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Energy and economic study of a multi-energy network including multiple hydrogen pathways in the University Campus of INSA Lyon, France

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ABSTRACT

Combination of storage systems and diverting the renewable energy sources can play a large role in increasing the free-carbon sources contribution in an energy consumption network and therefore reducing greenhouse emissions. This project focuses its efforts in studying both in energy and economical way different hydrogen energy storage systems or pathways with the aim of concluding which could be the best option to increase the renewable and grid independency factors of the University Campus of INSA Lyon, France. It is concluded that in a place where silence is very important, from different studied renewable sources, only photovoltaic panels can be installed as a source. Power-to-Power and Methanation hydrogen pathways are studied more in detail by developing different energy and economic simulations with diverse software, namely: HOMER, OPENMODELICA and TRNSYS. This approach will be done with the main objective of increasing even more the renewable energy factor and reducing the fatal electricity injection to the grid.

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1. INTRODUCTION

In this study, a novel multi-energy system is going to be proposed to increase the renewable factor of an existing case of study. This will also increase the consumer's independency from the energy grid due to the installation of in-place energy producers such as photovoltaic panels and the introduction of hydrogen as an energy vector. In this section, the background, the justification and the goals of this project are going to be explained and discussed in order to place the reader before starting with the technic case.

1.1. Background

The huge human energy needs have caused a remarkable attrition of the non-renewable energy sources, consuming the coal, petrol and natural gas that have been stored during millions of years. This has also produced an increasing of the carbon dioxide (CO2) emissions and the consequent global warming rising. As the non-renewable energy sources are going to come to their end in the future due to their inability to regenerate themselves, it is important to invest, rely in and enhance the renewable energy technologies to ensure the energy supply and maintain, or also increase, the current live level of our society.

While the bulk of non-renewable energy sources come curiously from unstable countries where they have very volatile governments, the renewable energy sources can be exploited in the own country where they have been installed. This will ensure the energy independency of the country that has invested their resources in these renewable technologies and will help to maintain the energy prices in a more stable way for the consumers, avoiding the well-known fluctuations of the different carbon sources.

After all the advantages of the renewable energy sources exposed before, it would be possible to say that they are the best way to improve the current energy scenario, but the true is that, currently, they are just a complement to the non-renewable sources. Due to their high price, their discontinuous energy production and the lower knowledge of these technologies, the energy investors may prefer to invest in other technologies which have a lower investment, continuous and modular energy production and more experimented technologies such as the non-renewable sources.

When an investor decides to finance a renewable energy installation (wind turbines and solar modules are the most representative cases), a typical problem may come out: the energy production and the energy consumption are not going to be balanced. This is because the renewable sources depend on the weather conditions, being the biggest energy production during the hours where the energy consumption is the lowest.

A good alternative to take advantage of the surplus of energy produced by the renewable sources when the energy consumption is lower than the production is to use Energy Storage Systems (ESS). These systems can play an important role in the penetration of the renewable technologies in the energy mix because they can balance the production, storing the energy surplus and using it when it is needed. This technic can also allow reaching a stand-alone system with only renewable sources. It is possible too to use this advantage providing auxiliary services to the grid.

Regarding the different ESS technologies, this project will concentrate the efforts in the study of sizing and performance improving of hydrogen as an energy vector. When the renewable energy production is bigger than the energy consumption, the surplus is going to be used to produce hydrogen thanks to an electrolyser. This gas can be stored until the consumption is bigger than the production. In this case, the hydrogen is going to be converted into electricity through the use of a Fuel Cell (FC). In the case where the solar production and the energy from the FC is not enough, electricity from grid is going to be consumed.

1.2. Justification

Being the hydrogen a promising way to allow a bigger penetration of the renewable energy sources through its role as an Energy Storage System, currently it exists a lack of economic and technical studies that let the concerned people know more about the feasibility of this systems and also let other people hear these systems for first time increasing the popularity and maybe find new investors.

For this reason, this project will use a real example as it is the University Campus of INSA LYON, performing an analysis of the different energy technologies in order to understand which can be the most economical way to produce energy in different scenarios. After that, the hydrogen technology is going to be implemented studying the possible benefits in the campus network. All these studies are going to be based in different simulations from different software.

1.3. Objectives

- Study of the electrical and thermal demand of a real case: University Campus of INSA LYON.
- Develop an economic study of different energy technologies that are allowed to install in the campus.
- Use the previously mentioned economic study to develop a project where it will be possible to understand the economic feasibility of introducing renewable energy sources in the real case of study in different scenarios.
- Compare the variations if the energy context was different.
- Introduction of the hydrogen technology in the university campus network.
- Perform a component ("type") in TRNSYS software through Fortran language to control various electrolysers.
- Develop a scheme in TRNSYS software where it will be possible to understand the technical feasibility of the introduction of the hydrogen as an energy vector in the campus network.
- Develop another scheme in TRNSYS software with the introduction of the methanation process.
- Compare and discuss the different results.

2. ENERGY STORAGE SYSTEMS (ESS)

As the renewable energy production is intermittent, it is necessary to introduce systems in the network to allow the energy storage when the production is higher than the consumption and then use this stored energy when the production is lower than the consumption. This fact will let increase the participation of the renewable energy sources in the energy mix. The systems that allow this process are called Energy Storage Systems and can be divided in:

- Pumped Hydro Storage (PHS)
- Compressed Air Energy Storage (CAES)
- Battery Energy Storage Systems (BESS)
    - Lead-Acid
    - Nickel-Cadmiun (Ni-Cd)
    - Sodium-Sulphur (NaS)
    - Lithium-ion (Li-ion)
- Flow Battery Energy Storage System (FBESS)
    - Vanadium Redox flow battery (VRB)
    - Zinc-Bromide flow battery (ZBB)
    - Polisulphide-bromide flow battery (PSB)
- Hydrogen based Energy Storage System (HESS)
- Flywheel Energy Storage System (FESS)
- Superconducting magnetic storage system (SMES)
- Supercapacitor energy storage system (SCESS)

2.1. Summary of the different ESS

In this section, a summary of the main characteristics of the different Energy Storage Systems is going to be presented.

Technology	Capital cost (€/kWh)	Specific energy (Wh/kg)	Specific power (W/kg)
PHS	10-20, 35-70	-	-
HESS	2-15	100-150, 400-1000	-
CAES	3-5, 10-70	3.5-5.5	-
VRB	500	20, 25-35	166
ZBB	415	60, 70-90, 75-85	45
PSB	125-150, 360-1000	-	-
NaS	210-250	100	115, 90-230
Lead-Acid	185, 210-270	30, 35-50	180, 200
Ni-Cd	330-2000	30-40, 45-80	100-150, 160
Li-ion	750-1000	80-150, 100-150, 160, 120-200	245-430, 400-500, 500-2000
SMES	-	10-75	-
FESS	330-660	20, 5-80, 5-100	11900
SCESS	6800	2-5, 5.69, 1-10, 10, 5-15, 30	800-2000, 2000-5000, 10000, 13800, 23600

Table 1: Main characteristics of different ESS [2].

In the next image, it is possible to see the different energy efficiency of each energy storage system:

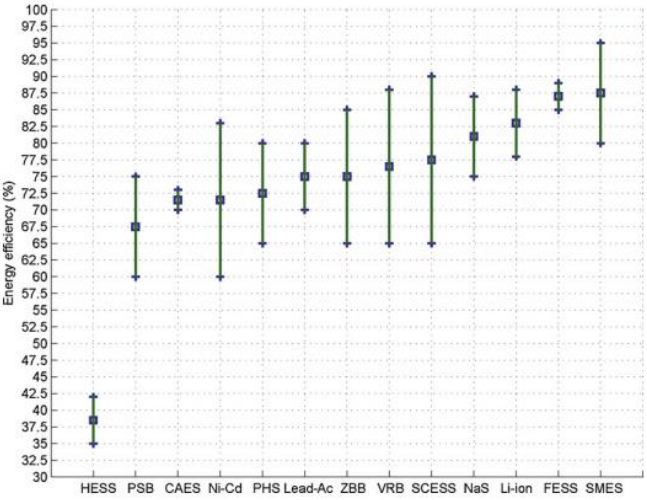


Image 1: Energy efficiency of ESS [2].

Now, an image with a comparison between rated power and energy of the different ESS technologies is shown.

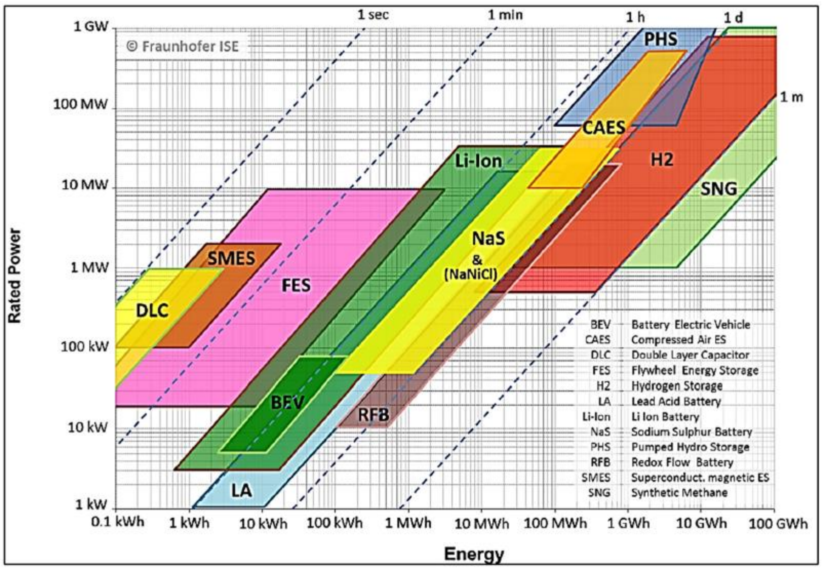


Image 2: Rated power and energy from different ESS technologies [5].

It is possible to note that the HESS technology is the one with the lowest energy efficiency of all of them with a significant difference, but at the same time, this technology has the biggest specific energy, which can allow reducing the energy storage size for the same amount between all the ESS technologies. Moreover, hydrogen produced from renewable sources has a very low CO_2 content.

For this reason and because HESS is not really developed and known in the market place, this project will try to study if this technology is suitable or not for a real case of study.

3. HYDROGEN AS AN ENERGY VECTOR

In Ref. [3] the following statement is proposed as definition for an energy vector: ‘‘an energy vector allows transferring, in space and time, a quantity of energy’’. So energy vectors allow making energy available for use at a distance of time and space from the source. As hydrogen can be produced from a source, stored, transported and can generate energy again, it can be proposed as a good energy vector. The main pathways that use the hydrogen as an energy vector are summarized in the next image.

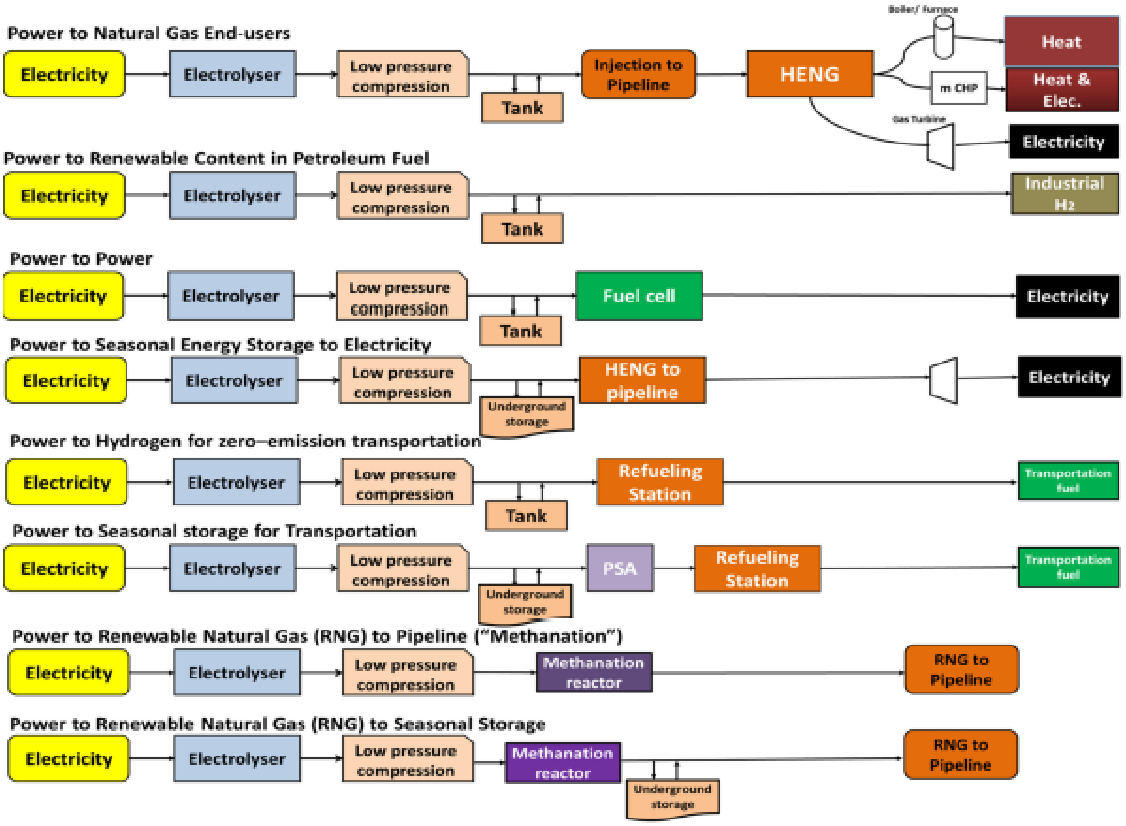


Image 3: Different Power-to-gas pathways [4].

Despite the fact that hydrogen is a chemical component that is plentiful in Nature, hydrogen can be produced using electricity by means of electrolysis and water or using fossil fuels. Hydrogen itself has no carbon emissions however the process of hydrogen production from different energy sources may imply carbon emissions that should be considered. The integration of intermittent renewables, the variation of electricity demand and temporal fluctuations into the energy systems require the operational flexibility of the power systems, which implies the need for the energy storage. Hydrogen-based technologies are suitable for broader range of storage applications including large-scale electricity storage applications, covering hourly to seasonal storage times [4].

For all these reasons, this project concentrates its efforts to design and explain a possible energy network including hydrogen as an energy vector. Both technical and economical ways are going to be studied in order to explain if this system is suitable or not and also to show possible stakeholders the advantages and disadvantages of this technology.

3.1. Power to Hydrogen to Natural Gas End-Users Pipeline Blending (HENG)

Hydrogen generated from surplus power including renewable energies can be injected to natural gas pipelines to decarbonize natural gas via direct blending to make hydrogen-enriched natural gas (HENG). 10% of H2 in natural gas has no major effect on the existing natural gas infrastructure or end-use equipment [5]. This HENG has lower CO2 emissions compared to the natural gas, and can be used for different purposes such as heating, electricity generation, or as a fuel for the transportation sector, without any modification to the equipment of HENG systems.

3.2. Power to increase renewable content in petroleum fuels

This pathway reduces the carbon intensity of petroleum fuels through the use of hydrogen produced from renewables by electrolysis for oil refining. This increases the renewable content in petroleum fuels, and decarbonizes the transportation sector on the life-cycle basis without the need to convert current vehicle power training or refuelling infrastructure. This ‘pathway’ is also complimentary with the addition of ethanol to gasoline, so the benefits of both methods for the introduction of renewable content can be applied at the same time.

3.3. Power to Power

Surplus power can be converted into hydrogen via electrolysers, pressurized and stored in storage systems, and then utilized when needed through fuel cells or hydrogen gas turbines to produce electricity. The main concern about this pathway is that the additional technologies have a potential of increasing the energy losses and cost. Moreover, the round trip efficiency is lower than battery energy storage. Nevertheless, this pathway can be favourable in remote applications or the emergency situation with a blackout. It is very interesting to increase the use of intermittent renewable production.

3.4. Power to Hydrogen for zero emission transportation

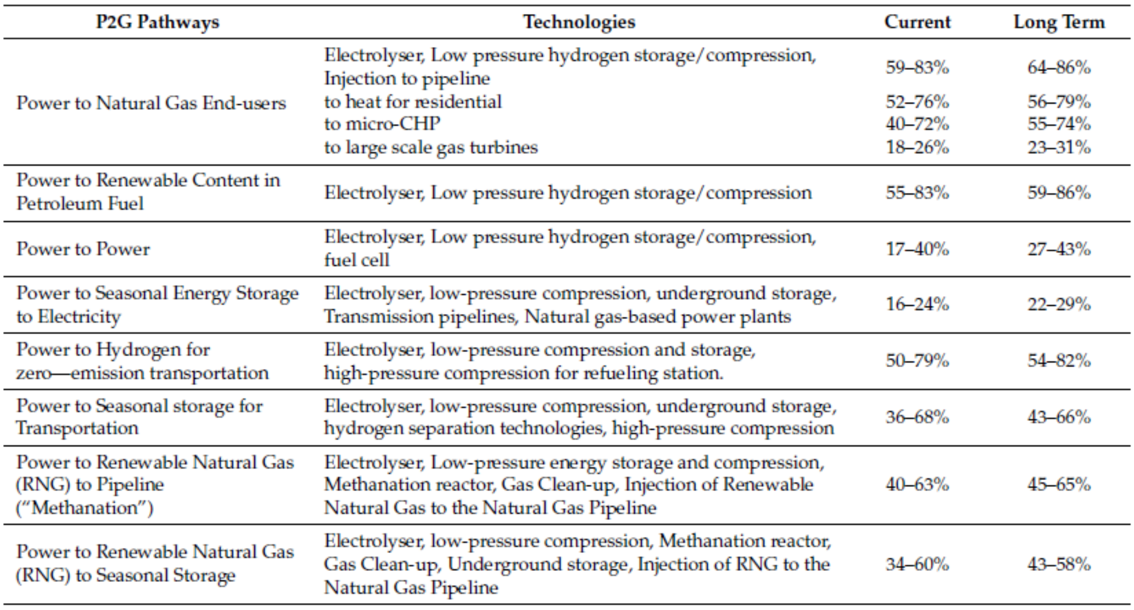
Hydrogen produced from renewable sources is compressed and stored at refuelling stations at high pressure ranging from 300 to 700 bar for hydrogen vehicles or lift trucks. It can integrate the electrical and hydrogen transport energy sectors and there is no requirement to upgrade electricity distribution systems as required for battery electric vehicles, so it will be a mix of transportation technologies.

3.5. Power to renewable natural gas (RNG) to pipeline (“Methanation”)

Hydrogen combined with carbon dioxide can used to create a stream of renewable natural gas which can be mixed with the natural gas distribution system. This methane production from electricity has a higher energy loss and cost compared to the simple hydrogen production and blending. However, the clear benefit of renewable methane is that there are no limitations on the amount of blending into the natural gas distribution system and moreover, there is a carbon capture step that converts the carbon dioxide (CO2) into renewable natural gas (RNG).

3.6. Efficiency Assessments and conclusions of the different pathways

In the next table it is possible to see the different energy efficiencies of the before explained hydrogen pathways. In this ways it will be easier to compare them.



P2G Pathways	Technologies	Current	Long Term
Power to Natural Gas End-users	Electrolyser, Low pressure hydrogen storage/compression, Injection to pipeline	59–83%	64–86%
	to heat for residential	52–76%	56–79%
	to micro-CHP	40–72%	55–74%
	to large scale gas turbines	18–26%	23–31%
Power to Renewable Content in Petroleum Fuel	Electrolyser, Low pressure hydrogen storage/compression	55–83%	59–86%
Power to Power	Electrolyser, Low pressure hydrogen storage/compression, fuel cell	17–40%	27–43%
Power to Seasonal Energy Storage to Electricity	Electrolyser, low-pressure compression, underground storage, Transmission pipelines, Natural gas-based power plants	16–24%	22–29%
Power to Hydrogen for zero—emission transportation	Electrolyser, low-pressure compression and storage, high-pressure compression for refueling station.	50–79%	54–82%
Power to Seasonal storage for Transportation	Electrolyser, low-pressure compression, underground storage, hydrogen separation technologies, high-pressure compression	36–68%	43–66%
Power to Renewable Natural Gas (RNG) to Pipeline ("Methanation")	Electrolyser, Low-pressure energy storage and compression, Methanation reactor, Gas Clean-up, Injection of Renewable Natural Gas to the Natural Gas Pipeline	40–63%	45–65%
Power to Renewable Natural Gas (RNG) to Seasonal Storage	Electrolyser, low-pressure compression, Methanation reactor, Gas Clean-up, Underground storage, Injection of RNG to the Natural Gas Pipeline	34–60%	43–58%

Table 2: Energy efficiency comparison of the different Hydrogen pathways [4].

As it is explained in the previous table, the pathways that can reach the best performance are the power to Natural Gas and Power to Renewable Content in Petroleum Fuel with a current value of 83%. This is because the technologies included in these pathways are the electrolysis and the low pressure storage/compression. Regarding the hydrogen for zero-emission transportation a value of 79% can be reached, being the second best performance of all of them. But in this case, it is only included the electrolysis, the compression and storage of the Hydrogen, not taking into account the performance of the fuel cell included in the automobiles. This must be highlighted in order to not be mistaken.

On the other hand, the pathway with the lowest performance is Power to Power with a current value of 40% as its highest possibility. This is because of the introduction of a new technology regarding the other pathways, such as the fuel cell.

It is also possible to remark the performance of the "Methanation", reaching a current value of 63%.

4. HYDROGEN TECHNOLOGIES: SELECTION AND DISCUSSION

In this project the implementation of different Hydrogen pathways in a real case of study is going to be studied. The first step is to select the most suitable ways for doing so and in order to reach it, it is necessary to study the energy demands of the case of study.

The University Campus of INSA Lyon is going to be proposed as the real case of study. After having asked to the responsible for the campus' energy management, it has been detected that there are three different energy ways to fulfil the energy needs:

- Electricity
- Natural Gas
- District Heating

Besides the introduction of Hydrogen pathways in a real energy consumption centre, the objective of this project is also to increase the renewable factor in the energy consumption. For this reason, only technologies that ensure the growth of this factor are going to be studied.

As the district heating is a technology that is supported by different energy agencies from different countries and commissions due to its possibility to reach high efficiencies and introduction of different renewable sources such as solar collectors, this energy supply is not going to be disturbed and it will be left as it is now.

Regarding the electricity demand, the best way to increase the renewable factor is to install a renewable source joined with the electricity grid. As this case of study is a University Campus and noise is an important factor when deciding the renewable energy technology, wind turbines are going to be dismissed due to its high level of noise production. Photovoltaic panels seem to be the best way to produce electricity from a renewable energy source as they are one of the cheapest technologies of this kind. All these modules are going to be installed in the different building roofs of all the Campus. As the area is a restriction factor and in order to keep increasing the renewable factor, the best Hydrogen pathway to install can be the "Power to Power" pathway.

Finally, in order to increase the renewable factor in the Natural Gas demand, two different Hydrogen pathways can be proposed: "power to natural gas end-users" and "methanation". As in the power to natural gas end-users pathway there is a maximum level of Hydrogen to inject in the natural gas network and the introduction of this high energy gas leads in a modification of the different systems in the network, this pathway is going to be discarded. In the methanation process methane is produced from hydrogen and carbon dioxide. This methane can be directly injected in the natural gas pipes without any restriction increasing significantly the renewable factor in this energy demand.

Summarizing, "Power to Power" and "Methanation" are the two different Hydrogen pathways that are going to be studied in this project due to their installation suitability.

The key needed technologies to reach these Hydrogen pathways are electrolysers, hydrogen storage/compression, fuel cells and methanation reactors. All of them are going to be studied in the next sections.

4.1. Electrolysers

Electrolysers are the technologies needed to convert electricity into fuel (Hydrogen). There are different types of electrolysers: Alkaline, Polymer Electrolyte Membrane (PEM), and Solid Oxide Electrolyser Cell (SOEC).

4.1.1. Alkaline electrolysers

When a sufficient voltage is applied between the two electrodes, at the cathode water molecules are reduced to atoms of hydrogen and hydroxyl ions. The hydrogen atoms combine to form gaseous hydrogen which escapes from the cathode. The hydroxyl (OH^-) ions migrate from the cathode under the influence of the applied electrical field through the electrolyte to the anode where the OH^- ions give up electrons releasing oxygen atoms which combine to form gaseous oxygen.

Alkaline electrolysers are the most widely deployed electrolysers for commercial production of hydrogen so they are very well proven and the most affordable ones. These electrolysers are very popular because they are very robust and have relatively long operational times (decades). This technology uses relatively cheap metals such as Nickel as catalyst unlike other electrolysers which use precious-metal catalysts. Alkaline electrolysers have been designed for operation at atmospheric pressure and at pressures up to 30bar and relatively low operational temperature range (50-100 ºC).

Regarding the main drawbacks, the used electrolyte in these electrolysers limits their response to fluctuating electrical and this has the effect of increasing energy wastage. As they work at a low pressure, auxiliary gas compression equipment must be added. Furthermore, the product gases from an alkaline electrolyser often contain traces of electrolyte (KOH) which has to be removed increasing the unit cost. The hydrogen produced has to be purified to about 99.998%.

4.1.2. PEM electrolysers

A PEM electrolyser uses an ionically conductive solid polymer. When potential difference is applied between the two electrodes, negatively charged Oxygen in the water molecules give up their electron to make protons, electrons, and O2 at the anode. The H+ ions travel through the proton conducting polymer towards the cathode where they take an electron and become neutral H atoms which combine to make H2. The electrolyte and two electrodes are sandwiched between two bipolar plates. The role of bipolar plate is to transport water to the plates, transport product gases away from the cell, conduct electricity, and circulate a coolant fluid to cool down the process. Also a purification system will clean the hydrogen to deliver high purity gas according to the customer’s specifications.

PEM electrolysers, which are in early state commercialization, have higher potential for cost reduction, durability, and efficiency improvement in the future [4].

4.1.3. SOEC electrolysers

A solid oxide electrolyser cell (SOEC) is a solid oxide fuel cell that runs in regenerative mode to achieve the electrolysis of water by using a solid oxide or ceramic, electrolyte to produce hydrogen gas and oxygen. The solid oxide electrolyser cells operate at temperatures which allow high-temperature electrolysis to occur, typically between 500 and 850 °C.

Steam is fed into the porous cathode. When a voltage is applied, the steam moves to the cathode-electrolyte interface and is reduced to form pure H2 and oxygen ions. The hydrogen gas then diffuses back up through the cathode and is collected at its surface as hydrogen fuel, while the oxygen ions are conducted through the dense electrolyte. The electrolyte must be dense enough that the steam and hydrogen gas cannot diffuse through and lead to the recombination of the H2 and O2−. At the electrolyte-anode interface, the oxygen ions are oxidized to form pure oxygen gas, which is collected at the surface of the anode.

Advantages of solid oxide-based regenerative fuel cells include high efficiencies, as they are not limited by Carnot efficiency. Additional advantages include long-term stability, fuel flexibility, low emissions, and low operating costs. However, the greatest disadvantage is the high operating temperature, which results in long start-up times and break-in times. The high operating temperature also leads to mechanical compatibility issues such as thermal expansion mismatch and chemical stability issues such as diffusion between layers of material in the cell.

4.1.4. Conclusion and summary of the main characteristics of the electrolysers

After having seen all the different electrolysers technologies, it is possible to understand that the only commercial available technologies are the PEM and alkaline. But between both of them, alkaline electrolysers are the ones the most available, mature and robust. For this reason, alkaline electrolysers are going to be the selected technology.

4.2. Hydrogen storage and compression

This is one of the most challenges in any hydrogen pathway as the optimal storage volume and the required type of storage are significantly dependent on the configuration and the operating parameters of the systems. There are different types of storage methods and they can be divided into three main groups: physical storage, materials-based storage and underground storage.

4.2.1. Physical storage systems

Physical hydrogen storage has far been the main hydrogen storage technology used and is currently the most mature technology. While compressed hydrogen storage is typically at ambient temperatures, cold (i.e., sub-ambient but greater than 150 K) and cryogenic (150 K and below) compressed hydrogen storage is also being investigated due to the higher hydrogen densities achievable [6].

Compressed storage tanks are the simplest storage systems, and despite the low storage density, higher pressure results in the higher density of storage and consequently higher costs. Low-pressure storage has larger capacities with pressures in the range of up to 30 bar, while the higher pressure storage vessels have a maximum operating pressure of 700 bar suitable for on-board storage in hydrogen-based refueling stations. The main issue about hydrogen storage in liquid form is the boil-off losses, which results in instability in pressure and limited time of storage. Storing hydrogen in cryo-compressed tanks can be a solution between pressurised and cryogenic systems.

4.2.2. Material-based storage systems

Material-based R&D approaches currently being pursued include reversible metal hydrides, hydrogen sorbents, and regenerable chemical hydrogen storage materials. It is important to underline that the applied materials-based hydrogen storage technology is still under investigation and it is difficult to find a commercial product like this in the market. These technologies are explained in the next lines:

- *Metal hydride materials:* Metal hydrides (MHx) are the most technologically relevant class of hydrogen storage materials because they can be used in a range of applications including neutron moderation, electrochemical cycling, thermal storage, heat pumps, and purification/separation [6]. Metal hydrides are composed of metal atoms that constitute a host lattice for hydrogen atoms.
- *Sorbent materials* Unlike other forms of solid-state storage, one of the advantages of using adsorbents as a storage medium is that dihydrogen retains its molecular form throughout the adsorption/desorption cycle with minimal activation energy. The primary disadvantage of using sorbents is the relatively weak adsorption enthalpies.
- *Chemical hydrogen storage materials:* This category refers to covalently bound hydrogen in either solid or liquid form and consists of compounds that generally have the highest density of hydrogen.

In the next image, it is possible to study the hydrogen capacity of each technology depending on the temperature.

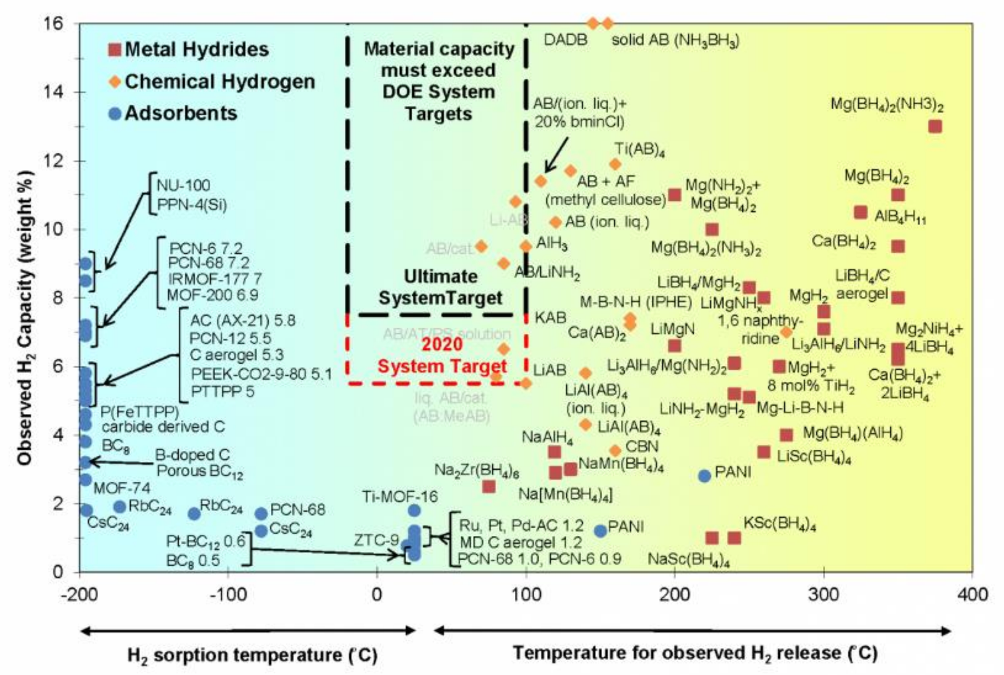


Image 4: Comparison of the different materials-based hydrogen storage systems [6]

4.2.3. Conclusion and summary of hydrogen storage technologies

It is possible to see in the next image the before mentioned hydrogen storage systems with their principal characteristics.

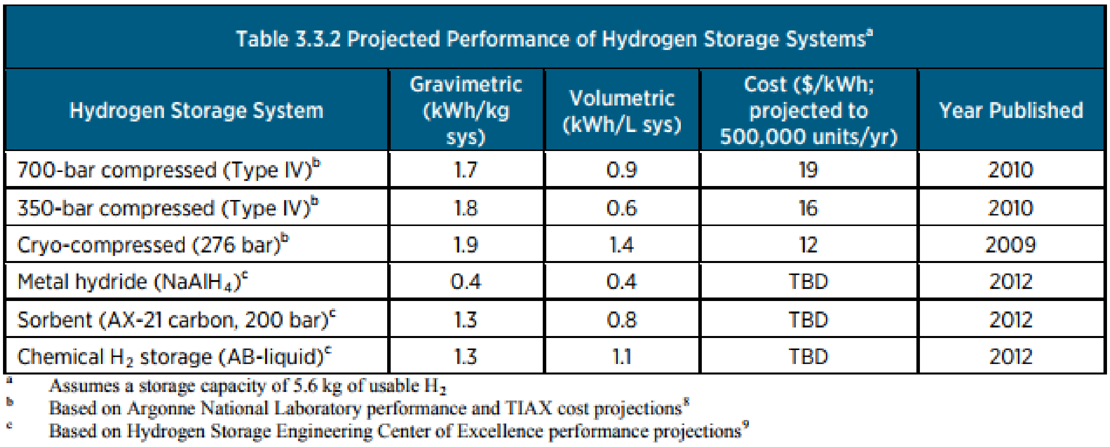


Table 3.3.2 Projected Performance of Hydrogen Storage Systems[a]

Hydrogen Storage System	Gravimetric (kWh/kg sys)	Volumetric (kWh/L sys)	Cost ($/kWh; projected to 500,000 units/yr)	Year Published
700-bar compressed (Type IV)[b]	1.7	0.9	19	2010
350-bar compressed (Type IV)[b]	1.8	0.6	16	2010
Cryo-compressed (276 bar)[b]	1.9	1.4	12	2009
Metal hydride ($NaAlH_4$)[c]	0.4	0.4	TBD	2012
Sorbent (AX-21 carbon, 200 bar)[c]	1.3	0.8	TBD	2012
Chemical H_2 storage (AB-liquid)[c]	1.3	1.1	TBD	2012

[a] Assumes a storage capacity of 5.6 kg of usable H_2

[b] Based on Argonne National Laboratory performance and TIAX cost projections[8]

[c] Based on Hydrogen Storage Engineering Center of Excellence performance projections[9]

Image 5: Projected performance of hydrogen storage systems [6].

After seen all the characteristics of the hydrogen storage systems, despite the fact that there are a lot of promising technologies in hydrogen storage, there are only a few of them available commercially with a well-proved operation. Between them the only technology that is suitable for this project is the low and high compression of hydrogen. For this reason, all of them are going to be studied with the characteristics given before, but only one technology is going to be proposed as a possible way to store hydrogen.

4.3. Fuel Cells

Fuel Cells are systems that can convert chemical energy directly in electric energy without any thermal or mechanical process. There are different types of Fuel Cells and in order to be brief, they are going to be explained with the next table.

Type	Ion	Electrolyte	T (ºC)	Applications	Advantages	Disadvantages
AFC	OH^-	Potassium hydroxide water solution	50 – 200	Military and spatial	Fast reaction in the cathode which leads in a high efficiency	It is complicated to remove the CO2 from the fuel and air
PEM	H^+	Solid organic polymer	30 – 100	Electric generation, portable applications and transport	Low corrosion and management problems, low temperature and fast starting	Expensive catalyst and high sensitivity to fuel impurities
DMFC	H^+	Solid organic polymer	20 – 90	Portable applications	Liquid fuel and cheap catalyst	Lower efficiency than in PEM
PAFC	H^+	Phosphoric acid	~220	Electric generation and transport	Reaches 80% of efficiency with cogeneration and can be used with impure H2	Platinum catalyst is needed, low power and big size
MCFC	CO_3^{2-}	Water solution of lithium sodium or potassium carbonates	~650	Electric generation	High efficiency, flexible fuel and can be used with different catalysts	The high temperature can produce corrosion and malfunction of the fuel cell
SOFC	O^{2-}	Zirconia oxide with yttrium oxide	600 – 1000	Electric generation	High efficiency and low corrosion and management problems	The high temperature can produce corrosion and malfunction of the fuel cell

Table 3: Different types of Fuel Cells.

As it is possible to distinguish, there are two big types of Fuel Cells: high temperature and low temperature Fuel Cells. In order to make this project simpler, only one of each type is going to be studied.

Regarding the low temperature Fuel Cells, PEMs are going to be selected because they are the only ones which can be used to electric generation. With regard to high temperature Fuel Cells, SOFCs are the selected ones.

4.4. Methanation reactors

By the methanation process, H2 and CO2 are converted to CH4 and H2O. The process can be carried out chemically or biologically. The biological methanation has positive characteristics such as operation at moderate temperatures (30–60 °C) and atmospheric pressure as well as a high tolerance against pollutant substances in the feed gas. However, the process suffers from very slow kinetics, poor mass transfer, and low flexibility. Chemical methanation is the most discussed technology nowadays [7]. The reaction equation of the chemical methanation of CO2 is expressed as follows:

$$4H_2 + CO_2 \rightleftarrows CH_4 + 2H_2O$$

The efficiency of the conversion amounts to 83% relating to lower heating value at the Standard Conditions, whereby the remaining 17% is released as heat. On the other hand, the reaction of the methanation is exothermic and its change in moles is negative, therefore the synthesis is thermodynamically favoured towards products at low temperature and high pressure [7].

As it is concluded in [7], the higher the pressure and the lower the temperature, the more favorable the methanation thermodynamically is. However, high operation pressure is not economical, and low operating temperature requires a sufficiently high active catalyst, which is currently one of the challenges for developing catalysts for methanation. A techno-economic compromise must be found. The kinetic barrier in methanation is high and because of that the reaction needs effective and efficient catalysts. On the other hand, the catalyst must provide high thermal stability as well as good resistance to coke formation. The catalyst system most used for the methanation reaction is Ni/Al2O3. Ni provides high activity and CH4 selectivity, and is relatively cheap. The main disadvantage of Ni is its high tendency to oxidize in oxidizing atmospheres. Nowadays different research projects are trying to develop new materials to substitute nickel [7].

The methanation is a relatively high exothermic reaction; as a consequence, heat management is very important in reactor design. It is also remarkable that the methanation is thermodynamically limited at elevated temperature while it is kinetically limited at low temperature. For this reason, heat dissipation and temperature control are the key parameters in designing methanation reactors. The most relevant reactors are shown in the next table with their advantages and drawbacks.

Reactor	Benefits	Drawbacks
Fixed-bed	Simple system, low capital costs	Hot spots and heat management
Monolith	Relatively high specific catalyst-surface, small pressure drop and short response time	Non-uniform gas distribution, scale-up limitation and short life-time
Microchannel	Good heat transfer	Single-use system
Membrane	Good temperature control and high CO2 conversion	Membrane replacements and costs
Sorption-enhanced	Almost 100% CO2 conversion and relatively low operating pressure	Discontinuous process and regeneration effort

Table 4: Type of methanation reactors and their principal characteristics.

5. ECONOMIC STUDY

As it is explained before, one of the multiple objectives of this project is to develop an economical study of the different energy technologies. With this work it will be possible to perform another study that will let the lector understand which are the most suitable energy technologies and their size for a specific application. In this section, each technology's price is going to be presented with its sources.

5.1. Photovoltaics

Different sources were found and their data is exposed briefly in the next table.

SOURCE		Cost 2010	Cost 2014	Cost 2015	Cost 2016
ADEME [8]	Investment	-	-	-	*2640 €/kW
	O&M	-	-	-	70 €/kW/year
PER [9]	Investment	3680 €/kW	-	1900 €/kW	-
	O&M	41.3 €/kW/year	-	-	-
IRENA [10]	Investment	-	4250 €/kW	-	-
	O&M	-	-	-	-
ENGIE [11]	Investment	-	-	-	*3kW→3,5 €/W *3-9kW →2,2-3 €/W *100kW→1,2-1,5 €/W
	O&M	-	-	-	115 €/year
PV.info [12]	Investment	-	-	-	*<3kW→2,8 €/W *3-9kW→2,2-2,8€/W *9-36kW→1,8-2,2€/W *36-100kW→1,15-1,8€/W *100-250kW→1,1-1,2€/W (+9.54 €/kW)
	O&M	-	-	-	Assurances→50 €/year

* +3000 €/kW to pay the connection to grid.

Table 5: Photovoltaics economical study.

As [8] is a French organization and the case of study is placed in Lyon (France), it would be fair to choose the data from this organization as its study is developed in this country with the appropriated taxes and taking into account real projects in this area.

Regarding the amount of money to pay the connection to grid, this price is not going to be taken into account as the objective of this project is to consume all the renewable electricity as possible and not selling anything.

From [9] the distribution of the technology price is shown in the next image:

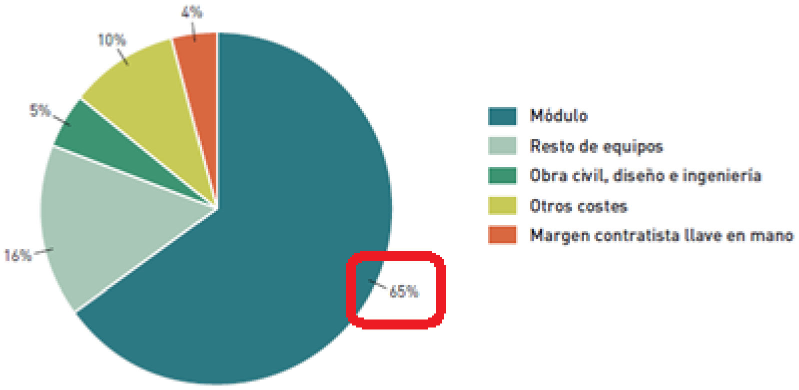


Image 6: Price distribution of photovoltaics [9].

From the aforementioned image, it is possible to understand that the module price can reach up to 65% of the total cost. For this reason, this percentage is going to be chosen as the substitution amount for this technology:

$$\begin{aligned}Substitution\ price &= Capital\ cost * module\ percentage = 2640\frac{€}{kW} * 0.65 \\ &= 1716\ €/kW\end{aligned}$$

5.2. Wind turbines

Sources and data from different organizations were found for this energy technology:

SOURCE		Cost 2010	Cost 2014	Cost 2016
ADEME [8]	Investment	-	-	1700 €/kW (66%replacement)
	O&M	-	-	52 €/kW/year
PER [9]	Investment	1307 €/kW	-	-
	O&M	45 €/kW/year	-	-
IRENA [10]	Investment	-	1779€/kW	-
	O&M	-	-	-
Noé Froissart [13]	Investment	-	-	1100 €/kW
	O&M	-	-	46 €/year

Table 6: Wind turbines economical study.

Following the same guide as before, data from [8] is going to be selected. This is because this organisation developed a study in the same area (France) where the case of study of this project is placed. Also data about replacement is provided.

5.3. Water electrolysis

Following the same approach as before for alkaline electrolysers:

SOURCE		Cost 2014	Cost 2017
[14]	Investment	1000 €/kW	-
	O&M	5% capex	-
[4]	Investment	-	850-1500 €/kW
	O&M	-	5-7 % capex

Table 7: Water electrolysis economical study.

In this case, because it is a more recent study, data from [4] is going to be selected. In order to take into account the worst possibility, 1500 €/kW and an OPEX of 7% are going to be the chosen values for the study. The substitution price is going to supposed equal to the investment price as it was impossible to find another value.

5.4. Hydrogen storage and compression

As explained in the pertinent section, for this study only compression storage is going to be taken into account for the economic analysis as the other technologies are still under development. It is also important to say that it was difficult to find prices even for a developed technology as simple compression is. Finally some information was found:

SOURCE		Cost 2017
[4]	Investment	3430 €/kg of H_2

Table 8: Hydrogen storage and compression economical study.

Regarding the replacement cost, as no more information was found, it is going to be supposed equal to the investment price and the operation and management cost equal to 1% of the CAPEX.

5.5. Fuel Cells

In this case, only SOFC and PEM technologies are going to be studied.

Different companies have been contacted but due to their privacy policies, any data about prices was provided. For this reason, only public information was found from the Department Of Energy of the USA (DOE).

SOFC

SOURCE		Cost 2014
[15]	Investment	2370 €/kW
	O&M	0.01 €/h

Table 9: SOFC economical study.

PEM

SOURCE		Cost 2014
[15]	Investment	5160 €/kW
	O&M	0.032 €/h

Table 10: PEM economical study.

The replacement price for both technologies is going to be supposed equal to the investment cost.

5.6. Converter

As the electricity demand in the case of study is consumed as AC and in order to convert electricity from DC to AC (for Fuel Cells) and AC to DC (for electrolysers) a converter is needed. In this case, a real system with its price was found: Conext XW+8548E from Schneider with a price of 3881.7€ and a power of 6.8 kW which means ~571 €/kW. The replacement cost will be supposed equal to the investment and the OPEX equal to 35 €/year.

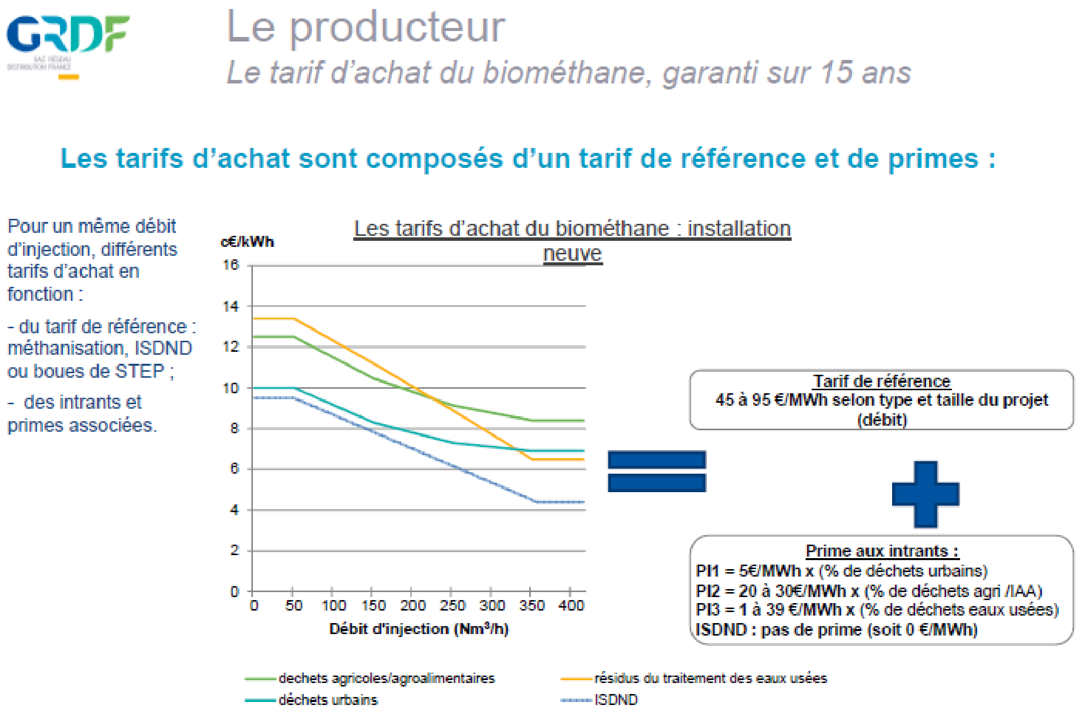
5.7. Methanation

Regarding the methanation process, few literatures is available about its investment costs. Luckily, in reference [16] it is exposed that the company Outotec GmbH published costs of 400 €/kW for a 5 MW plant and 130 €/kW for a 110 MW plant. It was not possible to find any value about the operation and maintenance costs, so it will be supposed to be 0.01% of the total installation price.

5.8. Sell price of methane

Photovoltaic panels are going to be proposed as the renewable energy source in the case of study. As in summer the electricity demand is low and the energy generation is high, there is going to be a big amount of surplus that can be converted to methane through methanation. As the thermal demand is also low during summers, not all the produced methane can be consumed and a good idea is to sell it directly to the grid instead of storing it. For this reason, it is interesting to know a sell price to take it into account in the economic study.

The following image presents a proposition from GRDF (gas distribution company from France) about biomethane sell prices. These prices are going to be taken into account in the economic study for further sections.



GRDF

Le producteur

Le tarif d'achat du biométhane, garanti sur 15 ans

Les tarifs d'achat sont composés d'un tarif de référence et de primes :

Pour un même débit d'injection, différents tarifs d'achat en fonction :

- du tarif de référence : méthanisation, ISDND ou boues de STEP ;
- des intrants et primes associées.

Les tarifs d'achat du biométhane : installation neuve

Tarif de référence
45 à 95 €/MWh selon type et taille du projet (débit)

Prime aux intrants :
PI1 = 5€/MWh x (% de déchets urbains)
PI2 = 20 à 30€/MWh x (% de déchets agri /IAA)
PI3 = 1 à 39 €/MWh x (% de déchets eaux usées)
ISDND : pas de prime (soit 0 €/MWh)

Image 7: GRDF sell prices of biomethane.

The worst value (45 €/MWh) will be used in the economic analysis in order to make a safer decision.

5.9. Annual interest rate

In order to develop a good economic study, it is necessary to know the annual interest rate to understand the evolution of the monetary amount in a project. According to the European Central Bank the evolution of the annual interest rate in France can be plotted as following:

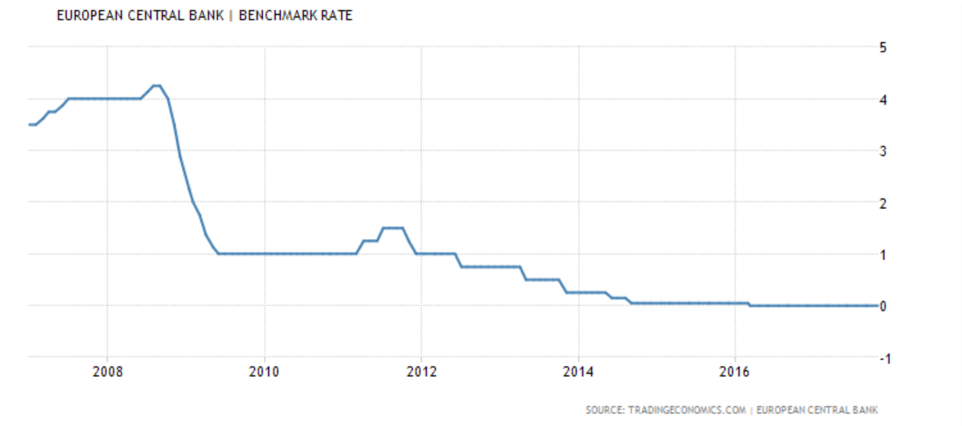


Image 8: Interest rate evolution in France.

It is possible to see that in the las years, the interest rate in France and in all Europe is around a value equal to 0. This means that there is no difference between investing money than keeping it. In order to not distort so much the results and make the program that it is going to be used in this project in a correct way, a value of 0.01 is going to be used as the interest rate.

6. CASE OF STUDY

To implement a new energy system with a hydrogen pathway it is necessary to know a demand in order to calculate the size of each element. This will also allow developing an economic study. In this project, the proposed case of study is the University Campus of INSA Lyon. In this section it will be possible to see the different energy consumptions of the campus, namely: electricity, natural gas and district heating. All of them were provided by the energy manager of the campus, this means that data is provided from real measurements.

6.1. Electric consumption

In the next figure it is possible to see how the electricity is consumed during a typical year.

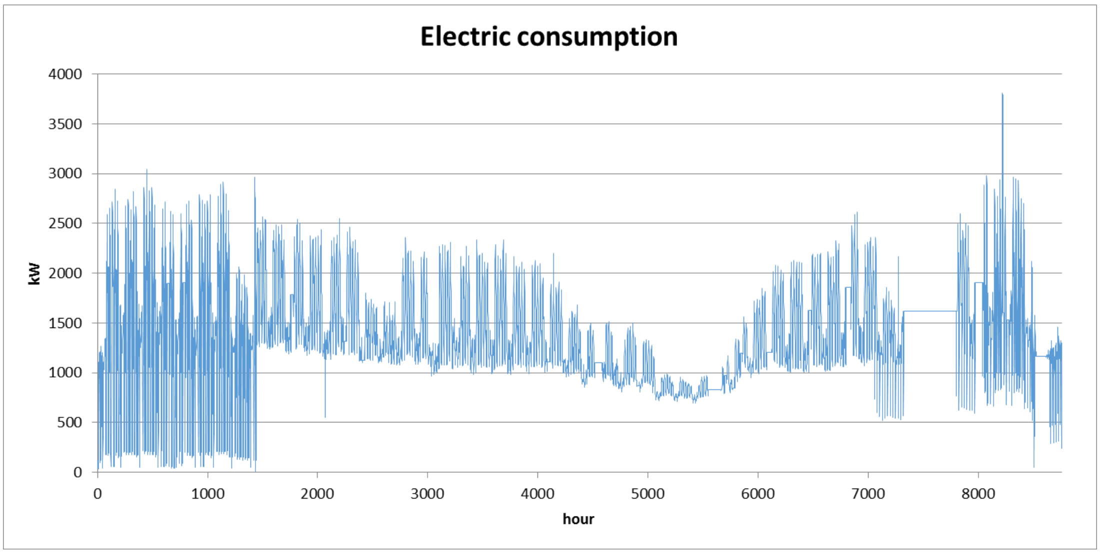


Figure 1: Electric consumption of INSA Lyon.

At the starting of the year, it is possible to see a high consumption during the day hours and then a very low consumption during nights (from 23 to 6 in the morning). It is also possible to underline that almost every 20h of each day there is a decrease in the consumption and then it increases until 22 to finally decrease as explained before. During summer the consumption is minimum but not as low as the starting and ending of the year. Before the hour 8000 there is a lineal consumption very strange that is probably a failure in the measurement system.

6.2. Natural Gas consumption

In order to fulfil the heating demand of the campus, it is necessary a natural gas consumption to feed the installed boilers. The next figure shows how this consumption variates during a typical year.

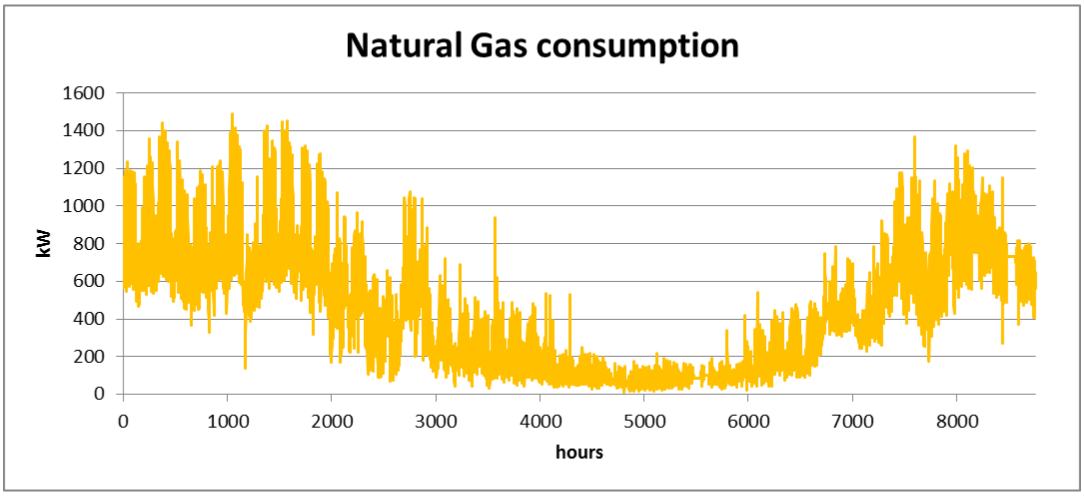


Figure 2: Natural Gas consumption from INSA Lyon.

This consumption is going to be proposed to reduce it by generating methane from hydrogen and CO_2.

6.3. District heating consumption

The biggest part of the heating demand in INSA Lyon is fulfilled by a district heating system. This scheme allows the campus generate the thermal energy by just a central disposal of boilers. Having a central system like this allows reaching a higher efficiency of the whole system than having a decentralized system. It will be also easier to install different renewable energy sources. For all these reasons, in this project it is believed that this system must be left as it is now due its high possibility to reach better performances and renewable penetration.

6.4. Photovoltaics installation and inverters

In order to increase the renewable factor in the energy consumption of the University campus, wind turbines and photovoltaics were proposed as possible sources to reach this objective. Due to the fact that the wind turbines can generate noise in a place where silence is a very necessary compound, only photovoltaics are going to be proposed for its installation.

In order to know a maximum size of photovoltaics that can be installed in the campus, a total and available surface was provided, reaching 69063 m^2. The selected photovoltaic module proposed for this study has the next characteristics (ANNEX I):

Model	ATERSA ULTRA A-330M
Power (W)	330
Dimensions (mm)	1965x990x40
Area (m^2)	1.945
I sc (A)	9.12
V oc (V)	46.78

Table 11: Photovoltaic module principal characteristics.

The first approach to know how many modules it is possible to install could be to divide the total available area by the area of each module. But it is important to take into account the shadow generated for each module to not cover the modules behind the different lines installed. For this reason, the next geometry calculus is going to be performed.

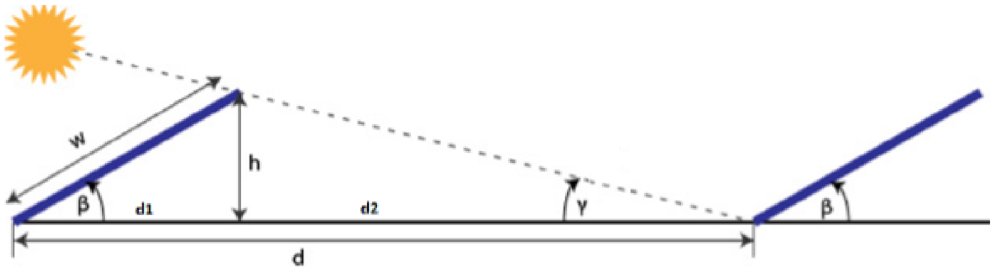


Image 9: Geometric approach to take into account the generated shadow by each PV module.

Being γ the lowest angle of the Sun position regarding the observer (21st December), δ the Earth inclination regarding the Sun the 21st December (23.5º), L the latitude of Lyon (45.75º) and β the best PV module inclination (35º from PVGIS):

$$\gamma = 90 - L - \delta = 90 - 45.75 - 23.5 = 20.75º$$

$$d1 = \cos\beta \times w = \cos 35 \times 1.965 = 1.61\ m$$

$$h = \tan\beta \times d1 = \tan 35 \times 1.61 = 0.763\ m$$

$$d2 = \frac{h}{\tan\gamma} = \frac{0.763}{\tan 20.75} = 2.013\ m$$

$$d = d1 + d2 = 1.61 + 2.013 = 3.623\ m$$

$$Occupied\ area\ per\ module = d \times module\ width = 3.586\ m^2$$

Now it is possible to calculate the total power of PV that can be installed.

$$\boldsymbol{Number\ of\ modules} = \frac{Total\ available\ area}{Occupied\ area\ per\ module} = \frac{69063\ m^2}{3.586\ m^2} \approx \boldsymbol{19256\ modules}$$

$$\boldsymbol{Total\ PV\ power\ that\ can\ be\ installed} = number\ of\ modules\ \times module\ power$$
$$= 19256\ modules \times 0.33\ kW = \boldsymbol{6354.48\ kW}$$

Knowing the total power installation of the photovoltaic field, it is possible to design the size and number of the inverter systems to produce AC current to fulfil the electric demand. The chosen option is to divide the PV field in three parts, each one with each inverter. The next tables show the feasibility of this option: voltage, current and power of the inverter (ANNEX II) are higher than those from the PV distribution.

Characteristics of each of the three parts of the PV field			
PV		Inverter	
Number of panels	6419	Inverter Model	ABB PVS980-58-1818kVA-I
In series	32	V max (V)	1500
In parallel	200	I max (A)	2400
V oc (V)	1496.96	P max (kW)	2910
I sc (A)	1824		
Power (kW)	2118.27		

Table 12: Electrical characteristics of each of the three parts of the PV field.

6.5. Proposed installation

Currently, the University campus of INSA Lyon is just composed by a grid connection, a district heating connection and different boilers disposed all around the emplacement. In order to increment the renewable fraction of the energy consumed and with the aim of including the hydrogen pathways explained and selected before, the next schemes are going to be studied. It is important to remark that AC current is going to be left because it is impossible to change all the consumption machines of all the campus to DC current. First, the Power-to-Power pathway:

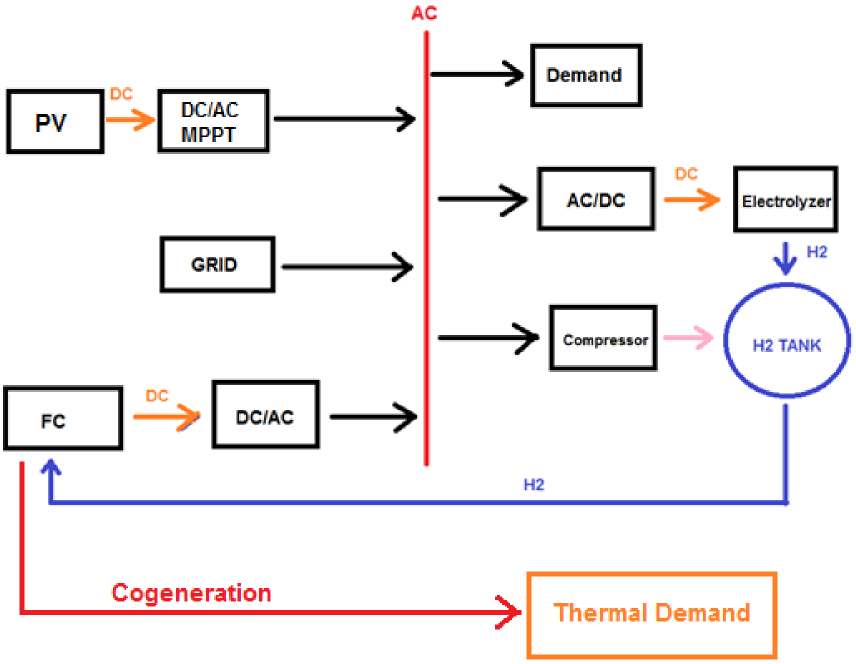


Table 13: Power-to-Power pathway proposed.

The second scheme proposed is the Methanation pathway.

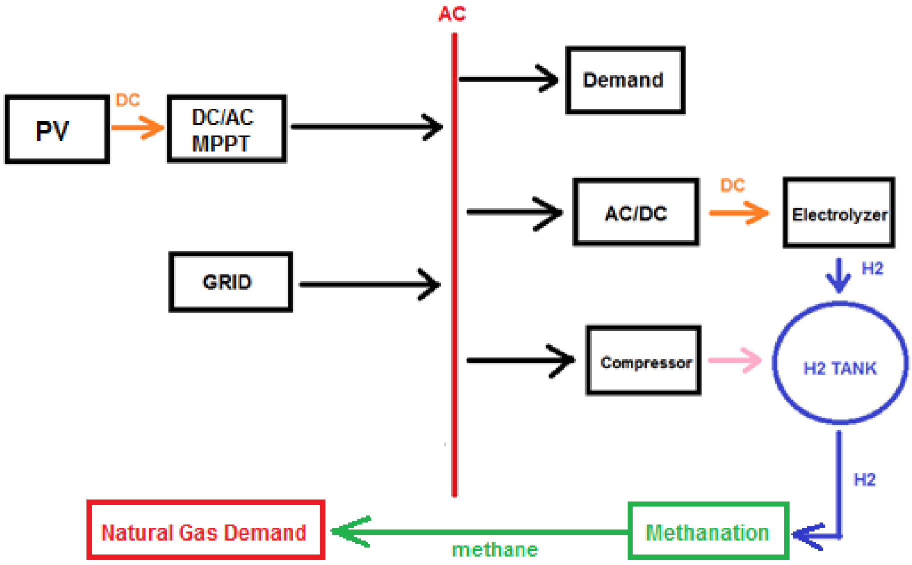


Table 14: Methanation pathway proposed.

7. HOMER

The HOMER (Hybrid Optimization of Multiple Energy Resources) microgrid software navigates the complexities of building cost effective and reliable microgrids that combine traditionally generated and renewable power, storage, and load management. Summarizing, this software can be useful to take energy initial decisions as: optimization of a generator size, total cost of the installation, optimal fuel cost to make an installation cost effective, the best generation source and if the demand can be fulfilled or not.

HOMER simulates the system operation by energy balance operations for each one of the 8760 hours of the year. For one of these hours, this software compares the total electrical and thermal demand with the total energy that can be produced, calculating every energy flow between all the components. One of the main drawbacks of this system is that it is impossible to take into account the operation transients.

For each simulation, it is possible to introduce in HOMER all the systems size that it is wanted to study. For each combination, this software calculates the energy balances to determine if the combination is feasible or not, if it is, it calculates the installation cost. At the end, HOMER makes a ranking with the best energy solutions between all the given combinations.

Different costs, restrictions and factors can be introduced in order to make the calculations more complex and therefore, nearer to reality.

7.1. HOMER simulations

The aim of using this software is to calculate the best economic way to increase the renewable consumption in this project's case of study. Different simulations are going to be carried out increasing the minimum renewable factor in every one. Moreover, different parameters are going to be changed (e.g. the emission cost) to understand how the system must change to be economically feasible.

HOMER just allows using components from its own library and, even though there are a lot of parameters that can be modified it is impossible to create a new component with the desired operation. For this reason, HOMER will be just useful to simulate the Power-to-Power hydrogen pathway.

All the economic data introduced in HOMER is given in Section 5.

In order to make the system the most simple as possible, every inverters both DC/AC and AC/DC are included in each energy technology. It is to say, the inverter investment and replacement costs (571 €/kW) is summed to each technology.

Finally, wind turbines, as explained before, are introduced just in some studies to know which of all the most known renewable technologies (wind turbines and PV) is the most economically feasible.

The next screenshot from the software shows the scheme used for every simulation. As it is possible to see, it is the same scheme as the proposed one in Section 6.5.

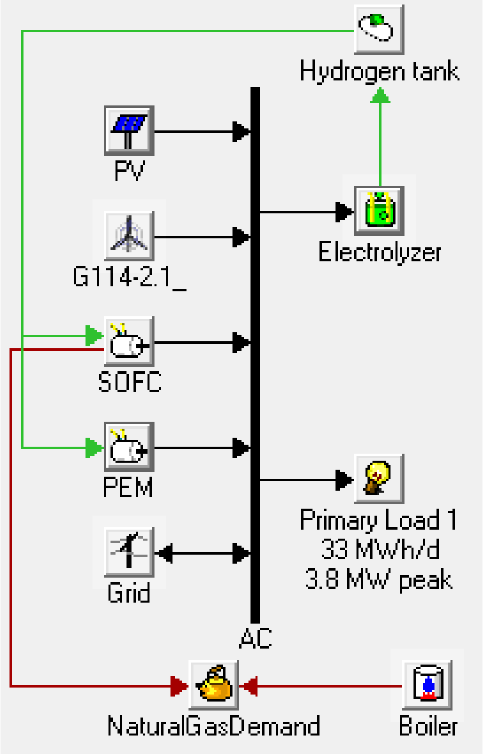


Image 10: Scheme used in HOMER for every economic simulation.

Now, every component of the previous scheme is going to be explained.

7.1.1. Electricity demand

To introduce the electricity demand in HOMER is as simple as import the electricity demand data as a ".csv" file. Moreover, HOMER provides some useful plots that can be shown here to better understand the consumption pattern of the University Campus of INSA Lyon.

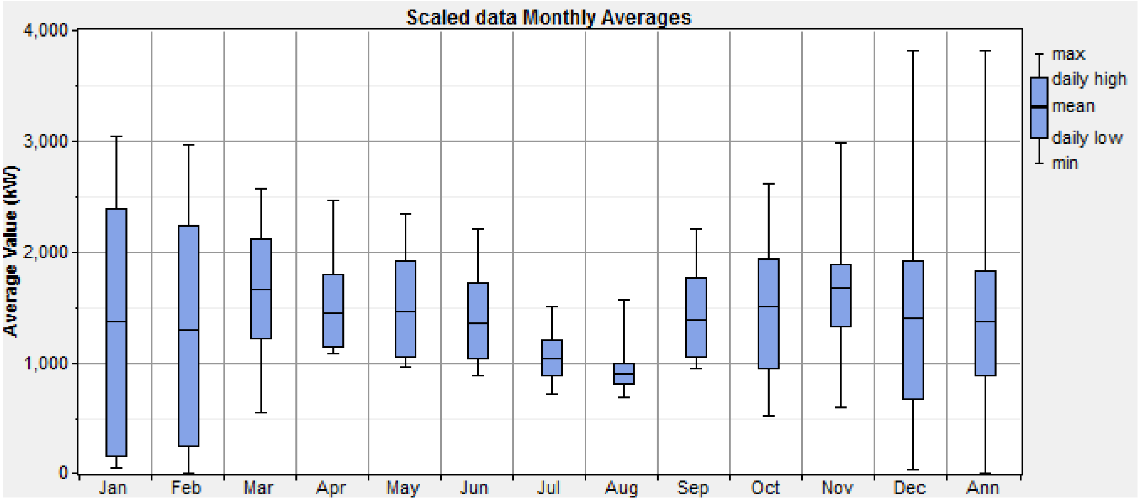


Figure 3: Scaled data with monthly electricity consumption averages.

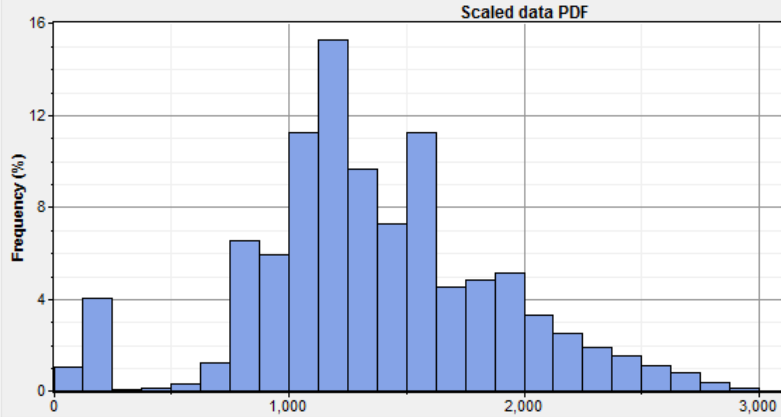


Figure 4: Frequency of the electricity consumption.

7.1.2. Natural Gas demand

As for electricity, it is possible to introduce the Natural Gas consumption in HOMER by the importation of a ".csv" format file. HOMER asks for a thermal demand and then, with the boiler efficiency, it calculates the NG consumption. As the NG consumption is already available, the boiler efficiency is going to be set to 100%.

It is possible to see in the following graphs that the natural gas consumption is bigger, as it is normal, during winter months, while in summer, this consumption decreases to its minimum.

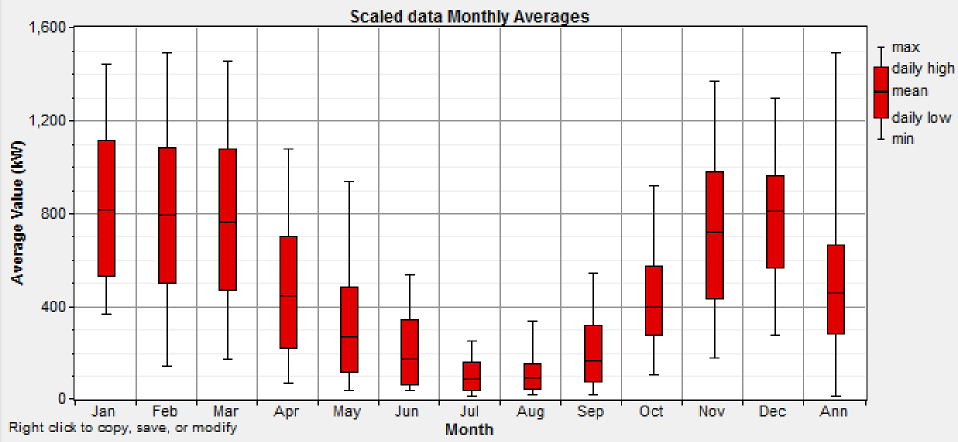


Figure 5: Natural gas monthly average consumption.

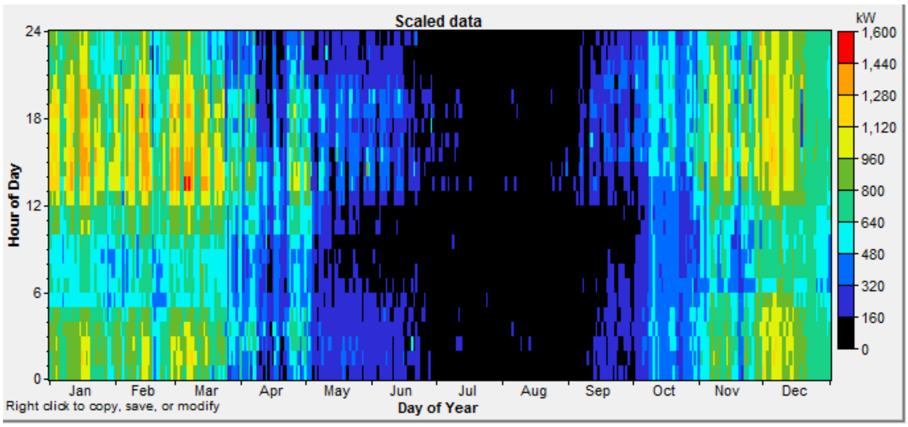


Figure 6: Natural Gas consumption DMap.

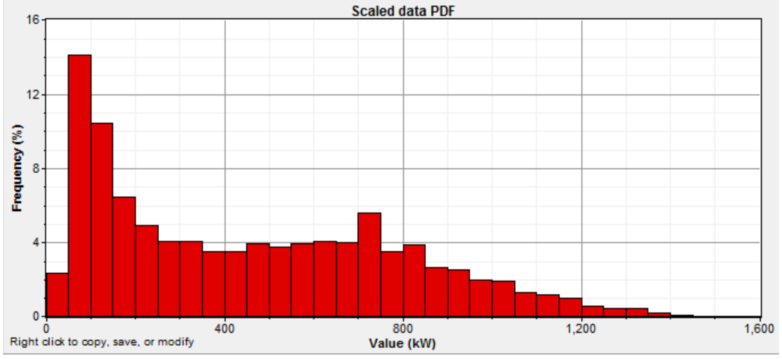
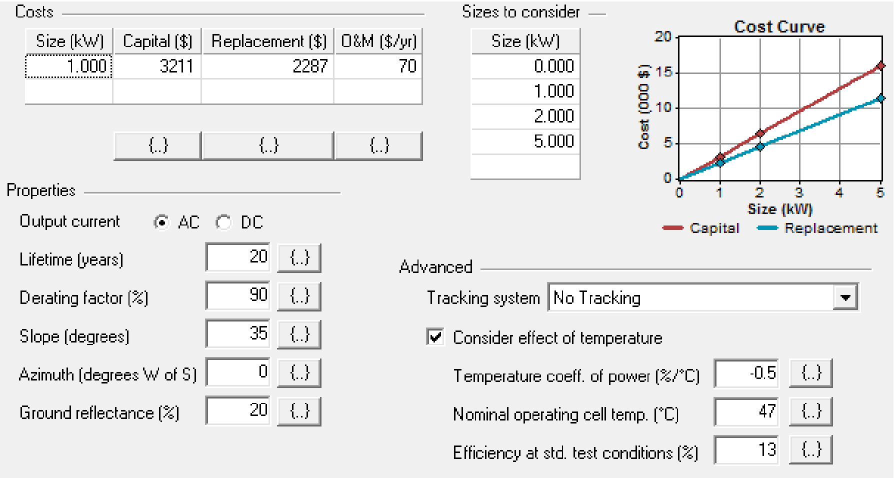


Figure 7: Natural gas consumption frecuency.

7.1.3. PV

Next HOMER software screenshot shows the cost data introduced. It is also possible to see that the lifetime of the installation is set up to 20 years due to the French technical law that says that this is the maximum lifetime for this kind of installations. Moreover, as they are going to be considered as no tracking modules, the optimal slope has been settled to 35º. Other parameter were left as default because it is believed they are suitable for this study.



Costs

Size (kW)	Capital ($)	Replacement ($)	O&M ($/yr)
1.000	3211	2287	70

Sizes to consider

Size (kW)
0.000
1.000
2.000
5.000

Properties

Output current ● AC ○ DC
Lifetime (years) 20
Derating factor (%) 90
Slope (degrees) 35
Azimuth (degrees W of S) 0
Ground reflectance (%) 20

Advanced

Tracking system No Tracking
☑ Consider effect of temperature
Temperature coeff. of power (%/°C) -0.5
Nominal operating cell temp. (°C) 47
Efficiency at std. test conditions (%) 13

Image 11: HOMER PV parameters.

To calculate the solar energy production, solar source must be imported to HOMER. This has been done by using the EnergyPlus database, choosing Lyon-Satolas as the most suitable weather file. Next figure show the monthly radiation received.

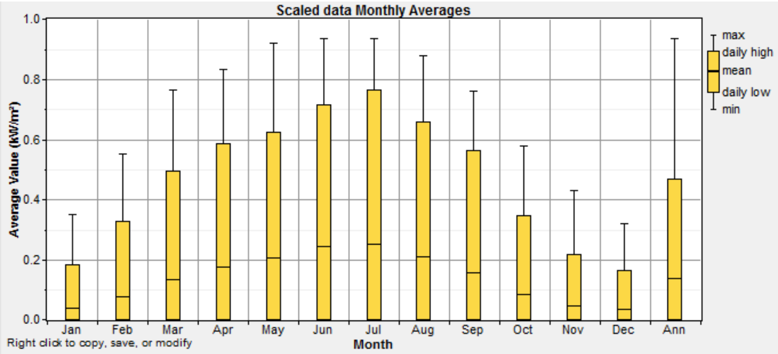
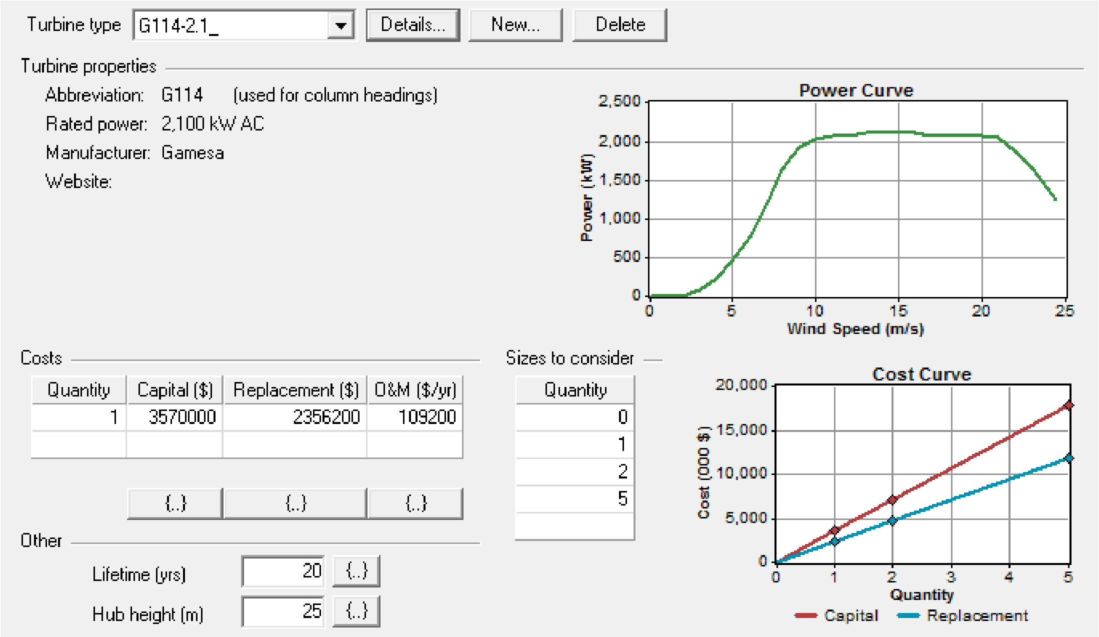


Image 12: Monthly solar radiation in Lyon.

7.1.4. Wind turbine

Regarding wind turbines, the next model of 2.1 MW was selected to make the economic analysis. It can be seen that the lifetime was set to 20 years for the same reason of the PV technology. The hub height is chosen to be 25 m.



Turbine type: G114-2.1_

Turbine properties

Abbreviation: G114 (used for column headings)
Rated power: 2,100 kW AC
Manufacturer: Gamesa
Website:

Costs

Quantity	Capital ($)	Replacement ($)	O&M ($/yr)
1	3570000	2356200	109200

Sizes to consider

Quantity
0
1
2
5

Other

Lifetime (yrs): 20
Hub height (m): 25

Image 13: HOMER wind turbine screeshot.

To calculate the energy generation from this wind turbine it is important to introduce wind date from Lyon. This has been done using the EnergyPlus data base. Next figure shows the wind distribution.

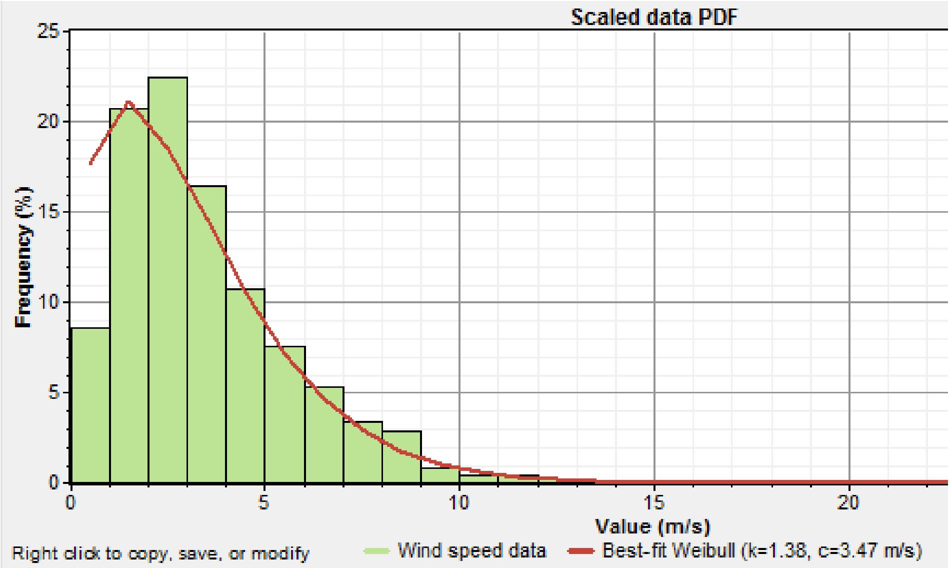
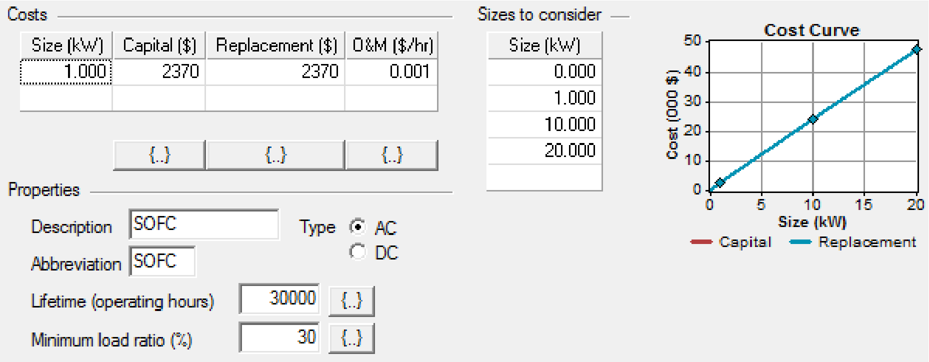


Image 14: Wind distribution in Lyon.

7.1.5. SOFC

Next screenshot shows data introduced in HOMER to perform every simulation. It has been taken from [15].



Costs

Size (kW)	Capital ($)	Replacement ($)	O&M ($/hr)
1.000	2370	2370	0.001

Sizes to consider

Size (kW)
0.000
1.000
10.000
20.000

Properties

Description: SOFC

Type: ● AC ○ DC

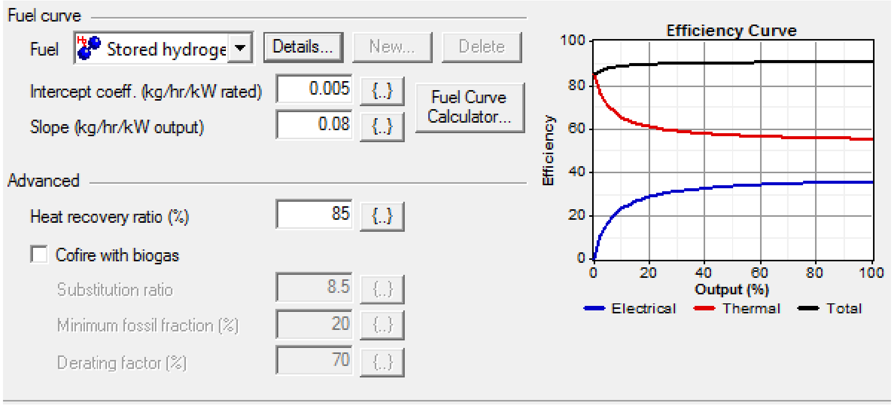
Abbreviation: SOFC

Lifetime (operating hours): 30000

Minimum load ratio (%): 30

Image 15: HOMER SOFC parameters.

From reference [15] it has been also possible to find different information as for example the energy electrical and thermal efficiencies, namely ~40% and ~60%.



Fuel curve

Fuel: Stored hydroge

Intercept coeff. (kg/hr/kW rated): 0.005

Slope (kg/hr/kW output): 0.08

Advanced

Heat recovery ratio (%): 85

☐ Cofire with biogas

Substitution ratio: 8.5

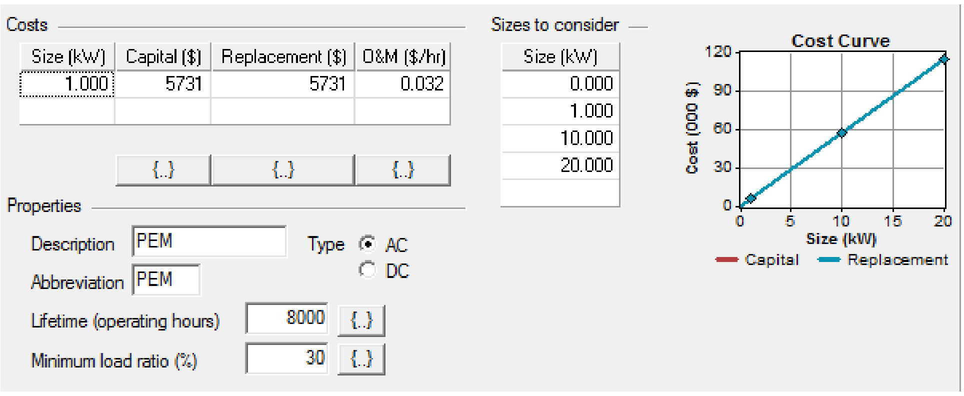
Minimum fossil fraction (%): 20

Derating factor (%): 70

Image 16: SOFC energy characteristics.

7.1.6. PEM

Following the same approach with SOFC, reference [15] provides enough information about costs and efficiencies of this technology. It is important to remark that the inverter costs were added to this component.



Costs

Size (kW)	Capital ($)	Replacement ($)	O&M ($/hr)
1.000	5731	5731	0.032

Sizes to consider

Size (kW)
0.000
1.000
10.000
20.000

Properties

Description: PEM

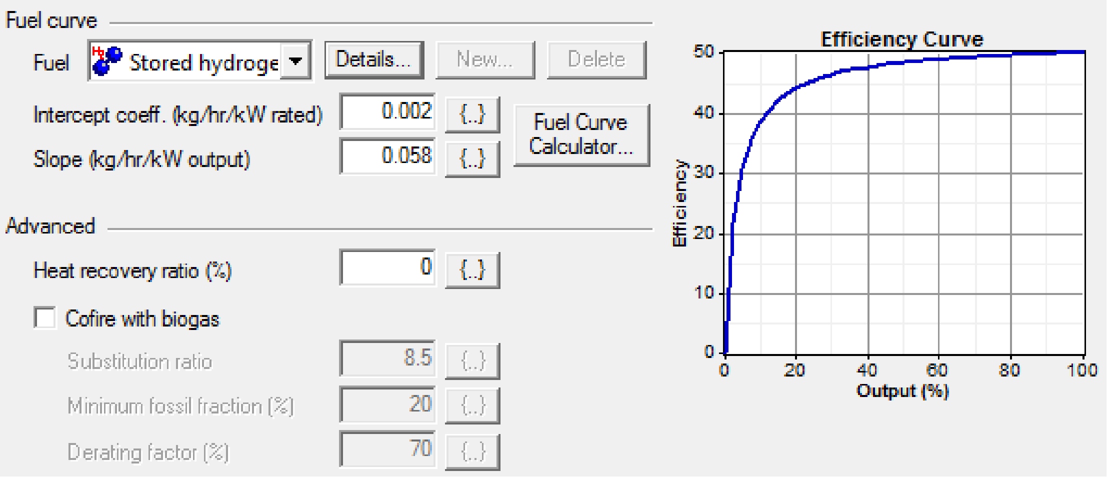
Type: ● AC ○ DC

Abbreviation: PEM

Lifetime (operating hours): 8000

Minimum load ratio (%): 30

Image 17: HOMER PEM parameters.



Fuel: Stored hydroge

Intercept coeff. (kg/hr/kW rated): 0.002

Slope (kg/hr/kW output): 0.058

Heat recovery ratio (%): 0

☐ Cofire with biogas

Substitution ratio: 8.5

Minimum fossil fraction (%): 20

Derating factor (%): 70

Image 18: PEM energy characteristics.

7.1.7. Grid

As a University campus is a sensible consumer where there can be multiple experiments on operation during all day all the demand must be fulfilled with a 0% of shortage capacity.

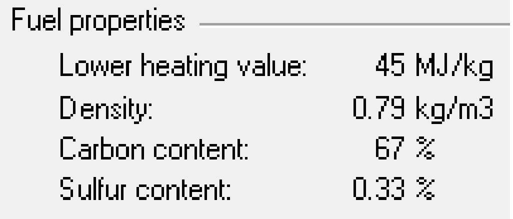
As it will be explained later, different studies to know how results can change regarding the emissions costs are going to be carried out. For this reason it is important to introduce the Grid emission factor. Following data provided by RTE-FRANCE, 73 g/kWh is going to take into account as the emission factor for the French grid.

Regarding the electricity price from the Grid, any electricity contract has been provided but the value of 0.09 €/kWh has been provided as the medium price of all a year, so this is the value that is going to be used.

7.1.8. Boiler

As explained before HOMER software asks for a thermal demand and then with boiler efficiency, it calculates the Natural Gas consumption. As the NG consumption is already available, the boiler efficiency is going to be set to 100%.

Regarding the natural gas properties, the next values are going to be taken into account.



Fuel properties

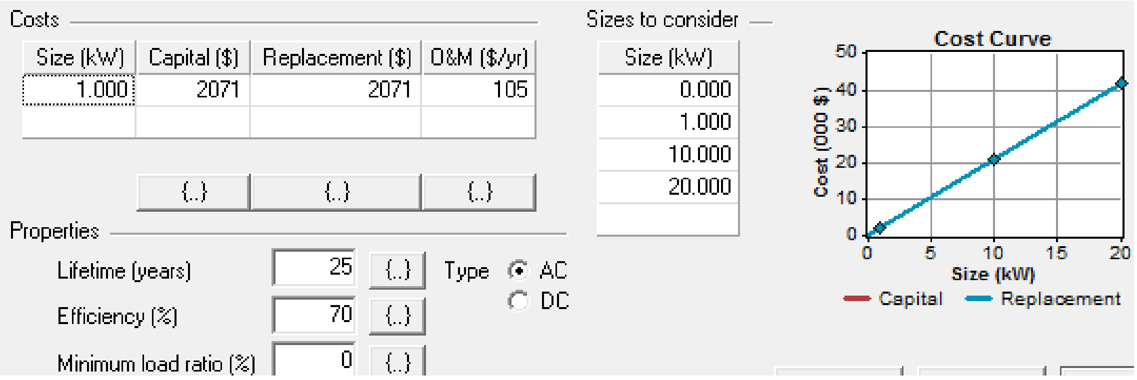
Lower heating value:	45 MJ/kg
Density:	0.79 kg/m3
Carbon content:	67 %
Sulfur content:	0.33 %

Image 19: Natural gas properties.

Finally, the fuel price is given as an annual media and the value is 0.051 €/m^3.

7.1.9. Electrolyzer

Next image shows the technology costs of the electrolyser taking into account the inverter cost too. In reference [4] it is said that the system efficiency currently variates between 62 and 82 %. In this case, an efficiency of 70% is going to be taken into account.



Costs

Size (kW)	Capital ($)	Replacement ($)	O&M ($/yr)
1.000	2071	2071	105

Sizes to consider

Size (kW)
0.000
1.000
10.000
20.000

Properties

Lifetime (years) 25

Efficiency (%) 70

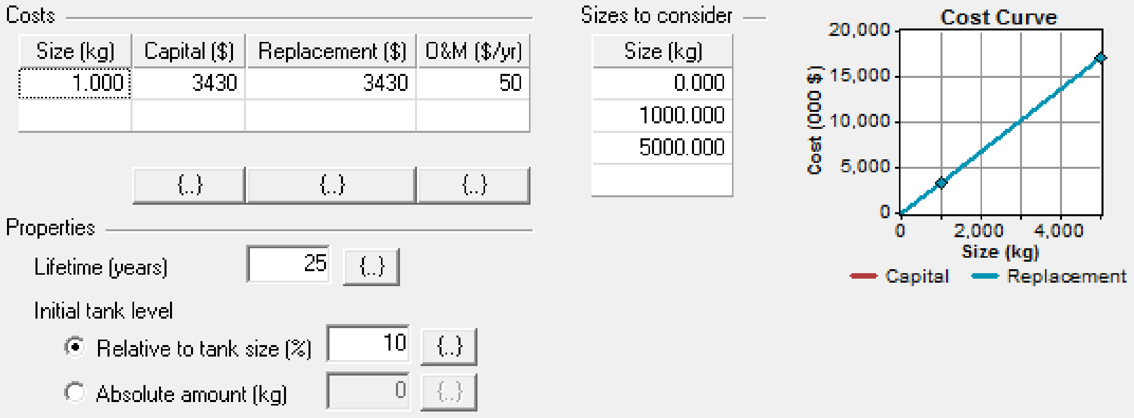
Minimum load ratio (%) 0

Type ● AC ○ DC

Image 20: HOMER electrolyzer parameters.

7.1.10. Hydrogen storage

Finally, the hydrogen storage economic parameters are introduced in HOMER in the following way.



Costs

Size (kg)	Capital ($)	Replacement ($)	O&M ($/yr)
1.000	3430	3430	50

Sizes to consider

Size (kg)
0.000
1000.000
5000.000

Properties

Lifetime (years) 25

Initial tank level

● Relative to tank size (%) 10

○ Absolute amount (kg) 0

Image 21: HOMER hydrogen storage parameters.

7.2. Results

In this section, different simulations are going to be performed including the before mentioned economic and energy parameters with the aim of understand how the energy network can change to fulfil different parameters.

As it is will be possible to see, different parametric simulations are going to be produced changing the following parameters: renewable fraction and CO_2 tax.

As it was said before, only Power-to-Power pathway is going to be studied because there is not any possibility to simulate the methanation in HOMER.

7.2.1. Renewable fraction parametrization

In this section a parametric simulation is performed. At each simulation the minimum allowable renewable fraction is going to be increased and it will be possible to see the PV size needed to reach this objective with its corresponding economic study.

Renewable fraction (%)	PV (kW)	SOFC (kW)	PEM (kW)	Elec. (kW)	H2 Tank (kg)	Initial Capital	Opex (€/year)	Total NPC	COE (€/kWh)	Natural Gas (m3)
0	0	0	0	0	0	0	1,100,831	21,993,520	0.09	405,585
10	1400	0	0	0	0	4,495,400	1,055,206	25,577,368	0.105	405,585
20	2860	0	0	0	0	9,183,460	1,041,674	29,995,082	0.123	405,585
30	4590	0	0	0	0	14,738,490	1,089,395	36,503,536	0.151	405,585
38	6354.5	0	0	0	0	20,404,236	1,169,706	43,773,804	0.181	405,585
40	6800	0	0	0	0	21,834,800	1,192,512	45,660,016	0.189	405,585
50	9800	0	0	0	0	31,467,800	1,361,119	58,661,612	0.243	405,585
60	14220	0	0	0	0	45,660,420	1,637,557	78,377,192	0.325	405,585
70	21480	0	0	0	0	68,972,280	2,117,708	111,282,000	0.462	405,585
80	35910	0	0	0	0	115,307,008	3,104,344	177,328,752	0.738	405,585
90	78910	0	0	0	0	253,380,016	6,092,671	375,105,568	1.563	405,585

Table 15: Renewable fraction parametric study.

It is possible to understand that the most economical way to increase the renewable fraction is to increase the photovoltaic size. As it is shown in the results, it is never recommended to use the Power-to-Power hydrogen pathway due its high cost and it is preferable to produce more electricity that it is needed. As it is shown, the maximum photovoltaic size that is possible to install in the University Campus of INSA Lyon (6354.5 kW) will allow to reach a renewable fraction up to 38%, after that, a bigger amount of PV panels will be necessary to install. The energy cost (COE) will increase as the renewable fraction is also increased due to the bigger PV installation.

As typically the solar production does not fit with the energy consumption, when it exists a big PV installation a lot of fatal electricity (electricity that it is not possible to consume) is generated. This can create big technical and management problems and for this reason it should be avoided. In the following studies, a new energy network will be proposed by introducing Power-to-Power hydrogen pathway trying to reduce this fact.

7.2.2. CO_2 tax parametrization

As one of the aims of this project is to increase to the maximum the renewable fraction and the independency of a consumer from the electricity grid, the maximum allowable PV size from Table 15: is going to be chosen, it is to say, the one with 6354.5 kW of PV power. With this scheme, the CO_2 tax is going to be increased in each simulation in order to study the economic variation of the system. As explained before the electricity grid emissions and CO_2 content in natural gas are 73 g/kWh and 65.5 % respectively.

€/tCO2	CO2 emissions kg/yr	PV (kW)	Initial Capital	Opex (€/year)	Total NPC	COE (€/kWh)
0	1,453,097	6354.5	20,404,236	1,169,706	43,773,804	0.181
10	1,453,097	6354.5	20,404,236	1,180,996	43,999,376	0.181
20	1,453,097	6354.5	20,404,236	1,192,287	44,224,956	0.181
30	1,453,097	6354.5	20,404,236	1,203,578	44,450,532	0.182
40	1,453,097	6354.5	20,404,236	1,214,868	44,676,104	0.182
50	1,453,097	6354.5	20,404,236	1,226,159	44,901,684	0.182
60	1,453,097	6354.5	20,404,236	1,237,450	45,127,260	0.183
70	1,453,097	6354.5	20,404,236	1,248,740	45,352,836	0.183
80	1,453,097	6354.5	20,404,236	1,260,031	45,578,412	0.183
90	1,453,097	6354.5	20,404,236	1,271,322	45,803,992	0.183
100	1,453,097	6354.5	20,404,236	1,282,612	46,029,568	0.184
150	1,453,097	6354.5	20,404,236	1,339,066	47,157,448	0.185
200	1,453,097	6354.5	20,404,236	1,395,519	48,285,336	0.187
250	1,453,097	6354.5	20,404,236	1,451,972	49,413,216	0.188
300	1,453,097	6354.5	20,404,236	1,508,426	50,541,100	0.189

Table 16: CO_2 tax parametrization.

As the studied energy system is always the same one, CO_2 emissions, PV power and initial capital cost do not change in any simulation. But it is possible to see that as higher is the CO_2 tax, higher is the operation and management cost which produces a higher cost of electricity.

With this program it is also possible to study at which CO_2 tax value it is preferable to install a renewable energy source than consuming just from grid. For this study only 2.1 MW wind turbines were considered while any PV size could be chosen. Next graph shows a parametric simulation where it is possible to see at what CO_2 tax it is better to install a renewable source, which renewable source and its size.

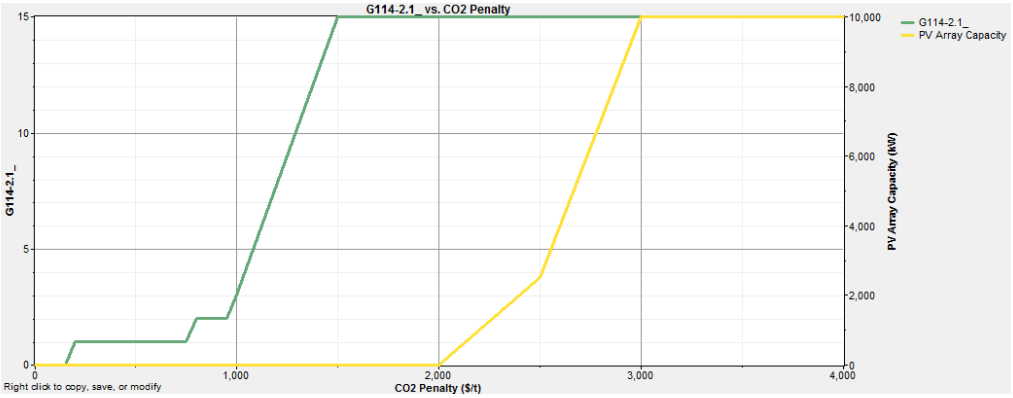


Figure 8: CO_2 parametrization against the best renewable source to be installed instead of consuming from grid.

Next table shows at which CO_2 tax it is better to install a renewable source and its size. In the 1st simulation both wind turbines and PV modules were included while in 2nd simulation only PV modules were simulated. This is because, due to their costs, it is cheaper to install wind turbines than PV panels.

	CO_2 tax (€/tCO_2)	Renewable source	Size
1st simulation	180	Wind turbine	1 generator (2.1 MW)
2nd simulation	1500	PV	1 kW

Table 17: CO_2 taxes to install renewable sources than keep consuming from grid.

It is possible to understand that the minimum CO_2 tax to prefer a renewable source than keep consuming from grid is 180 €/tCO_2. This is a very high value and this is because in France the emissions linked to the electricity grid are very low due the big percentage of nuclear power plants. If it is only possible to install solar panels, a tax of 1500 €/tCO_2 should be reached.

7.2.3. Electricity energy mix comparison

As explained before, the minimum CO_2 tax to prefer a renewable source than keep consuming from grid is 180 €/tCO_2 in France due to the big contribution of nuclear power plants in the energy mix. But if the energy mix has different energy sources and proportions, this value could change. In order to study this fact, the energy mixes from Spain and Germany are going to be used while the energy prices and parameters will keep with the same value, it is to say, the simulations will calculate the same situation as before but just changing the electricity grid emissions. Next table shows the main parameters and results.

Country	Electricity emissions	CO_2 tax to prefer a renewable source	Renewable source
France	73 g/kWh (RTE-France)	180 €/tCO_2	1 wind turbine (2.1 MW)
Spain	357 g/kWh [17]	37 €/tCO_2	1 wind turbine (2.1 MW)
Germany	610 g/kWh [18]	25 €/tCO_2	1 wind turbine (2.1 MW)

Table 18: Electricity energy mix comparison and CO_2 taxes to prefer renewable sources.

8. OPEN MODELICA

The Modelica language was introduced in 1997, as the product of an international cooperative effort to define an object-oriented language for the modelling of generic physical models. These models are described by a set of algebraic, differential, and event-triggered difference equations; these describe how the modelled object behaves. The boundary conditions are not necessarily declared as input or outputs: this is essential to achieve truly object-oriented modelling of physical systems, since the model of a physical is always the same, irrespective of what is connected to it. The declarative approach allows writing the model code in a way that tightly matches the way equations are written on the paper and this greatly eases the model development, documentation, modification and reuse [17].

The main objective of this project is to develop an annual simulation about a multi-energy system. This is going to be performed with a software called TRNSYS. As in this program the creation of the different modules is hard, tedious and slow it is necessary the use of other software that allows fast simulations and modifications of the different modules to verify if they work properly to use them later in TRNSYS without wasting too much time. This is the reason why Open Modelica is going to be used.

The modules that have been performed in this software are the Electrolysers and the Fuel Cells Controllers. Those modules must allow the introduction of each system on a step-by-step basis taking into account the minimum and maximum power of each one. It is to say (e.g. for Electrolysers): when the power surplus of the system is bigger than the minimum power allowed by this electrolyser, this system starts to work. This process continues until this electrolyser reaches its maximum allowable power. If the surplus continues its growth and it reaches a value bigger than the maximum power of the first electrolyser and the minimum power of the second electrolyser (in green), this last system can start to work. All this process is extendible to a bigger amount of electrolysers and also to Fuel Cells (in this case in the contrarious way as Fuel Cells generate power instead of consuming it). The next image shows the simulation results of the Electrolysers Controller.

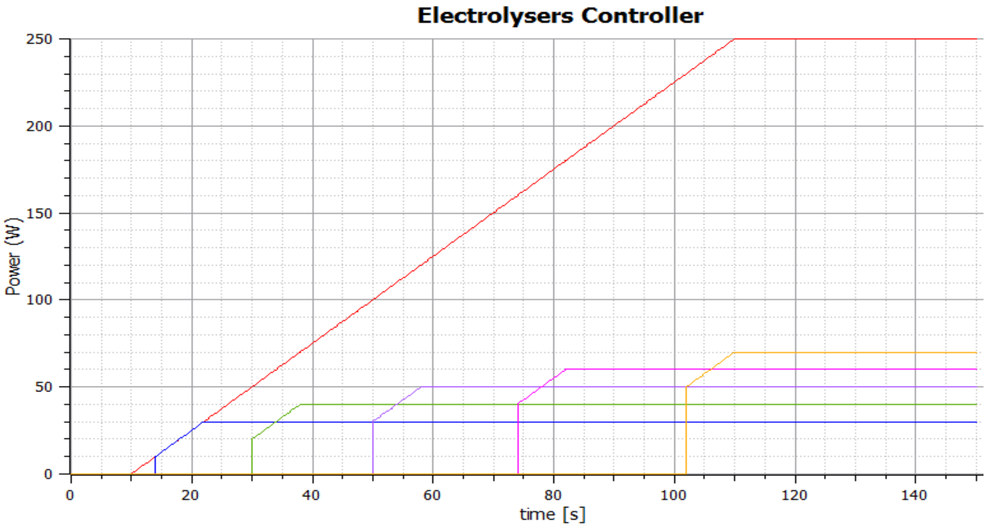


Figure 9: Electrolysers Controller simulation in OpenModelica.

The power surplus is represented in red colour. It is possible to see that when the surplus reaches the minimum power (10 W) allowable by the first electrolyser (in blue), this electrolyser starts to work until it reaches its maximum power (30 W). While the surplus increases, the second electrolyser starts to work when the surplus (50 W) is bigger than the sum of the maximum power allowable by the first electrolyser (30 W) and the minimum power allowable by the second one (20 W). After having seen the results, it is possible to say that this module, as it is programed, works as it is expected.

The same approach has been used to test the Fuel Cells Controllers. In this case, each fuel cell must provide a demanded power, also taking into account their minimum and maximum power limits. Results are shown in the next figure.

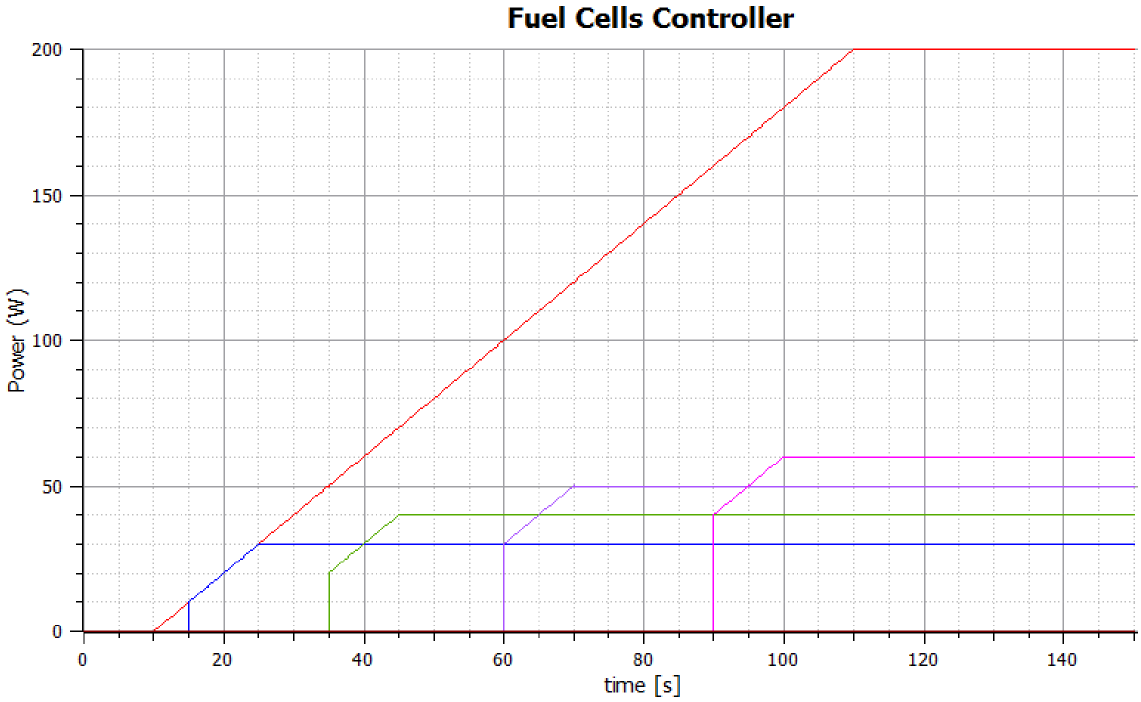


Figure 10: Fuel Cells Controller simulation in OpenModelica.

It is possible to see in red the demanded power to the Fuel Cells. When it reaches the minimum value allowable by the first system (in blue), the first fuel cell starts to work providing the demanded power. When the summation of the maximum power of the first fuel cell and the minimum power allowable by the second fuel cell is smaller than the demanded power, the second fuel cell starts to work while the first one stays at its maximum level.

The OpenModelica programs can be seen in ANNEX III.

9. TRNSYS

TRNSYS is an extremely flexible graphically based software environment used to simulate the behaviour of transient systems, including multi-zone buildings. It was developed by the Solar Energy Laboratory of Wisconsin-Madison University and enriched by the contributions of TRANSOLAR Energietechnik GMBH, Centre Scientifique et Technique du Bâtiment (CSTB) and Thermal Energy Systems Specialists (TESS).

It is simple and intuitive to create a new project in TRNSYS: the different components of the system (called "types" in TRNSYS) can be connected graphically through its visual interface, Simulation Studio. Each type is described as a mathematical model with FORTRAN programming and an associated icon (called "proforma" in TRNSYS). This last one describes the component as a black box with inputs, outputs and different parameters.

This software has an extensive library where it is possible to find standard types to use in a project. But it is also possible to create new components with the desired mathematical model and this is one of the things for which TRNSYS has still a lot of success in the engineering world.

9.1. Logic structure

In order to achieve the project's objectives, TRNSYS will utilize the next flow diagram for a logical approach.

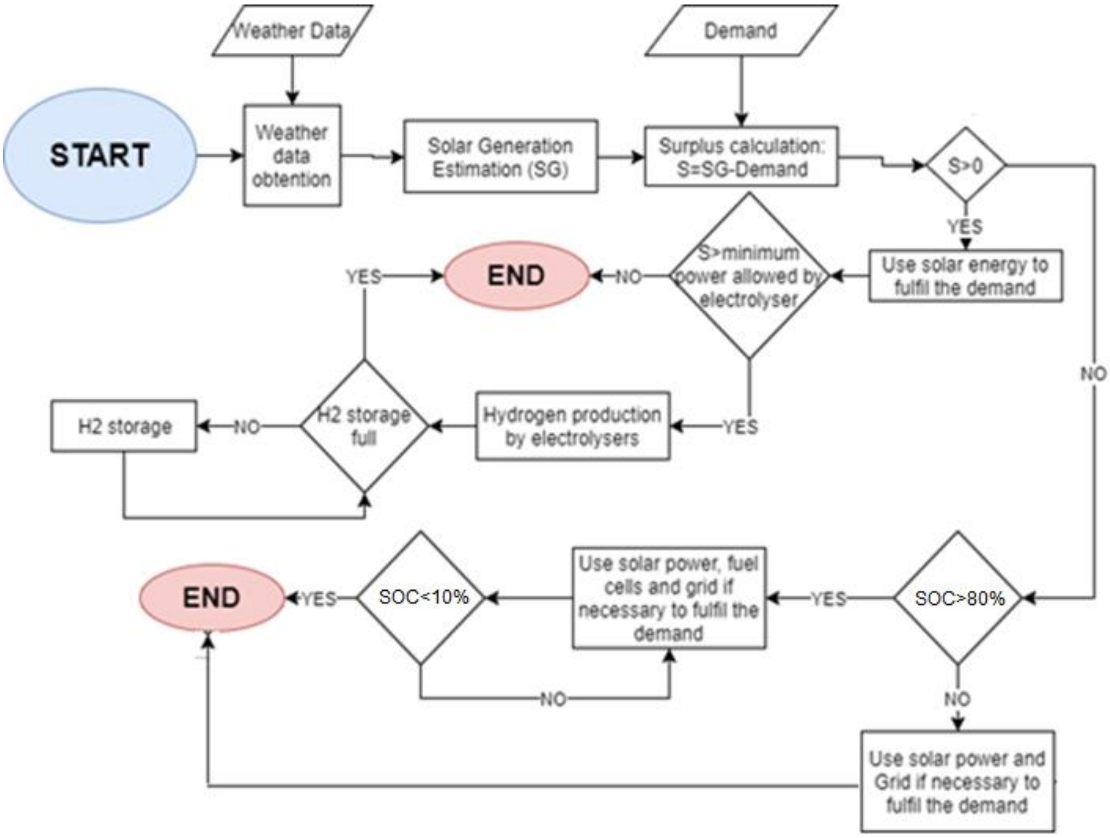


Figure 11: Logical flow diagram for TRNSYS program.

9.2. Components

In this section, different components utilized in TRNSYS are going to be described. As it is be very complex to describe all the parts that compose the TRNSYS system, only the main types are going to be explained, doing this section simpler.

9.2.1. Weather

In order to know the solar energy production it is necessary to understand which are the weather conditions of that place as for example solar radiation or temperature. This can be done in TRNSYS with “Type 109”. This component serves the main purpose of reading weather data at regular time intervals from a data file. Lyon Satolas, from Meteonorm data base, is going to be the selected data file.

9.2.2. Demand

As it is obvious, TRNSYS needs to read the University Campus demand in order to do all the calculous for the energy installation. As the demand was given, it is just necessary to modify it and convert it in a “.txt” format file. After that “Type 9e” serves the purpose of reading this data at regular time intervals from a logical unit number, converting it to a desired system of units, and making it available to other TRNSYS Units as time varying forcing functions.

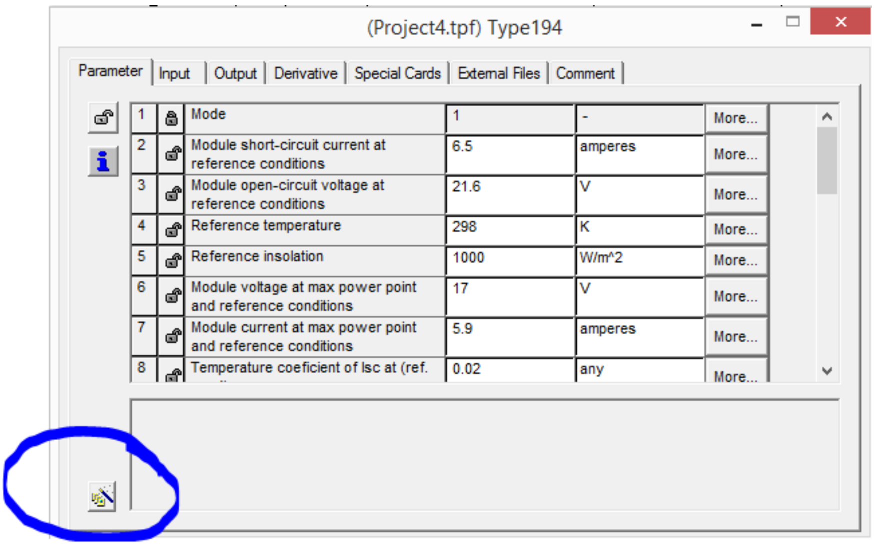
9.2.3. Compressor

The hydrogen storage, as explained before, needs to be pressurized in order to not occupy a big volume. For this reason, a compressor is needed. As the pressure needed can be high, it is important to take into account the energy consumption of this compressor. In TRNSYS “Type 167” will be used. This system is a multi-stage polytropic compressor model. The model calculates the work and cooling need for a polytropic compressor of 1 to 5 stages. In the project, a compressor of 3 stages is going to be used. Knowing the hydrogen flow generated from electrolysers (that is given in normal conditions), the storage pressure and the output pressure of the electrolysers, this type calculates the energy consumption of a possible compressor.

9.2.4. PV modules

Having a weather data base it is important to simulate with the biggest precision as possible the real PV module that it is going to be installed. This will allow calculating the energy produced in a more detailed way.

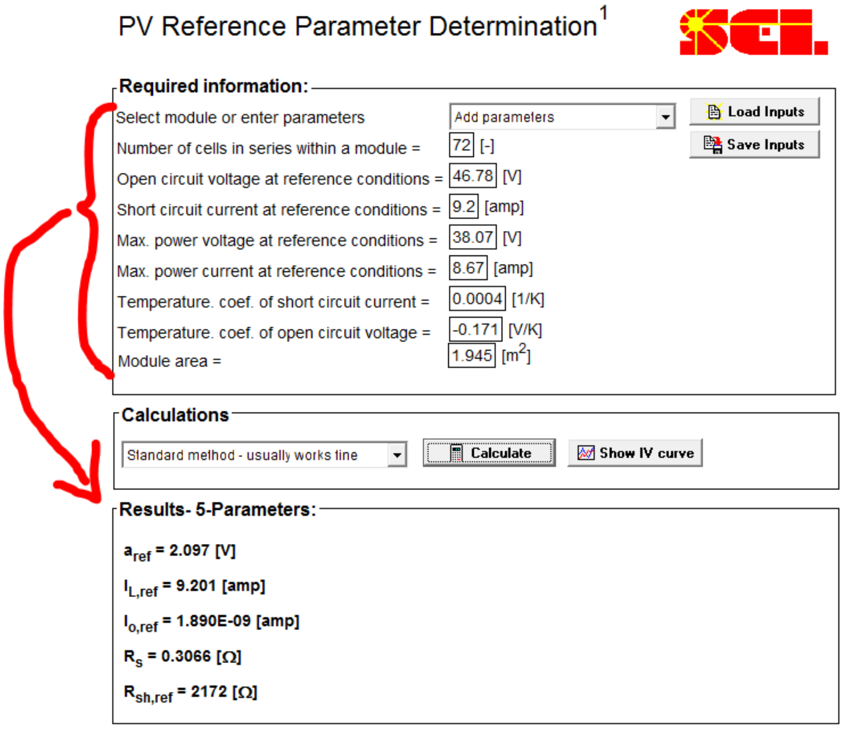
In order to do this, “Type 194” is going to be used at first. This type has a tool that connects with the software EES to calculate the different parameters needed by TRNSYS from the typical parameters given from PV producers.



1	Mode	1	-	More...
2	Module short-circuit current at reference conditions	6.5	amperes	More...
3	Module open-circuit voltage at reference conditions	21.6	V	More...
4	Reference temperature	298	K	More...
5	Reference insolation	1000	W/m^2	More...
6	Module voltage at max power point and reference conditions	17	V	More...
7	Module current at max power point and reference conditions	5.9	amperes	More...
8	Temperature coeficient of Isc at (ref.	0.02	any	More...

Image 22: EES tool accessible from Type 194.

Parameters of ATERSA 330 PV module are going to be introduced (ANNEX I) as this is the system that is going to be used in the project. After that, EES software will calculate the needed parameters for TRNSYS simulation.


PV Reference Parameter Determination[1]

Required information:

Select module or enter parameters: Add parameters
Number of cells in series within a module = 72 [-]
Open circuit voltage at reference conditions = 46.78 [V]
Short circuit current at reference conditions = 9.2 [amp]
Max. power voltage at reference conditions = 38.07 [V]
Max. power current at reference conditions = 8.67 [amp]
Temperature. coef. of short circuit current = 0.0004 [1/K]
Temperature. coef. of open circuit voltage = -0.171 [V/K]
Module area = 1.945 [m^2]

Calculations

Standard method - usually works fine

Results- 5-Parameters:

a_{ref} = 2.097 [V]
$I_{L,ref}$ = 9.201 [amp]
$I_{o,ref}$ = 1.890E-09 [amp]
R_S = 0.3066 [Ω]
$R_{sh,ref}$ = 2172 [Ω]

Image 23: PV parameters calculated from EES software.

Now, "Type 194b" is going to be used for the simulations but with the before calculated parameters. This type owns a MPPT inverter that maximizes the solar energy production and a DC/AC inverter that makes the scheme simpler. As explained before, the PV field has three branches connected to each inverter. In order to simulate this, in TRNSYS, only one branch is going to be drawn and then, by the use of a TRNSYS calculator, the output is going to be multiplied by 3. Also parameters from the selected inverter must be introduced in this type.

9.2.5. Electrical Grid

Regarding the economic analysis, it is necessary to calculate the energy consumed by the grid as it is a payable energy. For this reason, a component that calculates the electricity consumed to meet the demand must be placed. In this project, a simple calculator is going to be used with the following equation:

$$\begin{aligned} & Grid\ consumption \\ & \qquad = -Fuel\ Cell\ generation - PV\ generation + Electricity\ Demand \\ & \qquad + Electrolyser\ consumption + Compressor\ consumption \end{aligned}$$

9.2.6. Storage

One of the main issues in a hydrogen pathway is the storage size as it can modify largely the economic analysis and the installation size. For this reason it is important to simulate it in order to know which size fits better. “Type 164a” from TRNSYS is going to be used. The main output of this system is the State of Charge of the storage and it can be calculated with the following parameters and inputs.

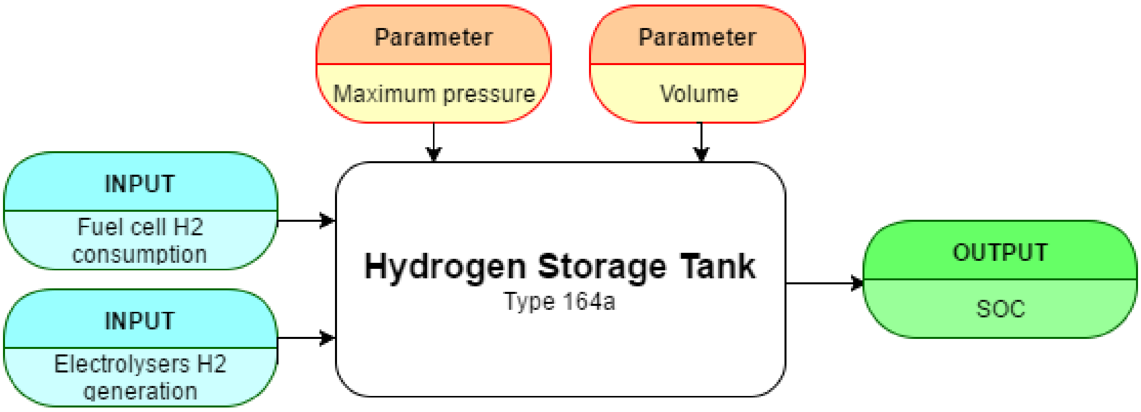


Figure 12: Storage Tank working diagram.

9.2.7. Electrolyser

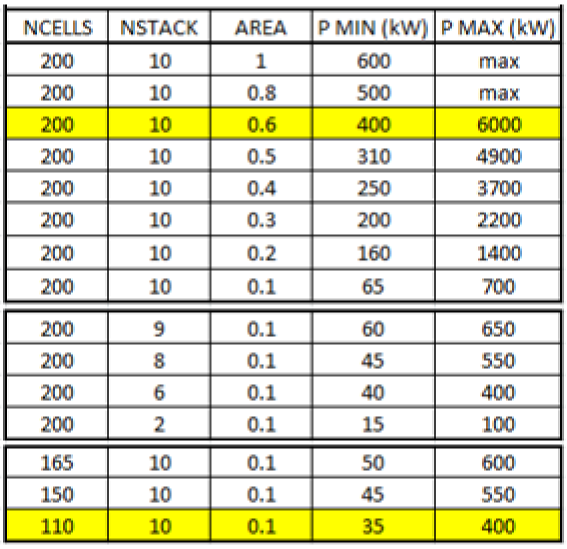
Firstly it is important to say that in TRNSYS it exists a special type to control the electrolyser but this type is like a black box where it is impossible to see which calculus are done in its interior. In addition this type only works with one electrolyser and in this project it is necessary to know how to implement various electrolysers in a step-by-step basis. For this reason, a new type has been created and validated with OpenModelica software as it can be shown in section 0. This new type has been called “Type 169” in TRNSYS.

As inputs to Type 169, it is important to introduce the hydrogen storage SOC, if it is bigger than a value that we can modify, the electrolysers cannot work. Also the power surplus must be introduced by a calculator with the following equation:

$$Surplus = PV\ generation - Electricity\ demand - Compressor\ consumption$$

Finally, another new type must be generated because the electrolyser TRNSYS type needs as an input a current in Amperes. This new type must read the electrolyser voltage and knowing the surplus power, calculate the appropriate current. This new type is called "Type 166" and the program can be shown in ANNEX III.

Regarding the electrolysers, three different parameters can be changed in order to get different maximum and minimum power consumptions. The next table shows how these powers variate as the parameters change.



NCELLS	NSTACK	AREA	P MIN (kW)	P MAX (kW)
200	10	1	600	max
200	10	0.8	500	max
200	10	0.6	400	6000
200	10	0.5	310	4900
200	10	0.4	250	3700
200	10	0.3	200	2200
200	10	0.2	160	1400
200	10	0.1	65	700
200	9	0.1	60	650
200	8	0.1	45	550
200	6	0.1	40	400
200	2	0.1	15	100
165	10	0.1	50	600
150	10	0.1	45	550
110	10	0.1	35	400

Table 19: Electrolyser maximum and minimum power variation with different parameters.

To understand the working principle of the different types explained in this point, the following chart can provide a good visualization of it.

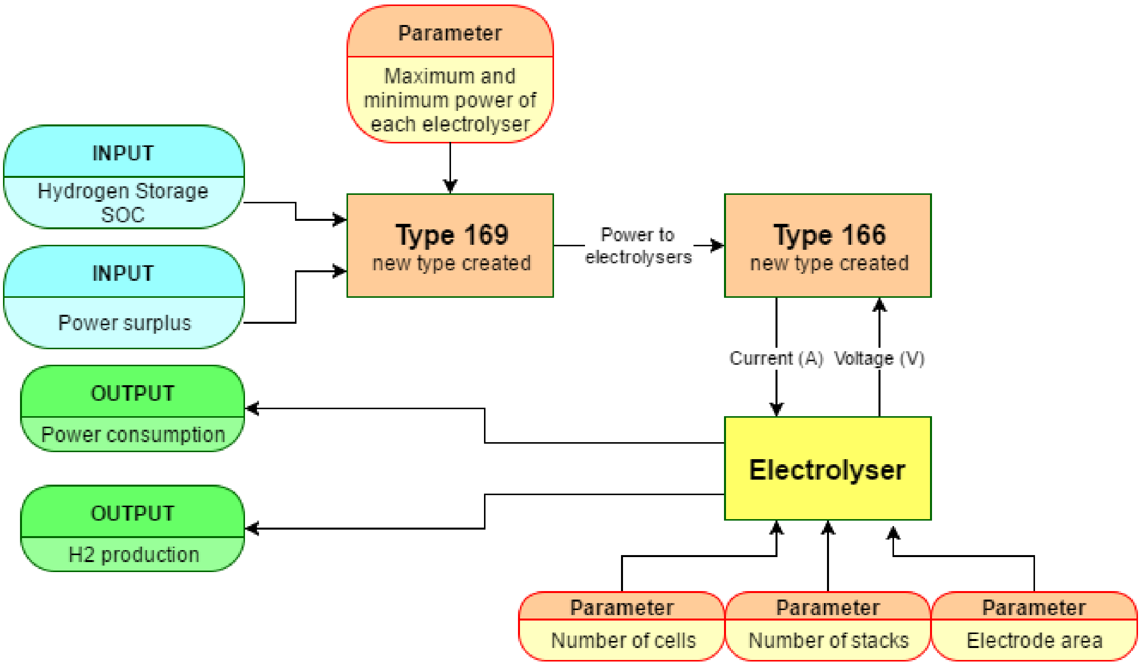


Figure 13: Electrolyser and created types operation flow.

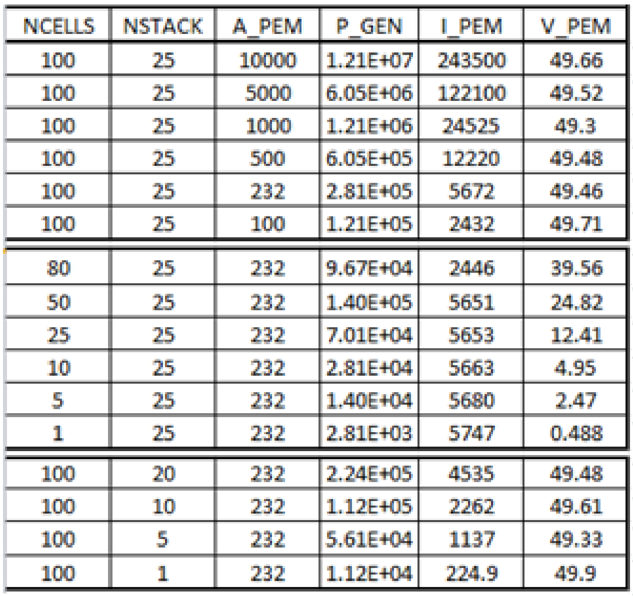
9.2.8. Inverter AC/DC

The electrolysers need DC current to work properly and as the electricity that comes from PV is already in AC it is necessary to convert it in DC. For this reason an inverter ("Type 175a" in TRNSYS) is going to be used. This system has a maximum allowable power of 2 GW and as the PV field produces more than that, it is necessary to reduce the power at the input and then multiply by the same facto the output. In this way it is possible to simulate the performance of the inverter without disrupt the rest of values.

Figure 14: Inverter AC/DC operation flow.

9.2.9. Fuel Cells

To simulate the operation of a fuel cell, "Type 170j" is going to be used. It is possible to change the power output of the fuel cell by changing different parameters that can be found in this TRNSYS type. The next table shows these variations.



NCELLS	NSTACK	A_PEM	P_GEN	I_PEM	V_PEM
100	25	10000	1.21E+07	243500	49.66
100	25	5000	6.05E+06	122100	49.52
100	25	1000	1.21E+06	24525	49.3
100	25	500	6.05E+05	12220	49.48
100	25	232	2.81E+05	5672	49.46
100	25	100	1.21E+05	2432	49.71
80	25	232	9.67E+04	2446	39.56
50	25	232	1.40E+05	5651	24.82
25	25	232	7.01E+04	5653	12.41
10	25	232	2.81E+04	5663	4.95
5	25	232	1.40E+04	5680	2.47
1	25	232	2.81E+03	5747	0.488
100	20	232	2.24E+05	4535	49.48
100	10	232	1.12E+05	2262	49.61
100	5	232	5.61E+04	1137	49.33
100	1	232	1.12E+04	224.9	49.9

Table 20: Fuel cell outputs variation.

In this case, the general controller provided by TRNSYS ("Type 105a") can be utilized. This is because in this type it is possible to introduce a minimum and maximum SOC at which fuel cells have to stop or start to work respectively. Type 105a will calculate the demanded power that is needed and it will provide a general switch to start or stop the fuel cells.

As type 105a is designed just for one fuel cell, it is necessary to create another type to get the step-by-step operation as it was explained in section 0. As it happened with the electrolysers, fuel cells need as input a current which is calculated with type 166 depending on the power demanded and the fuel cell voltage.

Next graph shows the operation flow of the fuel cells in this TRNSYS project.

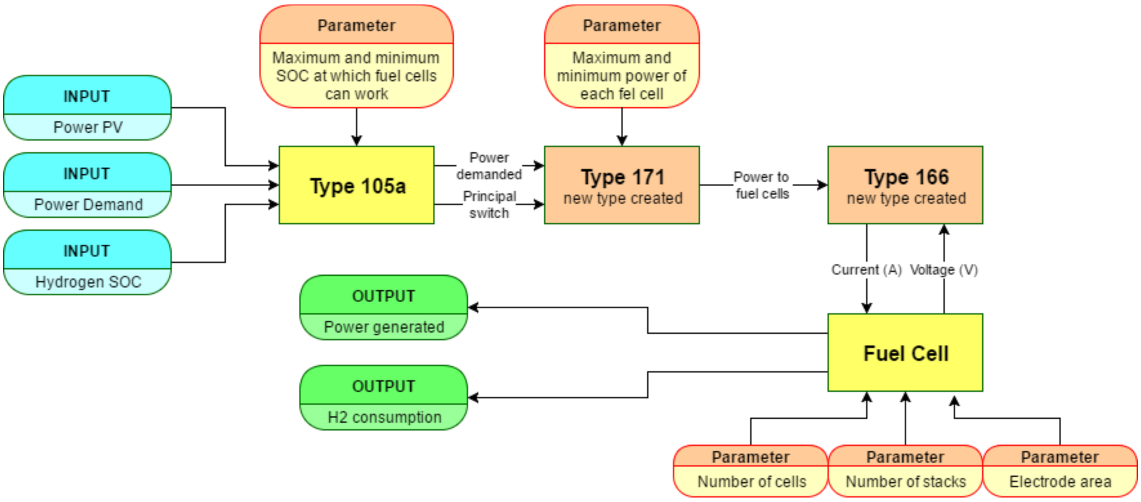


Figure 15: Fuel cells operation flow.

9.2.10. Inverter DC/AC

As the electricity demand of the University campus is in AC and to change it to DC is very difficult, fuel cells (that generate electricity in DC) must be coupled to a DC/AC inverter. Type 105a calculates the demanded power without taking into account this DC/AC inverter loses. For this reason, the power that the fuel cell must provide should be higher than type 105a calculates to deal with the inverter performances. The approach to take this into account is to use a calculator that increases the power demanded taking into account the inverter performance and then the same calculator reduces the fuel cell power generation to well-perform the energy balance as it is shown in the next graph.

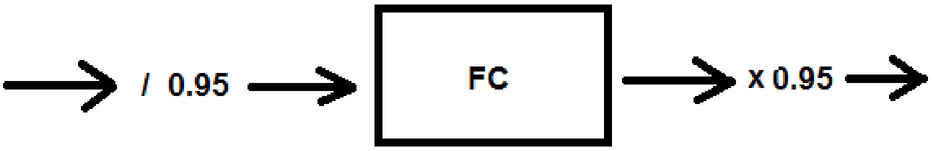


Figure 16: How to take into account the DC/AC inverter in fuel cells.

9.2.11. Graphs

Finally, “Type 65c” can help to plot any variable of TRNSYS model. In this project many of these types are used to identify if the model is working properly or not.

As many of the parameters calculated are power variables, some integrations are needed in order to calculate the energy generated or consumed by the different components. In order to do so, “Type 24” is used.

9.2.12. Methanation

Regarding the methanation hydrogen pathway, there is not any standard type in TRNSYS library and because there was not enough time in this project, only an energy balance about how much methane can be possible to generate is going to be performed.

In this case, a set of electrolysers are going to be installed in order to be able to use all the PV power surplus. Methane production can be calculated from the hydrogen production following the next equations. All of these equations are going to be performed by a calculator in TRNSYS model.

$$INPUT = H_2(m^3)$$

$$H_2(kg) = H_2(m^3) \times H_2\ density$$

$$H_2(W) = H_2(kg) \times LHV\ H_2 \times \frac{10^6}{3600}$$

$$Methane(W) = H_2(W) \times methanation\ efficiency$$

$$Methane(m^3) = \frac{\frac{Methane(W)}{LHV\ methane}}{density\ methane}$$

With:

$$H_2\ density = 0.0899\ \frac{kg}{Nm^3}$$

$$LHV\ H_2 = 120\ \frac{MJ}{kg}$$

$$methanation\ efficiency = 0.8$$

$$LHV\ methane = 13.89\ \frac{MJ}{kg}$$

$$density\ methane = 0.656\ \frac{kg}{Nm^3}$$

It has to be remarked that in this case, any storage tank was contemplated. It is supposed that all the hydrogen production can be directly transformed in methane taking into account the methanation efficiency (~80%).

9.3. General model

In this page, it is possible to see all the TRNSYS models with its connections for the Power-to-Power pathway.

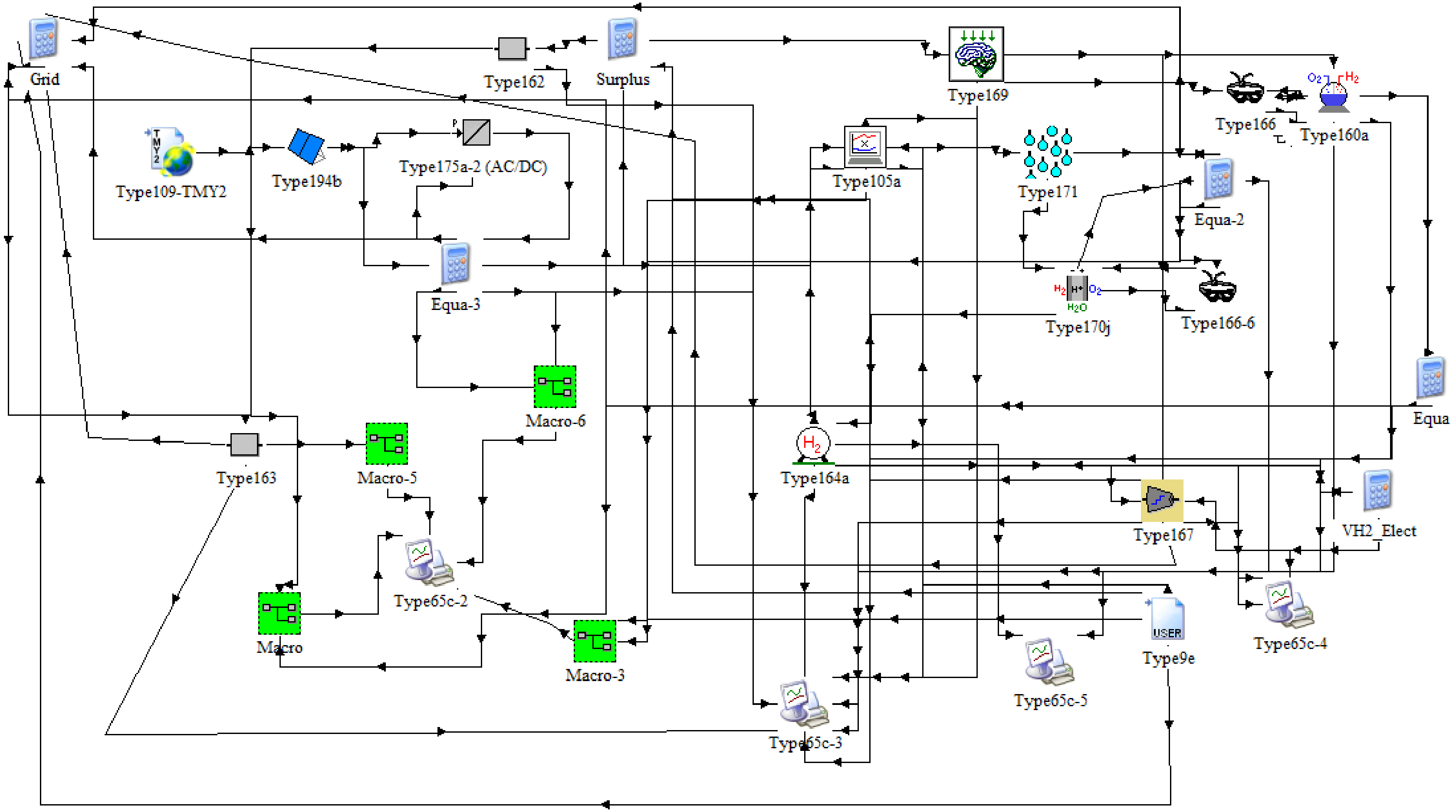


Image 24: TRNSYS general scheme for Power-to-Power pathway.

The next image corresponds to the methanation pathway.

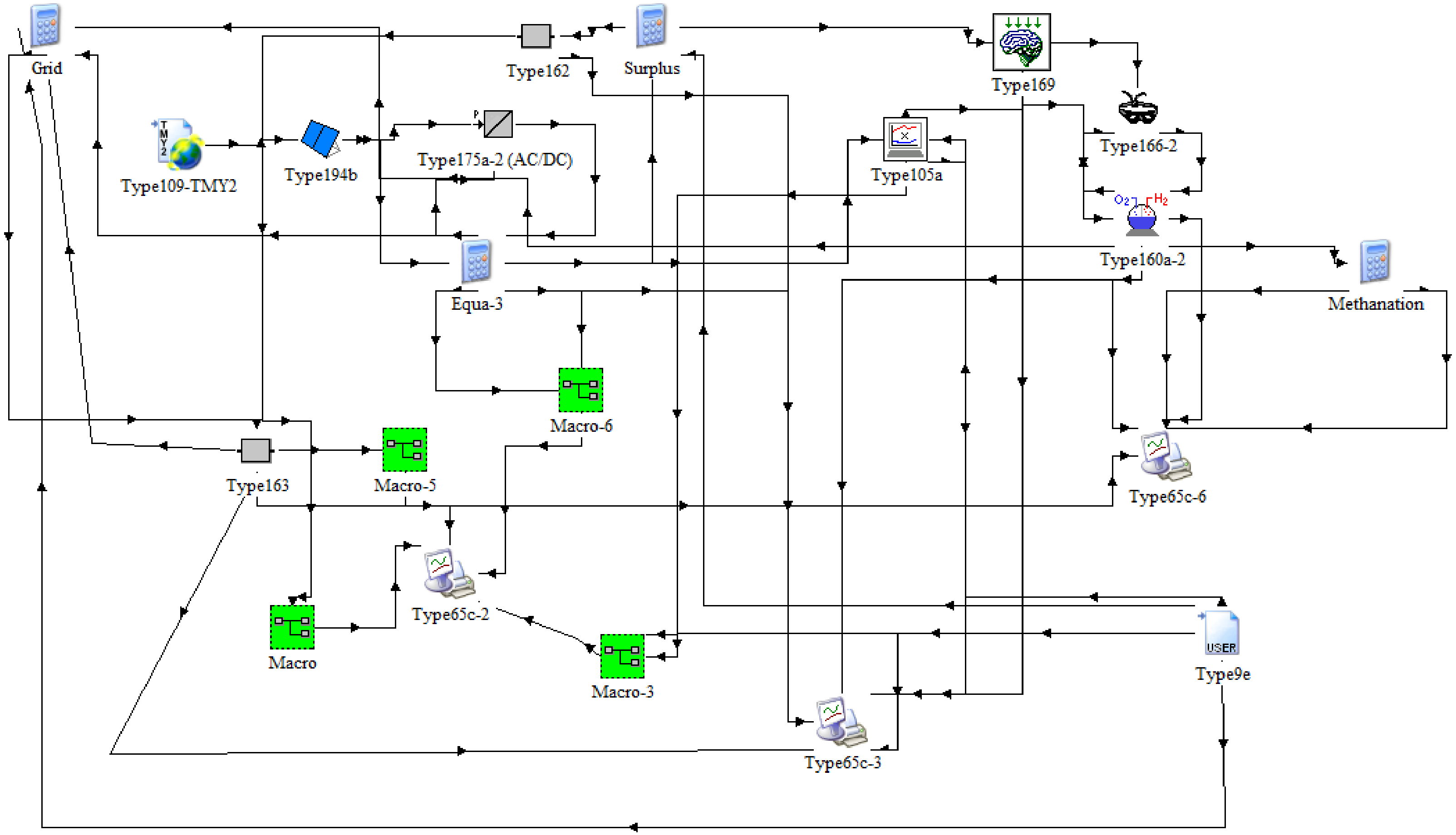


Image 25: TRNSYS general scheme for methanation pathway.

9.4. Results

Results from HOMER show that the most economical way to increase the renewable factor is to install more photovoltaic panels. As explained before, solar production is usually higher when the demand is lower and this produces a lot of electricity that has to be injected to the main network. This fact can produce a network overload and a difficult energy management, decreasing the electrical network performance. This can be avoided by introducing and energy storage system and for this reason in this project it is proposed to use hydrogen as an energy vector. In this section, different hydrogen pathways are going to be studied by simulating them with TRNSYS to finally understand their possible benefits and drawbacks. All those simulations come from the system were the maximum number of photovoltaic panels can be installed (6354.5 kW).

9.4.1. Power-to-Power TRNSYS simulations

Modules from section 9.2 and Image 24: were used in this section to determinate how much the renewable fraction can increase by introducing Power-to-Power hydrogen pathway; it is to say, by installing electrolysers, hydrogen storage and fuel cells. As explained before, these simulations were performed with a constant value of 6354.5 kW of solar field and the electricity demand of the University Campus of INSA Lyon.

Regarding the hydrogen storage tank, the fuel cells cannot start to work until the tank state of charge (SOC) reaches at least 80% and they have to stop when this SOC decreases to 10%. This will allow to the fuel cells working more time instead of making a fast start-stop operation, which decreases their lifetime.

Electrolysers can work until the tank is not full (SOC=100%). When the tank reaches this value, electrolysers must stop to work and cannot start again until the SOC decreases to 95% in order to make an operation band and not creating too many start-stop situations.

The most suitable sizes of each system are summarized in the next table.

System	Units	Size	
PV	3	2118.27 kW each branch	
Electrolysers	2	1st	Minimum power: 45 kW Maximum power: 550 kW
		2nd	Minimum power: 250 kW Maximum power: 3700 kW
Hydrogen Storage	1	Max. pressure: 500 bar	
		Volume: 60 m^3	
Fuel Cell	1	700 kW	
Inverter DC/AC	1	700 kW	
Inverter AC/DC	3	2910 kW each	
Demand	-	3.8 MW	
Compressor	1	3 stages	
		150 kW	

Table 21: Power-to-Power system sizes from TRNSYS simulation.

Next graphs show the operation of the system with the before mentioned parameters.

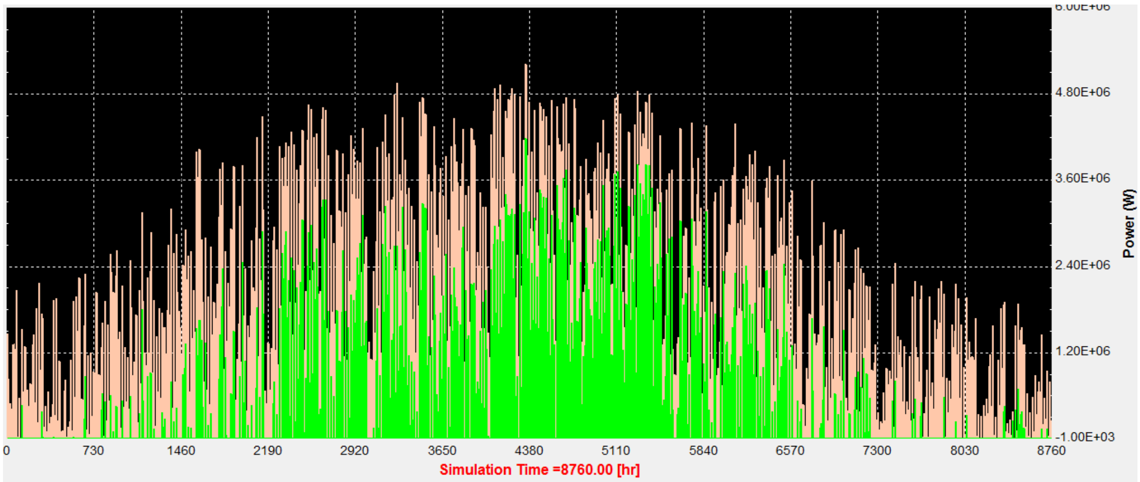


Figure 17: PV generation (yellow) and Power Surplus (green).

In Figure 17: it is possible to the total PV electricity generation and the power surplus. When it is possible, energy from solar panels is directly used to fulfil the demand and for this reason, the power surplus is lower. Anyway, the power surplus is too high to inject it to the grid because it can create serious technical and management problems.

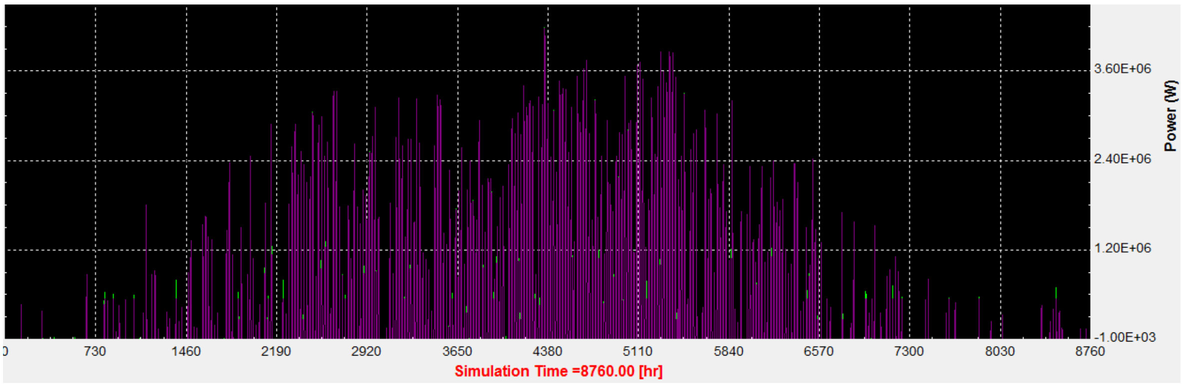


Figure 18: Power surplus (green) and power consumed by electrolysers (purple).

In the previous figure it is possible to see how many power surplus can be consumed from electrolyser and therefore converted into hydrogen. It is possible to distinguish that there are some power surplus that cannot be used. Next figure shows that power surplus that cannot be consumed and therefore injected to the grid. It is possible to see that it is very low (max=230 kW).

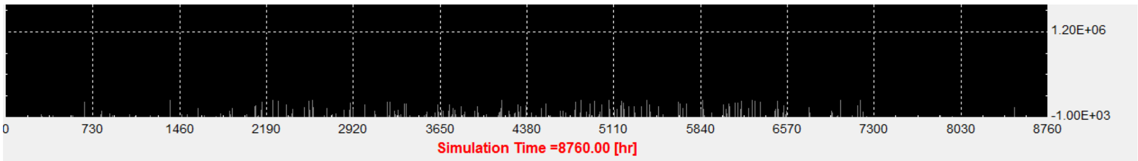


Figure 19: Power to Grid.

From next graph, it is possible to see the hydrogen tank state of charge (SOC) and the power generated by the fuel cell, this last one reaches up to 700 kW. Regarding the storage SOC, it is possible to notice that it never reaches 100% and this has been done on purpose. Following different simulations, the storage volume has been increased until it never reaches this value. In this way, all the volume can be used and it is neither too small nor oversized. Finally, it is possible to see that the fuel cell can only start to work when SOC is higher than 80% and it stops when it decreases to 10%.

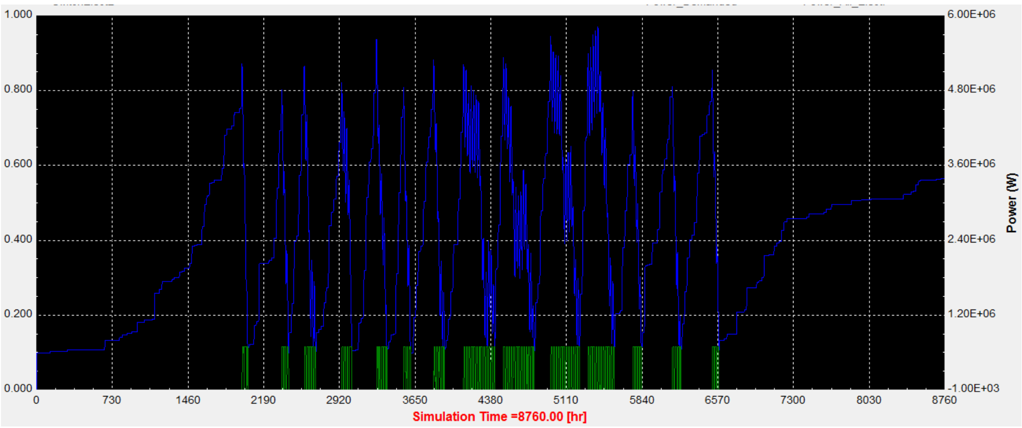


Figure 20: Hydrogen tank SOC (blue) and Fuel Cell generated power (green).

Finally, next figure show the electricity demand of the University Campus of INSA Lyon in purple, the fuel cell generated power in green and the necessary electricity from the grid to fulfil the demand.

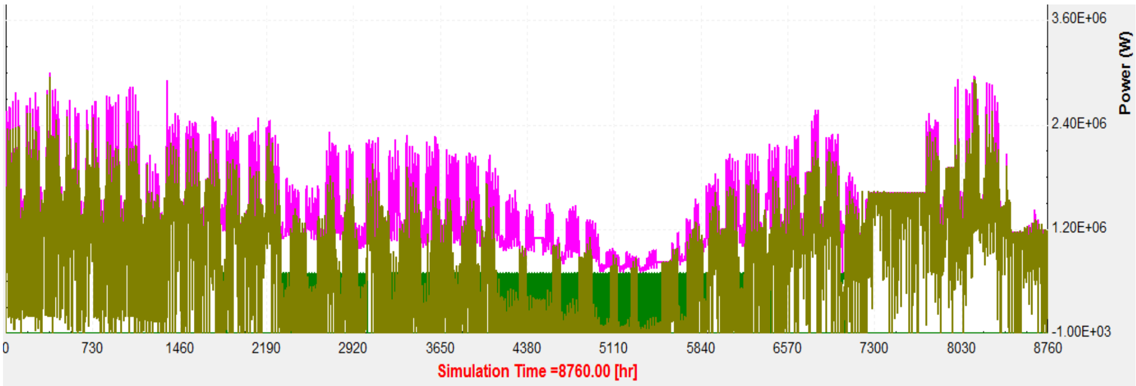


Figure 21: Demanded power (light purple), power from grid (yellow) and Fuel cell power (green).

Some key values that can be calculated are shown in the next table.

Energy demand	12,000	MWh
Solar energy production	6,501.2	MWh
Energy surplus	2,375.8	MWh
Energy consumed by electrolysers	2,354.9	MWh
Energy from grid	7,161.1	MWh
Energy from fuel cell	790.72	MWh
Energy to grid	21.582	MWh
Energy compressor	75.095	MWh

Table 22: Key values from TRNSYS simulation.

Following, some interesting factors that can be calculated from the previous table are shown.

Renewable factor with PV only (without thermal)	34	%
Renewable factor with PV only (with thermal)	26	%
Renewable factor with PtP (without thermal)	41	%
Renewable factor with PtP (with thermal)	31	%
Hydrogen pathway efficiency	34	%
Power surplus utilization	99	%

Table 23: Interesting factors from Power-to-Power pathway in INSA Lyon.

It is possible to see that the renewable factor if only PV is used reaches 34.4%, which is similar but lower than HOMER's value (38%). Introducing the Power-to-Power hydrogen pathway, this renewable factor can increase until 41%. It is also possible to understand that the step-by-step electrolysers operation can improve the power surplus utilization (in this case up to 99.1%). Finally it is possible to calculate the overall Power-to-Power energy efficiency (33.6%) which is very similar to the data provided by reference [4] (17-40 %).

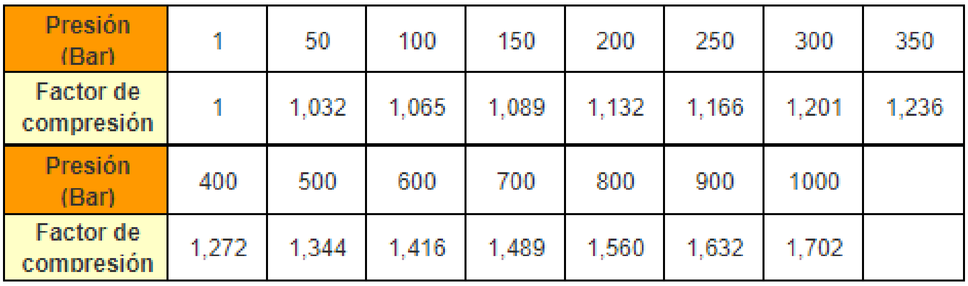
Next table shows the economic study of this system, taking into account the Power-to-Power systems, and compares it with the one performed with HOMER software. This study has been performed with the same cost data from section 5 without emission taxes and with the electrical and thermal demands of the University Campus of INSA Lyon (being the natural gas consumption of 405585 m^3). It is also important to take into account the renewable fraction differences (38% without Power-to-Power pathway and 41% with it).

Softw.	PV (kW)	PEM (kW)	Elec. (kW)	H2 Tank (kg)	CAPEX (€)	Opex (€/year)	Total NPC	COE (€/kWh)
HOMER	6354.5	0	0	0	20,404,236	1,169,706	43,773,804	0.181
TRNSYS	6354.5	700	4250	2007	39,030,379	1,986,656	74,880,685	0.312

Table 24: Economic comparison between TRNSYS and HOMER.

It is possible to conclude that the installation with the hydrogen Power-to-Power pathway has a very higher cost increase. This is because the high cost of every hydrogen technologies that are available currently.

Finally, a hydrogen storage study with all the storage technologies explained in section 4.2 has been performed. For doing so, the following pressure factors from reference [20] and different storage characteristics from Image 5: have been used. Also densities of 0,0899 kg/Nm3 (gas) and 0,0708 kg/l (liquid) were used.



Presión (Bar)	1	50	100	150	200	250	300	350
Factor de compresión	1	1,032	1,065	1,089	1,132	1,166	1,201	1,236
Presión (Bar)	400	500	600	700	800	900	1000	
Factor de compresión	1,272	1,344	1,416	1,489	1,560	1,632	1,702	

Table 25: Hydrogen pressure factors.

Storage size from TRNSYS simulation has been used (60 m^3 at 500 bar → 2007 kg). Results are summarized in the following tables.

Pressure (bar)		1	100	200	300	400	500	600	700	800
Tank volume (m^3)	Gas storage	22321	238	126	89	71	60	53	47	44
	Liquid storage	28.343	0.302	0.160	0.113	0.090	0.076	0.067	0.060	0.055

Table 26: Hydrogen storage pressure comparison.

Technology	Storage volume (m^3)
Metal hydride	198
Sorbent	99
Chemical	72

Table 27: Material-based hydrogen storage systems comparison.

It is possible to see that the storage option that allows a smaller volume is the liquid storage technology. Material-based storages also offer a very suitable storage volume knowing they operate at not high pressures. But as explained before, only gas pressure storage tanks are now available in the market and for this reason this is the chosen technology to perform the system.

Regarding the gas storage option, it has been studied how the consumption increases while the pressure increases too. This allows reducing the total storage volume as it is possible to see in the next figure.

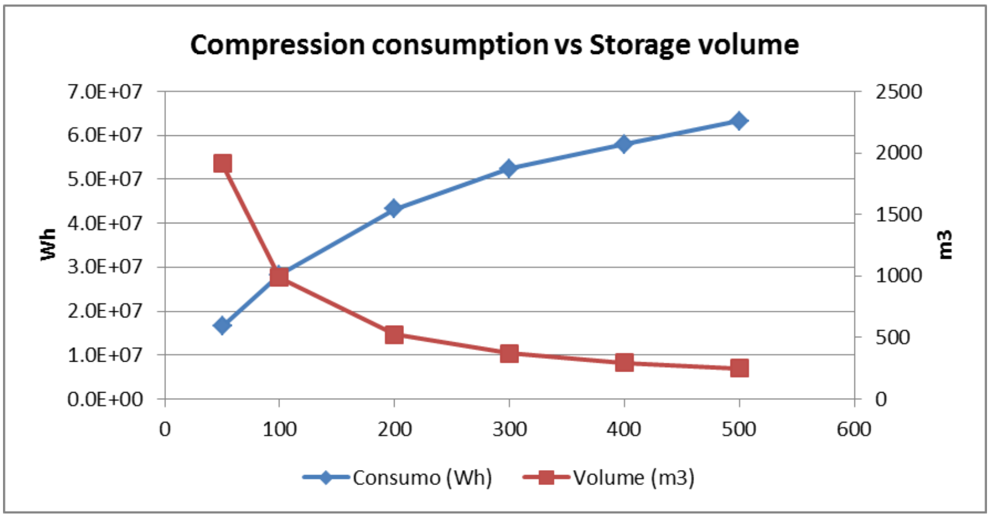


Figure 22: Compression consumption variation with storage volume.

Regarding the costs, volume costs are much higher than electricity costs and for this reason the volume is the parameter to decrease. This can only be done by increasing the storage pressure. In order to select a standard pressure available in the market and following standards from different literature, the selected pressure is 500 bar.

9.4.2. Methanation TRNSYS simulations

Following the same approach as in Power-to-Power hydrogen pathway, in this section, economic values from section 5 and explanations from section 9.2.12 are going to be taken into account.

In order to summarize, there is not any TRNSYS component to simulate the methanation process. For this reason and because it is out of the bound of this project, a TRNSYS calculator is going to be used to simulate this process. It has to be remarked that in this case, any storage tank has been contemplated. It is supposed that all the hydrogen production can be directly transformed in methane taking into account the methanation efficiency (~80%) and can be also directly sold by a price of 45 €/MWh. All the methane that can be consumed in situ should be taken into account; in this case there should be a methane production at the same time that there is a NG need. The quantity of methane consumed should not overpass the NG needs in that time.

The most suitable sizes of each system are summarized in the next table.

System	Units	Size	
PV	3	2118.27 kW each branch	
Electrolysers	2	1st	Minimum power: 45 kW Maximum power: 550 kW
		2nd	Minimum power: 250 kW Maximum power: 3700 kW
Inverter AC/DC	3	2910 kW each	
Demand	-	3.8 MW	
Methanation	1	2475 kW	

Table 28: Methanation sizes from TRNSYS simulation.

As it is possible to see, the photovoltaic and electrolysers installations are the same then in the Power-to-Power hydrogen pathway. As the electrical demand is also the same, the power surplus and hydrogen production are going to have the same value.

Next graphs show the methanation process.

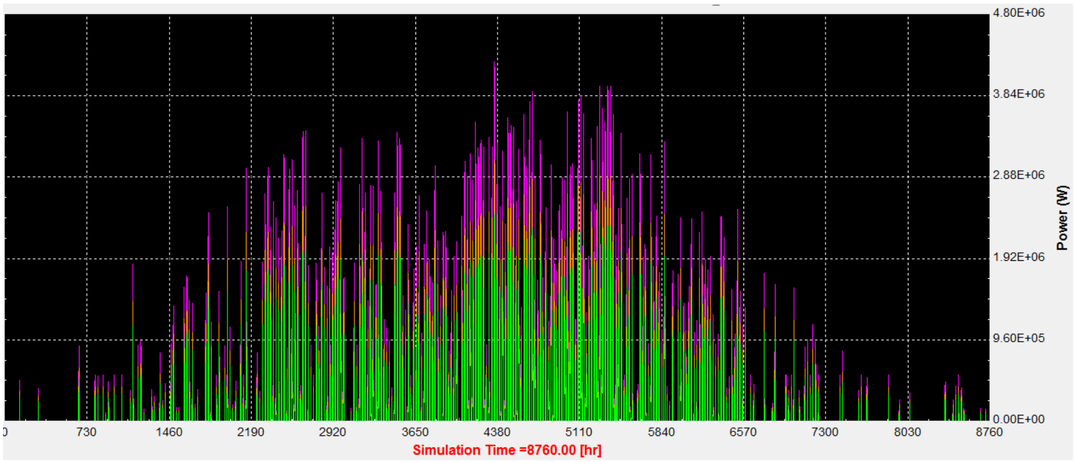


Figure 23: Power consumed by the electrolysers in W (purple), hydrogen production in W (orange) and methane production in W (green).

From previous graph it is possible to see how the power decreases in each process due to the efficiency of each system.

Next image shows, in m^3, the conversion from hydrogen to methane. It is very important to take into account the axis values (left for hydrogen and right for methane). The volume of hydrogen is lower due to its higher calorific power. This must be taken into account if in the future it is planned to study a storage method because it would be better to store hydrogen than methane.

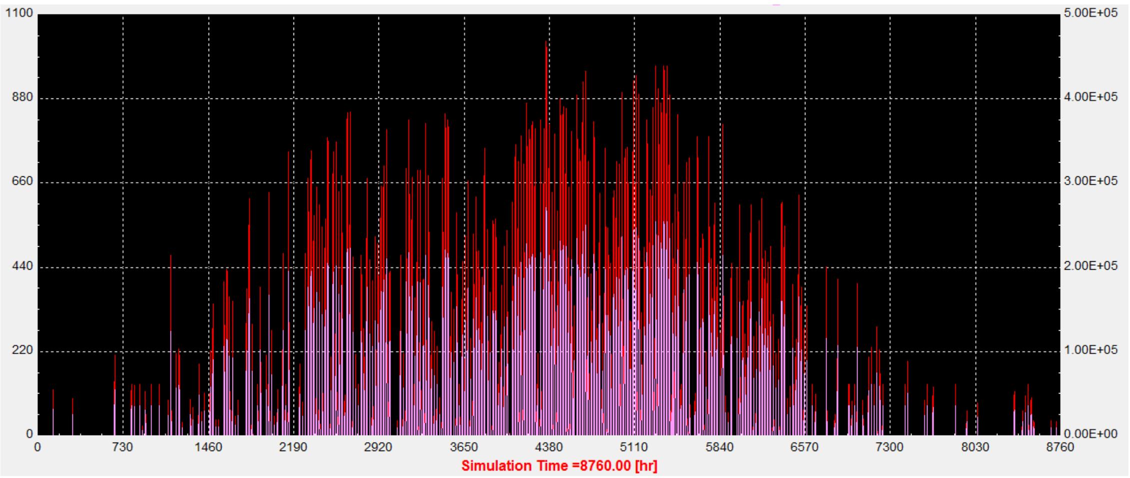


Figure 24: Hydrogen production in m^3 (in red and left axis) and methane production in m^3 (in pink and right axis).

Some key values that can be calculated are shown in the next table.

Energy demand	12,000	MWh
Solar energy production	6,501.2	MWh
Energy surplus	2,375.8	MWh
Energy consumed by electrolysers	2,354.9	MWh
Energy from grid	12,000	MWh
Energy to grid	21.582	MWh
NG demand	4006	MWh
Methane production	1456	MWh
New NG consumption	3682	MWh
Available methane to sell	324	MWh

Table 29: Key values from methane TRNSYS simulation.

Following, some interesting factors that can be calculated from the previous table are shown. In this case electrical and thermal demands are going to be taken into account to calculate the renewable factors.

Renewable factor with PV only (without thermal)	34	%
Renewable factor with PV only (with thermal)	26	%
Renewable factor Methanation (without thermal)	34	%
Renewable factor Methanation (with thermal)	28	%
Hydrogen pathway efficiency	60	%
NG reduction	8	%

Table 30: Interesting factors from methanation pathway in INSA Lyon.

Taking into account the thermal energy it is possible to see that the renewable fraction is reduced due to the fact that there is more energy from non-renewable sources. If methanation is included in this calculus, it does not increase too much because a very small amount of methane is used (it involves a reduction of only 8% in the natural gas).

Regarding the methanation pathway efficiency, it is possible to see that it is possible to reach a bigger value than in Power-to-Power process. This is because there are fewer systems involved in the entire pathway and the performance of all the system is higher (60%). This value is very similar to the one provided by reference [4] (40-63 %).

Next table shows the economic study of this system, taking into account the Methanation systems, and compares it with the Power-to-Power (PtP) option. This study has been performed with the same cost data from section 5, without emission taxes and with the electrical and thermal demands of the University Campus of INSA Lyon. The methane sell cost is fixed to 0.045 €/kWh.

Pathway	PV (kW)	PEM (kW)	Elec. (kW)	H2 Tank (kg)	Methanation (kW)
PtP	6354.5	700	4250	2007	0
Meth	6354.5	0	4250	0	2475

Pathway	CAPEX (€)	Opex (€/year)	Total NPC (€)	COE (€/kWh)
PtP	39,030,379	1,986,656	74,880,685	0.312
Meth	29,125,710	2,163,231	68,162,415	0.284

Table 31: Economic comparison between Power-to-Power and Methanation hydrogen pathways.

It is possible to conclude that the installation with the hydrogen Methanation pathway has a very high cost but it is lower than the one of Power-to-Power.

It is also important to say that in Methanation pathway it has not been considered any CO_2 capture or buying system. This could highly variate the economic study.

10. CONCLUSIONS

First, a review of different energy storage systems was developed concluding that the best options to feed the University Campus of INSA Lyon are photovoltaic panels as the main renewable source and Power-to-Power and Methanation hydrogen pathways as energy vectors systems that can allow to increase even more the renewable fraction of the energy consumed, decrease the grid dependency and reduce the fatal electricity injected to the grid.

In this project, it has been possible to develop an economic study of different renewable sources and hydrogen pathways in the French context.

Having an electrical and thermal demand it could be possible, with different simulations, to produce a parametric study where it can be seen how much photovoltaic panels must be installed to reach each minimum renewable factor required in the system.

Due to the fact that the available area for installing PV panels is limited, a maximum power of 6354.5 kW can be selected. With this maximum value, another parametric study has been developed to understand how a possible carbon dioxide tax can change the economic situation of the network. With this parametric study and in the University Campus of INSA Lyon it has been also possible to calculate the minimum tax emission value to prefer installing a renewable source than keep consuming directly from the grid in France. If both wind turbines and photovoltaic panels are studied, after 180 €/tCO_2 it is prefereable to install a wind turbine of 2.1 MW. Otherwise, if only PV technology is simulated, the emission tax must increase up to 1500 €/tCO_2 to prefer to install this renewable source. Finally, another study has been performed by variating the energy context, introducing emission factors from other countries. It was concluded that in Spain an emission tax of 37 €/tCO_2 and in Germany an emission tax of 25 €/tCO_2, keeping the same case of study and costs from France, will make it possible to prefer a renewable source than the electricity grid.

As the aim of this project is to increase to the maximum the renewable factor, the maximum PV power has been selected and thanks to HOMER software it could be possible to calculate de levelized cost of electricity: 0.181 €/kWh in 20 years.

Following, it has been possible to design both electrolyser and fuel cell controllers with OpenModelica software to afterwards implement it in TRNSYS software to produce annual energy simulations. With TRNSYS it was possible to simulate the two possible hydrogen pathways with the given electrical and thermal demand. It was concluded that with Power-to-Power pathway an energy efficiency of 33.6% and a COE of 0.312 €/kWh in 20 years can be reached. Regarding the Methanation process, the results have been 60% and 0.284 €/kWh.

Studying those results it can be obvious to say that Methanation pathway is economically more suitable than Power-to-Power but due to the fact that a better simulation of the Methanation process was out of the bounds of this project, it is not possible to categorically affirm that this is the best option while it seems that it could be.

For this reason, a possible continuation of this project could be to better study all the energy and economic operations of the Methanation hydrogen pathway.

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ANNEX I

atersa
grupo elecnor

+Ultra
nueva gama

Módulo fotovoltaico
A-320M / A-325M / A-330M (TYCO 3.2)

+Ultra**Tolerancia positiva**
Positiva 0/+5 Wp

+Ultra**Calidad**
Anti Hot-Spot

+Ultra**Garantía**
10 años de garantía de producto

+Ultra**Fiabilidad**
En el mercado desde 1979

+Ultra**Resistencia**
Cristal templado de 3.2 mm

+Ultra**TES**
Verificación eléctrica célula a célula

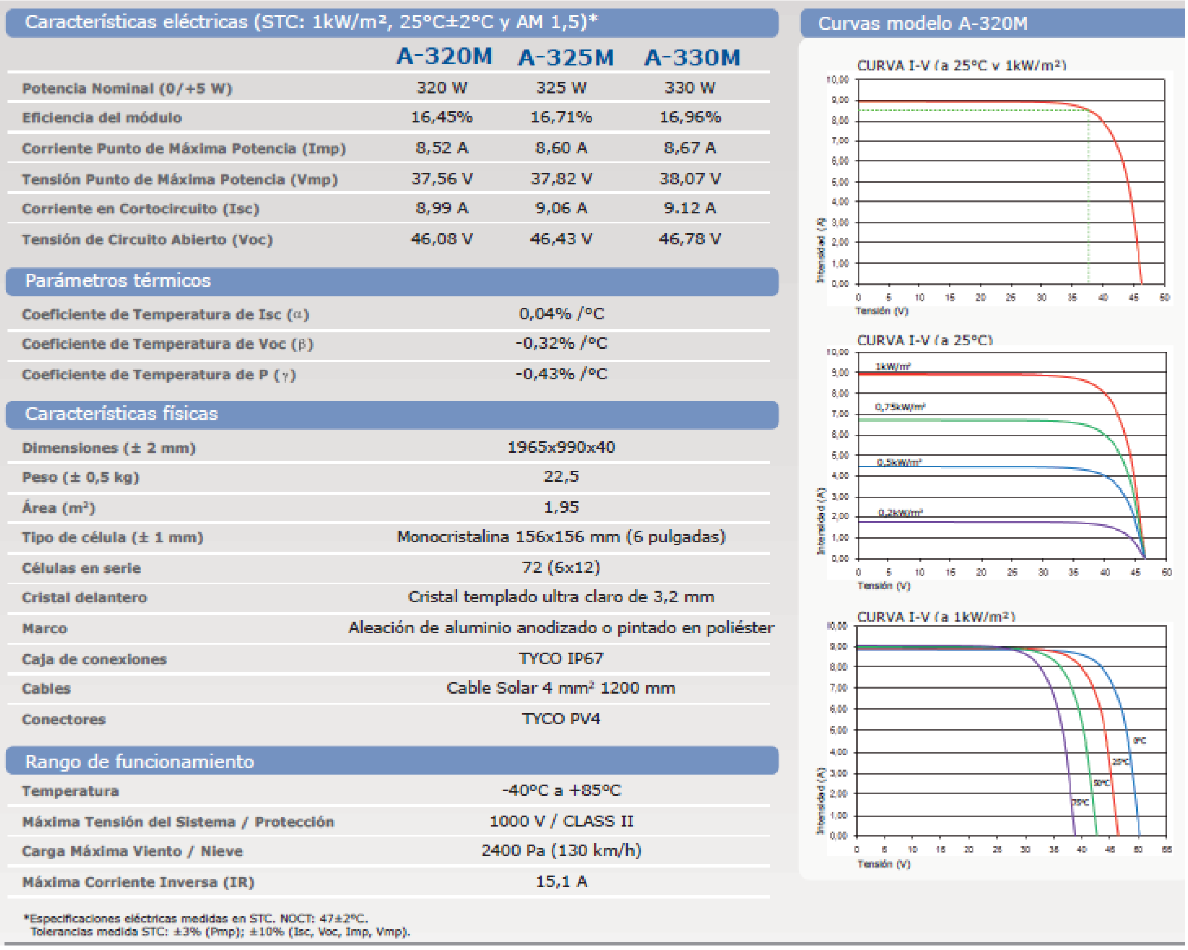
made in SPAIN

TES Verified

Sistema único en el mercado, patentado por Atersa.

Para una información más detallada de los términos de la garantía, consultar:
→ www.atersa.com

Nueva gama Ultra con Tolerancia positiva



Características eléctricas (STC: 1kW/m², 25°C±2°C y AM 1,5)*

	A-320M	A-325M	A-330M
Potencia Nominal (0/+5 W)	320 W	325 W	330 W
Eficiencia del módulo	16,45%	16,71%	16,96%
Corriente Punto de Máxima Potencia (Imp)	8,52 A	8,60 A	8,67 A
Tensión Punto de Máxima Potencia (Vmp)	37,56 V	37,82 V	38,07 V
Corriente en Cortocircuito (Isc)	8,99 A	9,06 A	9.12 A
Tensión de Circuito Abierto (Voc)	46,08 V	46,43 V	46,78 V

Parámetros térmicos

Coeficiente de Temperatura de Isc (α)	0,04% /°C
Coeficiente de Temperatura de Voc (β)	-0,32% /°C
Coeficiente de Temperatura de P (γ)	-0,43% /°C

Características físicas

Dimensiones (± 2 mm)	1965x990x40
Peso (± 0,5 kg)	22,5
Área (m²)	1,95
Tipo de célula (± 1 mm)	Monocristalina 156x156 mm (6 pulgadas)
Células en serie	72 (6x12)
Cristal delantero	Cristal templado ultra claro de 3,2 mm
Marco	Aleación de aluminio anodizado o pintado en poliéster
Caja de conexiones	TYCO IP67
Cables	Cable Solar 4 mm² 1200 mm
Conectores	TYCO PV4

Rango de funcionamiento

Temperatura	-40°C a +85°C
Máxima Tensión del Sistema / Protección	1000 V / CLASS II
Carga Máxima Viento / Nieve	2400 Pa (130 km/h)
Máxima Corriente Inversa (IR)	15,1 A

*Especificaciones eléctricas medidas en STC. NOCT: 47±2°C.
Tolerancias medida STC: ±3% (Pmp); ±10% (Isc, Voc, Imp, Vmp).

Curvas modelo A-320M

ANNEX II

ABB central inverters

PVS980 – 1818 to 2091 kVA

Technical data and types

Type designation	**PVS980-58-1818kVA-I**	**PVS980-58-1909kVA-J**	**PVS980-58-2000kVA-K**	**PVS980-58-2091kVA-L**
Input (DC)				
Maximum recommended PV power ($P_{\text{PV, max}}$) [1]	2910 kWp	3055 kWp	3200 kWp	3346 kWp
Maximum DC current ($I_{\text{max (DC)}}$)	2400 A	2400 A	2400 A	2400 A
DC voltage range, mpp ($U_{\text{DC, mpp}}$) at 35 °C	850 to 1500 V	893 to 1500 V	935 to 1500 V	978 to 1500 V
DC voltage range, mpp ($U_{\text{DC, mpp}}$) at 50 °C	850 to 1100 V	893 to 1100 V	935 to 1100 V	978 to 1100 V
Maximum DC voltage ($U_{\text{max (DC)}}$)	1500 V	1500 V	1500 V	1500 V
Number of MPPT trackers	1	1	1	1
Number of protected DC inputs	8[2] to 24 (+/-)	8 [2] to 24 (+/-)	8 [2] to 24 (+/-)	8 [2] to 24 (+/-)
Output (AC)				
Maximum power ($S_{\text{max (AC)}}$) [3]	2000 kVA	2100 kVA	2200 kVA	2300 kVA
Nominal power ($S_{\text{N(AC)}}$) [4]	1818 kVA	1909 kVA	2000 kVA	2091 kVA
Maximum AC current ($I_{\text{max (AC)}}$)	1925 A	1925 A	1925 A	1925 A
Nominal AC current ($I_{\text{N(AC)}}$)	1750 A	1750 A	1750 A	1750 A
Nominal output voltage ($U_{\text{N(AC)}}$) [5]	600 V	630 V	660 V	690 V
Output frequency [5]	50/60 Hz	50/60 Hz	50/60 Hz	50/60 Hz
Harmonic distortion, current [6]	< 3%	< 3%	< 3%	< 3%
Distribution network type [7]	TN and IT	TN and IT	TN and IT	TN and IT
Efficiency				
Maximum [8]	98.8%	98.8%	98.8%	98.8%
Euro-eta [8]	98.6%	98.6%	98.6%	98.6%
CEC efficiency [9]	98.0%	98.5%	98.5%	98.5%
Power consumption				
Self consumption in normal operation	≤ 2500 W	≤ 2500 W	≤ 2500 W	≤ 2500 W
Standby operation consumption	235 W	235 W	235 W	235 W
Auxiliary voltage source [10]	External, 1-phase	External, 1-phase	External, 1-phase	External, 1-phase

[1] DC/AC ratio over 1.6 might decrease maintenance intervals

[2] As standard

[3] At 35 °C

[4] At 50 °C

[5] ±10%

[6] At nominal power

[7] Inverter side must be IT type

[8] Without auxiliary power consumption at min U_{DC}

[9] With auxiliary power included

[10] Internal as option

ANNEX III

ELECTROLYSERS CONTROLLER

```
model Electro_Controller_3
  Modelica.Blocks.Interfaces.RealInput Surplus "Power
surplus" annotation(
    Placement(transformation(origin = {-100, -50}, extent =
{{-15, -15}, {15, 15}}, rotation = 0)));
  Modelica.Blocks.Interfaces.RealInput SOC "State of
Charge" annotation(
    Placement(transformation(origin = {-100, 50}, extent =
{{-15, -15}, {15, 15}}, rotation = 0)));
  parameter Real Pidle1 = 10;
  parameter Real P_max_ef1 = 20;
  parameter Real P_max1 = 30;
  parameter Real Pidle2 = 10;
  parameter Real P_max_ef2 = 20;
  parameter Real P_max2 = 30;
  parameter Real Pidle3 = 10;
  parameter Real P_max_ef3 = 20;
  parameter Real P_max3 = 30;
  parameter Real Pidle4 = 10;
  parameter Real P_max_ef4 = 20;
  parameter Real P_max4 = 30;
  parameter Real Pidle5 = 10;
  parameter Real P_max_ef5 = 20;
  parameter Real P_max5 = 30;
  parameter Real SOC_max = 100;
  output Real Switch1;
  output Real Switch2;
  output Real Switch3;
  output Real Switch4;
  output Real Switch5;
  output Real P_elect1;
  output Real P_elect2;
  output Real P_elect3;
  output Real P_elect4;
  output Real P_elect5;
algorithm
  if Surplus < Pidle1 or SOC > SOC_max then
    P_elect1 := 0;
    P_elect2 := 0;
    P_elect3 := 0;
    P_elect4 := 0;
    P_elect5 := 0;
  end if;
//In TRNSYS this had been changed because it cannot be 0 --
> Pidle1
//Also changed in TRNSYS 0 --> Pidle2
  if Surplus > Pidle1 and SOC < SOC_max and Surplus <
P_max1 then
    P_elect1 := Surplus;
```

```
    P_elect2 := 0;
    P_elect3 := 0;
    P_elect4 := 0;
    P_elect5 := 0;
  end if;
//Also changed in TRNSYS 0 --> Pidle2
  if SOC < SOC_max and Surplus > P_max1 and Surplus <
P_max1 + P_max2 and Surplus - P_max_ef1 < Pidle2 then
    P_elect1 := P_max1;
    P_elect2 := 0;
    P_elect3 := 0;
    P_elect4 := 0;
    P_elect5 := 0;
  end if;
//Also changed in TRNSYS 0 --> Pidle2
  if SOC < SOC_max and Surplus > P_max1 and Surplus <
P_max1 + P_max2 and Surplus - P_max_ef1 > Pidle2 and
Surplus < P_max_ef1 + P_max_ef2 then
    P_elect1 := P_max_ef1;
    P_elect2 := Surplus - P_max_ef1;
    P_elect3 := 0;
    P_elect4 := 0;
    P_elect5 := 0;
  end if;
  if SOC < SOC_max and Surplus > P_max1 and Surplus <
P_max1 + P_max2 and Surplus - P_max_ef1 > Pidle2 and
Surplus > P_max_ef1 + P_max_ef2 and Surplus - P_max_ef2 <
P_max1 then
    P_elect1 := Surplus - P_max_ef2;
    P_elect2 := P_max_ef2;
    P_elect3 := 0;
    P_elect4 := 0;
    P_elect5 := 0;
  end if;
  if SOC < SOC_max and Surplus > P_max1 and Surplus <
P_max1 + P_max2 and Surplus - P_max_ef1 > Pidle2 and
Surplus > P_max_ef1 + P_max_ef2 and Surplus - P_max_ef2 >
P_max1 then
    P_elect1 := P_max1;
    P_elect2 := Surplus - P_max1;
    P_elect3 := 0;
    P_elect4 := 0;
    P_elect5 := 0;
  end if;
  if SOC < SOC_max and Surplus > P_max1 + P_max2 and
Surplus-P_max1-P_max2<Pidle3 then
    P_elect1 := P_max1;
    P_elect2 := P_max2;
    P_elect3 := 0;
    P_elect4 := 0;
    P_elect5 := 0;
```

```
  end if;
  if SOC < SOC_max and Surplus > P_max1 + P_max2 and
Surplus-P_max1-P_max2>Pidle3 then
    P_elect1 := P_max1;
    P_elect2 := P_max2;
    P_elect3 := Surplus-P_max1-P_max2;
    P_elect4 := 0;
    P_elect5 := 0;
  end if;
  if SOC < SOC_max and Surplus > P_max1 + P_max2 and
Surplus-P_max1-P_max2>P_max3 then
    P_elect1 := P_max1;
    P_elect2 := P_max2;
    P_elect3 := P_max3;
    P_elect4 := 0;
    P_elect5 := 0;
  end if;
  if SOC < SOC_max and Surplus > P_max1 + P_max2 + P_max3
and Surplus-P_max1-P_max2-P_max3>Pidle4 then
    P_elect1 := P_max1;
    P_elect2 := P_max2;
    P_elect3 := P_max3;
    P_elect4 := Surplus-P_max1-P_max2-P_max3;
    P_elect5 := 0;
  end if;
  if SOC < SOC_max and Surplus > P_max1 + P_max2 + P_max3
+P_max4 then
    P_elect1 := P_max1;
    P_elect2 := P_max2;
    P_elect3 := P_max3;
    P_elect4 := P_max4;
    P_elect5 := 0;
  end if;
  if SOC < SOC_max and Surplus > P_max1 + P_max2 + P_max3
+P_max4 and Surplus-(P_max1 + P_max2 + P_max3
+P_max4)<Pidle5 then
    P_elect1 := P_max1;
    P_elect2 := P_max2;
    P_elect3 := P_max3;
    P_elect4 := P_max4;
    P_elect5 := 0;
  end if;
  if SOC < SOC_max and Surplus > P_max1 + P_max2 + P_max3
+P_max4 and Surplus-(P_max1 + P_max2 + P_max3
+P_max4)>Pidle5 then
    P_elect1 := P_max1;
    P_elect2 := P_max2;
    P_elect3 := P_max3;
    P_elect4 := P_max4;
    P_elect5 := Surplus-(P_max1 + P_max2 + P_max3 +P_max4);
  end if;
```

```
  if SOC < SOC_max and Surplus > P_max1 + P_max2 + P_max3
+P_max4 + P_max5 then
    P_elect1 := P_max1;
    P_elect2 := P_max2;
    P_elect3 := P_max3;
    P_elect4 := P_max4;
    P_elect5 := P_max5;
  end if;
//It is important to put this at the end because in TRNSYS
it is really necessary. The electrolyzers must be ON only
when the power is over their idling power, if not an error
will appear in TRNSYS//
  if P_elect1 > Pidle1 then
    Switch1 := 1;
  else
    Switch1 := 0;
  end if;
  if P_elect2 > Pidle2 then
    Switch2 := 1;
  else
    Switch2 := 0;
  end if;
  if P_elect3 > Pidle3 then
    Switch3 := 1;
  else
    Switch3 := 0;
  end if;
  if P_elect4 > Pidle4 then
    Switch4 := 1;
  else
    Switch4 := 0;
  end if;
  if P_elect5 > Pidle5 then
    Switch5 := 1;
  else
    Switch5 := 0;
  end if;
  annotation(
    Icon(graphics = {Rectangle(origin = {5, 0}, extent =
{{-87, 96}, {87, -96}})}));
end Electro_Controller_3;
```

FUEL CELLS CONTROLLER

```
model FC_Controller
  Modelica.Blocks.Interfaces.RealInput Demand "Power
demanded" annotation(
    Placement(transformation(origin = {-100, -50}, extent =
{{-15, -15}, {15, 15}}, rotation = 0)));
    parameter Real P_min1=10;
    parameter Real P_max1=30;
    parameter Real P_min2=10;
    parameter Real P_max2=30;
    parameter Real P_min3=10;
    parameter Real P_max3=30;
    parameter Real P_min4=10;
    parameter Real P_max4=30;
    parameter Real P_min5=10;
    parameter Real P_max5=30;
    parameter Real P_min6=10;
    parameter Real P_max6=30;
    output Real P_FC1;
    output Real P_FC2;
    output Real P_FC3;
    output Real P_FC4;
    output Real P_FC5;
    output Real P_FC6;
    output Real Switch1;
    output Real Switch2;
    output Real Switch3;
    output Real Switch4;
    output Real Switch5;
    output Real Switch6;


    algorithm
      if Demand<P_min1 then
        P_FC1:=0;
        P_FC2:=0;
        P_FC3:=0;
        P_FC4:=0;
        P_FC5:=0;
        P_FC6:=0;
      end if;
      if Demand>P_min1 and Demand<P_max1 then
        P_FC1:=Demand;
        P_FC2:=0;
        P_FC3:=0;
        P_FC4:=0;
        P_FC5:=0;
        P_FC6:=0;
      end if;
      if Demand>P_max1 and Demand-P_max1<P_min2 then
```

```
        P_FC1:=P_max1;
        P_FC2:=0;
        P_FC3:=0;
        P_FC4:=0;
        P_FC5:=0;
        P_FC6:=0;
      end if;
      if Demand<P_max1+P_max2 and Demand-P_max1>P_min2 then
        P_FC1:=P_max1;
        P_FC2:=Demand-P_max1;
        P_FC3:=0;
        P_FC4:=0;
        P_FC5:=0;
        P_FC6:=0;
      end if;
      if Demand>P_max1+P_max2 and Demand-P_max1-
P_max2<P_min3 then
        P_FC1:=P_max1;
        P_FC2:=P_max2;
        P_FC3:=0;
        P_FC4:=0;
        P_FC5:=0;
        P_FC6:=0;
      end if;
      if Demand>P_max1+P_max2 and Demand-P_max1-
P_max2>P_min3 then
        P_FC1:=P_max1;
        P_FC2:=P_max2;
        P_FC3:=Demand-P_max1-P_max2;
        P_FC4:=0;
        P_FC5:=0;
        P_FC6:=0;
      end if;
      if Demand>P_max1+P_max2+P_max3 and Demand-P_max1-
P_max2-P_max3<P_min4 then
        P_FC1:=P_max1;
        P_FC2:=P_max2;
        P_FC3:=P_max3;
        P_FC4:=0;
        P_FC5:=0;
        P_FC6:=0;
      end if;
      if Demand>P_max1+P_max2+P_max3 and Demand-P_max1-
P_max2-P_max3>P_min4 then
        P_FC1:=P_max1;
        P_FC2:=P_max2;
        P_FC3:=P_max3;
        P_FC4:=Demand-P_max1-P_max2-P_max3;
        P_FC5:=0;
        P_FC6:=0;
      end if;
```

```
      if Demand>P_max1+P_max2+P_max3+P_max4 and Demand-
P_max1-P_max2-P_max3-P_max4<P_min5 then
        P_FC1:=P_max1;
        P_FC2:=P_max2;
        P_FC3:=P_max3;
        P_FC4:=P_max4;
        P_FC5:=0;
        P_FC6:=0;
      end if;
      if Demand>P_max1+P_max2+P_max3+P_max4 and Demand-
P_max1-P_max2-P_max3-P_max4>P_min5 then
        P_FC1:=P_max1;
        P_FC2:=P_max2;
        P_FC3:=P_max3;
        P_FC4:=P_max4;
        P_FC5:=Demand-P_max1-P_max2-P_max3-P_max4;
        P_FC6:=0;
      end if;
      if Demand>P_max1+P_max2+P_max3+P_max4+P_max5 and
Demand-P_max1-P_max2-P_max3-P_max4-P_max5<P_min6 then
        P_FC1:=P_max1;
        P_FC2:=P_max2;
        P_FC3:=P_max3;
        P_FC4:=P_max4;
        P_FC5:=P_max5;
        P_FC6:=0;
      end if;
      if Demand>P_max1+P_max2+P_max3+P_max4+P_max5 and
Demand-P_max1-P_max2-P_max3-P_max4-P_max5>P_min6 then
        P_FC1:=P_max1;
        P_FC2:=P_max2;
        P_FC3:=P_max3;
        P_FC4:=P_max4;
        P_FC5:=P_max5;
        P_FC6:=Demand-P_max1-P_max2-P_max3-P_max4-P_max5;
      end if;
      if Demand>P_max1+P_max2+P_max3+P_max4+P_max5+P_max6
then
        P_FC1:=P_max1;
        P_FC2:=P_max2;
        P_FC3:=P_max3;
        P_FC4:=P_max4;
        P_FC5:=P_max5;
        P_FC6:=P_max6;
      end if;


      if P_FC1>P_min1 then
        Switch1:=1;
      else
        Switch1:=0;
```

```
      end if;
      if P_FC2>P_min2 then
        Switch2:=1;
      else
        Switch2:=0;
      end if;
      if P_FC3>P_min3 then
        Switch3:=1;
      else
        Switch3:=0;
      end if;
      if P_FC4>P_min4 then
        Switch4:=1;
      else
        Switch4:=0;
      end if;
      if P_FC5>P_min5 then
        Switch5:=1;
      else
        Switch5:=0;
      end if;
      if P_FC6>P_min6 then
        Switch6:=1;
      else
        Switch6:=0;
      end if;

annotation(
    Icon(graphics = {Polygon(origin = {-2.98251, 5.01195},
points = {{8.98251, 86.988}, {-83.0175, -1.01195},
{0.982509, -87.012}, {82.9825, 2.98805}, {8.98251,
86.988}}), Text(origin = {-4, 2}, extent = {{-38, 18}, {38,
-18}}, textString = "FC controller")},
coordinateSystem(initialScale = 0.1)));
end FC_Controller;
```