacional de Energías Renovables) in 2006. Like the previous tool, it can perform a techno-economic analysis of integrated wind-hydrogen systems based on static mathematical models. However, it is currently in development phase for introducing dynamic

operation of equipment in order to implement it in wind farms as a management tool in real time.

- Merit: a computer simulation tool developed by the Energy Systems Research Unit (ESRU) at the University of Strathclyde. It can match different electrical demand profiles with a wide range of renewable energy systems and also it has integrated climate and demand data base (University of Strathclyde, 2013).
- HOGA (Hybrid Optimization by Genetic Algorithms): developed by the Electrical Engineering Department of the University of Zaragoza. Unlike the previous software, this is based on genetic algorithms intended to optimize the equipment components as well as the control strategy. More recently, a specific simulation tool called GRYSHO (Grid-connected Renewable Hybrid Systems Optimization) for integrating wind energy with hydrogen technology has been developed by the aforementioned department. This software relies on the same modelling than HOGA and it is not free software.
- THESIS (Tyndall Hydrogen Economy Scenario Investigation Suite): developed by Rutherford Appleton Laboratory, it aims to evaluate the economical, technical and environmental impact associated with the integration of energy systems coupled with hydrogen storage for electrical supply, transport and cold-hot applications.
- H_2 RES: developed in 2000 by the Technical Institute of Lisboa (Portugal) and the Mechanical Engineering and Naval Architecture College of Zagreb (Croacia). It has been designed for evaluating the integration of renewable energy and hydrogen technology in energy systems operating in isolation, like islands.
- Hydrogems: developed by the Technical Institute of Energy in Norway in 1995, it is currently integrated into TRNSYS software since 2006 and requires more interaction from the user.
- ESSFER (Simulation Setting of Systems based on Renewable Energy Resources): developed and owned by the Energetic Engineering Department of the University of Sevilla since 2002. Like Hydrogems it performs technical analysis meanwhile the economical analysis requires more interaction from the user.

After reviewing the simulation tools listed above, HOMER has been arisen as the most suitable software for the present study. The main reasons are its ability to undertake pure technical analysis, suitability for analysing different equipment combination sizes, the wide range of input data options, easy interface and free license.

3 Model Description

3.1 Calculation Process

The model for performing a technical and economic analysis described in this section particularises to a specific location and wind turbine model. However, it can be applied to other location within Spanish territory by introducing the new wind turbine inputs as well as wind data.

The following diagram explains the sequence of steps that comprises the calculation process carried out in the present dissertation. Furthermore, it can be seen the configuration of the model designed and the integration of inputs in it, which are going to be explained in the following sections.

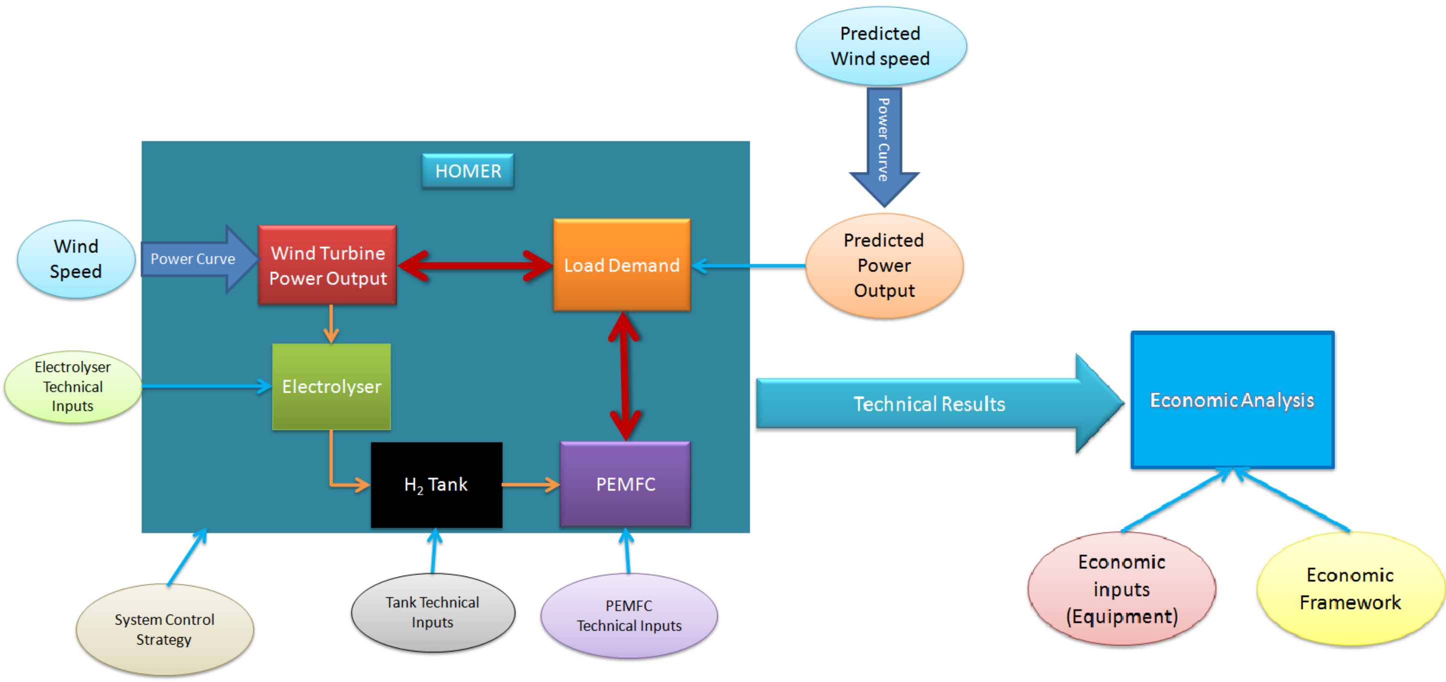


Figure 8. Calculation Process

3.2 Model Assumptions and Shortcomings

It should be noticed that the model to be simulated relies on the following assumptions:

- The predicted power generation of the wind farm coincides with the power contracted in the Daily Energy Market. Other commercial factors are ignored for the power contracted by the wind farm operator.
- All electricity is traded in the Daily Energy Market.
- The Daily Market Price is constant along the year and hence the penalization cost per unit.
- Penalization associated with deviations will be applied to the wind farm operator regardless its variation respects the prediction and all deviations are considered against the energy balance of the system.
- The excess of electricity generated is always injected into the grid (unless the wind farm without energy storage), incurring in penalization if applicable (unfavourable deviations). Hence, the grid operator does not have any control on the operation of wind turbines.
- Installation cost of equipment is disregarded. Only capital cost will be considered.
- The replacement cost of equipment is assumed to be equal the capital cost.
- An economy of scale is not considered for the calculation of equipment capital costs.
- The project is based on a hypothetic wind farm with a lifetime of 20 years.
- The interest rate for working out the Net Present Value is defined as 3%.
- The wind data collected in 2007 is assumed as wind data of the year 2012.
- The electrolyser efficiency is constant, regardless its power consumption.
- Compressor efficiency is 100%.
- The heat realised by the electrolysis reaction in the PEMFC is not used.
- The water pump and water consumption are ignored in the techno-economical analysis.
- The water is assumed to flow in close loop between PEMFC and electrolyser.
- A higher number of turbines in the economical analysis respect the simulations are considered in order to take into account non-ideal operating

conditions and unavailability of turbines caused by fails or maintenance works.

- When applicable, the H_2 load is assumed to be equal the H_2 generation over the maximum H_2 level of the tank predefined.
- The Wind-H_2 farm is simulated in HOMER as a stand-alone system, independent of the grid.
- All equipment sizes considered in the simulations can be installed through combination in series of commercial sizes.
- Equipment and facilities required for hydrogen discharge in tank trucks are ignored.

However, due to confidential and complex nature of some data as well as the limitations associated with the simulation software, the present model incurs in the following shortcomings:

- It does not simulate voltage and frequency stability of the grid, so all excess of electricity is assumed to be sold (unless the wind farm without energy storage case study).
- Commercial factors involved in the real energy market process are ignored and hence the power contracted in the Daily Energy Market matches the predicted power generation of the wind farm.
- As HOMER does not allow introducing variations in electricity prices, an average Daily Market Price is assumed for the whole year.
- The initial investment of each case study does not comprise installation costs, only capital costs.
- Equipment capital cost does not consider economy of scale.
- Constant electrolyser efficiency is assumed, despite that in reality it depends on the power consumption.
- The power estimation is obtained by multiplying the predicted power generation for one turbine by the total number of turbines considered.

3.2.1 Wind Resource

The hypothetical wind farm is placed at the location of a meteorological station near the wind farm “El Perdón” (further information is explained in *Section 4.1 Proyect Site*) This meteorological station records weather data each 10 minutes during the whole year which is published by the Government of Navarra in the following web page:

http://meteo.navarra.es/estaciones/mapadeestaciones.cfm

The data selected for the present case study consists of mean and maximum speed (each 10 minutes) as well as their direction at 10 meters height for the year 2007. The data has been processed with the WAsP Climate Analyst 2.0 software obtaining the graphs presented in Figure 11 and Figure 12 where wind speed is expressed in m/s and wind direction in degrees.

From this data can be deducted the high variability of the wind speed along the year 2007, in contrast to wind direction which has a predominant behaviour. The average wind speed is 7.80 m/s with a mean power density of 540 W/m^2. The Weibull distribution for this site has an “A” and “k” parameter of 8.8 and 2.05 respectively. Furthermore the wind rose of Figure 12 shows that a predominant wind direction of 0º with a frequency of 32.5% followed by 330º with 25.4%. Besides this, the direction 0º presents the highest mean speed (10.60 m/s) with an average power density of 999 W/m^2. The Weibull distribution associated with this direction shown in Figure 12 has an “A” and “k” parameter of 11.8 m/s and 3.15 respectively.

It should be noticed that during the first few hundred meters, the wind speed is strongly affected by the friction of the air with the earth´s surface. As this wind resource data has been recorded at 10 meters height and the hub height of the wind turbine considered is 60 metres, HOMER correlates that data to 60 meters height. For this purpose, HOMER offers to different formulas: logarithmic or power law. The logarithmic formula has been selected to carry out the calculations as it is more suitable for the data available and it has a theoretical basis in aerodynamics (Gilbert, M., 2004). The logarithmic formula is expressed as follows:

$$\left(\frac{v}{v_0}\right) = \frac{\ln\left(H/_z\right)}{\ln\left(H_0/_z\right)}$$

where,

v: wind speed at height H (in the case study 60 m)

v_0: wind speed at height H_0 (in the case study 10 m)

z: friction coefficient that represents the terrain characteristics due to its great impact on the friction with the air. The friction coefficient value introduced into HOMER for the specific site selected is 0.10 corresponding to a smooth hard ground which is published by the Institute for Diversification and Energy Saving (IDAE) in the following web page:

http://atlaseolico.idae.es/

Figure 9 and Figure 10 are screenshots of the Wind Resource Inputs section of HOMER. With this data and the power curve of the turbine that is going to be explained later on, HOMER works out the real power generated by the wind turbine.

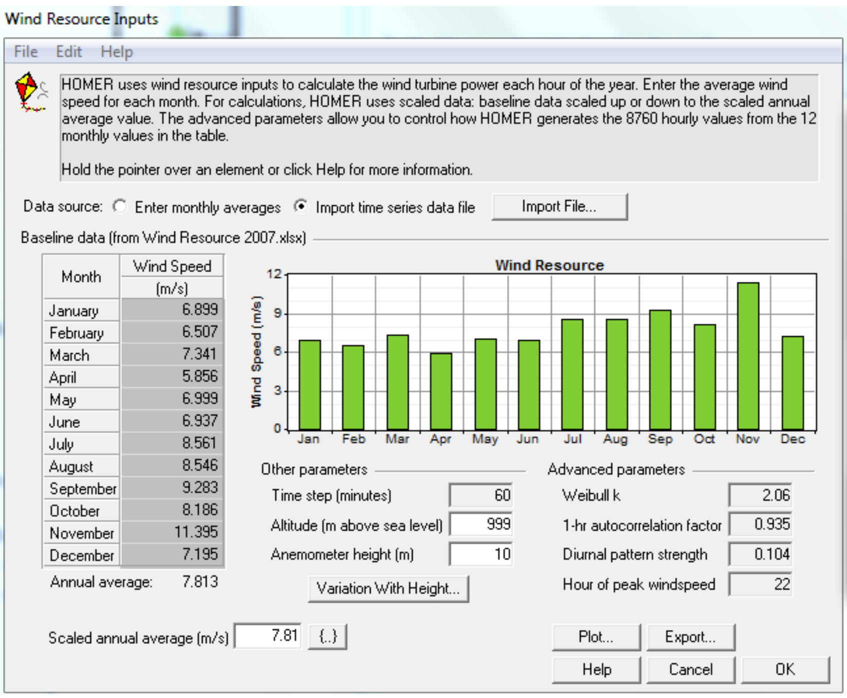


Figure 9. Wind Resource Inputs section of HOMER

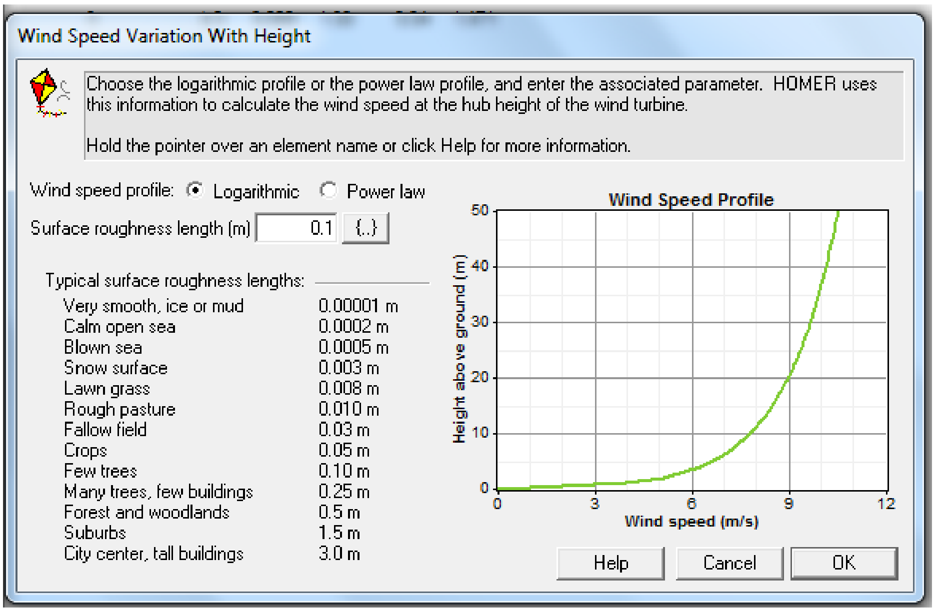


Figure 10. Wind speed variation with height section of HOMER

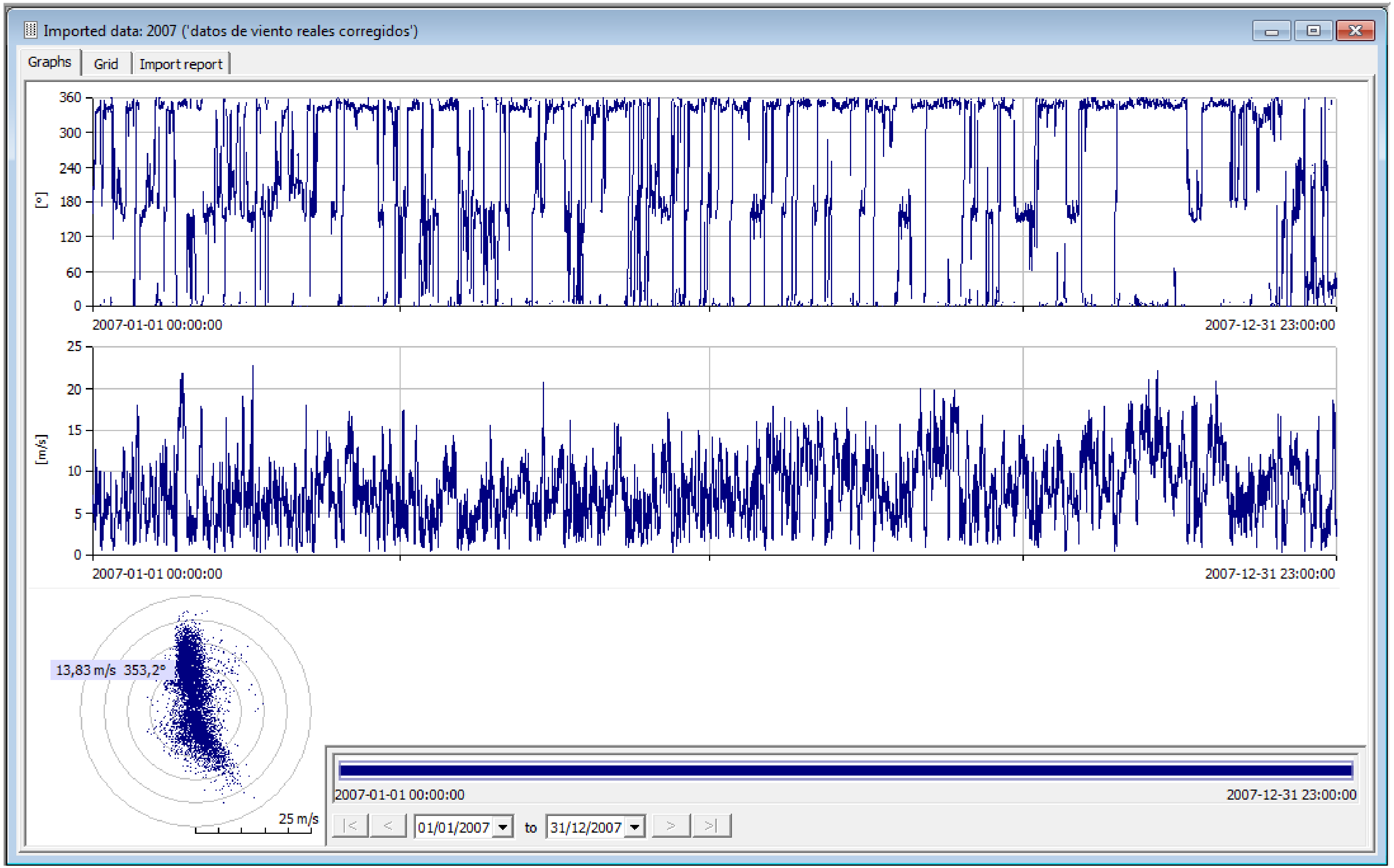


Figure 11. Mean wind speed and mean direction during year 2007

Climate | Histogram bins | Generation report | Statistics

Sector		Wind climate				Power	Quality	
number	angle [º]	frequency [%]	Weibull-A [m/s]	Weibull-k	mean speed [m/s]	power density [W/m²]	Speed discrepancy [%]	quality [%]
1	0	32,5	11,8	3,15	10,60	999	2,526%	0,992%
2	30	4,2	6,3	1,44	5,69	325	-5,248%	2,205%
3	60	1,0	4,8	1,28	4,45	190	-5,800%	2,632%
4	90	0,9	3,5	1,15	3,31	97	-7,836%	5,439%
5	120	1,6	4,4	2,02	3,91	69	1,940%	1,450%
6	150	13,8	8,7	2,13	7,67	497	-1,083%	0,608%
7	180	10,6	6,6	2,18	5,87	218	0,011%	0,880%
8	210	5,0	5,3	1,95	4,68	123	-0,243%	1,321%
9	240	2,4	4,5	1,55	4,04	105	-3,006%	2,071%
10	270	1,1	3,6	1,62	3,22	50	-2,492%	1,964%
11	300	1,5	4,8	1,50	4,32	134	-2,764%	2,156%
12	330	25,4	8,5	2,97	7,57	375	-0,565%	0,926%
All (fitted)			8,8	2,05	7,80	540	-0,273%	0,438%
Source data					7,82	539		

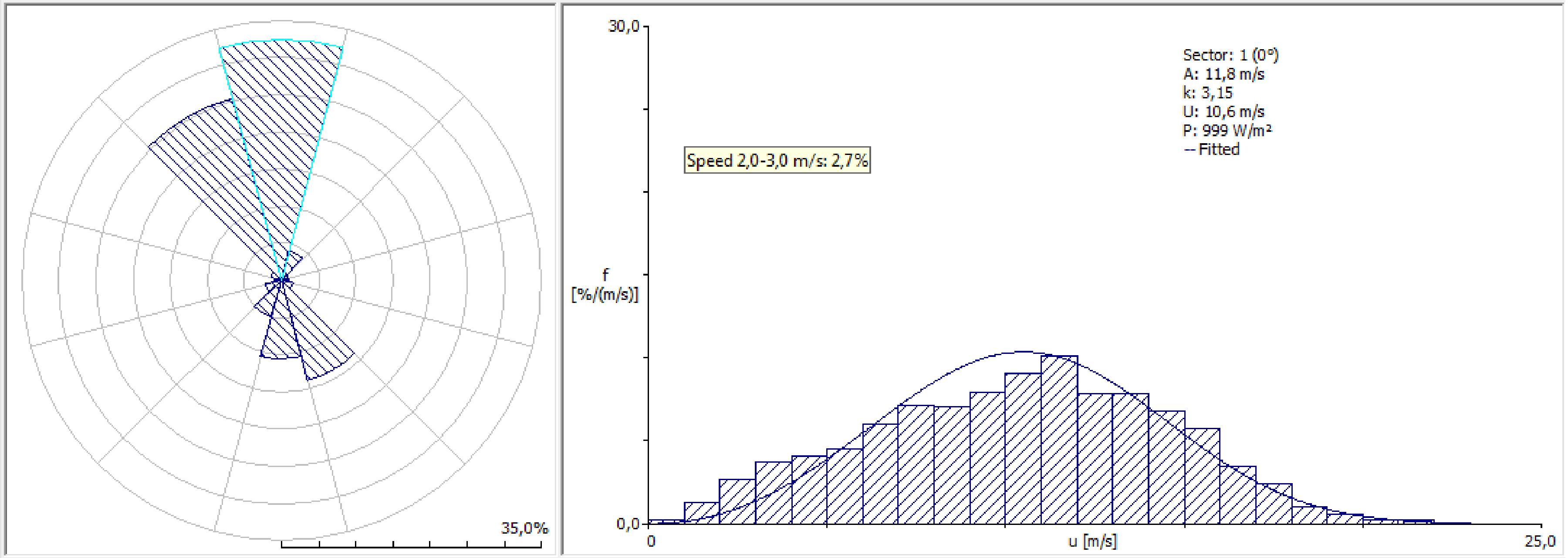


Figure 12. Wind rose and Weibull distribution for the site considered

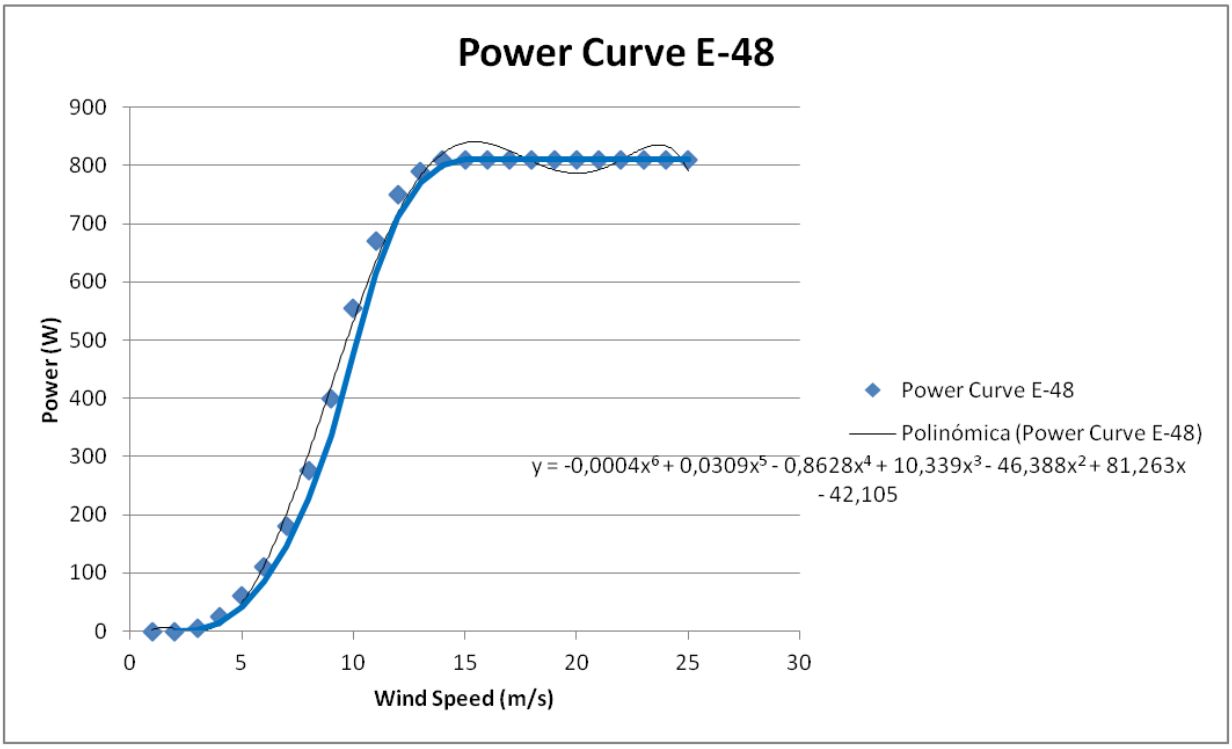
3.2.2 Wind Speed Prediction Model

The wind speed prediction has been provided by CENER (National Renwable Energy Center). This data consists of wind speed predictions at 10 metres height recorded each 10 minutes during the year 2007 in a location near the aforementioned meteorological station (see its coordinates in

Table 12).

For the numerical weather prediction (NWP), CENER uses a mesoscale model called SKIRON. SKIRON was developed for operational use by the Helenic National Meteorological Service and it is supported by the University of Athens. The model is based on the Eta limited area weather forecasting model based on finite differences over a semi-staggered E grid. CENER uses Global Forecasting System (GFS, from NCAR/NCEP) as forcing database to initialize the model daily at 12 UTC. The horizontal resolution is 0.05ºx0.05º latitude/longitude and simulates 50 Eta vertical levels with a time step of 10 seconds to yield hourly forecasts for a 48 hours prediction (although it can reach 52 hours prediction). The model simulates a single domain that captures the dominant synoptic patterns of the region of interest without nesting. Turbulence is parameterized with 2.5-order scheme with Monin-Obukhov similarity theory imposed at the surface layer based on stability functions (CENER; Gastón, et al., 2008).

As this data represents in the model the power that the wind farm operator has contracted in the energy market, it will be introduced in the primary load inputs of HOMER. Hence, it is necessary converting that wind speed predicted data into power prediction data. This has been achieved through a correlation of the turbine power curve described later on as can be seen in Graph 1. This correlation is a function of the wind speed in m/s allowing working out the predicted power generation associated to the wind speed predicted data for the year 2007. It should be noticed that the predicted power obtained for each time step is related to one turbine, so in order to predict the power output of each Wind-H_2 farm size considered, that data has been multiplied by the number of turbines. Once the predicted power data is obtained, it is introduce in the primary load inputs section of HOMER as shown in Figure 13, which provide valuable information about predicted power patterns.



Graph 1. Power curve of the wind turbine and correlation

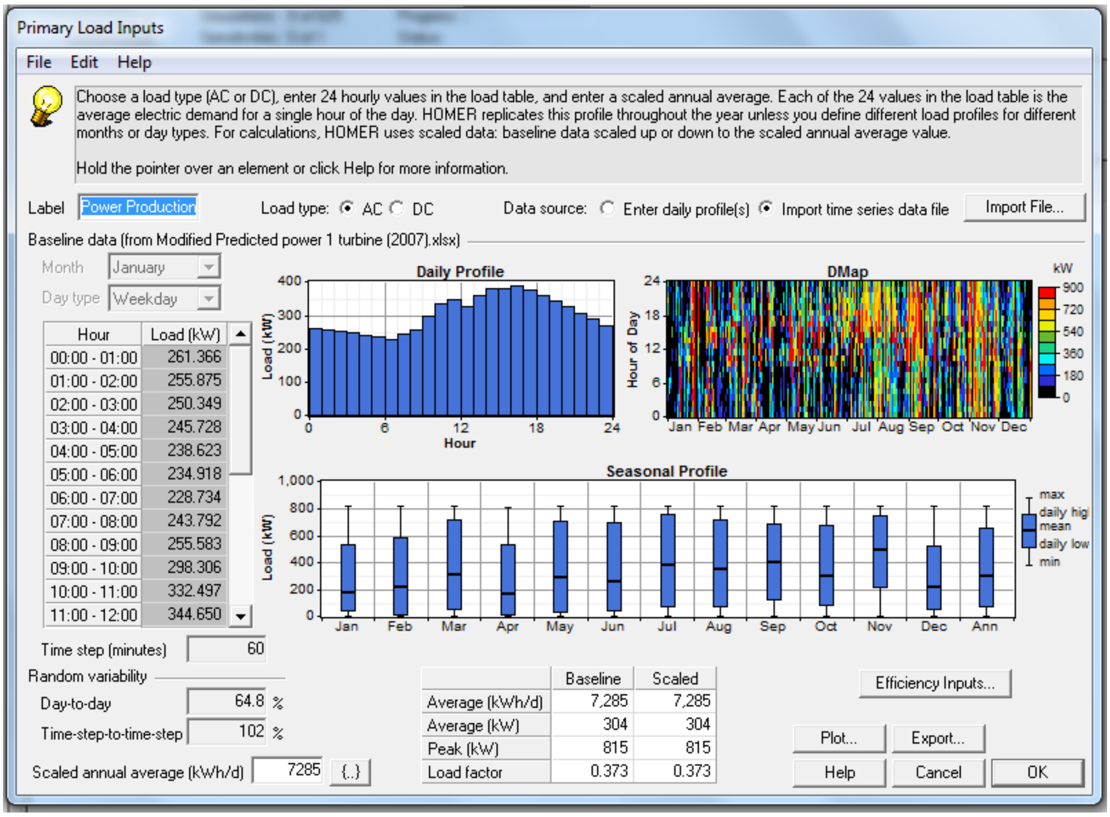
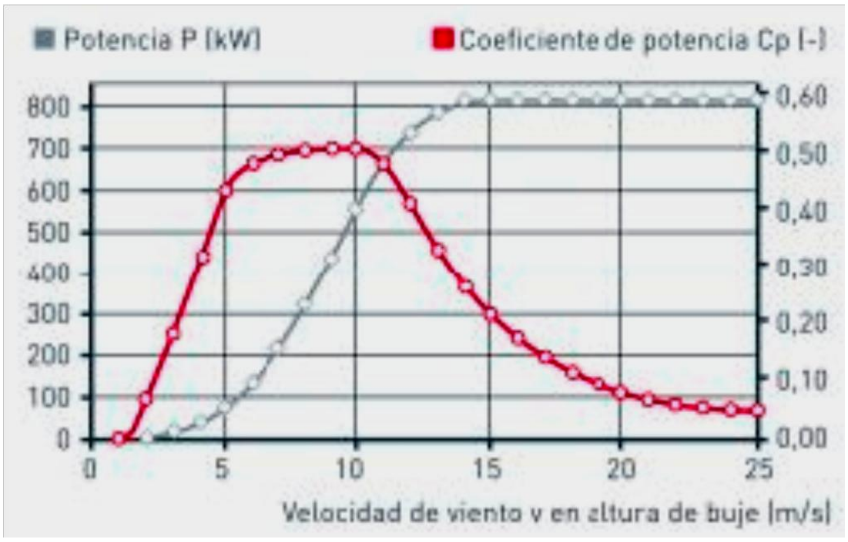


Figure 13. Primary load inputs section of HOMER

3.2.3 Wind-H_2 System Components

3.2.3.1 Wind Turbine Model

As the site location of the hypothetic wind farm is near the wind farm "El Perdón", a wind turbine of similar characteristics has been selected for this case study. This wind turbine is an ENERCON E-48 with a power rate of 800 kW, 3 blades, rotor diameter of 48 metres and hub height of 60 metres. The power curve (grey line) and power coefficient (red line) of this turbine for different wind speeds are presented in Graph 2. Further technical information about the aforementioned wind turbine can be found in the web page http://www.enercon.de/en-en/.



Graph 2. Power Curve and Power Coefficient of E-48 (Enercon, 2013)

Apart from the power curve, HOMER requires to introduce its lifetime defined as 20 years (Morthorst, n.d.) and the number of turbines. With regards the latter, as one of the objectives of the present dissertation is to evaluate the economical feasibility of a wide range of Wind-H_2 system sizes, different simulations have been carried out for 1, 10, 25, 35 and 50 turbines. Due to HOMER does not allow to introduce any unavailability parameter to take into account neither turbine fails, maintenance works and performance parameters, the power output of the each number of turbines follows a lineal dependence. In order to overcome this constraint, the number of turbines considered in the economical analysis for each simulation has been 1, 11, 28, 39 and 56 turbines respectively. The following screenshot shows the wind turbine inputs section of HOMER:

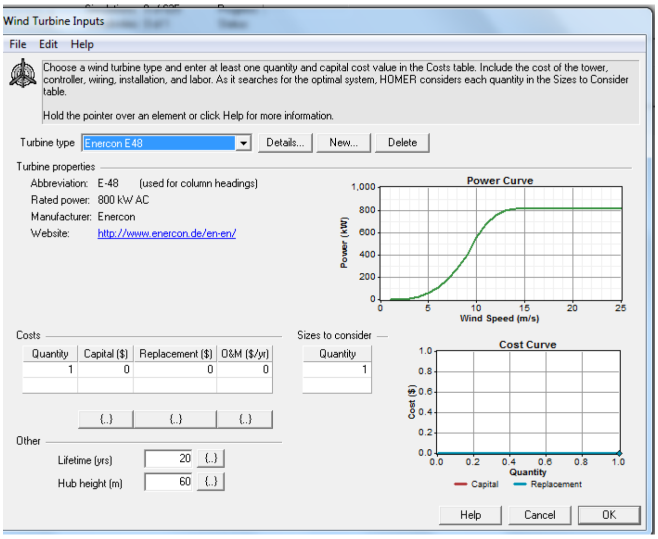


Figure 14. Wind Turbine Inputs section of HOMER

Besides, the following cost data has been defined so as to undertake the economic analysis:

- Turbine capital cost: 973112 € (831720 £). It is neglected due to this study is based on an existing wind farm, unless the wind farm without energy storage case study. This value has been obtained discounting a height variation cost of 9750 £ (Danish Wind Industry Association, n.d.) to the prize of the E-48 with a tower height of 76 meters (Renewablesfirst.co.uk., 2011)
- O&M cost per year: 29250 € (25000 £) equivalent to 3% of the turbine capital cost which (Morthorst, n.d.).

3.2.3.2 Electrolyser

The type of electrolyser selected for the present case study is unipolar alkaline electrolyser because of its lower capital and maintenance cost as well as higher power capacities than PEM electrolysers. Therefore, technical and cost data correspondent to a typical commercial electrolyser have been introduce in the model as follows:

Range of size considered (kW)	300-25000	
Lifetime (years)	10	(Swalla, et al., 2008)
Efficiency based on the HHV (%)	80	(Tsiplakides, 2011)

Minimum power load (% respect the power rate)	15 (Mengíbar, 2011)
Operating pressure (bar)	Atmospheric pressure (Swalla, et al., 2008)
Capital cost (€/kW, £/kW)	2374, 2302 (Pino, 2010)
Replacement cost (€/kW, £/kW)	2693, 2302
O&M cost per year (€, £)	2% of the capital cost (Charles, et al., 2009)

Table 6. Technical and economical electrolyser inputs of the electrolyser

Besides this, the operating mode of the electrolyser has been defined in HOMER as optimized mode, which means that the electrolyser will work as required to minimize excess of electricity. In Figure 15 and Figure 16 it can be seen a typical alkaline electrolyser and the electrolyser input section of HOMER respectively.

Figure 15. Alkaline electrolyser installed in the experimental Wind-H2 farm "Sotavento" (Rey, 2008)

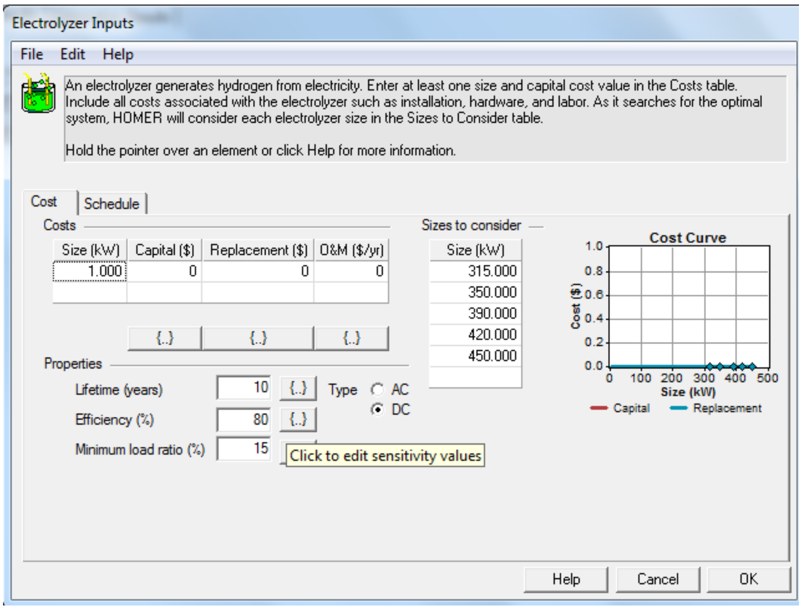


Figure 16. Electrolyser inputs section of HOMER

3.2.3.3 Hydrogen storage tank

For storing the hydrogen produced by the electrolyser, a pressurized tank at 200 bar has been selected as it is the most common technology used in this type of energy systems. At this pressure, the hydrogen has a density of 18 kg/m^3. This kind of pressurized hydrogen tanks usually have a cylindrical shape, made of steel that can be integrated in modules of different sizes. The technical and economical data associated with the hydrogen tank introduced in HOMER is presented in the following table Table 7:

Range of size considered (kg)	1000-50000
Lifetime (years)	20 (Shangai, 2013)
Relative to tank size* (%)	0
Storage pressure (bar)	200
Capital cost (€/kg, £/kg)	456, 390 (Shangai, 2013)
O&M cost per year (€, £)	2.5% of the capital cost (Charles, et al., 2009)

Table 7. Technical and economical inputs of the hydrogen tank

*HOMER requests to specify the hydrogen level of the tank and the beginning of the simulation as a percentage respect the tank size.

A typical pressurized hydrogen tank and the hydrogen tank input section can be seen in Figure 17 and Figure 18:

Figure 17.Pressurized hydrogen tanks installed in the experimental Wind-H2 farm "Sotavento" (Rey, 2008)

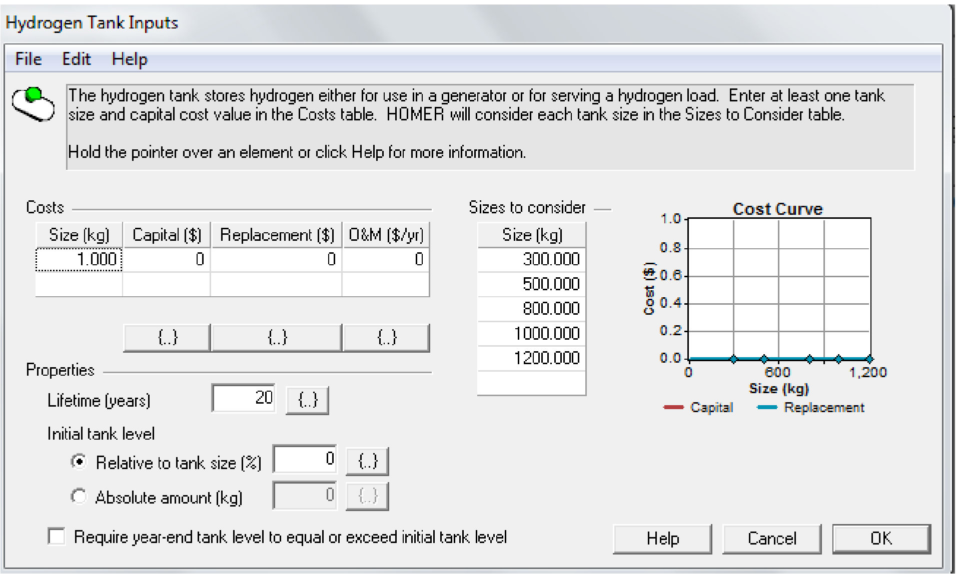


Figure 18. Hydrogen tank inputs section of HOMER

As it will be described later on, some of the energy management strategies covered in the present dissertation considers hydrogen trading. Therefore, the hydrogen discharge process would be carried out on site in a truck. As liquefaction of hydrogen is economically viable, hydrogen could be transported in liquid form by a tank truck with storage capacities between 360-4300 kg of liquid hydrogen (Fernández, 2005). Other option is the transport of compressed hydrogen in tube trailers, composed by stainless steel cylinders as shown in Figure 19, with a capacity up to 24000 kg of hydrogen (Calvera, n.d.).

Figure 19. Compressed hydrogen transportation (Calvera, n.d.)

As the latter option would avoid further costs associated with hydrogen liquefaction equipment, it seems the most suitable option for the present case study. However, the equipment and facilities required for the hydrogen discharge process are not considered in this project.

3.2.3.4 Fuel Cell

The fuel cell selected for the case study is a PEM fuel cell due to its lower O&M costs and longer lifetime compared with other types of fuel cell. What is more, it is more suitable for a non-stationary operation with quicker start-up time than other types of fuel cell.

HOMER simulates the fuel cell as an electric generator whose fuel type selected is hydrogen. Moreover, it is necessary to build an efficiency curve which is derived from the fuel consumption associated with different power outputs. As HOMER allows establishing an operating schedule of the PEMFC, a forced operation mode has been defined forcing the PEMFC disconnection between 1 am and 8 am. The reason is that although an average electricity price has been assumed for the all day, it varies during the year and also along the day. Due to this price is usually lower at night between 1 am and 8 am, the high capital and maintenance cost of the PEMFC and its energy losses, it is preferred to storage that hydrogen for generating electricity when electricity prices are higher or sell it directly in order to maximize the profitability of the Wind-H_2 system. In this way, the forced operation mode aforementioned would simulate better the real operation. With regards the emissions associated with this PEMFC to be introduced in HOMER are assumed as zero.

Technical and cost data of the PEMFC selected for this model are presented in the following table:

Range of size considered (kW)	500-20000
Lifetime (operating hours)	4000 (Sudol, 2009)
Efficiency (%)	42 (Shiroudi and Hosseini, 2011)
Minimum power load (% respect the power rate)	6 (Shangai, 2013)
Hydrogen consumption (Nm^3/kWh)	4.5 (Pino, 2010)
Capital cost (€/kW, £/kW)	2374, 2028 * (Roads2HyCom, 2013)
Replacement cost (€/kW, £/kW)	2374, 2028
O&M cost per year (€/kWh, £/kWh)	0.038 ,0.0325 ** (Roads2HyCom, 2013)

Table 8. Technical and economical inputs of the PEMFC

*For PEMFC power capacities between 10-200kW the capital cost is 2028 £/kW meanwhile rate power lower than 10 kW costs 3055 £/kW

** As the O&M cost is expressed in kWh, it should be noticed that the total O&M cost will depend on the operating hours of the PEMFC during the year.

Figure 20 and Figure 21 show a typical PEMFC and the generator (PEMFC) input section of HOMER.

Figure 20. PEMFC H-500 comercialized by Horizon Fuel Cell Technologies (Direct Industry, 2013)

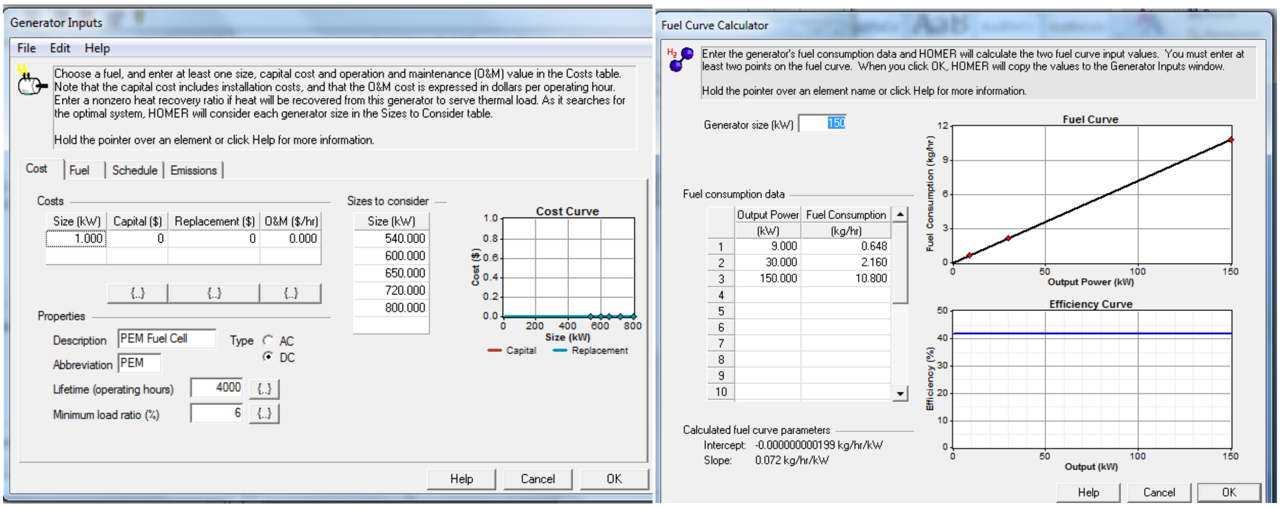


Figure 21. Generator inputs section of HOMER

3.2.3.5 Auxiliary Equipment

Converter (Rectifier/Inverter)

As mentioned in section 2.6, a converter is required to adjust voltages and intensity between the AC and DC side of the Wind-H_2 system. Therefore, the converter data introduced in HOMER and the cost data used for the economic analysis is shown in Table 9:

Range of size considered (kW)	500-20000
Lifetime (years)	20
Inverter efficiency (%)	95 (Zoulias and Lymberopoulos, 2007)
Rectifier efficiency (%)	90 (Bernal and Dufo, 2008)
Capacity relative to inverter (%)	100
Capital cost (€/kW, £/kW)	248, 212 (Bernal and Dufo, 2008)
O&M cost per year (€/kW, £/kW)	Included in the O&M cost of the fuel cell as suggested by Bernal and Dufo (2008)

Table 9. Technical and economical inputs of the converter

Hydrogen Compressor

Due to the hydrogen storage is carried out in a pressurized tank at 200 bar and the electrolyser operates at atmospheric pressure, a compressor is required to overcome that difference between hydrogen conditions. Therefore, the technical and cost data correspondent to the hydrogen compressor chosen for the case study is shown in

Table 10:

Pressure (bar)	200
Horse power (hp)	100 (Corban Energy Group, 2011)
Capital cost (€/hp, £/hp)	760, 650 (RAMGEN Power Systems, 2008)
O&M cost per year (€, £)	1.5 of the capital cost (Charles, et al., 2009)

Table 10. Technical and economical inputs of hydrogen compressor

3.2.4 System Control Strategy

As previously mentioned, the implementation by the wind farm operator of a proper control strategy for the operation of a Wind-H_2 system is necessary in order to minimize power deviations and optimize the lifetime and maintenance of equipment (Pino, 2010). This coupled with at correct sizing of equipment will result in a optimization of the revenue derived from a reduction of penalizations associated with power deviations and increment of electricity sold coupled with reduction of replacement and maintenance cost of equipment. Therefore, the control strategy was defined for the present case study partially based in control strategies studied by Dufo, et al., (2006) and Aguado, et al., (2009):

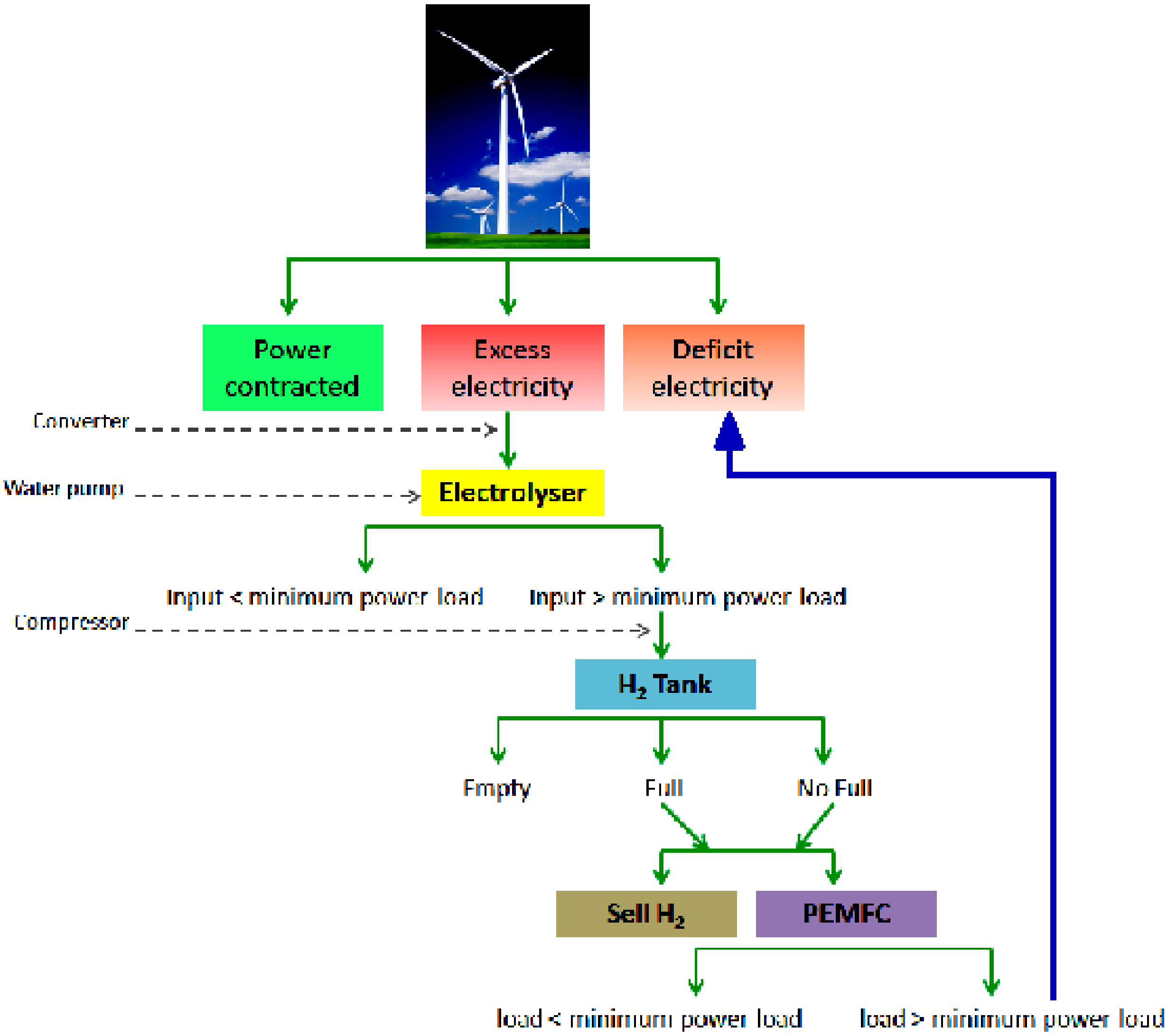


Figure 22. System control strategy defined for the case study

Regarding the control strategy described above, the Wind-H_2 system would process the electrical surplus generated by the wind farm when there is an electrical generation deficit respect the power contracted if:

- The electrical input (excess of electricity generated by the wind farm) is higher than the minimum power load of the electrolyser.
- H_2 of the tank is lower than 100%.
- The power generation deficit exceeds the minimum power load of the PEM fuel cell and the H_2 tank is not completely empty.

If all these conditions are not fulfilled, the excess of electrical generation cannot be managed and the wind farm operator will incur in a penalization. On the other hand, when the power deficit is lower than the minimum power load of the PEM fuel cell or its power output does not meet the deficit incurred by the turbine, the wind farm operator will also incur in a penalization.

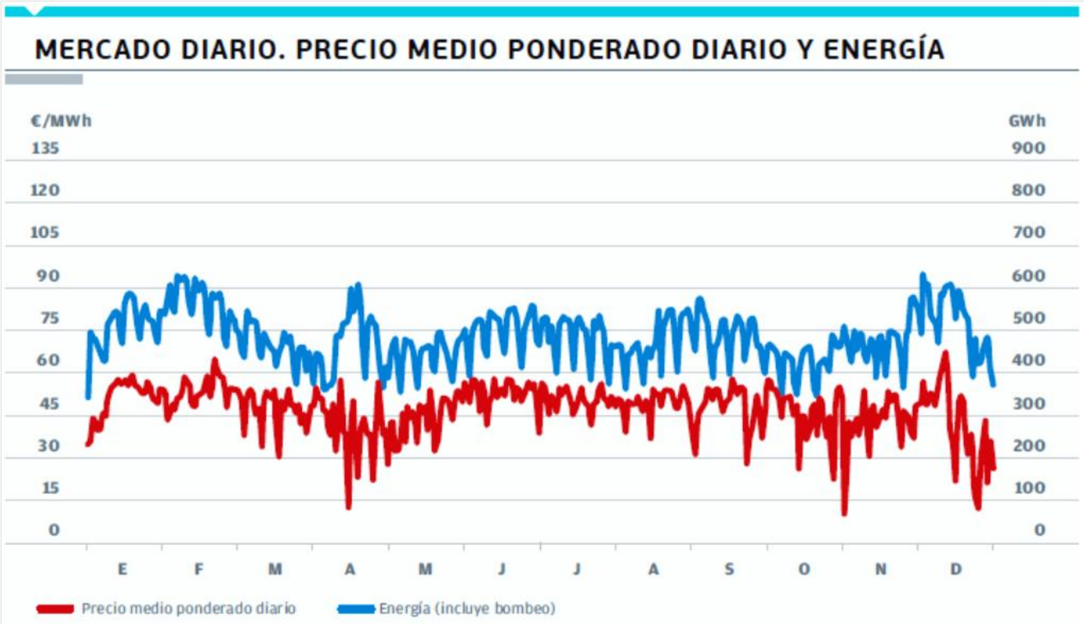
Nevertheless, in order to avoid excess of electricity caused by a 100 % H_2 level in the tank, other control strategy can be established reducing significantly the penalization associated with over electrical generation. This control strategy consists of defined a maximum H_2 level of the tank above which all H_2 is sold. In this way, the optimization of revenue is achieved by reducing penalizations associated with over electrical production and increasing incomes from H_2 market.

Furthermore, another control strategy that is going to be analyzed in this dissertation is selling all H_2 produced, avoiding the necessity of a PEM fuel cell which will have a substantial impact on capital and O&M cost reduction of the Wind-H_2 system. It should be noticed that this control strategy requires H_2 market.

3.2.5 Economic Framework

The economic analysis carried out in the case study presented here is based on the Spanish economic regimen for renewable energy already described in the *section 2.2*. With regards the different parameters involved in the remuneration process for the electricity generated by the wind farm are assumed as follows:

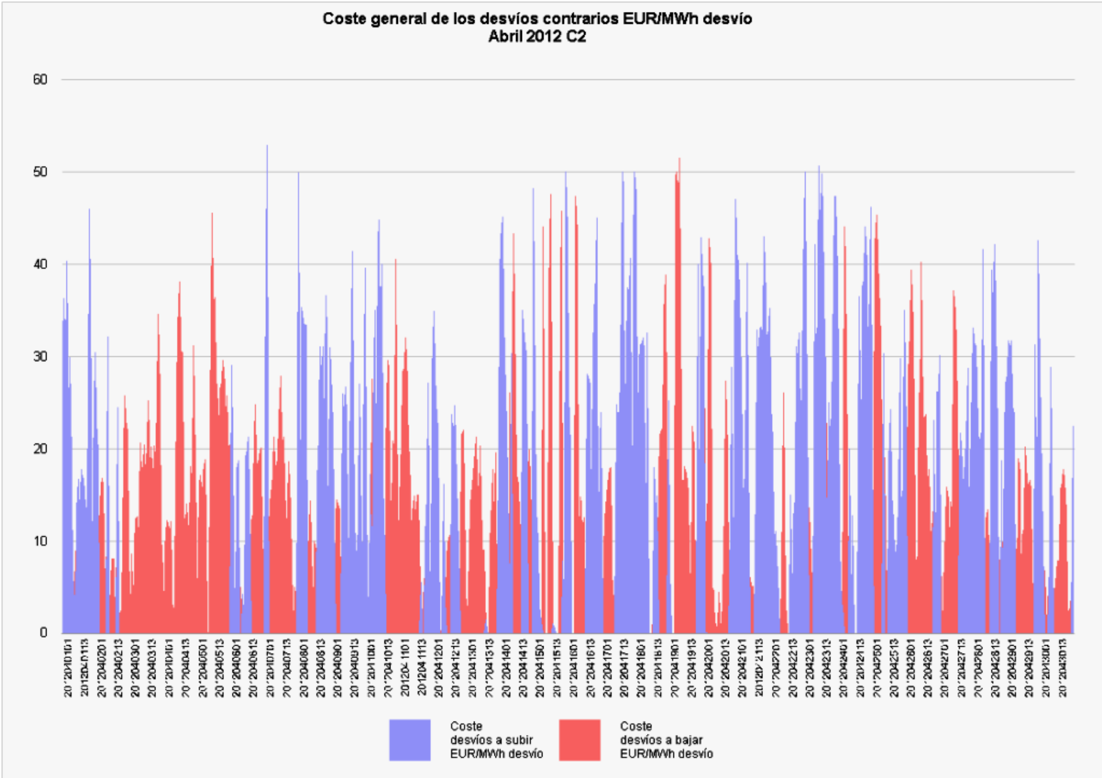
- Daily Market Price (PMD): due to its variability for each hour of the year and the fact that HOMER software cannot process this data, its value is based on the average PMD for the year 2012 in Spain. Hence, PMD is assumed to be 48,42 €/MWh (41,16 £/MWh) for the total number of hours of the year 2012 of the present case study (Red Eléctrica de España (REE), 2013).
  In the following graphs the daily average PMD (red line) during the year 2012 is shown, proving its high variability.



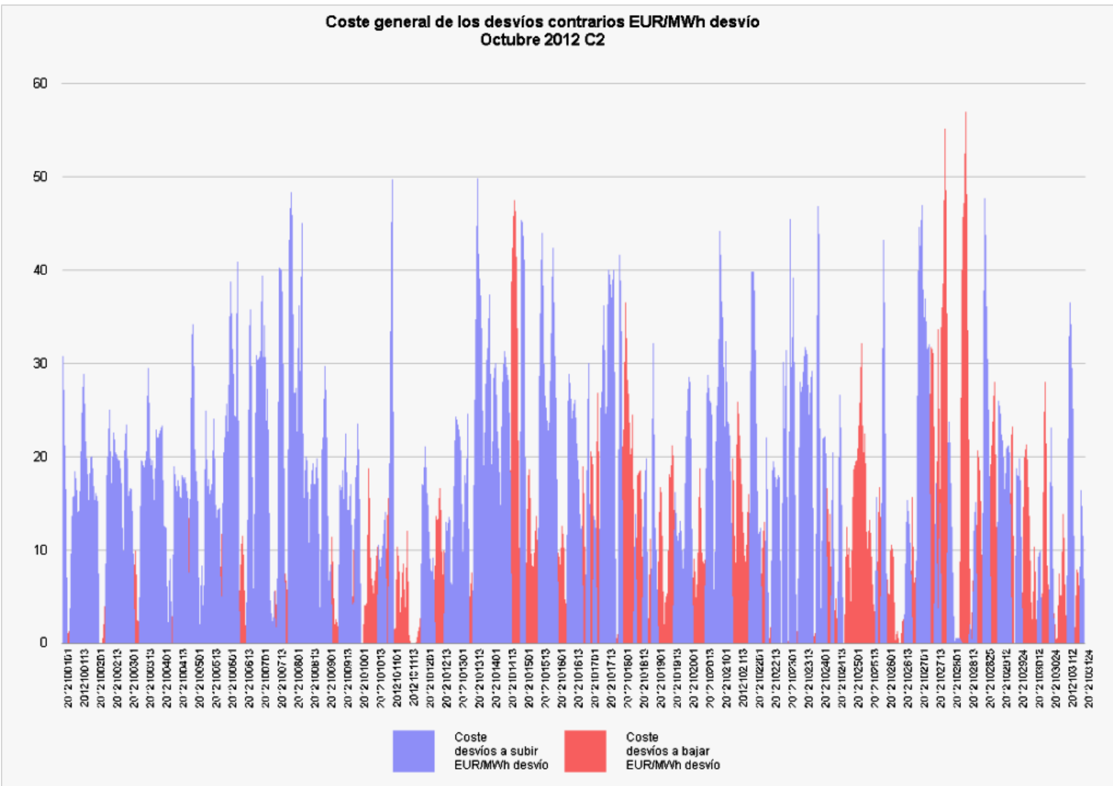
Graph 3. Average daily PMD during 2012 (Red Electrica de España, 2013)

- Unfavourable Deviation Cost (DC): its value results from a complex calculation depending mainly on the PMD established for the time of the year considered, leading to significant variations along the year. Therefore, an average "Deviation Cost UP" and "Deviation Cost DOWN" are assumed to be 25 €/MWh (21 £/MWh) and 18 €/MWh (15 £/MWh) respectively for the year 2012. This values are based on the Deviation Cost of the year 2012 published by REE (Spanish National Grid) in www.esios.ree.es. Moreover, the deviation cost values presented suggest that over electrical generation is more penalized than deficit of electricity, having a considerable impact on the wind farm revenue.

  Unlike the Spanish economical regime, in the present case study the penalization associated with deviations will be applied to the wind farm operator regardless its variation respects the prediction and all deviations are considered against the energy balance of the system. Graph 4 and Graph 5 show the Deviation Cost UP (blue) and DOWN (red) for April 2012 and October 2012. It should be noticed from Graph 3, Graph 4 and Graph 5 that the variability of PMD and Deviation Cost can lead to 0 or even negative remuneration received for the excess electricity injected into the grid if the Deviation Cost is equal or higher than PMD for the time considered.



Graph 4. Unfavourable Deviation Cost, April 2012 (Esios.ree.es, 2013)



Graph 5. Unfavourable Deviation Cost, October 2012 (Esios.ree.es, 2013)

With regards the liquidation methodology considered in the present case study, it is a simplification of the liquidation process established by the Spanish framework for renewable energy. In this way, the total revenue of the wind farm operator associated with the electricity sold is as follows:

$$Total\ Revenue\ (electricity\ sold) = I\ power\ gen - Pup - Pdown$$

where,

I power gen: income associated to electricity generated by the system during the year 2012 (power injected to the grid + excess electricity). For the case of Wind-H_2 system considered in this study, the power injected to the grid is composed by the electrical output of the wind turbine and fuel cell. It is calculated as follows:

$$Ipower\ gen = Pgen\ .PMD$$

Pup: penalization associated with "Power Deviation UP" incurred along the year 2012. It is calculated as follows:

$$Pup = \sum Deviation\ up\ .\mathrm{D}Cup$$

where,

DCup: Deviation Cost for overproduction of electricity

∑Deviation up: excess of electricity respect the electricity contracted in the Energy Market during 2012.

Pdown: penalization associated with "Power Deviation DOWN" incurred along the year 2012. It is calculated as follows:

$$Pdown = \sum Deviation\ down * DCdown$$

where,

DCdown: Deviation Cost for deficit production of electricity

∑Deviation down: deficit of electricity respect the electricity contracted in the Energy Market during 2012.

Moreover, for the Wind-H_2 system with H_2 market case study, the income associated with the H_2 sold is as follows:

$$Revenue\ (H_2\ sold) = H_2\ sold\ \times P_{H2}$$

where,

P_{H2}: is the price of H_2 assumed as 12.93 €/kg (11.05 £/kg) equivalent to the compressed hydrogen price of 17 $/kg in United States published by the National Hydrogen Association (Bromaghim, et al., 2010)

In this case the global revenue derivates from the electricity and H_2 sold calculated as follows:

$$Global\ Revenue = Total\ Revenue\ (Electricity\ Sold) + \ Revenue\ (H_2\ sold)$$

In summary, the unit values associated with each economical parameters are shown in Table 11:

Currency	PMD per kWh	H_2 price per kg	Deviation Cost UP per kWh	Deviation Cost DOWN per kWh
€	0.4842	12.93	0.025	0.018
£	0.4116	11.05	0.021	0.015

Table 11. Economical parameters price summary

4 Case Study. Simulation and Results

4.1 Project Site

As mentioned above, the case study that is going to be analyzed is based on a hypothetic wind farm located in the province of Navarra (Spain) near a wind farm called “El Perdón” where a meteorological station records weather conditions each 10 minutes during the whole year. Furthermore, this Wind-H_2 project is assumed to have a lifetime of 20 years. Real wind data associated to the aforementioned meteorological station is published by the Autonomic Government of Navarra (http://meteo.navarra.es/estaciones/mapadeestaciones.cfm) and the predicted wind data has been provided by the National Center of Renewable Energy Systems (CENER) that uses the SKIRON prediction model already described. These wind data both real and predicted has been recorded in year 2007 at 10 meters height. The coordinates of meteorological station and the nearest point of the SKIRON prediction model are presented in the following table (CENER):

	Latitude	**Longitude**
Meteorological station/ Wind Farm	42.733º	-1.708º
SKIRON point	42.750º	-1.700º

Table 12. Coordenates of associated with the wind data

Moreover, the lifetime of the geographic location of the meteorological station/hypothetic wind farm and the SKIRON model point can be seen in Figure 23 and Figure 24:

Figure 23. Location of meteorological station/hypothetic wind farm and SKIRON modelling point (Google earth)

Figure 24. Location of meteorological station/hypothetic wind farm and SKIRON modelling point (Google earth)

4.2 Results

The simulations undertaken for the Wind-H_2 system described are based on the three different control strategies aforementioned, being:

1. Wind-H_2 system with load following control strategy
2. Wind-H_2 system with load following and H_2 trade
3. Wind-H_2 system with H_2 trade

Furthermore, these strategies are going to be simulated for different sizes of wind farm (1, 10, 25, 35, 50 turbines) so as to study the economical feasibility of this technology in relation with the equipment size. It is necessary to mention that the economical study will consider 1, 11, 28, 39 and 56 turbines respectively in order to ideal operating conditions and take into account unavailability of turbines as previously mentioned.

It should be noticed that the economical data of the model is not introduced in HOMER as it will be used in an independent economical study (using a Microsoft Excel template) due to HOMER cannot simulate the economical framework described above (especially penalization costs). Hence, the results provided by HOMER correspond to a technical optimization instead of economical optimization. This means that HOMER will rank the equipment size of the Wind-H_2 system regarding its minimization of excess and deficit of electricity. However, this technical optimum usually requires large equipment which may work with low capacity factors (relation between mean input load and rate power) and high costs, moving away from the economical optimum. Thus, a sensitivity analysis of the combinations suggested by HOMER is going to be undertaken, balancing the excess/deficit of electricity and the equipment size. This sensitivity analysis was performed only for the results obtained for the first control strategy simulated (Wind-H_2 system with load following control strategy). In consequence, the equipment sizes simulated for the rest of control strategy coincides with the equipment size combinations resulted from the aforementioned sensitivity analysis.

Besides, a simulation of a wind farm without energy storage (traditional wind farm) is carried out in order to analyze its economical feasibility regarding the new *RDL 9/2013 12th July* that regulates the renewable energy generation in Spain since July 2013 and compare it with Wind-H_2 technology.

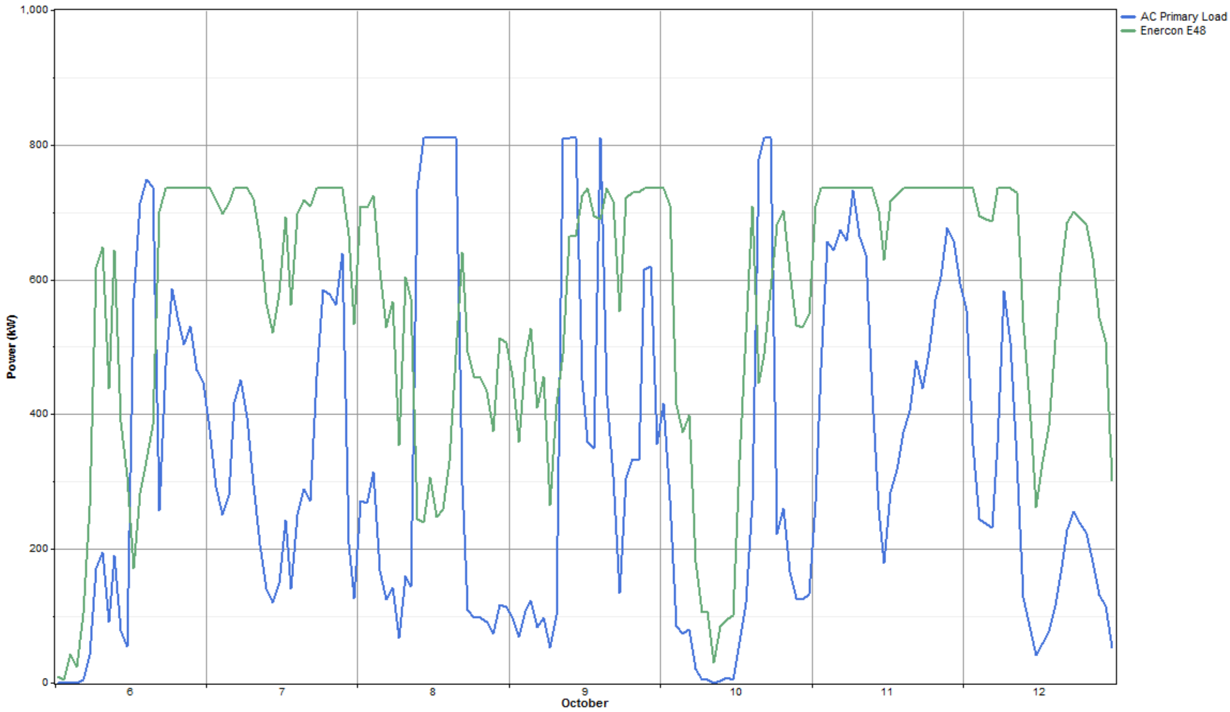
4.2.1 Wind farm without energy storage (1 turbine)

In order to evaluate the economical feasibility of current wind farms within the Spanish framework for RES and compare it with the Wind-H_2 technology, a technical and economical study will be performed for different wind farm sizes (1, 11, 28, 39 and 56 turbines).

As mentioned in the *Model Assumptions* section, there is no restriction to the power injected into the grid so the excess of electricity will be accommodated by the grid operator with a penalization.

Moreover, it should be mentioned that graphs as a function of turbines number presented in this dissertation are specific for the wind turbine considered in this study (described in section 3.2.3.1). However, they can study as a function of the power capacity of the wind farm by multiplying the number of turbines by its rate power of the model selected (800 kW).

Focusing in the simulation for a wind farm composed by one turbine, it was obtained a mean turbine output of 436 kW representing a capacity factor of 54.5% and 8486 hours (although this value does not coincide with a real wind farm) for the year 2012. Graph 6 displays a comparison between the power output of the turbine and the power predicted between 6th October and 12th October. From this graph, it can be deducted deviations of excess of electricity and deficit of electricity incurred during that period.



Graph 6. Turbine power output vs predicted power of 1 turbine (traditional wind farm)

Table 13 shows technical results for a traditional wind farm resulted from the simulation. The meaning of each data presented in the table is the following:

> *Predicted power*: comprises the power served to the grid and unmet power served
>
> *Wind turbine power output*: sum of power served to the grid and excess of electricity.
>
> *Excess electricity*: over electrical generation respect the predicted power.
>
> *Power served*: power injected into the grid which had been previously predicted.
>
> *Unmet power predicted*: power that could not be injected into the grid although it had been previously predicted.

The data presented in Table 13 shows a big difference between the predicted power and the real power production, being the latter 44 % higher than the predicted power. Moreover, it can be deducted that the biggest deviation respect the power prediction is associated with the excess of electricity, being 42% of the power generated by the wind turbine meanwhile unmet power corresponds to 17% respect the power predicted. What is more, from the comparison between excess of electricity and power served to the grid arises the high over-electrical production of the wind turbine reaching nearly the power served level. Thus, decreasing deviations associated with over electrical generation (Power Deviation UP) would have a stronger impact on revenue rather than deviations for deficit of electricity, also supported by the greater Deviations Cost UP.

Wind Farm without storage (1 turbine)			
	kWh/yr (2012)	% on predicted	%on production
Predicted power	2.659.043		
Wind turbine power output	3.819.057		
Excess electricity	1.600.461		41,9
Power served	2.218.677	83,4	58,1
Unmet power predicted	440.366	16,6	

Table 13. Technical results obtained for a traditional wind farm

Regarding the values of the economical parameters presented in Table 11, Table 14 shows the annual cash flow of the wind farm considered here, that proves the great impact of excess of electricity on the annual electricity sold income, representing 22% respect the total power production income.

	kWh/yr (2012)	**REVENUE (£)**
Wind turbine power served	3.819.138	157.184
Excess electricity	1.600.461	-34.010
Unmet power predicted	440.366	-6.738
Electricity sale income		116.437
O&M cost		-25.000
Annual cash flow		91.437

Table 14. Annual cash flow of a traditional wind farm

Nevertheless, it should be noticed that as HOMER cannot simulate the electrical stability of the grid, this model assumes that all power production of the turbine is accommodate by the grid operator, which is not the real procedure. In reality, when stability of the grid is at risk (caused by over electrical generation of wind farms),the grid operator switch off the required number of wind turbines to maintain grid voltage and frequency stable. Therefore, cash flow estimation (see Table 15) that disregards the excess electricity trade has been undertaken in order to adapt more to the real procedure.

	kWh/yr (2012)	REVENUE (£)
Wind turbine power served	2.218.677	91.314
Excess electricity	0	0
Unmet power predicted	440.366	-6.738
Electricity sale income		84.576
O&M cost		-25.000
Annual cash flow		59.576

Table 15. Annual cash flow of a traditional wind farm (without excess of electricity sale)

From the results obtained in this case, it is very remarkable the significant cash flow difference respect the previous case, representing a 35% cash flow reduction in the latter case. Therefore, the following economical feasibility study will be based on the latter case as it suits better the real procedure.

Although the annual cash flow obtained is positive, it is necessary to take into account the initial inversion of the project in order to study its economical feasibility. As the purpose here is evaluating the economical feasibility of a traditional wind farm without any additional equipment, the initial inversion assumed comprises the capital cost of the turbine and the land rent expenditures fixed at 2975 £/MW installed per year, regarding Regueiro, et al. (2009). The following table displays the Net Present Value (NPV) of the total inversion during the lifetime of the project (20 years), assuming a discount rate of 3%. The NPV obtained for this case study is 7028 £ (8223 €).

NET PRESENT VALUE		
Year	Cashflow	NPV (£)
0	-879.320	-879.320
1	59.576	57.841
2	59.576	56.157
3	59.576	54.521
4	59.576	52.933
5	59.576	51.391
6	59.576	49.894
7	59.576	48.441
8	59.576	47.030
9	59.576	45.660
10	59.576	44.331
11	59.576	43.039
12	59.576	41.786
13	59.576	40.569
14	59.576	39.387
15	59.576	38.240
16	59.576	37.126
17	59.576	36.045
18	59.576	34.995
19	59.576	33.976
20	59.576	32.986
Discount rate(%)	3	
NPV		7.028

Table 16. Economical feasibility of a traditional wind farm

Moreover, the previous technical and economical study has been performed for the rest of wind farm sizes obtaining the Net Present Values presented in Table 17:

Wind farm size	NPV
1	7.028
11	-1.180.823
28	-3.577.781
39	-4.758.277
56	-7.155.661

Table 17. NPV vs. Wind farm size (without energy storage)

Table 17 shows how the larger wind farm sizes the less economically feasible is the project regarding the current Spanish framework. The main reason is the curtailment of electricity prices with the Feed-In Tariff suppression. Thus, the rise electricity sold income obtained by increasing the number of turbines cannot balance the increment of penalties associated with unmet power served as well as capital and O&M costs of the equipment.

In light of the results obtained, it can be concluded that the suggested wind farm project is economically feasible after 20 years only for small wind farm (between 1 and 10) regarding the RDL 9/2013, although due to the low NPV obtained, it would require some remuneration to become "reasonable profitable" as established in the aforementioned law. However, the NPV values resulted for bigger projects suggest that larger wind farm (above 10 turbines) are economically unfeasible within the current Spanish framework. Furthermore, another conclusion derived from the technical results is the urge necessity of energy storage in wind farms based on current power prediction models regarding a technical point of view. The following chapters are going to study if this technical necessity of energy storage is supported by an economical necessity from the wind farm operator standpoint. For this purpose, apart from study the increment of the annual cash flow, the initial investment associated with the energy storage will be considered.

4.2.2 Wind-H_2 system based on load following control strategy

With a load following energy management, the wind farm operator seeks to achieve the best match between electrical supply and demand, through storing the electrical surplus to be injected into the grid when the wind farm cannot meet the demand. In this way, the economical benefit of this technology is based on the increment of electricity sold derived from the reduction of penalties for over electrical generation and unmet electrical production.

After performing the sensitivity analysis of the equipment sizes combinations proposed by HOMER, the following equipment sizes has been chosen for the integration with different sizes of wind farm, which accomplish the best techno-economical balance (reduction of power deviations vs. cost of equipment).

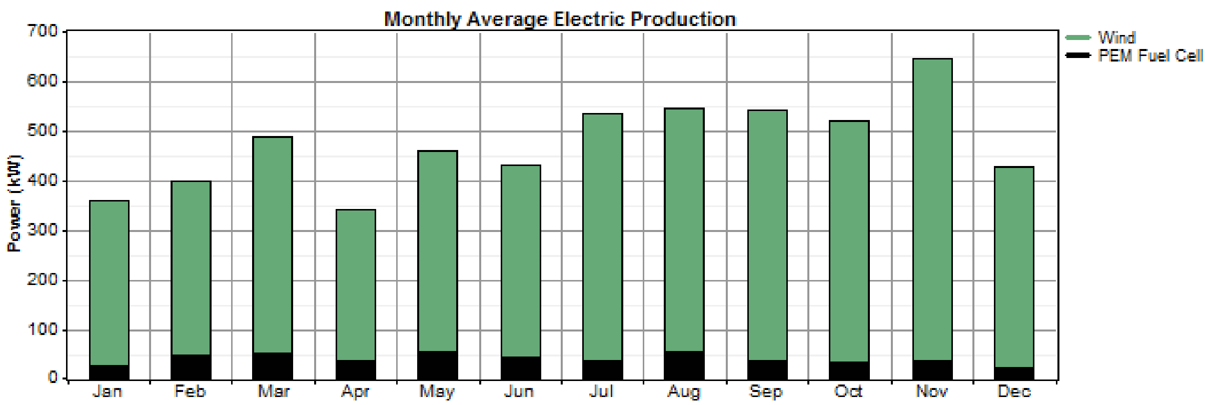
TURBINES	CONVERTER (kW)	ELECTROLYSER (kW)	H_2 TANK (kg)	PEMFC (kW)
1	620	420	1000	650
11	3900	4000	5000	4000
28	16000	10500	25000	12000
39	17000	13500	35000	12600
56	19000	23000	50000	18000

Table 18. Best techno-economical combinations of equipment size for a Wind-H2 system based on load following strategy

Focusing on the Wind-H_2 system composed by one turbine, although the capacity factor and operating hours of the turbine are equal to the wind farm without energy storage, it is very striking the significant reduction of excess of electricity and unmet power served (87% and 73% respectively compared with the case of wind turbine without energy storage) presented in Table 19. Therefore, it is very remarkable the contribution of the H_2 technology during insufficient electrical production of the turbine respect predicted, which allows to meet the 95.5% of the power predicted (12.9% supplied by the PEMFC). This contribution of the PEMFC in the total power generation of the Wind-H_2 system during the year 2012 can be seen in Graph 7:

Wind-H_2 system. Load following strategy (1 turbine)			
	kWh/yr (2012)	% on predicted	% on production
Predicted Power	2.659.038		
Wind turbine power output	3.819.057		
Converter power losses	156.588		4,1
Electrolyser losses	251.398		6,6
Fuel cell losses	480.560		12,6
Fuel cell power output	343.252	12,9	9,0
Excess electricity	208.605		5,5
Sistem power served	2.540.200	95,5	
Turbine power served	2.196.948	82,6	57,5
Unmet power predicted	118.838	4,5	
Hydrogen producted (kg)	25.494		
Hydrogen content at the end of the year (kWh)	26.000		0,68

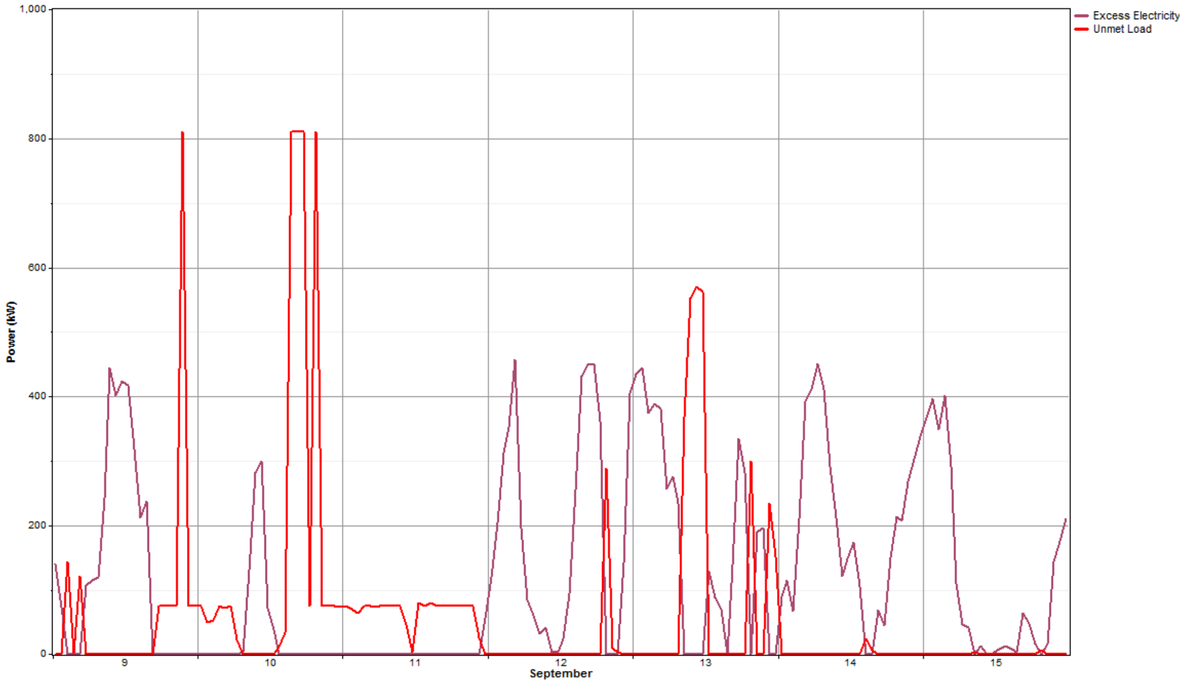
Table 19. Technical results obtained for a Wind-H2 system based on load following control strategy



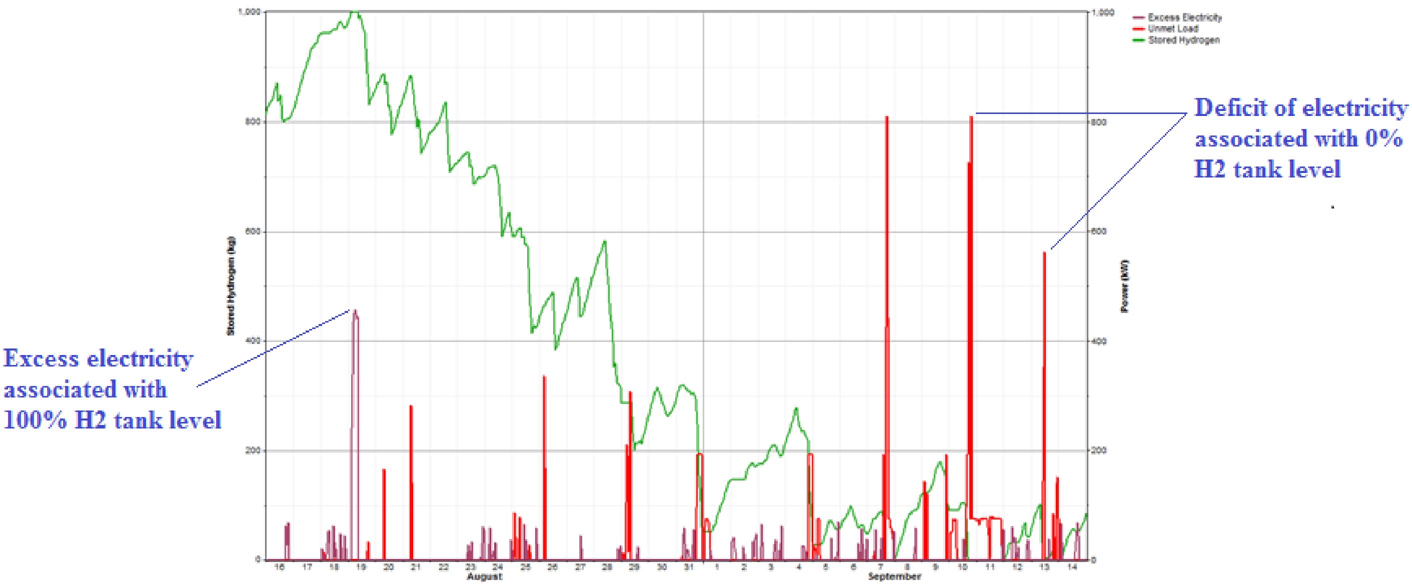
Graph 7. Contribution of the turbine and PEMFC in the total electrical production

On the other hand, it should be noticed the power losses of the equipment that comprises the Wind-H_2 system, representing the 63.6% of the total electrical input of the electrolyser. This is the main reasons why electricity derived from the H_2 storage side should be managed efficiently, selling it when the PMD is high. Besides, it should be highlighted the low operational lifetime of the PEMFC accounting to 2.7 years approximately which impact considerably in the replacement costs of the system.

Graph 8 and Graph 9 are a comparison between power deviations incurred by the traditional wind farm analyzed in the previous section and the current Wind-H_2 system. When comparing both graphs, it is very noticeable the significant reduction of the excess electricity of the Wind-H_2 system although it is limited by full tank level conditions (see Graph 9), which prevents the start up of the electrolyser. However, with regards the reduction of unmet power served is not so substantial due to the lack of H_2 available in the tank as a consequence of the low PEMFC efficiency. Therefore, this issue could be partially solved by improving PEMFC efficiency in the future.

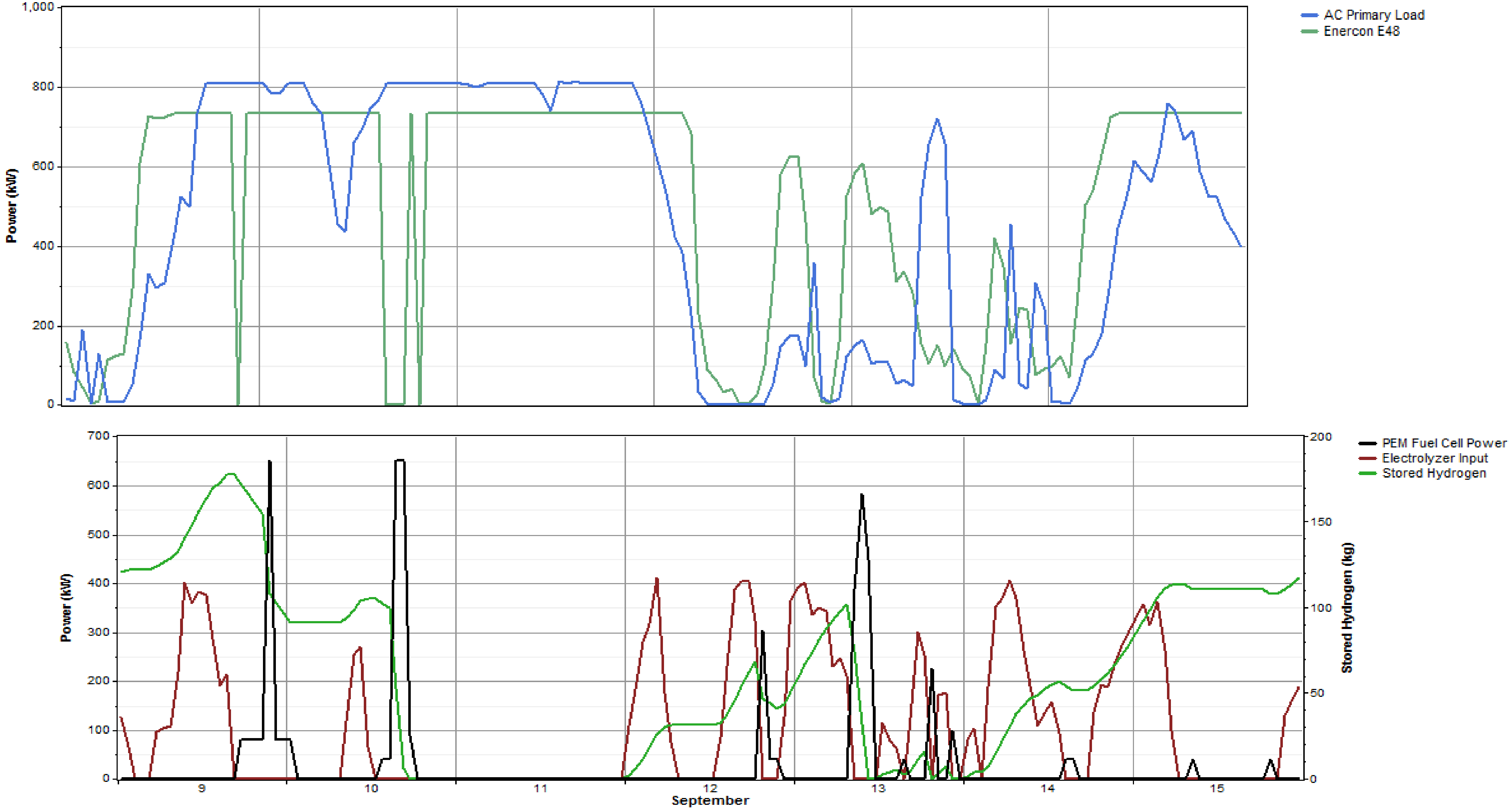


Graph 8. Evolution of power deviations incurred by a traditional wind farm (9 September-15 September)



Graph 9. Evolution of power deviations incurred by a Wind-H2 system and the H2 storage (16 August-14 September)

Moreover, Graph 10 displays how each component of the Wind-H_2 system (Electrolyser, H_2 storage and PEMFC) operates depending on the relation between the power output of the turbine and power predicted.



Graph 10. Operating of the Wind-H2 systems as a function of the power deviations incurred by the turbine (9 Septiembre-15 Septiembre)

The graphs above show how the electrolyser starts up when the output power of the turbine exceeds the "AC Primary load" (defined as the power predicted), increasing the H_2 level of the tank. On the other hand, the PEMFC operates when the output power of the turbine does not reach the power predicted, the load surpasses the minimum power load of the PEMFC and there is enough H_2 storage.

From an economical point of view, in Table 20 it can be seen how the deviation reduction aforementioned leads to a penalization reduction for excess and deficit of electricity of the same order of magnitude. Note that unlike the wind farm without storage case study, this time is assumed that grid operator will accommodate the excess of electricity as its proportion is much lower. As can be seen in Table 20, the income associated with electricity sales rises up to 106881 £ representing a 17 % of increment respect the wind farm without energy storage. Nevertheless, the high maintenance cost of the equipment that comprises the Wind-H_2 system accounts to 52% reduction of the income in contrast to 29.5% for the traditional wind farm. Despite that its electricity sale income is higher than the traditional wind farm, the expensive O&M cost associated with the H_2 equipment results in a 56% reduction of annual cash flow respect the wind farm without energy storage.

		kWh/yr (2012)	REVENUE (£)
Wind-H_2 system power served		2.748.805	113.133
Excess electricity		208.605	-4.433
Unmet power predicted		118.838	-1.818
Electricity sale income			106.881
O&M cost	Turbine		-25.000
	Converter		0
	Electrolyser		-14.280
	Compressor		-975
	H_2 tank		-9.750
	PEMFC		-30.784
Annual cash flow			26.092

Table 20. Annual cash flow of a Wind-H2 system with load following strategy (1 turbine)

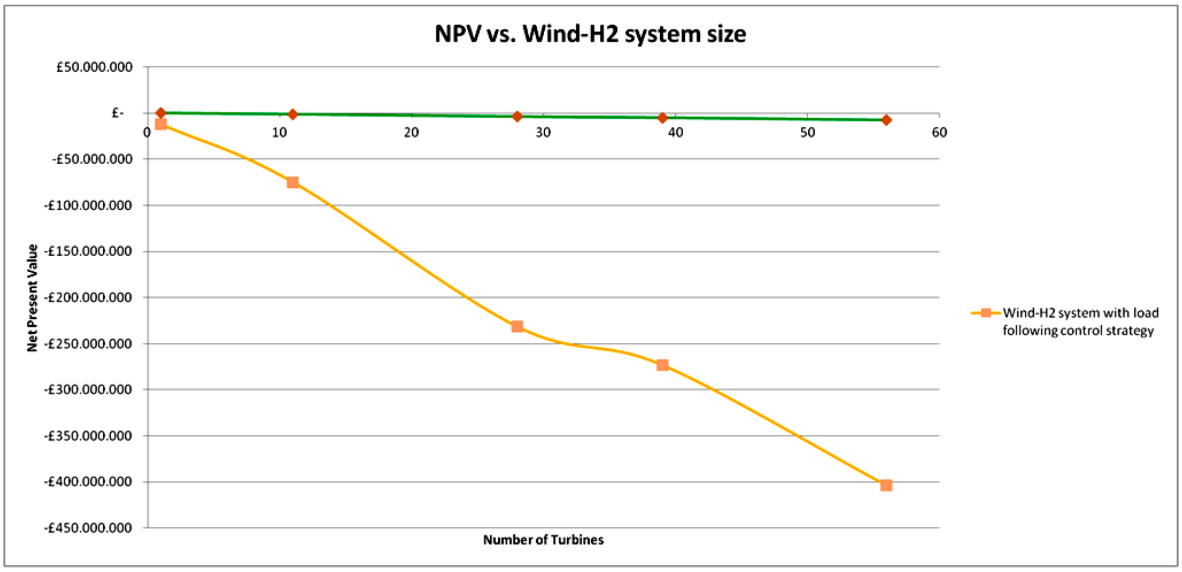
Like the wind farm without energy storage case, apart from the annual cash flow it is necessary to consider the initial inversion of the project so as to analyse its economical feasibility. Unlike the traditional wind farm, this case study is based on an existing wind farm, and hence turbine capital cost and land rent expenditures are not considered. The initial inversion comprises only the capital cost associated with the hydrogen equipment (converter, electrolyser, compressor, tank and PEMFC). In this way, the NPV at the end of the project (20 years) reaches a negative value of -12171850 £ (-14241064 €) proving that this technology is not economically feasible nowadays regarding the model assumed. Therefore this money should be provided to this Wind-H_2 system to become economically feasible if the retribution regulated by the RDL 9/2013 is applicable.

NET PRESENT VALUE		
Year	Cashflow	NPV
0	-12.560.040	-12.560.040
1	26.092	25.333
2	26.092	24.595
3	26.092	23.878
4	26.092	23.183
5	26.092	22.508
6	26.092	21.852
7	26.092	21.216
8	26.092	20.598
9	26.092	19.998
10	26.092	19.415
11	26.092	18.850
12	26.092	18.301
13	26.092	17.768
14	26.092	17.250
15	26.092	16.748
16	26.092	16.260
17	26.092	15.786
18	26.092	15.327
19	26.092	14.880
20	26.092	14.447
Discount rate(%)	3	
NPV		-£ 12.171.850

Table 21. Economical feasibility of a Wind-H2 system with load following strategy (1 turbine)

In order to evaluate how the economical feasibility varies depending on wind farm size, the previous study has been carried out for each Wind-H_2 system presented in Table 18. In light of the results obtained, it can be concluded that all combinations presented similar percentages of power deviations and contribution of the H_2 technology than the Wind-H_2 system composed by 1 turbine. Therefore, the annual cash flow increases proportionally meanwhile the NPV of the project decrease also proportionally as economy of scale was not considered for estimating the equipment capital and O&M costs. This can be seen in Graph 11 where the NPV value associated with each Wind-H_2 system size is displayed. Besides this, it can be deducted from the graph below that NPV decreases to a lesser extent above 30 turbines as the equipment size required are more similar and hence their capital cost meanwhile electricity incomes rises.

Furthermore, Graph 11 presents the NPV obtained for different sizes of wind farms without energy storage covered in the previous section 4.2.1. Comparing both NPV for wind farm with storage and without storage, the fact that the latter is still less economically unfeasible than Wind-H_2 systems arises.



Graph 11. NPV vs. Wind-H2 system size with load following control strategy

From the results obtained it can be conclude that despite the technical necessity of energy storage in wind farms, Wind-H_2 technology based on a load following control strategy is far from becoming a cost-effective technology if the following conditions are not fulfilled:

1. Enhancement of H_2 equipment efficiency: especially that associated with the PEM fuel cell which has an important impact on the power losses of the H_2 side (63.6 %), depicting the amount of energy that have been lost during the process and cannot be sold to the grid.
2. Improvements in the lifetime of electrolysers and PEM fuel cells, especially the latter because it accounts to 2.7 years approximately, increasing considerably the replacement costs aided by its great capital cost.
3. Capital cost reduction of the H_2 equipment, reducing in this way the initial inversion.

4.2.3 Wind-H_2 System based on load following control strategy coupled with H_2 trade

This energy management strategy seeks to solve the technical constraints associated with the load following strategy and at the same time optimize revenues derived from electricity and hydrogen sales. Hence, this system focuses more in the economical optimization rather than technical optimization (based on minimizing power deviations). This is achieved by selling the hydrogen generated when the hydrogen level in the tank overcome a predefined level. Therefore, the aims of this energy management are as follows:

- Minimize power deviations for excess of electricity as the hydrogen level in the tank is maintained below a certain level allowing always the start up of the electrolyser. Thus, this will impact directly in the reduction of penalization costs.
- Diminish power losses associated with PEMFC as the hydrogen is partially derived for trade, increasing energy sales (electricity + hydrogen) as energy losses in the PEMFC are avoided.
- Increase revenues by selling part of the hydrogen produced.

The equipment sizes combinations for this energy management strategy are those resulted in the previous case unless the H_2 tank size:

TURBINES	CONVERTER (kW)	ELECTROLYSER (kW)	H_2 TANK (kg)	PEMFC (kW)
1	620	420	900 600*	650
11	3900	4000	4300 3500*	4000
28	16000	10500	24000 22000*	12000
39	17000	13500	33000 30000*	12600
56	19000	23000	45000 40000*	18000

Table 22. Best techno-economical combinations of equipment size for a Wind-H2 system based on load following coupled with H2 trade

* H_2 tank level above which all hydrogen production is derived for trade

It should be mentioned that the hydrogen trade has been simulated by HOMER as a hydrogen load. For this purpose, the hydrogen load inputs introduced in the model corresponds to the hydrogen produced per hour by the electrolyser when the hydrogen level limit is overcome. This applies to section *4.2.5-Wind-H2 system with H2 trade* except that the hydrogen level limit is zero. The following picture displays the hydrogen load inputs section of HOMER where it can be seen that largest hydrogen generation coincides with autumn and winter.

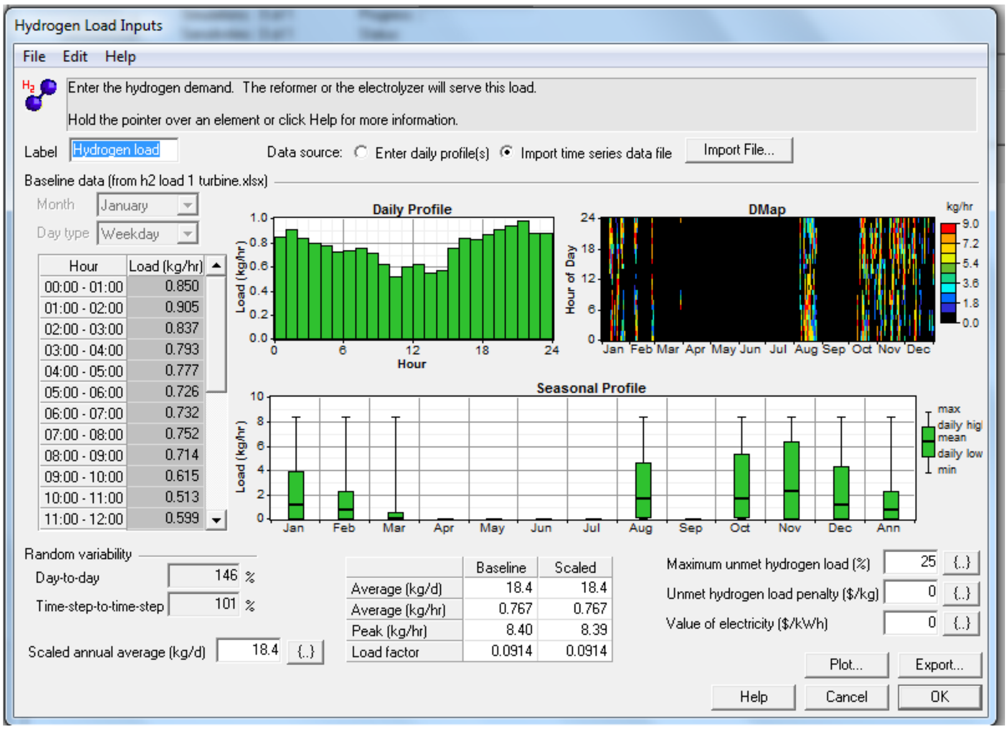


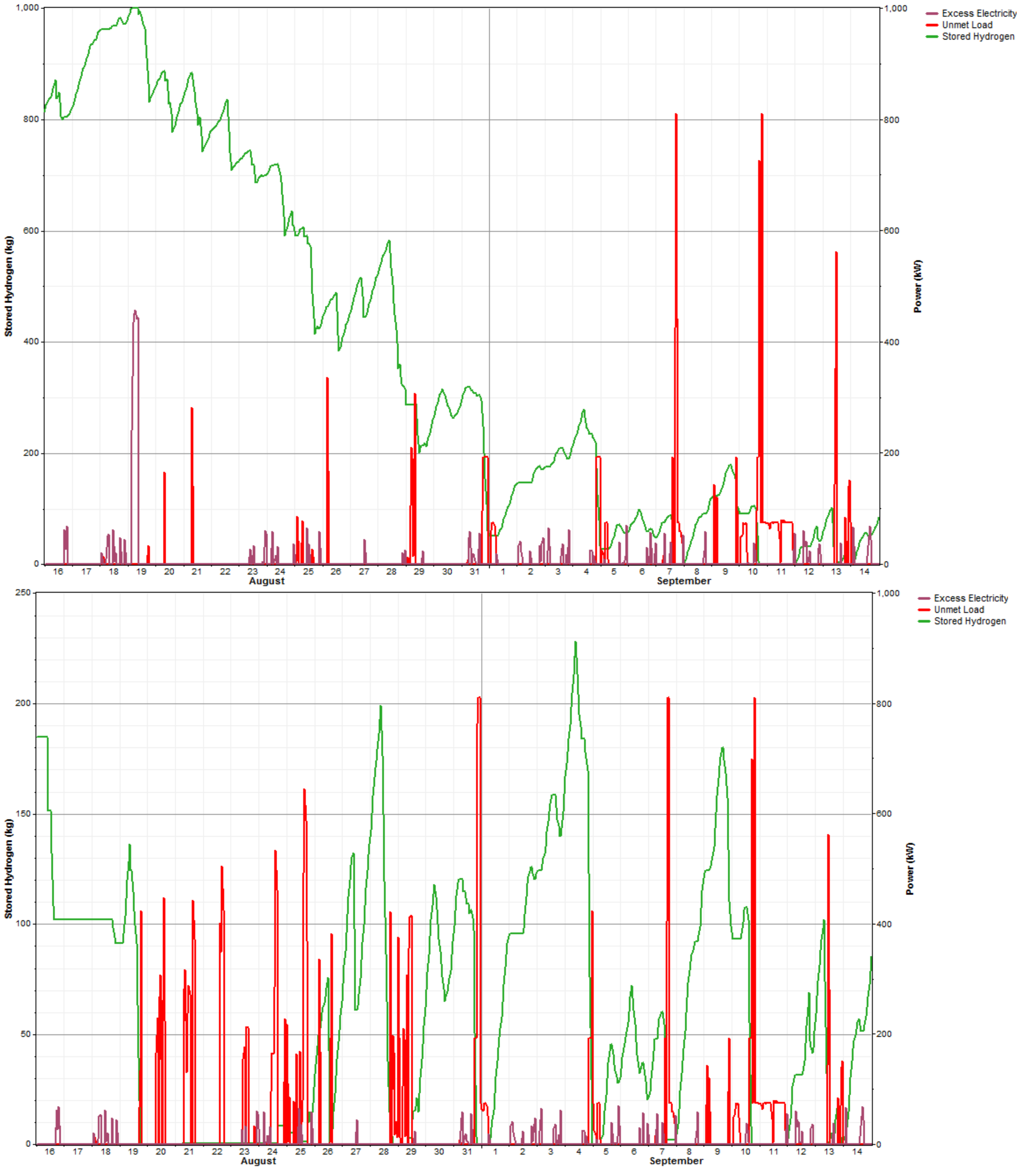
Figure 25. Hydrogen load inputs section of HOMER

As expected, the values presented in Table 23 proves that this control strategy minimizes the electrical surplus up to 1% of the power output of the turbine at the expense of diminishing slightly the power contribution of the PEMFC (2% reduction approximately) as consequence of more frequent lack of hydrogen in the tank. Accordingly, the power served by the Wind-H_2 system is barely lower respect the load following strategy (93.8% compared with 95.5% of the load following strategy) which is balanced by the hydrogen sold that reaches 10.4% of the wind turbine output power. Moreover, it should be noticed the higher lifetime of the PEMFC compared with the previous case study, reaching 3.13 years which benefits considerably the reduction of replacement cost.

Wind-H_2 system (1 turbine) with H2 trade			
	kWh/yr (2012)	% on predicted	% on production
Predicted Power	2.659.034		
Wind turbine power output	3.819.057		
Converter power losses	171.142		4,5
Electrolyser losses	281.932		7,4
Fuel cell losses	412.600		10,8
Fuel cell power output	294.713	11,1	7,7
Excess electricity	38.561		1,0
Sistem power served	2.494.478	93,8	
Turbine power served	2.199.765	82,7	57,6
Unmet power predicted	164.556	6,2	
Hydrogen producted (kg)	28.590		
Hydrogen load (kg/yr)	6.716		
Hydrogen load served (kg/yr)	6.716		10,4
Unmet hydrogen load (kg/yr)	0		
Hydrogen content at the end of the year (kWh)	21.833		0,57

Table 23. Technical results obtained for a Wind-H2 system based on load following coupled with H2 trade

The graph below displays a comparison between both energy management strategies in terms of power deviations and hydrogen storage level in the tank during the period 16th August- 14th September. It can be seen how with hydrogen trade the power deviations for excess electricity disappear in contrast to the increment of unmet power served caused by lack of hydrogen available in the tank.



Graph 12. Comparison of power deviations and H2 storage between both management strategies (16 August-14 September)

In addition to this, it is necessary to analyze if this energy management strategy is more convenient for the wind farm operator than load following from an economical point of view. The comparison between Table 20 and Table 24 proves that hydrogen trade balances the reduction of electricity sold, implying an annual cash flow increment of 381% over the load following strategy. The reason is the high price of hydrogen, so 5966 £ loss associated with electricity sales are compensate with 74212 £ income derived from the hydrogen trade.

		kWh/yr (2012)	REVENUE (£)
Wind-H_2 system power served		2.533.039	104.252
Excess electricity		38.561	-819
Unmet power predicted		164.556	-2.518
Electricity trade income			100.915
Hydrogen served		6.716	74.212
Total income			175.127
O&M cost	turbine		-25.000
	converter		0
	electrolyser		-14.280
	compressor		-975
	h2 tank		-8.775
	PEM		-26.582
Annual cash flow			99.515

Table 24. Annual cash flow of a Wind-H2 system with load following strategy coupled with H2 trade (1 turbine)

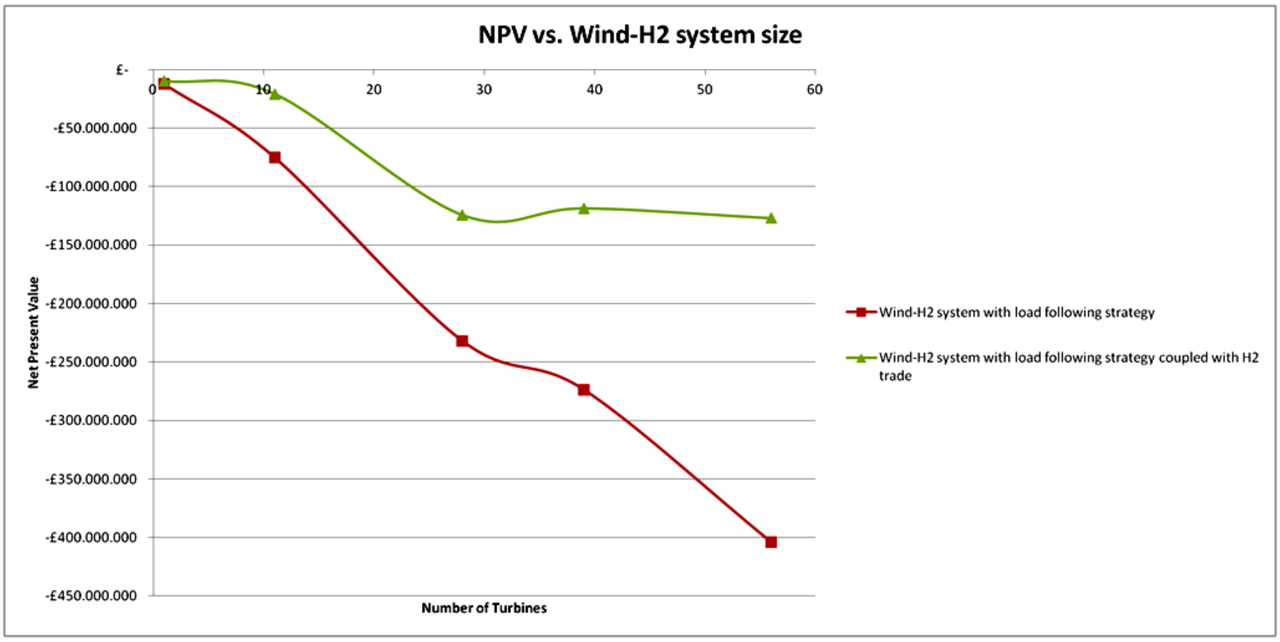
The evaluation of the NPV for this Wind-H_2 project after its lifetime gives a negative value of £ -9722315 (-11375105 €) proving that this technology is currently unfeasible from an economical point of view, due to the high capital costs of hydrogen equipment can be compensate with the increase revenue from hydrogen sales. Nevertheless, comparing this NPV with the NPV obtained for the system with load following strategy arise the fact that hydrogen trade enhances the profitability of load following strategy (20 % reduction of NPV) due to the high price of hydrogen and the reduction of replacement cost of PEMFC.

NET PRESENT VALUE		
Year	Cashflow	NPV
0	-11.202.840	-11.202.840
1	99.515	96.616
2	99.515	93.802
3	99.515	91.070
4	99.515	88.417
5	99.515	85.842
6	99.515	83.342
7	99.515	80.914
8	99.515	78.558
9	99.515	76.270
10	99.515	74.048
11	99.515	71.891
12	99.515	69.798
13	99.515	67.765
14	99.515	65.791
15	99.515	63.875
16	99.515	62.014
17	99.515	60.208
18	99.515	58.454
19	99.515	56.752
20	99.515	55.099
Discount rate(%)	3	
NPV		-£ 9.722.315

Table 25. Economical feasibility of a Wind-H2 system with load following strategy coupled with H2 trade (1 turbine)

As the previous case study, this analysis has been carried out for each Wind-H_2 system presented in Table 22 in order to study the profitability of the system regarding the wind farm size. From the analysis of power deviations and H_2 technology contribution obtained for each combination, it can be seen that they are strongly dependent on the hydrogen tank level above which all hydrogen production is sold. Moreover, it can be seen that a Wind-H_2 system composed by more than 10 turbines, the hydrogen income overcome the income derived from electricity sales. This suggests that hydrogen trade is more profitable than electricity sale. However, it should be kept in mind that the primary purpose of a Wind-H_2 system is selling electricity.

With regards the NPV for each wind farm size, Graph 13 shows that Wind-H_2 system based on load following strategy coupled with H_2 trade are less profitable with the larger wind farm size although is always more convenient than the system based only on load following strategy especially for large wind farm (larger than 30 turbines equivalent to 24 MW) reaching a NPV reduction of 69%. As can be seen in Graph 13 wind farms with more than 30 turbines (24 MW) present a lesser decrement derived from the greater amount of hydrogen sold coupled reductions in capital cost and replacement cost associated with the PEMFC. This suggests the fact that the more hydrogen sold the more profitable is the Wind-H_2 system.



Graph 13. NPV vs. Wind-H2 system size (load following strategy and H2 trade)

4.2.4 H_2 Equipment Cost Reduction

Focusing on the best case scenario, which is the Wind-H_2 system based on a load following strategy coupled with hydrogen trade (1 turbine), the following graphs display a breakdown of equipment capital and O&M cost that comprises the Wind-H_2 system. Regarding Figure 26, it is very striking the significant contribution of PEMFC in the initial investment of the Wind-H_2 system, accounting to 82% of the total investment. The main reason is the high capital cost of PEMFC aided by its poor lifetime resulting in high replacement costs.

With regards the O&M costs, Figure 27 shows how maintenance cost associated with PEMFC and wind turbines constitute the vast majority of expenditures (35% and 33% respectively) followed by the electrolyser (19%).

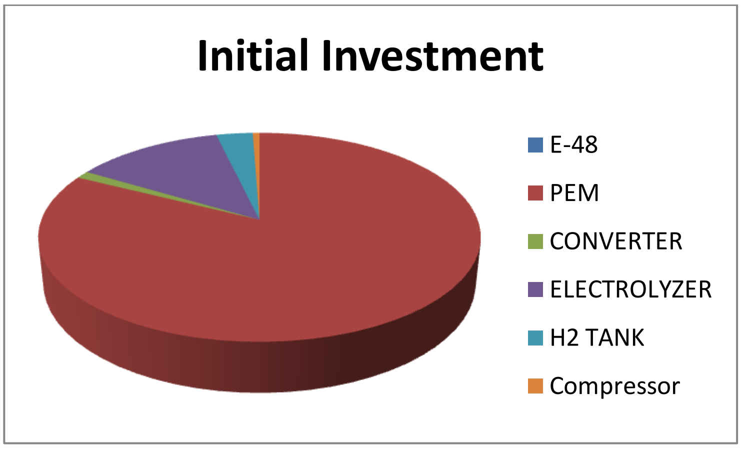


Figure 26. H_2 equipment capital cost breakdown

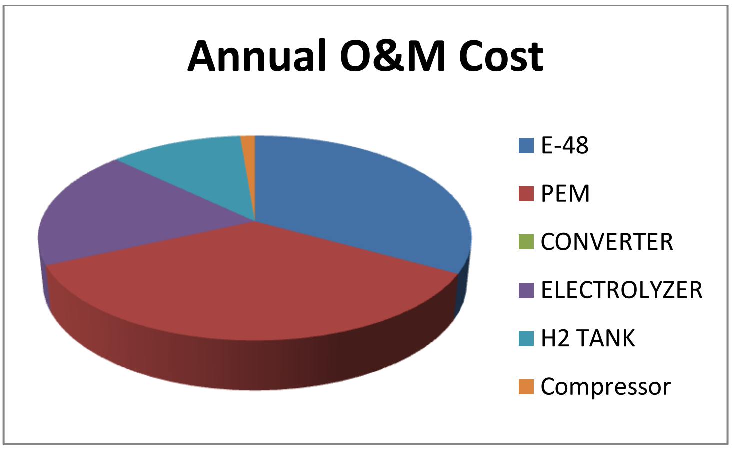


Figure 27. H_2 equipment O&M cost

The above proves the necessary reduction of capital and O&M cost associated with the PEMFC and electrolyser in order to achieve the economical feasibility of the Wind-H_2 systems. Therefore, the reduction cost required based on the current efficiency and lifetime of equipment is as follows:

		Cost reduction required	Efficiency	Lifetime (years)
Wind Turbine	O&M cost		50%	20
Converter	Capital cost		90-95%	20
	O&M cost			
Electrolyser	Capital cost	49%	80%	10
	O&M cost	49%		
Compressor	Capital cost		100%	20
	O&M cost			
H2 tank	Capital cost			20
	O&M cost			
PEMFC	Capital cost	50%	42%	3,13
	O&M cost	50%		

Table 26. Equipment cost reduction required (current technology)

Concerning Table 26, the Wind-H_2 system based on load following and hydrogen trade evaluated in this project requires a capital and maintenance cost reduction of 49% for the electrolyser and 50% for the PEMFC. Nevertheless, lifetime and efficiency improvements, especially for the PEMFC due to its high cost, would curtail the aforementioned reductions. For instance, Table 27 proves that PEMFC efficiency improvement up to 5 years (9000 operating hours approximately) would require a 21.8% cost reduction associated with the electrolyser and 23% for PEMFC to make this technology economically feasible for a 20 years lifetime project.

		Cost reduction required	Efficiency	Lifetime (years)
Wind Turbine	O&M cost		50%	20
Converter	Capital cost		90-95%	20
	O&M cost			
Electrolyser	Capital cost	21.8%	80%	10
	O&M cost	21.8%		
Compressor	Capital cost		100%	20
	O&M cost			
H2 tank	Capital cost			20
	O&M cost			
PEMFC	Capital cost	23%	42%	5
	O&M cost	23%		

Table 27. Equipment cost reduction required (with PEMFC lifetime improvement)

4.2.5 Wind-H_2 system with H_2 trade

In light of the results presented in Graph 13 about the NPV evolution for different wind farm sizes, the higher profitability of hydrogen trade than electricity sales arises, despite the penalizations incurred by the wind farm for deficit of electrical generation. Furthermore, PEMFC presents important technical and economical constraints such poor efficiency and lifetime as well as expensive capital and O&M costs that prevent Wind-H_2 systems to become economically feasible regarding a load-following control strategy. Thus, in this section a Wind-H_2 system that sells all hydrogen produced (called Wind-H_2 station) are going to be evaluated from a technical and economical point of view. The best advantage of this energy management strategy is the PEMFC removal which decrease considerably the capital and O&M costs as well as improve the energy efficiency of the global system.

The equipment sizes combinations analysed for this energy management strategy are those resulted in the previous case unless the H_2 tank size and PEMFC:

TURBINES	CONVERTER (kW)	ELECTROLYSER (kW)	H_2 TANK (kg)
1	620	420	700
11	3900	4000	7500
28	16000	10500	18000
39	17000	13500	25000

56	19000	23000	25000

Table 28. Best techno-economical combinations of equipment size for a Wind-H2 system with H2 trade

This time, the criteria used for selecting the hydrogen tank size has been the number of hydrogen discharges required taking into account the annual hydrogen produced and the tube trailer size aforementioned.

Focusing on the Wind-H_2 system composed by 1 turbine, Table 29 proves that a wind farm operating at the same time as a hydrogen station accomplish the lowest excess of electricity (0.9%) meanwhile its unmet power predicted maintains similar values to the wind farm without energy storage. What is more, the power losses of this Wind-H_2 system accounts to 28% (or 72% of efficiency) in contrast to 63.6% of the system composed by PEMFC.

Wind-H2 system with H2 trade (1 turbine)			
	kWh/yr (2012)	% on predicted	% on production
Predicted Power	2.659.043		
Wind turbine power output	3.819.057		
Converter power losses	156.626		4,1
Electrolyser losses	281.932		7,4
Excess electricity	34.177		0,9
Sistem power served	2.218.677	83,4	58,1
Unmet power predicted	440.366	16,6	11,5
Hydrogen producted (kg)	28.590		18,0

Table 29. Technical results obtained for a Wind-H2 system with H2 trade

With regards income and expenditures that this system incurs annually, it is very remarkable the high income derived from hydrogen sale, which overcomes the revenues from electricity sales in 370%. Thus, the annual cash flow incurred by this system is 353696 £ (413824 €), representing an increment of 355% over the wind farm with load following strategy coupled with H_2 trade. This dramatic growth of net revenues is mainly due to the high price of hydrogen as well as avoidance of Capital and O&M costs associated with the PEMFC.

		kWh/yr (2012)	REVENUE (£)
Wind-h2 system power served		2.252.854	92.721
Excess electricity		34.177	-726
Unmet power predicted		440.366	-6.738
Electricity sold income			85.257
Hydrogen served		28.590	315.920
Total income			401.176
O&M cost	Turbine		-25.400
	Converter		0
	Electrolyser		-14.280
	Compressor		-975
	H2 tank		-6.825
Annual cash flow			353.696

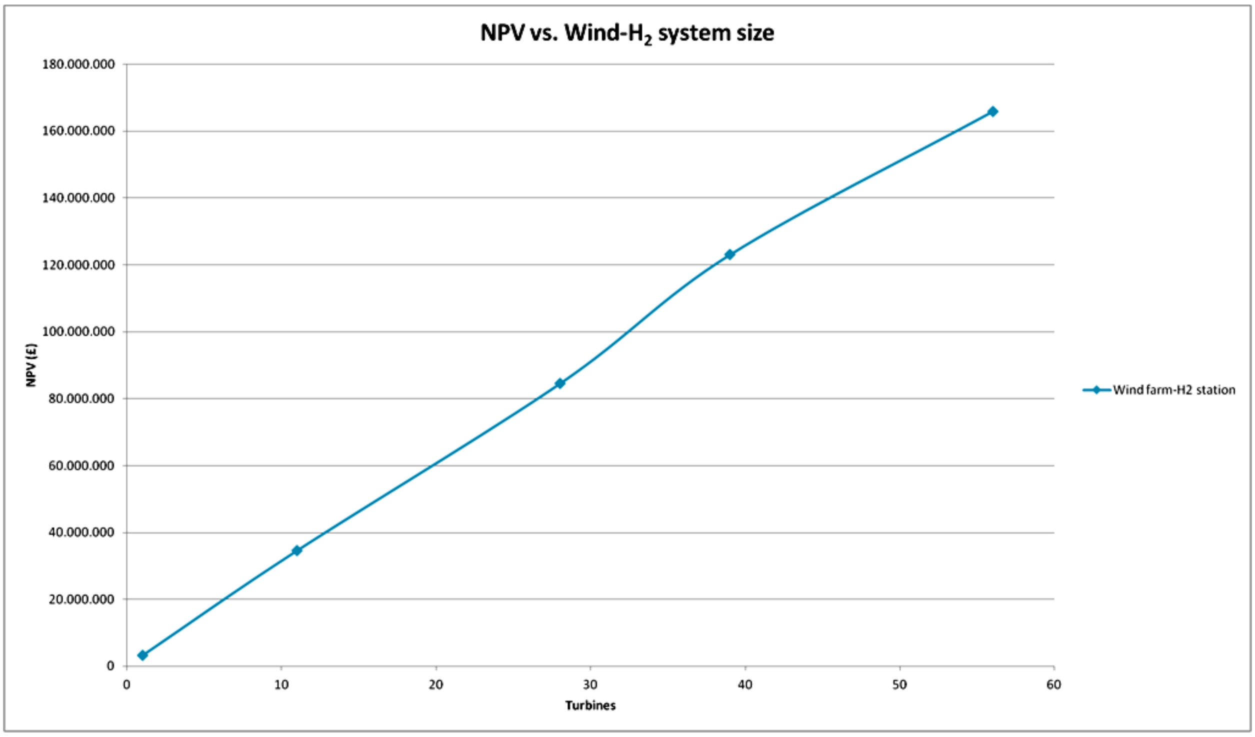
Table 30. Annual cash flow of a Wind-H2 system with H2 trade (1 turbine)

Apart from working out the annual cash flow of the system, the initial investment of the project and the annual cash flow has been analysed for carrying out the feasibility study of the project. Therefore, the NPV analysis of the present case study gives a value of £ 3364669 (3936662 €) after 20 years (see Table 31), proving its economical feasibility within the current Spanish economical framework for renewable energy production (RDL 9/2013) if the hydrogen is sold in Spain at the aforementioned price.

NET PRESENT VALUE		
Year	Cashflow	NPV
0	-1.897.440	-1.897.440
1	353.696	343.395
2	353.696	333.393
3	353.696	323.682
4	353.696	314.255
5	353.696	305.102
6	353.696	296.215
7	353.696	287.588
8	353.696	279.211
9	353.696	271.079
10	353.696	263.183
11	353.696	255.518
12	353.696	248.076
13	353.696	240.850
14	353.696	233.835
15	353.696	227.024
16	353.696	220.412
17	353.696	213.992
18	353.696	207.759
19	353.696	201.708
20	353.696	195.833
Discount rate	3	
NPV		3.364.669

Table 31. Economical feasibility of a Wind-H2 system with H2 trade (1 turbine)

Like in previous cases, the above techno-economical study has been undertaken for the rest of equipment combinations presented in Table 28, obtaining the Net Present Values displayed in Graph 14.



Graph 14. NPV vs. Wind-H2 system with H2 trade

Regarding the NPV values presented in Graph 14, wind farms sizes covered in this study (between 1 and 56 turbines) are economically feasible within the RDL 9/2013 context if the hydrogen is sold at the hydrogen price aforementioned. Furthermore, in Graph 14 it can be seen that the profitability increase gradually with the wind farm size due to the augmentation of revenues derived from electricity and hydrogen trade. Nevertheless, as the hydrogen price may decrease in the future with the development of a hydrogen economy, a minimum hydrogen price that ensures the economical feasibility of this technology has been evaluated. The results obtained for the largest wind farm proves that even a price of 3.1 £/kg (3.6 €/kg) would guarantee the economical feasibility of a Wind-H_2 station in Spain.

However, there is a important constraint associated with large wind farms which is the big equipment size required. A possible solution for wind farm operators who are interested in implementing this technology in large wind may be a multi-hydrogen generation systems integrated in the wind farm. This idea consists of independent hydrogen systems (electrolyser + hydrogen tank + auxiliary equipment) integrated each one with the number of turbines that achieves the technical and economical optimum.

5 Conclusions

In light of the results obtained in the present dissertation, different conclusions can be drawn as follows:

- ✓ The suppression of the Feed-In Tariff for renewable energy generation by the new Real Decree-law 9/2013 makes wind power generation economically unfeasible, requiring high remunerations to become "reasonable profitable". The aforementioned law establishes that wind farms shall compete with the rest of technologies in the Energy Market (regulated by the *Law/54/1997*), selling the electricity at the Dairy Market Price (PMD) which is lower than the electricity prices (for RES) regulated by the abolished *RD 661/2007.* As a consequence, the electricity sale income is not high enough to balance the penalization for deficit of power generation as well as capital and O&M costs of the equipment, especially in wind farms with rate power larger than 8 MW.

- ✓ There is an urge necessity of storing the great excess of electricity incurred by wind farms and if possible re-injecting it into the grid when power generation was over estimated, regarding a load following control strategy. This energy management represents the best option for guarantee the stability of power generation regardless weather conditions Moreover, it should be noticed that the vast majority of deviations correspond to excess of electricity rather than deficits. Besides, it should be mentioned that the aforementioned necessity of energy storage would be partially diminished by wind speed estimation enhancements of the prediction models used by wind operators.

- ✓ Wind-H_2 systems based on either load following or load following coupled with H_2 trade are economically unfeasible regarding the RDL 9/2013, although the latter energy management presents better results derived from hydrogen sale. Nevertheless, these systems present some constraints to be solved in order to become a technical and economically feasible option in the future. Firstly, the low efficiency of the H_2 technology, especially PEMFC, accounting to a system global efficiency of 36.4%. Moreover, a capital and O&M cost reduction of H_2 equipment as well as life time enhancement, especially PEMFC are required. For instance, the economical feasibility of Wind-H_2 system would be accomplished by a PEMFC lifetime of 5 years coupled with an electrolyser and PEMFC capital and O&M cost reduction of 21.8% and 23% respectively. Furthermore, a development of larger PEMFC sizes would be desirable for integration in big wind farms.

- ✓ Wind-H_2 systems based on H_2 trade, this is operating as hydrogen stations, are economically feasible within the current Spanish framework for RES if the hydrogen is sold in Spain at the same price than U.S (at 12.93 €/kg or 11.05 £/kg), minimizing the excess of electricity and energy losses in the process. Therefore, the high profitability of hydrogen trade compensates the penalizations associated with unmet power served which is equal to wind farms without energy storage. What is more, in order to take into account a future decrease of hydrogen price derived from the development of a "hydrogen economy" a price of 3.1 £/kg (3.6 €/kg) was obtained as the minimum price that would ensure the economical feasibility of Wind-H_2 stations in Spain. Furthermore, the results for different wind farm sizes prove their feasibility is enhanced with the size. For larger wind farms where the equipment size required is not commercially available, arises the idea of integrating independent multi-hydrogen generation systems, each one with the number of turbines that accomplish the technical and economical optimum of the project.

To sum up, meanwhile the technical and economical constraints associated with hydrogen technology are not solved, Wind-H_2 stations seems to be the best option for fulfilling the current necessity of energy storage in wind farms. What is more, from an economical point of view, hydrogen trade arises as an alternative to guarantee the economical feasibility of current wind farms affected by the Royal Decree-law 9/2013 in Spain.

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