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Corso di Laurea Magistrale in Ingegneria energetica e nucleare

Classe n. LM – Innovazione nella produzione di energia

Business analysis of H2 energy storage solutions under different economic and regulatory contexts

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ANNO ACCADEMICO 2018 / 2019

Abstract

EU requires a strong commitment from all Member States to meet post-2020 targets.
To meet the targets imposed by Europe it is necessary to improve the penetration of the renewables like wind and solar.

The main problem associated to the renewables is linked to their intermittency nature, indeed the power produced from solar and wind is subjected to daily and seasonal fluctuations which give rise to a grid stability problem.

This will result in produce mismatching between power produced by the renewable energy sources system and requested power from the grid, leading to a period of over-production by the renewable energy sources and other of energy shortage for the users.

The issue of intermittency has to be solved and one significant option is developing energy storage solutions that are cost-effective, energy dense, reliable.

In the case of isolated micro-grid or off-grid remote areas, the business case of energy storage is different, as the network is essentially non-existent or there is the interest of managing the local network in an independent way.

A good solution so, is to integrate the intermittent RES with fuel cell and H_2-based power-to-power (P2P) systems, which can provide a reliable, cost-effective, and decarbonized alternative to the on-site generation of electricity through the local diesel engines. P2P system is seen to be the most credible option, with medium to long-term storage capabilities for the lower scales and maybe soon could be also competitive in the larger one.

This thesis will support the EU REMOTE project demonstrating the technical and economic feasibility of fuel cells-based H2 energy storage solutions in isolated and off-grid remote areas.

The development of this project will pave the way to create technological learning for the different component of the system, so that the larger energy storage market could be also assessed in the near future with this kind of system.

This means that the replicability can be huge especially in countries characterized by long distances and remote communities.

Different scenarios will be analyzed through the HyOpt model developed by Sintef to better understand the real value of this system.

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1. INTRODUCTION

1.1. Energy context

At the United Nations climate change conference in Paris, COP 21, governments agreed that mobilizing stronger and more ambitious climate action is urgently required to achieve the goals of the Paris Agreement[1].
Action must come from governments, cities, regions, businesses and investors.
The EU requires a strong commitment from all Member States in order to develop a Resilient Energy Union whose main core is to provide EU consumers with secure, sustainable, competitive and affordable energy.
In March 2007 the 2020 package was launched, and it consists in a set of mandatory legislation to ensure that the European countries meet the goal imposed for the climate and energy in the 2020.
The package is composed by three main key targets[2]:

- 20% cut in greenhouse gas (GHG) emissions (from 1990 levels)
- 20% of EU energy from renewables
- 20% improvement in energy efficiency

In July 2009, the leaders of the European Union and the G8 announced an objective to reduce greenhouse gas emissions by at least 80% below 1990 levels by 2050[2].
In October 2014 The European Council agreed on a new 2030 Framework for climate and energy, including EU-wide targets and policy objectives for the period between 2020 and 2030[2].
The main targets for the 2030 are[2]:

- a 40% cut in greenhouse gas emissions compared to 1990 levels
- at least a 27% share of renewable energy consumption
- indicative target for an improvement in energy efficiency at EU level of at least 27% (compared to projections), to be reviewed by 2020 (with an EU level of 30% in mind)

- support the completion of the internal energy market by achieving the existing electricity interconnection target of 10% by 2020, with a view to reaching 15% by 2030

These targets lead to achieve a more competitive, secure and sustainable energy system and to meet 2050 greenhouse gas reductions target.
Therefore, to meet post-2020 targets, a high deployment of renewable energy sources is needed.

1.2. Renewable energy sources

In the DNV GL energy outlook the global total final energy annual demand is expected to be 450 exajoules per year by 2050 compared with 400 EJ in 2016[3]. Demand peaks in 2035 at 470 EJ per year, then starts to decline slightly. Before the peak, demand grows at 0.9% per year, but this rate slowly declines due to both energy-efficiency improvements and electrification exceeding the continued growth in population and productivity[3].

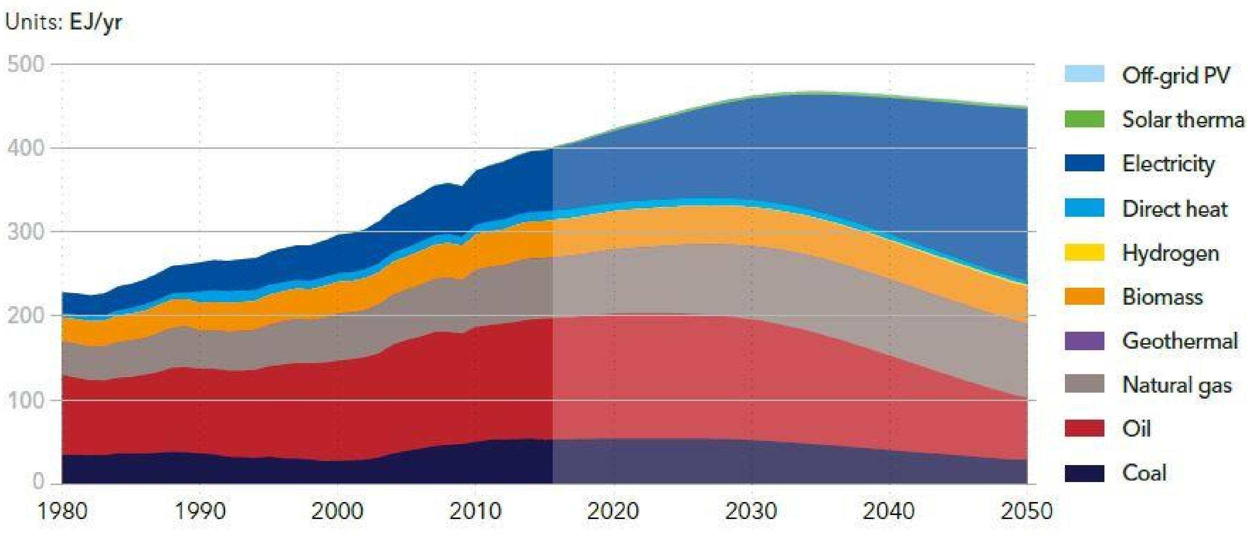

Figure 1 Global energy demand per source[3]

The forecast shows an acceleration on the electrification of industry and society towards 2050. The electrification will rise rapidly by 160% from 25 in 2016 to 66 petawatt-hours per year in 2050, thereby increasing its share of total demand from 19% to 45%[3].

The electricity sector is on the spot of a large shift towards low-carbon electricity generation. Power systems after 2030 may consist largely of two low-carbon generator types: intermittent Renewable Energy Sources such as wind and solar PV and thermal generators such as power plants with carbon capture.

The primary supply mix changes dramatically with the influx of solar photovoltaic and wind and the reduction in coal, oil and gas. Renewables will dominate world electricity generation, with solar PV capturing a 40% share and wind 29% by 2050[3]. With this high amount of variable power, stability in the power network system will become crucial.

In the following figure we can notice the forecast of the change in the supply mix for the electricity generation.

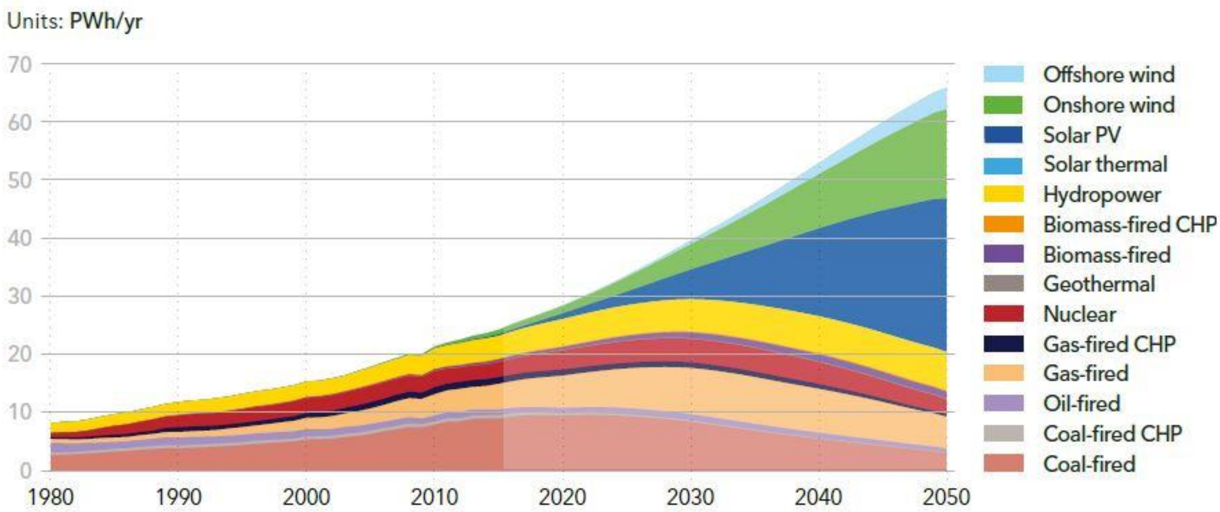

Figure 2 Supply mix in electricity generation[3]

And focusing our attention on our days:

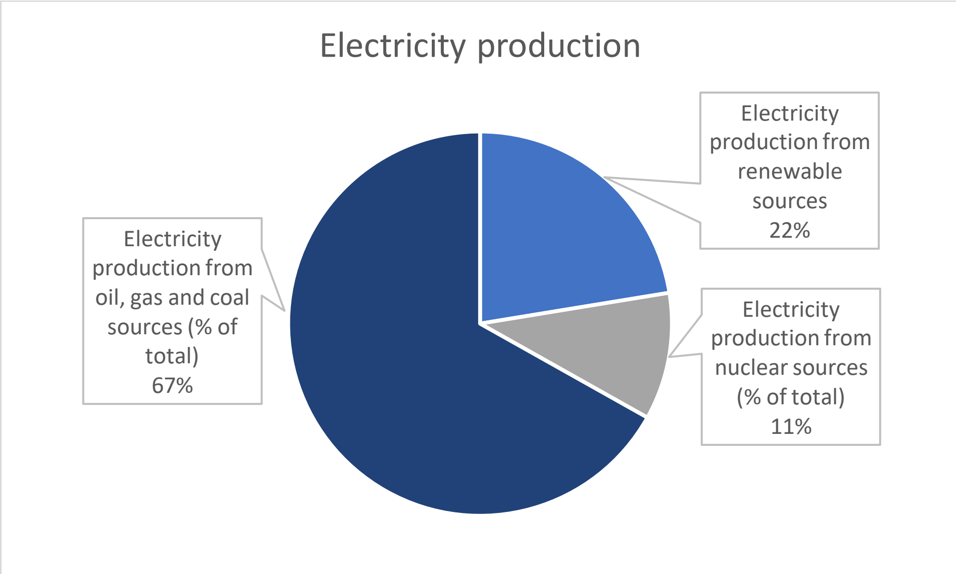

Figure 3 Electricity production per source [4]

The renewables, nowadays, as we can noticed from the previous figure, account for around the 20% of the total electricity generation.

Among the renewable energies, as shown in the following figure, the ones which play the main role are the biomass and biogas which account for more than the 50% of the total share followed by the hydropower 22%, instead the contribution of the new renewables, like wind and the solar, accounted respectively only for the 14% and 5%[4].

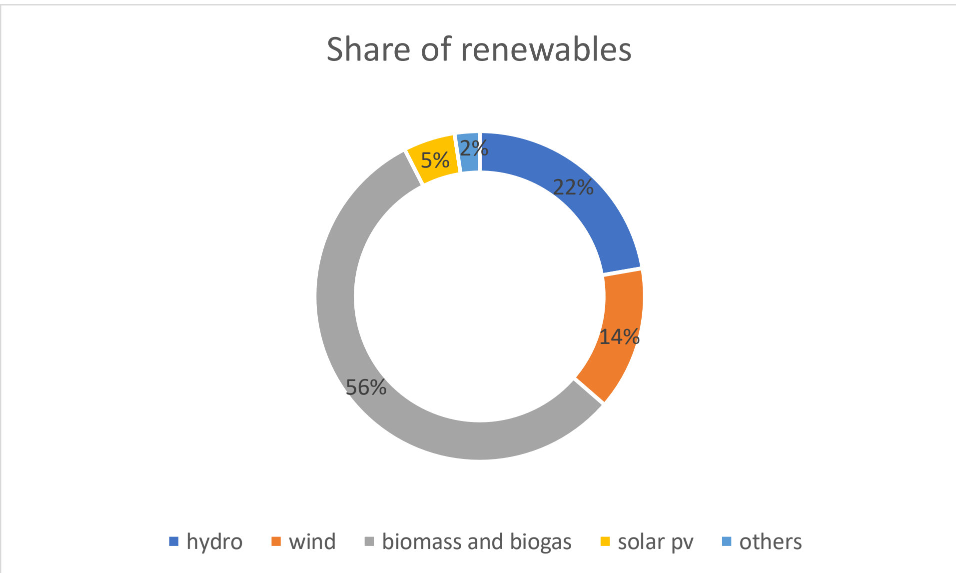

Figure 4 Share of renewable energy soures

To meet the targets imposed by Europe it is necessary to improve the penetration of the new renewables with respect to the older one, since they present a higher power density than biomass, so they could fit better for our needs.
The main problem associated to the new renewables is linked to their intermittency nature, indeed the power produced from solar and wind is subjected to daily and seasonal fluctuations which give rise to a grid stability problem.
This will result in produce mismatching between power produced by the renewable energy sources system and requested power from the grid, leading to a period of over-production by the renewable energy sources and other of energy shortage for the users.
The issue of intermittency has to be solved and one significant option is developing energy storage solutions.
Moreover, the renewable energy deployment in off-grid systems is growing steadily due to the declining costs and increasing performance of the renewable energy sources, like wind e photovoltaic, as well as declining costs and technological improvements in electricity storage and control systems.
In the short- to medium-term, the market for off-grid renewable energy systems is expected to increase through the hybridization or replacement of existing diesel grids with renewable energy sources, especially on islands and in rural areas[2].
So, in an off-grid system the energy storage will play a fundamental role for the deployment of renewable energy sources.

1.3. Energy storage

As highlighted by the European Commission, energy storage becomes a key element in achieving goals in energy sustainability that lead to energy and cost savings. They represent good solution for the intermittency problem, could be to develop bulk energy storage solutions for electricity that are cost effective, energy dense and reliable.
Energy storage system enhances the existing power plant and at the same time prevents expensive upgrades. They could act as a regulator that manages the fluctuations of electricity from RE resources.

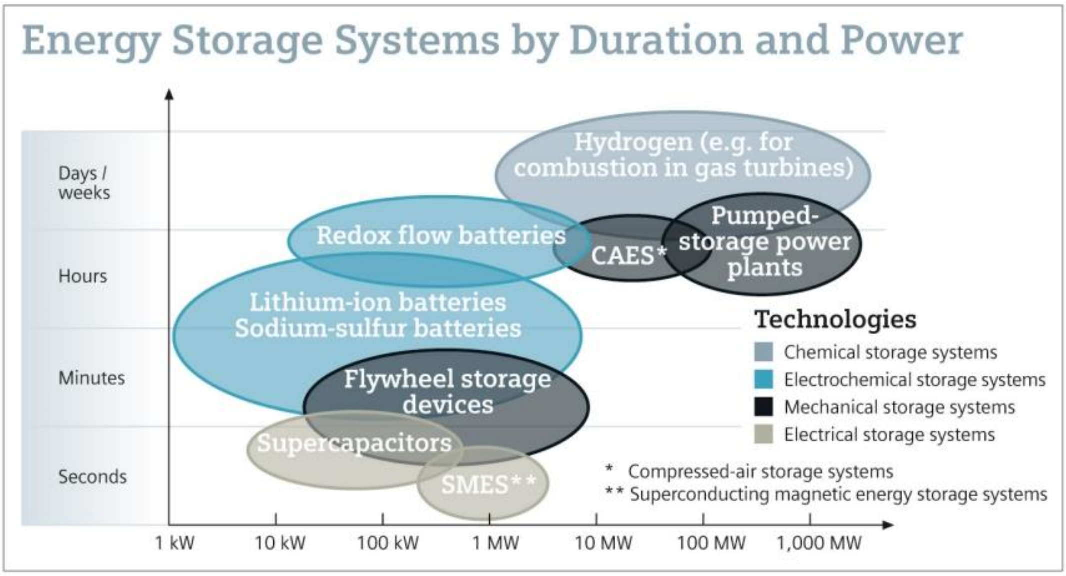

Figure 5 Energy storage systems[5]

Energy storage system technologies can be used for different application depending on various characteristics such as: energy and power density, response time, cost and economies scale, lifetime, monitoring and control equipment, efficiency and operating constraint.

A suitable energy storage system should have a number of properties:

- high gravimetric and volumetric energy and power densities
- easy deployment and integration with RE sources and the existing energy network
- high energy efficiency
- economic viability in storing large amount of energy
- extended life span and reliability of the systems and components
- safe in operation

Among energy storage systems, batteries are the most common choice for short-term storage. However, for longer-term energy storage, their application might be inappropriate owing to their low energy storage density and unavoidable self-discharge. If large-scale bulk energy storage has many technology alternatives like the pumped-hydro, and CAES and competing available applications, at lower scales like isolated and remote areas energy storage is required to build a competitive business case. Indeed, energy storage is required to achieve consistently high self-consumption rates of PV productions and increase profitability of PV investment. In this respect, the energy storage systems based on hydrogen technologies are one of the most interesting options.

In hydrogen storage systems, excess electricity can be converted to hydrogen through an electrolyser and stored in pressurized tanks. The stored hydrogen can later be used to produce electricity through a fuel cell.

1.4. Hydrogen storage system

Increasing production of fluctuating renewable energy intensifies the need for electricity storage to ensure network reliability and flexibility. While short term energy storage can be met by small decentralized storage systems, mid to long term electricity storage technologies are still behind schedule.

However, the deployment of renewable energy sources raises the issue of the massive energetic storage due to their intermittent nature and the grid stabilization. The numerous solutions already available to achieve this role are still not satisfactory. Therefore, hydrogen-based energy storage technologies appear and become modern competitive options. Using hydrogen as a mean to store energy in the long run may in the future help address the challenge of grid balancing when large quantities of fluctuating renewable electricity are introduced in the energy mix.

As we mentioned before, a good solution so, is to integrate the intermittent RES with fuel cell and H_2-based power-to-power (P2P) systems, which can provide a reliable, cost-effective, and decarbonized alternative to the on-site generation of electricity through the local diesel engines. P2P system is seen to be the most credible option, with medium to long-term storage capabilities for the lower scales and maybe soon could be also competitive in the larger one.

In the case of isolated micro-grid or off-grid remote areas, the business case of energy storage is different, as the network is essentially non-existent or there is the interest of managing the local network in an independent way.

Off-grid systems could become an important vehicle to support the development of renewables-based grids[6].

The EU REMOTE project aims are to demonstrate the technical and economic feasibility of fuel cells-based H2 energy storage solutions in isolated and off-grid remote areas.

In REMOTE four different DEMOs based on P2P energy storage solution will be demonstrated from a technical and economical point of view, with different renewable energy sources, contexts and final users.

In these DEMOs the electricity will be produced on site by the local renewable energy sources, avoiding the construction or the updating of distribution lines and the transport of fossil fuel in remote areas, which are often impractical or with high cost associated, with a consequent reduction of local cost of electricity[7].

The development of these projects will pave the way to create technological learning for the different component of the system, so that the larger energy storage market could be also assessed in the near future with this kind of system.

This means that the replicability is then huge especially in countries characterized by long distances and remote communities.

For what concern the environmental and social impact, this project will lead a reduction of carbon dioxide emissions from electricity generation close to 100% for each DEMO, reducing significantly or even totally the fossil fuel consumption.

Today, diesel generators ensure electricity generation in many island and off-grid settings, despite their high generation cost and carbon dioxide emissions, simply because there is no simple, feasible alternative. This is a huge market, since 600 GW of diesel generator capacity are installed around the world.

Using the following assumptions[8]:

- average genset full time use: 3000 $\left[\frac{h}{year}\right]$
- hourly consumption on average for 250 kW genset: 55$\left[\frac{l}{h}\right]$
- CO_2 emissions: 2.65 $\left[\frac{kg_{CO_2}}{l}\right]$

we can obtain a reduction of around 437$\left[\frac{ton}{year}\right]$ of CO_2 emissions only thanks to the four DEMOs.

The local communities of isolated and remote areas so, will benefit of secure and clean energy supplies, thus increasing significantly their energy independency.

2. TECHNICAL REVIEW

2.1. *Objective of the thesis*

In this thesis we will use economic and technical specifications obtained from the Ginostra DEMO case in the EU REMOTE project to analyse the future business case of off-grid fuel cell based H_2 storage solutions.

A technical review of the Ginostra demo case will be done, with a detailed description of the main component of the power-to-power system adopted.

The business analysis will utilise the techno-economic optimisation model developed at SINTEF to analyse the future business case under different economic and regulatory context, by simulating the case study with appropriate data, taking into account the variability of the solicitation profiles for the off-grid solution and associated economic variables.

Recommendations will be made on future market potential in the EU, by underlining the strengths, weaknesses, opportunities and threats of the H_2 energy storage solution.

The DEMO plant shall become a clear example of business in the domain of energy storage in isolated micro grids or off-grid situations and this thesis aims supporting the European project REMOTE.

2.2. Description of the system

The main working principle of the system is that the renewable energy sources are converted into electricity to meet the specific load requested.

In case of excess power generation from the renewable energy sources, the energy can be used to charge the battery or can be supplied to the electrolyser, which turns on to produce hydrogen gas, which is delivered to the hydrogen storage tanks.

In case of a deficit in power generation, the FC begins to produce electrical energy for the load using hydrogen gas from the H_2 tanks.

So, in case of lack of energy from the renewable energy sources the remaining part of energy to fully satisfy the load will be provided by the fuel cell through hydrogen consumption or by the discharging of the battery.

A general layout of the plant is represented in the following figure.

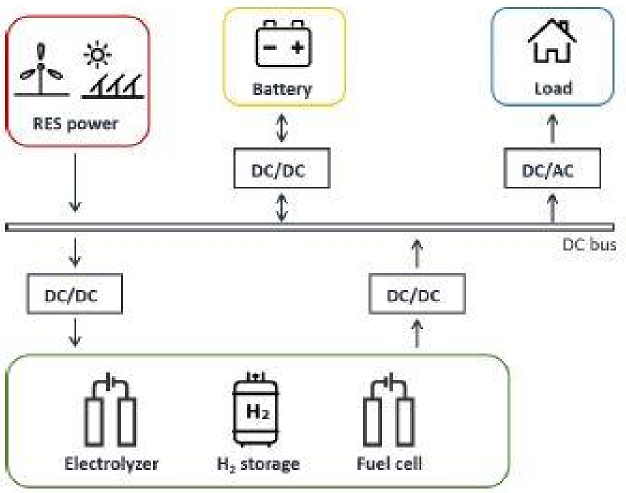

Figure 6 General layout of the P2P system[9]

The electrochemical devices have to stay within specific boundaries for a safe and efficient operation, indeed working outsides the proper operating range leads to a reduced efficiency

As we can notice, all the energy sources are attached to a common Direct Current (DC) bus through power converters which must be properly controlled for an adequate energy management.

The DC/DC converters are employed to permit the battery, electrolyser, and fuel cells to exchange the correct amount of energy. A DC/AC inverter is also required for the user load.

Efficiencies for DC/DC converters can be up to 95%, for DC/AC ones up to 90%.

In the next sections the analysis of the main components of the system is illustrated.

2.2.1. PEMFC

A fuel cell is an electrochemical reactor, where redox electrochemical reactions occur, with production of electric and thermal power.

There exist many types of fuel cells, and they differ one from the other for many characteristics. The most relevant is associated to the choice of the electrolyte. Nowadays mainly five types of electrolyte exist:

- Alkali (AFC)
- Molten carbonate (MCFC)
- Phosphoric acid (PAFC)
- Proton exchange membrane (PEMFC)
- Solid oxide (SOFC)

The type of electrolyte affects the type of the fuel that has to be supplied to the fuel cell and the working temperature at which they operate.

For this project we will focus our attention in a fuel cell system, developed by EPS, based on proprietary pure oxygen and hydrogen PEM fuel cell stack.

This electrochemical device has high efficiencies (over 50%) and low environmental impact, it delivers high-power density while providing low weight, cost and volume. These kinds of cells operate at low temperature (70-90°C) so, the activation of the half-reactions is due mainly using expensive catalyzer. For this reason, on both sides is present a porous electrode with catalyzers. The union of the membrane and electrode is called MEA and they can be connected in series, using usually bipolar plates, assembling in this way the stack of the cell.

The total reaction that occurs is:

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

And considering that in normal operating condition the PEMFC works at 60°C the OCV associated will be around 1.18 V.

This value represents a very low amount to produce a significant power, therefore there is the necessity to stack the cells in a series configuration.

The produced power in a stack of cells will be:

$$W_{el} = n_c * V_c * I = n_c * V_c * i * s$$

Each cell in the stack may be producing a different voltage with respect to the others, since they could undergo different thermodynamic conditions.

Efficiency

PEM fuel cells are not 100% efficient, usually in converting hydrogen energy into electricity, efficiencies are normally about 50%. It means that a certain amount of heat is generated due to the exothermicity of the reaction and the irreversibility.

$$\phi_{th,stack} = \phi_{react} + \phi_{irr} = \left(-\frac{\Delta h}{z*F} - V_c\right) * I*\mathrm{nc}$$

This thermal power has to be removed to avoid drying effect on the membrane which could cause several problems as discussed before. This is achieved thanks to microchannels cut into the bipolar plate. A cooling fluid is sent to microchannels to remove heat. Another way of cooling cell is to make extra channels in the bipolar plates through which cooling air, different form the reactant one, can be blown.

The electrical efficiency of a PEMFC can be defined as the ratio of the electric power and the low heating value of hydrogen multiplied by the fuel mass flow rate:

$$\eta_{el} = \frac{W_{el}}{G_{H_2} * LHV_{H_2}} = \frac{n_c * V_c * I}{\frac{I}{z * F} * n_c * \lambda_{H_2} * \bar{M}_{H_2} * LHV_{H_2}}$$

where:

- LHV represents the low heating value of the hydrogen $\left[\frac{MJ}{kg}\right]$
- $\bar{M}_{H_2}$ is the molecular weight of hydrogen $\left[\frac{kg}{kmol}\right]$
- n_c is the number of the cell in series that constitute the stack
- λ_{H_2} is the term that accounts the excess of fuel

Simplifying the previous equation, we can obtain the following one:

$$\eta_{el} = \frac{z * F * V_c}{\lambda_{H_2} * \bar{M}_{H_2} * LHV_{H_2}}$$

Using pure oxygen in place of air

The use of oxygen does improve the performance of a PEM fuel cell. This results from different effects[6]:

- The open circuit voltage rises because of the increase in the partial pressure of oxygen, as it can be observed in the Nernst equation
- The activation overvoltage reduces
- The limiting current increases, thus reducing the mass transport or concentration overvoltage losses. This is due to the absence of nitrogen gas, which is a major contributor to this type of loss
- Higher power density
- Higher electrical efficiency
- Independence on environmental condition

It has been estimated that a using oxygen instead of air can increase the power of a PEM fuel cell of 30%[10].

On the other side the use of air avoids the need of oxygen purification and oxygen storage at system level and gives more flexibility in the supply chain.

In our case of study as we see later it is mandatory the use of oxygen instead of air due to the particular location: in particular the air quality of our location could affect the performance of the fuel cell.

PEMFC by EPS

The fuel cell system is based on proprietary pure oxygen and hydrogen PEM fuel cell stack.

The technical data of 25kW fuel cell, named Electro25, are reported in the following table.

Table 1 PEMFC by EPS

Description	**Unit**	**Value**
Nominal Power	kW	22.5
Maximum power	kW	25
Minimum power	kW	5
H_2consumed at maximum power	Nm^3/h	18
O_2consumed at maximum power	Nm^3/h	9
Efficiency (HHV) @9kW	%	45
Efficiency (HHV) @25kW	%	40
H_2O produced per Nm^3 of consumed hydrogen	l/Nm^3	0.7
Modulation range	%	15-100
Maximum operating pressure	barg	0.5
Operating temperature	°C	55

2.2.1. Alkaline electrolytic cell

Electrolysers use electricity to split water into hydrogen and oxygen. They are the opposite of a fuel cell.

So, all the basic theory is the same that we discussed for the fuel cells except for the fact that the reactions involved go the other way with respect to which of the fuel cell.

There exist different types of electrolysers and the most relevant are:

- Alkali electrolytic cell (AEC)
- Proton exchange membrane electrolytic cell (PEMEC)
- Solid oxide electrolytic cell (SOEC)

It is not very practical to use the high-temperature electrolysers, since steam should have been supplied, so it is not convenient as the use of liquid water. So, in practice the only electrolytes that are used are the alkaline liquids and solid proton exchange membranes.

The size range of commercial alkaline electrolysis system is available from 1.8 to 5300 kW. Hydrogen production rate for commercial systems is around 0.25-760 $\frac{Nm^3}{h}$ and the operating temperature range is between 5°C and 100°C.

As far as concerned for the pressure, some models are operating at atmospheric pressure and other at higher pressure, which can reach values typically close to 25 - 30 bar. In general, the hydrogen generation efficiency of common industrial electrolysers is around 70%.

The main drawback of such a system is high power dissipation.

The electrolyte is usually a 20-40 wt% aqueous solution of potassium hydroxide (KOH) which enhances the ionic conductivity of the electrolyte.

The sodium hydroxide (NaOH) can be also used as an electrolyte because of its higher conductivity.

The chemical reaction which are taken place in an alkaline electrolyser are the following:

$$\text{cathode: } 2H_2O + 2e^- \rightarrow 2OH^- + H_2$$

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

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

Performances

The performances of an electrolyser can be measured through a parameter called specific consumption and it represents the energy spent for Nm^3 of produced gas. Actually, the specific consumption can be evaluated as the ratio between the power absorbed and volumetric flow rate of gas produced, as we can observe on the following equation:

$$E_{sp} = \frac{W_{el}}{\dot{V}}$$

where:

- $\dot{V}$ represents the volumetric flow rate of gas

And the previous formula can be rewritten in the following way, remembering the expression for the power and the Nernst's law:

$$E_{sp} = \frac{W_{el}}{\dot{V}} = \frac{\frac{n_c * V_c * I}{1000}}{\frac{I * n_c}{z * F} * 3600 * V_m}$$

where:

- The coefficient 1000 and 3600 are present to obtain the desired unit of measure [kWh]
- V_m is the molar volume and is equal to 0.022414 $\left[\frac{Nm^3}{mol}\right]$

We obtain so, for the water splitting, the final expression for the specific consumption:

$$E_{sp} = 2.44 * V_c$$

And as far the electrolysers as concerned the lowest possible value of V_c is OCV. In case of water splitting:

$$OCV = 1.23\ [V]\ @\ T = [25°C]$$

It follows that the resulting minimum consumption will be:

$$E_{sp} = 3.0012\ \left[\frac{kWh}{Nm^3{}_{H_2}}\right]$$

so, it is the minimum theoretical amount of energy required to produce $1[Nm^3]$ of hydrogen from water electrolysis. In the real operation this value will be around $5\left[\frac{kWh}{Nm^3{}_{H_2}}\right]$.

Efficiency

We can relate the operating voltage of an electrolytic cell to its efficiency starting from the following equation:

$$\eta = \frac{\dot{n}_{H_2} * HHV_{H_2}}{W_{el}} = \frac{n_c * I * \Delta h_f}{n_c * V_c * I * z * F}$$

and so, simplifying the previous expression we obtain:

$$\eta = \frac{1}{V_c} * \frac{\Delta h_f}{z * F}$$

where the term assumes value of[10]:

- 1.48V if using the HHV
- 1.25V If using the LHV

so, finally the cell efficiency can be written as:

$$\eta = \frac{1.48}{V_c}$$

Real values of V_c are around 1.6 to 2.0 V, depending on the current density[6]. An electrolyser can operate very efficiently at this voltage value if the current density is kept low, but this involves a slow rate of production of hydrogen or the fact to work with an over-sized electrolyser.

There is always a balance to be reached between efficiency of production and high rate of production.

Integration of electrolysers on renewable energy sources

The production of hydrogen through electrolysis using a renewable energy source, as primary source, can be split in three different typologies:

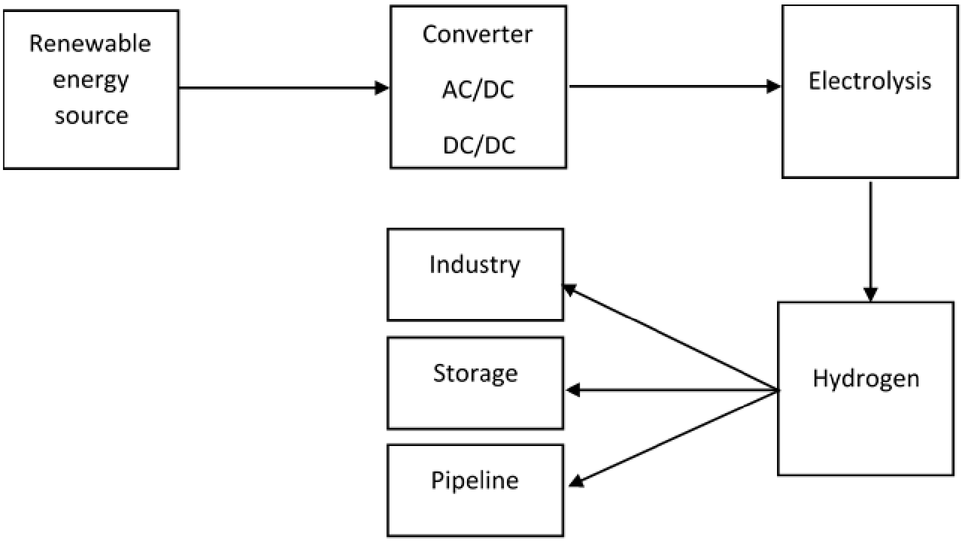

Figure 7 hydrogen production from electrolyser fed by renewable energy sources

For what concern the storage, which is our case of interest, we talk about off-grid plants, in which the electrical energy is directly used from the user and moreover the hydrogen has been produced in the periods of energy surplus to store the renewable energy and to reuse it in the period of deficit of the source.

The electrolyser absorbs energy in direct current. The wind and hydroelectric plants normally produce energy in alternate current and so a converter AC/DC is requested, while the photovoltaic plants produce directly in direct current. But even in this case it is better to insert a converter to maximize the power coming from the photovoltaic plant.

EPS electrolyser

EPS electrolyser is based on proprietary 30 bar alkaline technology. The main characteristics of the 25 kW P2G, named Self25, are reported in the following table:

Table 2 Electrolyser by EPS

Description	**Unit**	**Value**
Nominal Power	kW	25
$H_2 produced$ at maximum power	Nm^3/h	5.5
$O_2 produced$ at maximum power	Nm^3/h	2.75
Efficiency (HHV) @25kW	%	78
Modulation range	%	20-100
Maximum operating pressure	barg	30
Operating temperature	°C	70

2.2.2. Hydrogen storage

The hydrogen storage is a reasonable way of storing electrical energy deriving from renewable energy sources

The electrolyser is used to convert the electrical energy into chemical fuel, which can be stored, during times of high supply and low demand.

Due to its importance in the world energy scene as a general-purpose energy vector it is necessary to pay attention to the difficult problem of hydrogen storage. The main drawback is related to its low density. In condition of normal temperature and pressure the density is equal to 0,089 $\frac{kg}{m^3}$. Therefore, even if present a very high graviometric energy density (120 $\frac{MJ}{kg}$), it presents very low volumetric energy density (9,72 $\frac{MJ}{m^3}$).

This means that to get a large amount of hydrogen into a relatively small space very high pressures are needed.

The main methods of storing hydrogen from water electrolysis are:

- compression in gas cylinders
- storage in metal hydride

In the hybrid energy storage system proposed by EPS the hydrogen will be stored in compressed cylinders.

The storage of hydrogen as a compressed gas

Storing hydrogen gas in pressurised cylinders is the most technically simple method and the most widely used.

The type of metal, which the pressure vessel is made from, needs a very accurate selection. Hydrogen is a very small molecule, of high velocity, and so it is capable of diffusing into materials that are impermeable to other gases.

Diffusion of atomic hydrogen into the material may then occur, which can affect the mechanical performance of materials in different ways.

Compressed hydrogen is responsible of the embrittlement process, that is a process of degradation of mechanical properties of metals constituting the vessel of the hydrogen storage. Due to this, hydrogen is able to break by grains of metal in much smaller one cracking the steel.

For this reason, the selection of material of the vessel is crucial and is commonly formed by three different layers:

- glass fiber
- graphite
- high density polymer

Nevertheless, this method is widely and safely used following the right procedures.

The main advantages of storing hydrogen as a compressed gas are as follows:

- Simplicity
- Indefinite storage time
- No purity limits on the hydrogen.

Hydrogen storage from EPS

The hydrogen tank level has to lie in a specific range for a correct operation as well: minimum pressure to overcome downstream pressure drops and maximum pressure, for safety reasons and need to be carefully selected.

The main technical data of the hydrogen storage solution adopted by EPS are listed below:

Table 3 Hydrogen storage by EPS

Pressure [barg]	30
Total gross energy (LHV) [kWh]	1924
Useful gross energy (LHV) [kWh]	1600

2.2.3. Li-ion Batteries

The Hybrid Energy Storage System ($HyESS^{TM}$) proposed by EPS is a vertically integrated energy storage concept that integrates both batteries and hydrogen storage modules. For what concern the batteries, they provide high system flexibility in load following, instead as we observed before, the hydrogen storage provide capacity. This storage system provides thus services to any kind of grid assuring seamless, safe and stable power supply.

Main characteristics

Batteries are closed electro-chemical cells which can work both in direct and inverse operation. Since they are closed systems, this means that there is no mass exchange with the external environment and the materials taking place to the chemical reaction are the same one constituting the electrodes and, in some case, also the electrolyte layer.

As we said, a battery can operate as a fuel cell producing power, in direct mode ($\Delta G < 0$), or as an electrolyser to restore the chemical potential of the reactants, absorbing power, in reverse operation mode ($\Delta G > 0$).

There exists different type of batteries and the Li-ion batteries one present the best performances and represent the most promising technology..

Discharge configuration

The half reactions and the total reaction which occurs in Li-ion battery in discharge configuration are:

- anode: $C_6Li_x \rightarrow 6C + xLi^+ + e^-$

- cathode: $Li_{1-x}MO_2 + xLi^+ + e^- \rightarrow LiMO_2$
- total: $C_6Li_x + Li_{1-x}MO_2 \rightarrow 6C + LiMO_2$

where:

- M is a generic metal
- x represents the amount of sites in which Li-ions can be intercalated in anode structure

The anode is usually composed by graphite and lithium, the electrolyte can be composed of liquid lithium salts (i.e. $LiPF_6$) or of solid polymer adding liquid lithium salts and the cathode is composed of mixed oxides.

When the battery is charged in open circuit conditions, the lithium atoms intercalated in the anode structure are in equilibrium with Li-ions in the electrolyte layer. As the circuit get closed, the equilibrium is broken and the Li-ions start travelling from the anode site to cathode one, producing the discharge process.

During the discharge process first of all the atoms neighboring the electrolyte layer are extracted, and as the discharge process goes on, all the atoms are extracted, until even those furthest away undergo intercalation. At the same time, Li ions that reached the cathode structure occupy the sites neighboring the electrolyte layer. The intercalation goes on until even the furthest sites are occupied.

During discharge process, as the amount of lithium in the anode structure varies, the term $\Delta g_{anode-cathode}$ will decrease until it is no more able to drive the operation.

Recharge configuration

The total reaction, the half reactions and the operating mode is the opposite of the one previous described. In this case is worth to be noticed that once the circuit get closed, the lithium concentration in the anode varies involving an increase of $\Delta g_{anode-cathode}$ until it reaches the value associated to the full charge state.

Cell characterization

The main characteristics of a lithium ions battery cell are listed below:

- capacity C [Ah]: is linked to the availability of sites in the electrodes hosting ions, it depends on the type and nano-structure of electrode material and the surface of the electrode
- energy stored E [kWh]: represents the energy that can be stored in a cell and it is given by the following formula:

$$E = C * V$$

and it depends on the capacity by the type and nano-structure of electrodes, on the surface of electrodes and on the number of cells present in the stack and on the state of discharge

- current [A]: the current is expressed as a multiple of C and is indicated as γC and it means that the battery is exchanging a number of amperes equal to γ times the ampere-hours that can be stored in the battery

Battery from EPS

The solution adopted in the system is a Li-ion battery developed by EPS. The battery bank is used to provide electricity for the daily operation of the control unit and auxiliary equipment. It can be also employed as a daily electricity energy buffer, smoothing the RES output and reducing the intermittency.

Maximum and minimum battery State of Charge (SOC) need to be considered: overcharging/discharging should in fact be controlled to protect the battery from being damaged.

The main technical data are listed in the following table:

Table 4 Battery from EPS

Rated energy [kWh]	600
Charge/discharge rate [kW/kWh]	0.5C
Efficiency [%]	95
SOC min [%]	20
SOC max [%]	80

3. DEMO 1

3.1. Ginostra-DEMO1

3.1.1. Overview

Ginostra is a small village located on the south-western part of Stromboli, in the Aeolian Islands.

The hamlet was inhabited until the beginning of the 20th century by around a thousand people. Nowadays only forty people are left in the island. During the summer the population can reach up to 300 people due to the tourism. The village is without any connections with the land and it can be reached only by sea.

Until 2004, the village had no electricity or running water. Electricity is now supplied by a combination of diesel generators and renewable energy sources, instead running water comes from rainwater collected in wells and is supplemented by ships from Naples.

Ginostra fits completely the requirements for the selection of one of the demo sites[8]:

- accessibility for installation, service and maintenance is complex and expensive
- current power supply is not reliable
- import of fuel is expensive resulting in high electricity price
- use of fossil fuel and CO2 emissions are high
- local commitment to go for 100% renewable energy system
- storage of local energy sources is not in place today

it could be a perfect location to solve the issue of island energetic self-sufficiency.

Ginostra has no connection with the Italian transmission and distribution lines and it is also disconnected from the Stromboli one. It is very difficult and very expensive to connect the Ginostra village to the main grid. Furthermore, due to its location the transportation of the fuel it is very expensive and presents different issues.

3.1.2. Actual situation

Ginostra is not connected to the Italian transmission and distribution grid and is also disconnected from the Stromboli one so, it can be classified as off-grid.

Currently, the total demand is satisfied by means of three 48 kW diesel generators and one 160 kW diesel generator[9]. Due to its particular location the transport of the fuel is done by helicopter leading to transportation and logistics issues and also to a high cost for the electricity generation, being three or four times higher than the ones associated with connection to network.

The following figures represents the actual situation of how the energy is supply, generated and transmitted into the village:

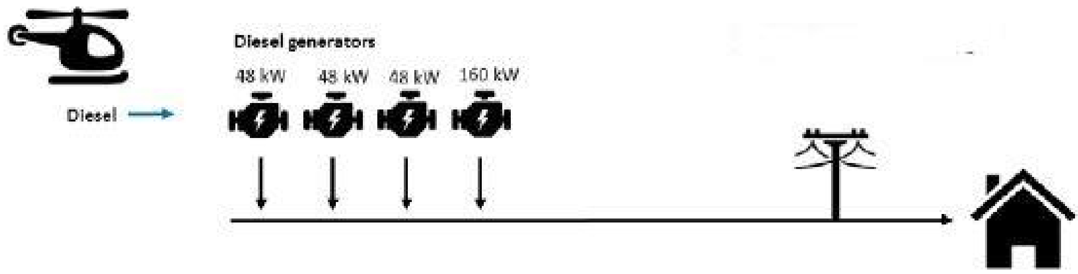

Figure 8 Ginostra actual situation[9]

so, the main drivers that lead to an alternative solution to the current situation and thus the adoption of an energy storage power plant in Ginostra can be resumed as follows:

- cost: high cost of electricity generation due to the high cost of fuel transport generally done by helicopter. It has been evaluated[8] that this increase the fuel cost of more than 2 $\left[\frac{€}{liter}\right]$ and thus affecting the final generation cost, that will result higher than 600 $\left[\frac{€}{MWh}\right]$. This value is around three times the average one needed to generate electrical energy in Italy
- environmental: reduction of the diesel consumption
- technological: improvement of the quality of the electricity service and implementation of innovative solutions so that permitting a high RES sharing in the production of electricity.

3.1.3. REMOTE proposal

The solution developed in the remote project is the Hybrid Energy Storage System based on Li-Ion battery and P2P hydrogen storage system provided by EPS: such integrated system could lead Ginostra to avoid the use of the diesel generators thus ensuring a higher energy efficiency and environment benefits.

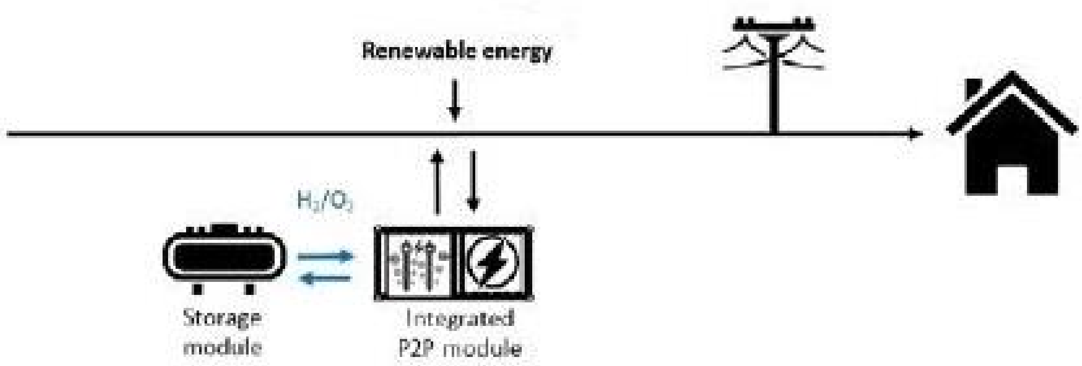

Figure 9 Ginostra REMOTE proposal[8]

The Diesel generators will cover at least a small amount of the overall energy demand and this from the cost view point will mean save a huge amount of money due to a reduction of fuel consumption.

The renewable energy sources will cover most of the requested demand from the load and the remaining part, will be served by the storage system.

The main objectives of developing this project in Ginostra are the following:

- to release the village independent from fossil fuels, or at least to minimize the use of diesel generators: this will lead in a strong reduction of pollutants produced by current generation plant;
- the hybrid energy storage allows a better and more efficient use of renewable sources. So, in this way it could be possible to avoid the waste of energy excess and an improvement of the electricity service and grid quality
- to reduce the electricity cost related to the geographical location of Ginostra
- high replicability potential considering plenty of minor islands in Europe in the same situation

3.2. Working Strategy

The main objectives of the P2P system management strategy are:

- the reliable coverage of the load request
- to protect the various components and avoiding their operation outside safe working ranges

The renewable energy sources are required to meet the load demand of the specific site.

Any surplus of energy can be stored by battery charging or in the form of hydrogen through water electrolysis and any shortage of power can be covered by the discharge of the battery or by the fuel cell operation.

Due to the intermittent nature of the photovoltaic, relevant fluctuations occur in the power production.

Fuel cell and electrolyser should be protected from recurrent start-ups and shut-downs, which could lead in acceleration of the performance degradation and lifetime reduction. The battery becomes therefore fundamental to alleviate the RES output, avoiding too frequent interventions of the electrochemical devices.

However, excessive operation and over-charging/discharging of the battery should be avoided to don’t have negative effects in its life span.

Appropriate power management strategy is therefore also essential for a correct operation of the system. Overcharging/discharging of both the storage options are prevented by imposing proper maximum/minimum SOC values as input parameters.

Two different working processes will be analyzed[9]:

- RES > Load: when the output power from RES is not sufficient to completely cover the load
- RES < Load: when excess power is produced.

3.2.1. CASE1: RES > Load

In the first case is analyzed the operation when excess renewable energy source power is produced, the surplus is first used to charge the battery.

When the battery exceeds the maximum state of charge, the remaining part is sent to the electrolyser for the hydrogen production and if also this process is not more possible, the power will be curtailed.

In particular, if the difference between the RES and the load is in the electrolyser working range, the P2G device starts operating to convert that power surplus in hydrogen and store it.

In case the maximum state of charge of the hydrogen would be exceeded, the electrolyser power is reduced and then stopped.

The remaining fraction of RES excess power is then curtailed.

If instead the difference between the RES and the load is lower than the electrolyser minimum power, all the RES power not consumed by the load is curtailed.

Finally, if the difference is higher than the electrolyser working range, the electrolyser is operated at its maximum power, if this not led to the exceedance of the hydrogen storage upper limit.

The logical diagram of this charging phase is reported in the following figure[9]:

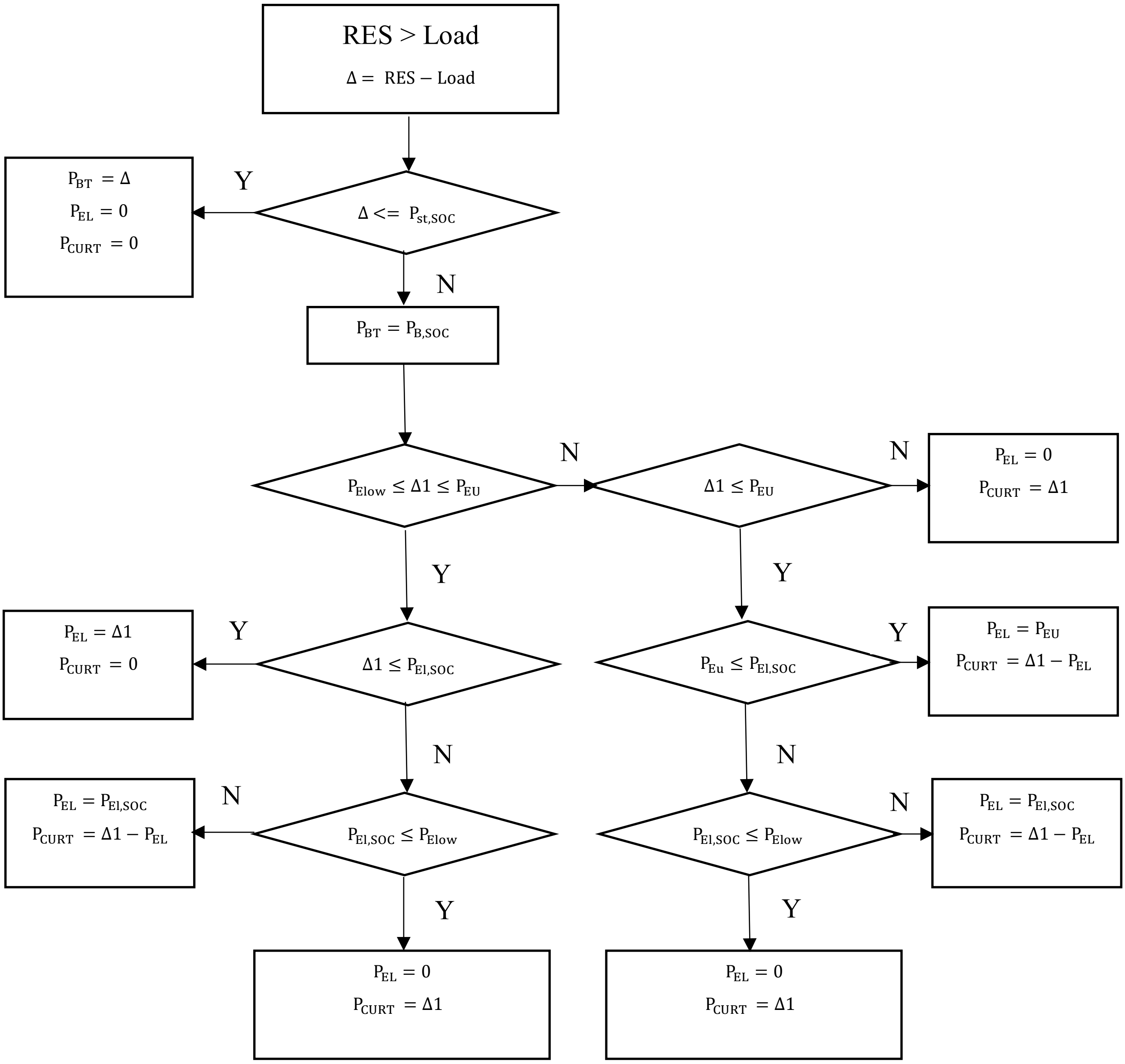

Figure 10 working strategy 1

3.2.2. CASE2: RES < Load

Instead, when the output power from the renewable energy source is not sufficient to satisfy the load requirements, the battery first intervenes to meet the required additional power.

If the battery SOC would go below the lower boundary imposed, the battery power is reduced and the remaining fraction to be satisfied is done by the fuel cell or the diesel generators.

So, it is checked if the fuel cell is able to cover the remaining power fraction. If the requested additional power is in between the fuel cell working range, the fuel cell is operated at a certain power to avoid that the state of charge hydrogen goes below its minimum value.

If a remaining power fraction to be covered is still present, the diesel generators will be employed.

If instead the difference between the load and RES is below the fuel cell lower limit, then the external source has to intervene.

Finally, if the difference is higher than the fuel cell upper limit, the fuel cell works at its maximum power if this does not lead the hydrogen level to go below its lower limit, otherwise the fuel cell power has to be reduced, even becoming null and the residual power then will be provided by the external source.

The logical diagram of this second operation mode is reported in the following figure[9]:

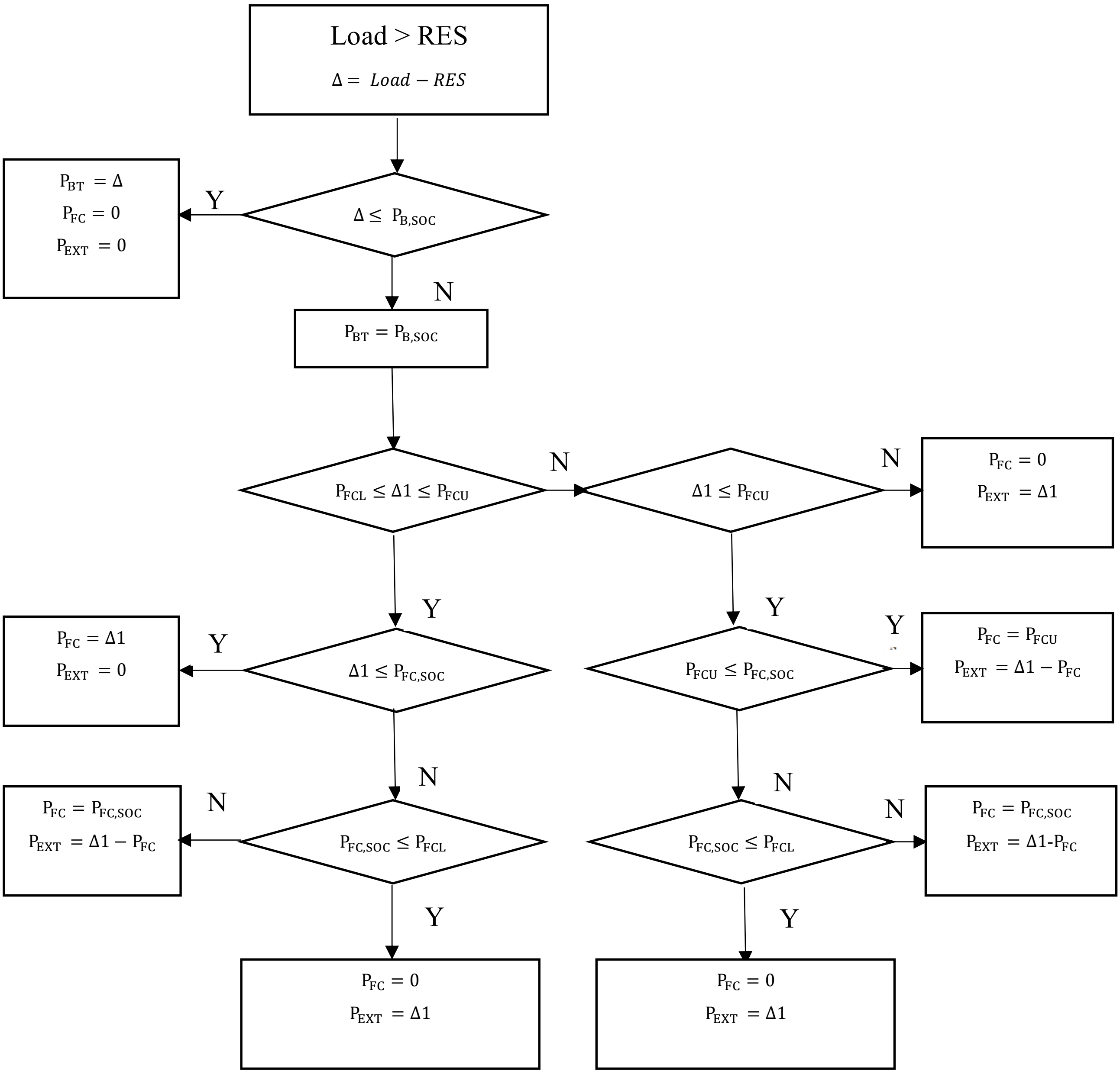

Figure 11 working strategy 2

where:

- P_{BT} represents in the first case the battery discharging power and in the second one the battery charging power
- $P_{B,SOC}$ represents in the first case the maximum battery discharging power which doesn't allow the battery to work below the lower SOC
- P_{FC} is the fuel cell power
- P_{EL} is the electrolyser power
- P_{FCU} is the fuel cell maximum power
- P_{FCL} is the fuel cell minimum power
- P_{EU} is the electrolyser maximum power
- P_{Elow} is the fuel cell minimum power
- $P_{FC,SOC}$ is the maximum fuel cell power which allows not to go below the lower hydrogen storage state of charge
- $P_{EL,SOC}$ maximum electrolyser power which allows not to go above the upper hydrogen storage state of charge
- P_{EXT} is the power provided by the diesel generators
- P_{CURT} is the curtailed power
- Δ is the difference between the RES and load in the first case and represents the lack of RES power in the second one
- $\Delta 1$ is the difference between delta and respectively the battery charging and discharging power for the first and second case.

3.3. Economic and regulatory framework

Before starting the analysis of the model ant different scenarios analyzed, it is necessary to analyse the economic and regulatory framework of the Ginostra demo case, this because the economic and regulatory framework conditions have a large effect on the technical definitions and the potential economic revenues of an electric system relying on RES and storage.
Ginostra is completely off-grid today, and it will be very costly to get the village connected to a central grid due to its island location and the costs of subsea cables.
In Italy, the electricity prices are similar all over the country and people who live in Ginostra, for instance, pay the same price for electricity as the people on mainland Italy. The extra costs due to high generation prices at Ginostra are covered by a component of the energy bill, called UC4[8], that basically covers the major costs of energy systems expenditures on Italian small islands.
At the demo site in Ginostra, current power demand is met by production from diesel generators. Due to the remote location of the island, the fuel must be imported by helicopter, leading to very high costs. The final generation cost is estimated to be more than 500 Euro per MWh. Additionally, the use of diesel generators leads to CO_2 emissions greater than 110 tons per year[8].
In the economic analysis published in 2012 by Terna, the Italian transmission system operator, it has been calculated that the implementation of the energy storage solutions would translate into savings of around 400000 $\left[\frac{€}{MW}\right]$ [11].
From a business point of view, the absence of energy storage-specific regulation may represent a risk for the operators and users of the installation sites.
To minimize this risk, there is a need to clarify the applicable regulations calling the attention of policy makers to legal barriers to be removed.
Progressive regulation is, however, currently being developed in many EU countries for energy storage, but there are present still many gaps that is necessary to fill.
For instance, in Italy there is not already a clear and defined regulatory framework for what concern the energy storage systems coupled with renewable energy sources.
The Decision 300/2017[12] represents an initial step towards storage system regulation development, since it defines the major criteria for renewable power plants

to provide grid services. In particular, the renewable generation assets must be coupled with energy storage systems.
The ”DM 14 Febbraio 2017”[13] aimed to promote renewable systems development on Italian islands. This will promote the development of energy storage systems to increment the renewable energy penetration in remote small islands not connected to the national grid.

4. MODEL

For the evaluation of the different scenarios that will be analyzed in the next chapter, the HyOpt model has been used.
The model used for the evaluation of the energy system is under development by Sintef. Since a mathematical description of the model does not exist already and I can't have access to the optimization model itself, but only to the input data, the model will be described only from a theoretical view point in this section.

4.1. Description of the model

4.1.1. Overview

HyOpt is an optimization model for the design and the evaluation of energy system including hydrogen-based technology. With the structure of the energy system, the expected energy demands and costs, the model will select which elements and which relative capacities will be included in the system, in order to optimize the objective function, which is typically the net present value of the entire system.
In addition the model also decides, in a dynamic way, operation of the elements and reports investment and operational costs over a determined time horizon.
Hyopt consists of two main parts[14]:

1. the Excel front end where the typical workflow starts by specifying the input, including the list of the proposed network elements and their properties, the time structure and all required time series.
2. The optimization model itself, written in the FICO Mosel optimization language. So, Mosel is running, and it reads the input data from excel, constructs an optimization-model, solves it using thee FICO Xpress solver, and then pushes back the results in the Excel file, that will be analyzed.

4.1.2. Structure of the optimization model

All the elements in the modelled system are represented as nodes with some specified properties.

For each pair of nodes, we can allow the flow of some products between them, which can be oxygen, hydrogen, water etc.

The main goal of this model is to find which of the include nodes should be installed, at what time and with the more appropriate capacity.

4.1.3. Nodes

The nodes represent the main building block of the model, since they represent each element of the whole system. All nodes share some common characteristics, and the most important are listed below

- existing capacity, if it is already present
- maximum allowed capacity
- CAPEX, both fixed and capacity dependent
- OPEX, both fixed and capacity and volume dependent
- lifetime and maintenance information

Most of the inputs that we can insert for running the model is optional, even though come costs are important to be inserted to avoid the installation of unlimited capacity from the model.

In the next tables are represented the main node and data that we can insert in order to model our system.

Table 5 Nodes input data 1

Node	Node type	Unit	Include
Power balance	Transport	MW	-
PV panels	Solar Power	MW	-
Water source	Market	kg	-
Electrolyser	Electrolyser	MW/ kg	-
Compressed H2 storage	Storage	kg	-
Fuel cell	Fuel Cell	MW	-
Battery	Battery	MWh	-
Power load	Power Load	MW	-
Hydrogen market	Market	kg / h	-
Diesel	Power Load	MW	-
Diesel market	Diesel	kg / h	-

Table 6 Nodes input data 2

Node	Existing capacity	Extendable	Binary investment	Min capacity per investment	Max capacity per investment	Max total capacity
Power balance	-	-	-	-	-	-
PV panels	-	-	-	-	-	-
Water source	-	-	-	-	-	-
Electrolyser	-	-	-	-	-	-
Compressed H2 storage	-	-	-	-	-	-
Fuel cell	-	-	-	-	-	-
Battery	-	-	-	-	-	-
Power load	-	-	-	-	-	-
Hydrogen market	-	-	-	-	-	-
Diesel	-	-	-	-	-	-
Diesel market	-	-	-	-	-	-

Table 7 Nodes input data 3

Node type	CAPEX Fixed [MNOK]	CAPEX Variable [MNOK per unit]	OPEX [% of CAPEX]	OPEX [MNOK per installed unit]	Fixed OPEX [MNOK]	Per unit cost [MNOK per unit prod]	Power consumption [MWh per unit prod]
Power balance	-	-	-	-	-	-	-
Pv Panels	-	-	-	-	-	-	-
Water source	-	-	-	-	-	-	-
Electrolyser	-	-	-	-	-	-	-
Compressed H2	-	-	-	-	-	-	-
Fuel Cell	-	-	-	-	-	-	-
Battery	-	-	-	-	-	-	-
Power Load	-	-	-	-	-	-	-
Hydrogen Market	-	-	-	-	-	-	-
Diesel Generator	-	-	-	-	-	-	-
Diesel Market	-	-	-	-	-	-	-

Table 8 nodes input data 4

Node	Capacity loss [% per year]	Lifetime [years]	Lifetime [op. hours]	Average capacity utilization [%]	Removal cost [% of CAPEX]
Power balance	-	-	-	-	-
PV panels	-	-	-	-	-
Water source	-	-	-	-	-
Electrolyser	-	-	-	-	-
Compressed H2	-	-	-	-	-
Fuel cell	-	-	-	-	-
Battery	-	-	-	-	-
Power load	-	-	-	-	-
Hydrogen market	-	-	-	-	-
Diesel	-	-	-	-	-
Diesel market	-	-	-	-	-

The following flow chart represents the model set-up of the REMOTE project.

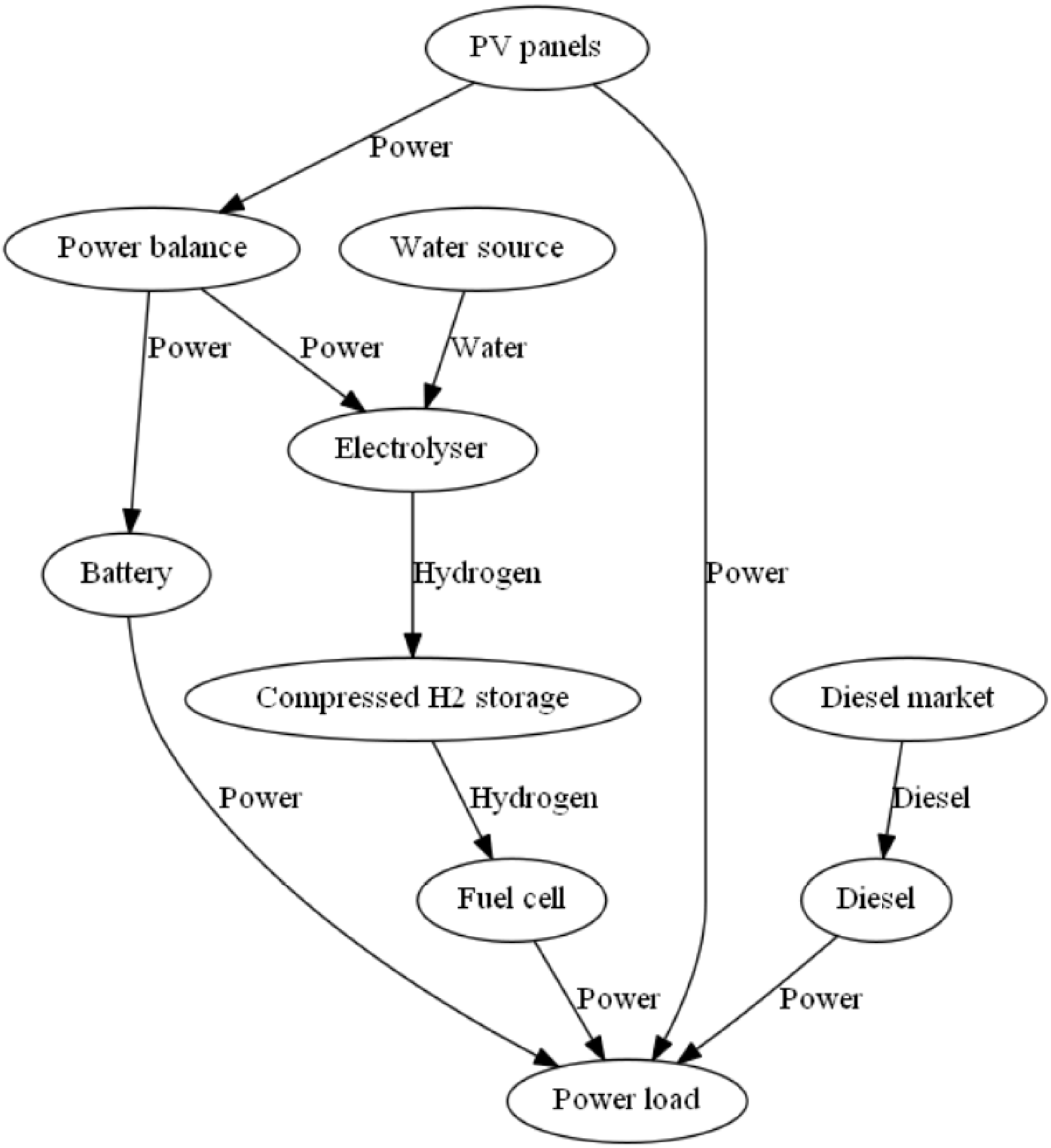

Figure 12 Complete model scheme

In the following table is reported how the main nodes can be linked. The model will consider only the nodes that will be included for the optimization of the specific scenario.

Table 9 Nodes link

From plant	Included [0/1]	To plant	Included [0/1]	Product
PV panels	-	Power balance	-	Power
Water source	-	Electrolyser	-	Water
Power balance	-	Electrolyser	-	Power
Electrolyser	-	Compressed H2 storage	-	Hydrogen
Compressed H2 storage	-	Fuel cell	-	Hydrogen
Fuel cell	-	Power load	-	Power
Power balance	-	Battery	-	Power
Battery	-	Power load	-	Power
PV panels	-	Power load	-	Power
Diesel market	-	Diesel	-	Diesel
Diesel	-	Power load	-	Power

As we can observe from the previous tables there exist several types of nodes which differ in function and so they have some type-specific data.
The main nodes can be classified as follows:

- PRODUCTION PLANTS: in this kind of node we have the conversion of one of several input products into one or more output products. Typical examples are electrolysers, fuel cells and diesel generators. For this kind of node so, we have to provide a production function which describes the amount of the output as a function of the input. We can distinguish different cases: in the simplest one the production function is represented by a simple multiplier. In other cases, we can model the conversion rate as a piecewise-linear function of the capacity utilization.
  In the following tables are listed the data used as input for the model of this type of node

Table 10 Production node charcteristic

Plant	Product	From unit	To unit	Linear function
Electrolyser	Hydrogen	MWh	kg	-
Electrolyser	Oxygen	MWh	kg	-
Electrolyser	Heat	MWh	MWh	-
Fuel cell	Power	kg	MWh	-
Fuel cell	Heat	kg	MWh	-
Diesel	Power	kg	MWh	-
Diesel	CO2	kg	kg	-
Diesel	NOx	kg	kg	-

For the fuel cell a piecewise-linear function has been used in order to take into account the different efficiencies with respect to its capacity utilization. An example of application is reported in the following table and graph.

Table 11 Fuel cell piecewise linear behaviour example

Node	Product	Interval	Lambda	Efficiency	Conv. rate
Fuel cell	Power	1	0.55	0.55	0.018315
Fuel cell	Power	2	0.2	0.5	0.01665
Fuel cell	Power	3	0.25	0.4	0.01332

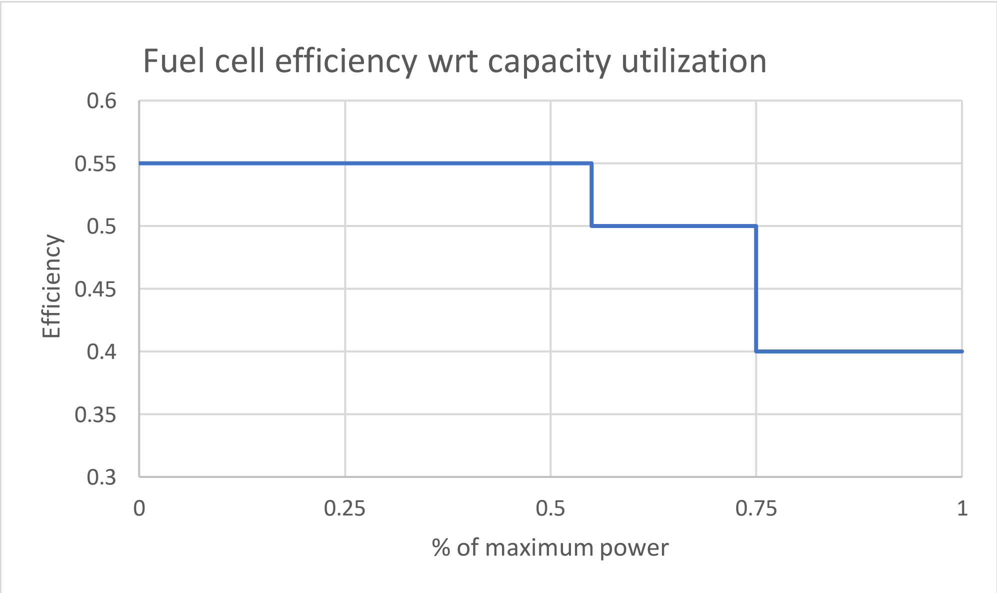

Figure 13 Fuel cell piecewise linear behaviour example

Table 12 Electrolyser production

Plant	Mode	Input	Multiplier	Unit
Electrolyser	-	Power	-	MWh
Electrolyser	-	Water	-	kg / MWh

In addition, for the PV panels we need the irradiance data that has been calculate with PVGIS as hourly data. PVGIS is an online tool which provide a large and accurate solar radiation database for Europe. The next graph shows the solar irradiance of Ginostra.

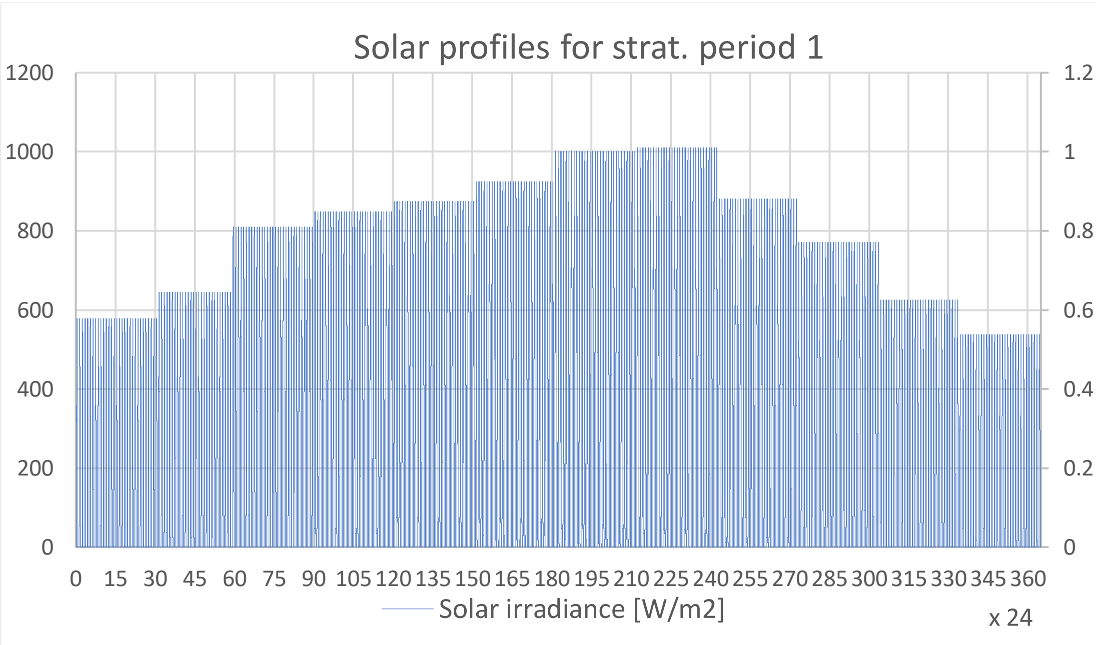

Figure 14 Solar profiles for Ginostra

- MARKETS: the market nodes are associated to the load, demand and supply for a specific product. A fundamental distinction is done between load, which has to be delivered, and demand, whose satisfaction is optional. For each of the three requests, we have to provide a time series profile with volumes and prices typically based in hourly data. In addition, we have to specify a penalty in case of non-delivered load and/or required regularity as a minimal fraction of the total load that has to be delivered.

Table 13 Market data 1

Market	Product	Unit	Include supply	Include demand	Include load
Power load	Power	MWh	-	-	-
Water source	Water	Kg	-	-	-
Diesel market	Diesel	Kg	-	-	-

Table 14 Market data 2

Market	Cost of unsatisfied load [€/unit]	Required regularity
Power load	-	-
Water source	-	-
Diesel market	-	-

The load profile for the Ginostra case is represented in the graph below:

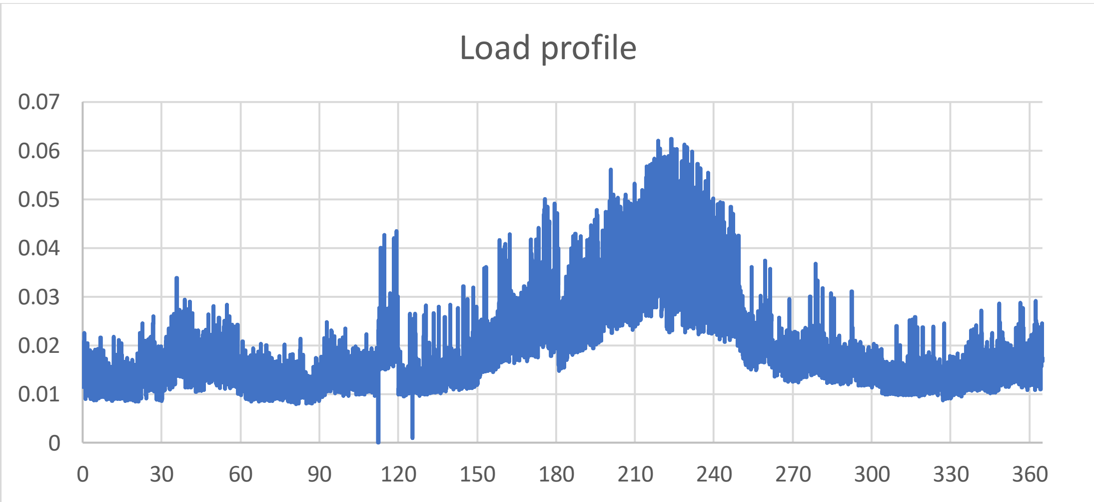

Figure 15 Load profile

- STORAGE: this kind of node is necessary to take into account the storage of some products between time periods. In our case of study, the storage is done with batteries and compressed-hydrogen storage. They have all the following additional input parameters:

- minimal fill level with the buffer function and it can be expressed either in absolute value or fraction of the total installed capacity
- maximal rate of filling and emptying measured in volume unit per hour for hydrogen storage and the maximal rate of charging and discharging in the fraction of the capacity per hour for what concern the batteries
- efficiency of filling and emptying only for the batteries

Table 15 Storage data characteristic 1

Storage	Product	Unit	Buffer level [%]	Eff. in [%]	Eff. out [%]
Compressed H2	Hydrogen	kg	-	-	-
Battery	Power	MWh	-	-	-

Table 16 Storage data characteristic 2

Storage	Max fill rate [cap / h]	Max empty rate [cap / h]	Max fill speed [unit / h]	Max empty speed [unit / h]
Compressed H2	-	-	-	-
Battery	-	-	-	-

- TRANSPORT: these nodes are related to the cases where we need an accurate control over the flow between nodes. Since in the model we do not include any type of edges or separate entities, the products simply flow between the selected pairs of nodes, without any limitations for what concern the limits and the cost.

Table 17 Transport node

Node	Product	Allow	Loss [%]
Power balance	Power	-	-

4.1.4. Time periods

The time horizon of the model is subdivided in strategic periods, which typically lasts one year or longer. In our case analysis we set two strategic periods lasting both ten years.

All the investment costs related to the infrastructures happen at the beginning of these periods. In addition, the available capacity gets update in ordered to take into account the ageing of the devices.

In each strategic period are present a sequence of operational periods in which the model uses the infrastructure. The total length of each operational period must be equal or shorter than the operational period they correspond to. So, the operation results will be scaled up to the desired length.

In order to clarify this concept, if the strategic period is for example, as we set, ten years and the operational one is referred to one year of operations, the results obtained will be multiplied by ten in order to obtain the volumes, costs and incomes related to the whole strategic period.

Table 18 Time period

Period	Dur [day]	Dur [t.u.]	Dur oper [t.u.]	Time mult
1	3650	87600	8760	10
2	3650	87600	8760	10

4.1.5. Other input data

The other main input data are relative to the products that are produced by the different devices. To connect he products that are not linked to any node it is necessary to add a slack. Finally, it is also possible to insert a slack cost, in this way we can insert costs referred to the CO_2 and NO_x emissions for example.

Table 19 Slack input data

Plant	Product	Compatibility	Add slack	Slack cost [NOK/unit]
PV panels	Power	-	-	-
Electrolyser	Hydrogen	-	-	-
Electrolyser	Oxygen	-	-	-
Electrolyser	Heat	-	-	-
Diesel	Power	-	-	-
Diesel	CO2	-	-	-
Diesel	NOx	-	-	-
Fuel cell	Power	-	-	-
Fuel cell	Heat	-	-	-

The usage based-maintenance are referred to the electrolyser and the fuel cell and will be inserted the data for taking into account their operational hours and the cost of the replacement of the stuck.

Table 20 Electrochemical device operating sharacteristics

Node	Interval [oper. hours]	Cost [% of CAPEX]	Use advanced modelling [0/1]	Reference capacity
Electrolyser	-	-	-	-
Fuel cell	-	-	-	-

4.1.6. Decisions variables

There exist two type of decision variables in the model:

1. Strategic variables: the strategic variables are used for decisions done at the beginning of the strategic period. The only real strategic decisions are what capacity has to be added or removed from the nodes in the network. The strategic variables are required for the calculation of the fixed CAPEX.
2. Operational variables: the operation variables are used for all decisions during the operational periods and are used for modelling the system's operations. The main operations are:

- production of the production nodes
- loads delivered to, or obtained from the market nodes
- storage levels at the storage nodes
- flows between the nodes

4.1.7. Constraint

Most of the constraint inserted in the model are technical and they model the production profiles, ensure continuity of balance, keep track of storage levels, etc. In addition, there is the possibility of use an optional policy constraint for putting the limit on yearly carbon dioxide emissions, either in absolute value or as a required reduction from a specific quantity.

Table 21 Constraint

Parameter name	Value
Base CO2 emissions [kg/kWh]	-
Min CO2 emission reduction [%]	-

4.1.8. Objective function

The model decides the optimal configuration of the system in order to optimize a given objective function. The goal is typically maximizing the net present value of the entire system. The net present value is calculated by discounting costs and income for a specified horizon and discount rate, that typically is assumed to be 4%[15].

5. SCENARIOS

Different scenarios have been analyzed in order to evaluate the real value of the power to power system in the DEMO case 1.

The scenarios have been subdivided in two different temporal frame, in order to evaluate the situation nowadays in the 2019 scenarios and in the near future 2030.

The main cases of study are listed below:

Scenarios 2019:

- Diesel 2019
- RES 2019
- P2P 2019

Scenarios 2030:

- Diesel 2030
- RES 2030
- P2P 2030
- P2P 2030+ hydrogen market

In this section a technical analysis of the different scenarios has been done, in particular the price and the technological aspects, like the efficiency, of the different devices and fuels has been investigated. The data obtained have been used has input data for the model. Once the model has been running the optimal configuration in terms of kilowatt installed has been obtained. The optimal configuration, as we have seen before in the description of the model, is the one that minimize the cost of electricity production. So, for each scenario will be shown the optimal configuration, the installation and operation cost relative to each node and main flux exchanged between the nodes.

Finally, will be reported the cost of electricity production and the emission of carbon dioxide.

5.1. Scenarios 2019

5.1.1. Diesel 2019

In this scenario the model has been ran with the actual situation of Ginostra, where the power load is supplied only by diesel generators.

The LHV of the Diesel is 0,0125 MWh/kg, and considering a plant efficiency around 40%, it is obtained that with 1 kg of Diesel we can produce 0,005 MWh.

The characteristics of the Diesel generators are reported in the following table:

Table 22 Diesel production function

Plant	Product	From unit	To unit	Conversion factor
Diesel	Power	kg	MWh	0,00492
Diesel	CO2	kg	kg	3,16
Diesel	NOx	kg	kg	0,8856

Since the total load corresponds to 168 MWh, the demand for the supply of diesel has been found being equal to 4 kg/h to fully satisfied the load and the diesel cost has been set greater than 2 €/liter.

Currently, the total demand is satisfied by means of three 48 kW diesel generators and one 160 kW diesel generator[16].

Table 23 Plant Diesel 2019

Plant	Size
Diesel generator	304 [kW]

For each scenario will be shown the main economic results, the flow inside and/or outside the different nodes of the system.

The results of the simulation are listed below:

Table 24 Economic results Diesel 2019

Node	Total cost [M€]	Per capacity OPEX [M€]	Supply cost [M€]
Diesel	0,234	0,234	0
Diesel market	0,947	0	0,947
Totals	**1,190**		

Table 25 Flow out of the nodes [MWh or kg / year] Diesel 2019

From	Power	Diesel
Diesel	168	-
Diesel market	-	34169

Table 26 Main results Diesel 2019

Delivered energy price [€/kWh]	0,521
CO_2 [kg/kWh]	0,642

As we can notice from the table of the economic results, the cost of the Diesel, due to the location of Ginostra, accounts for the 80% on the total final cost.

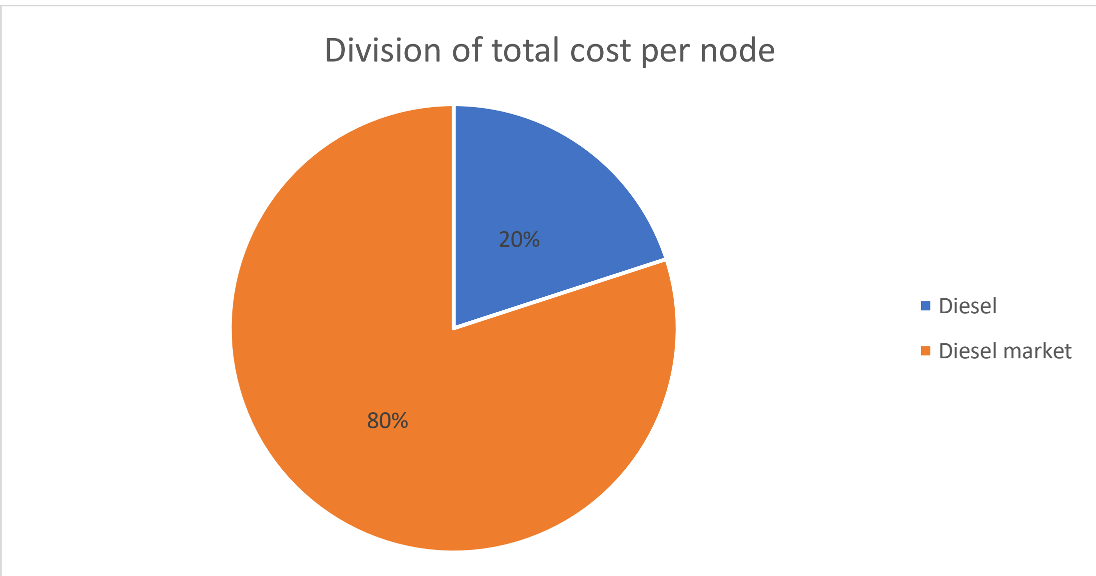

Figure 16 Share of total cost Diesel 2019

5.1.2. Res 2019

In this scenario has been evaluated the case when the system is fed by the photovoltaic system and the diesel generators as back-up system.

The price for the installation of the photovoltaic has been selected equal to 1300 €/kW, according to the figure below, and the OPEX has been evaluated to be the 1,5% of the CAPEX[17].

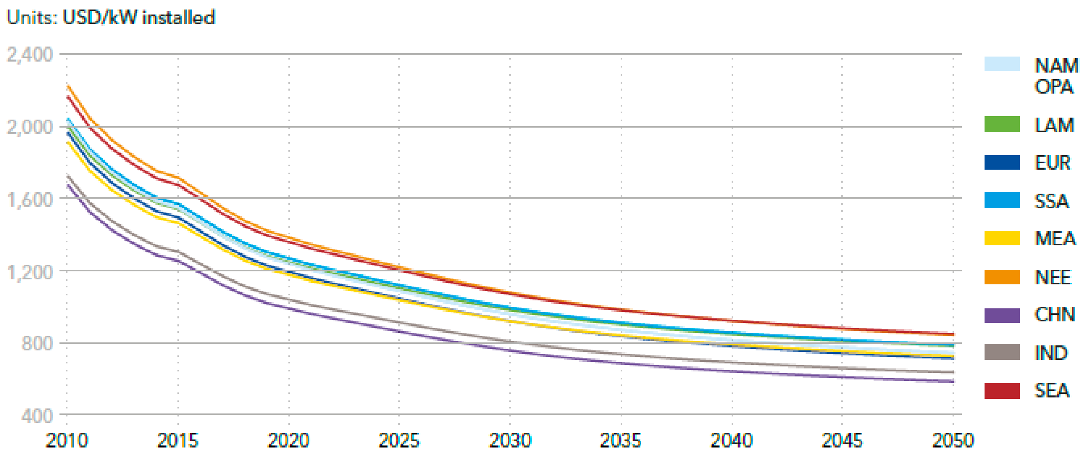

Figure 17 PV price in the different region of the world[3]

No limitations have been applied for the sizing of the photovoltaic plants.

Table 27 Economic results Res 2019 1

Node	Installed Capacity [MW]	Total Capacity [MW]	Total cost [M€]	**CAPEX** [M€]
PV panels	0,06	0,06	0,084	0,070
Diesel	0	0	0,223	0
Diesel market	0	0	0,553	0
Total			**0,870**	**0,070**

Table 28 Economic results Res 2019 2

Node	**Relative OPEX** [M€]	**Per capacity OPEX** [M€]	**Supply cost** [M€]
PV panels	0,015	0	0
Diesel	0	0,223	0
Diesel market	0	0	0,553

Table 29 Flow out of the nodes [MWh or kg / year] RES 2019

From	Power	Diesel
Diesel	98	-
Diesel market	-	19962
PV panels	70	-

Table 30 Flow of el. Power [MWh]

From	Power load
Diesel	98
PV panels	70

Table 31 Main results Res 2019

Delivered energy price [€/kWh]	0,381
CO2 [kg/kWh]	0,375

As we can observe, this situation presents a reduction both in the electricity power price and in the CO2 emissions. The main problem associated to the photovoltaic system, as seen before, is linked to its intermittency nature, and it can be solved developing energy storage solutions, with which it is possible to obtain dramatic reduction in the CO2 emissions.

The energy storage solution is analyzed in the following scenario.

5.1.3. P2P 2019

In this scenario the power-to-power solution has been implemented. As we have analysed before the main component are the electrolyser, the fuel cell, the Li-ion battery and the hydrogen storage.

The CAPEX value selected for the battery in the 2019 is shown in the next figure:

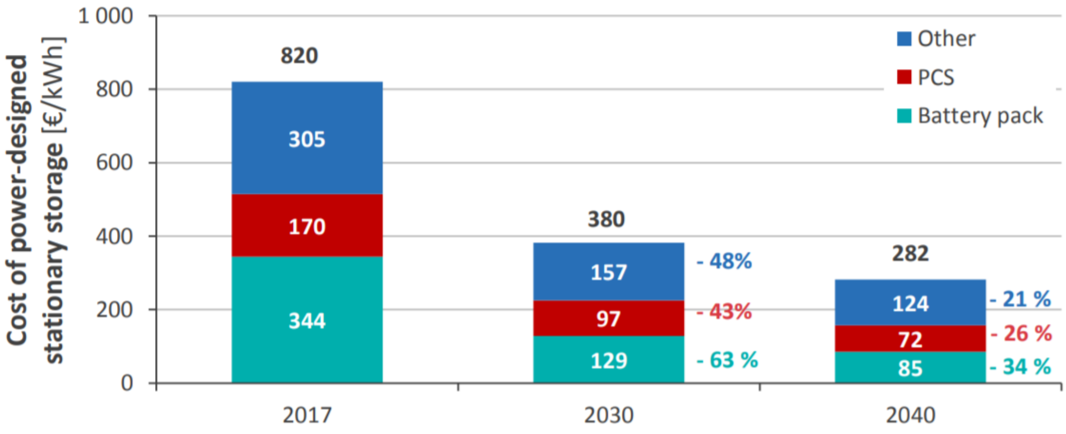

Figure 18 Battery cost evolution

The 25 kW fuel cell system cost is 2,500 €/kW. How this value has been obtained is shown in the section relative to the P2P optimized configuration.

The CAPEX of electrolysers for small electrolysers (<1 MW) has been set according to a confindential value.

For what concern the electrolyser and the fuel cell the following production functions have been evaluated:

Using the formula mentioned in technical review part we can simply obtain the following production function:

Table 32 Electrochemical devices production function

Plant	Product	From unit	To unit	Conversion factor
Electrolyser	Hydrogen	MWh	kg	18,3
Electrolyser	Oxygen	MWh	kg	146,4
Electrolyser	Heat	MWh	MWh	0,22
Fuel cell	Power	kg	MWh	0,016
Fuel cell	Heat	kg	MWh	0,01

For the fuel cell the piecewise-linear function has been adopted in order to take into account, as we have seen before in the description of the model, the different efficiencies with respect to its power utilization[16].

Table 33 Fuel cell efficiency

Node	Product	Interval	Lambda	Efficiency	Conv. rate
Fuel cell	Power	1	0,55	0,5	0,01665
Fuel cell	Power	2	0,25	0,45	0,014985
Fuel cell	Power	3	0,2	0,4	0,01332

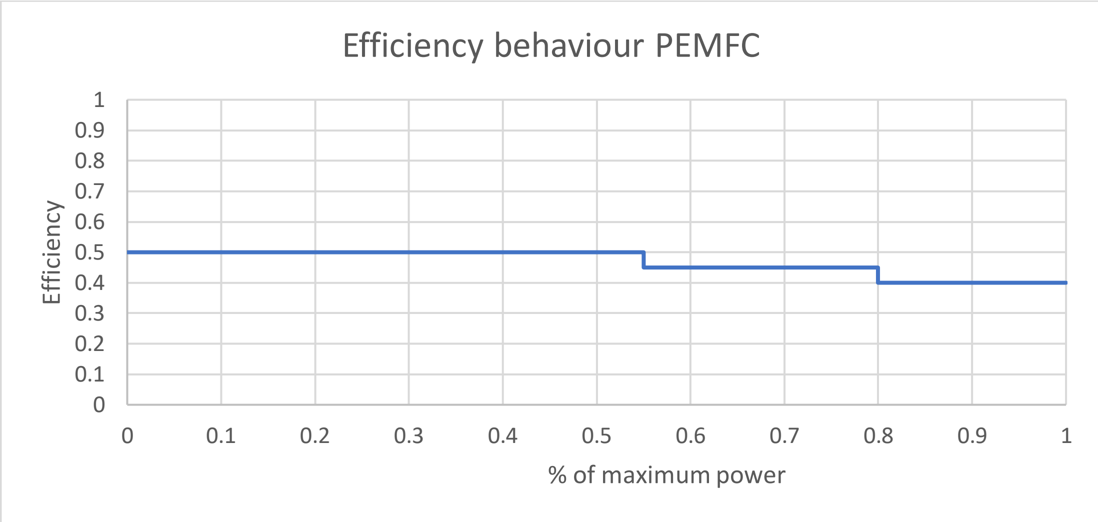

Figure 19 Fuel cell 2030 efficiency with respect to power utilization

For the storage devices, the following characteristics have been inserted as input data[16]:

Table 34 Hydrogen storage characteristic

Storage	Unit	Buffer level [%]	Max fill speed [kg/ h]	Max empty speed [kg / h]
Compressed H2 storage	kg	20 %	100	100

Table 35 Battery storage characteristic

Storage	Unit	Buffer level [%]	Max fill rate [cap / h]	Max empty rate [cap / h]	Efficiency in [%]	Efficiency out [%]
Battery	MWh	40 %	0,5	0,5	95 %	95 %

Benchmark solution

First of all, the model has been ran using the sizing data foreseen by the developers of the project. The configuration is the following one[8]:

Table 36 Benchmark configuration

Plant	Size
PV	170 [kW]
AEC	50 [kW]
PEMFC	50 [kW]
Li-ion battery	600[kWh]
Hydrogen storage capacity	1920[kWh]
Diesel generators	304[kW]

In this case the model is not optimized from the point of view of the best economic solution, but it evaluates the optimal working strategy with these pre-defined data.

Benchmark solution results

Table 37 Economic results Benchmark configuration

Node	Installed Capacity [MW/MWh/Kg]	Total Capacity [MW/MWh/Kg]	Total cost [M€]	CAPEX [M€]	Relative OPEX [M€]
PV panels	0,17	0,17	0,267	0,221	0,046
Electrolyser	0,05	0,05	0,135	0,095	0,040
Compressed H2 storage	49,00	49,00	0,039	0,034	0,005
Fuel cell	0,05	0,05	0,160	0,125	0,035
Battery	0,60	0,50	0,594	0,492	0,102
Totals			**1,185**	**0,967**	**0,228**

Table 38 Flow into the nodes [MWh or kg / year] Benchmark solution

To	Power	Water	Hydrogen
Battery	136	-	-
Compressed H2 storage	-	-	517
Electrolyser	28	4 652	-
Fuel cell	-	-	517
Power balance	164	-	-
Power load	170	-	-

Table 39 Flow out of the nodes [MWh or kg / year] Benchmark solution

From	Power	Water	Hydrogen
Battery	123	-	-
Compressed H2 storage	-	-	517
Electrolyser	-	-	517
Fuel cell	9	-	-
PV panels	202	-	-
Power balance	164	-	-
Water source	-	4 652	-

Table 40 Flow of electrical power [MWh] Benchmark solution

From	Electrolyser	Battery	Power balance	Power load
Battery	-	-	-	123
Fuel cell	-	-	-	9
PV panels	-	-	164	38
Power balance	28	136	-	-

Table 41 Main results Benchmark

Delivered energy price [€/kWh]	0,519
CO2 [kg/kWh]	0

With respect to the previous case, RES 2019, the cost is increased, and it is similar to the Diesel 2019 scenario. The CO2 emissions are zero thanks to the storage system that permit to avoid the use of Diesel generators as back-up.

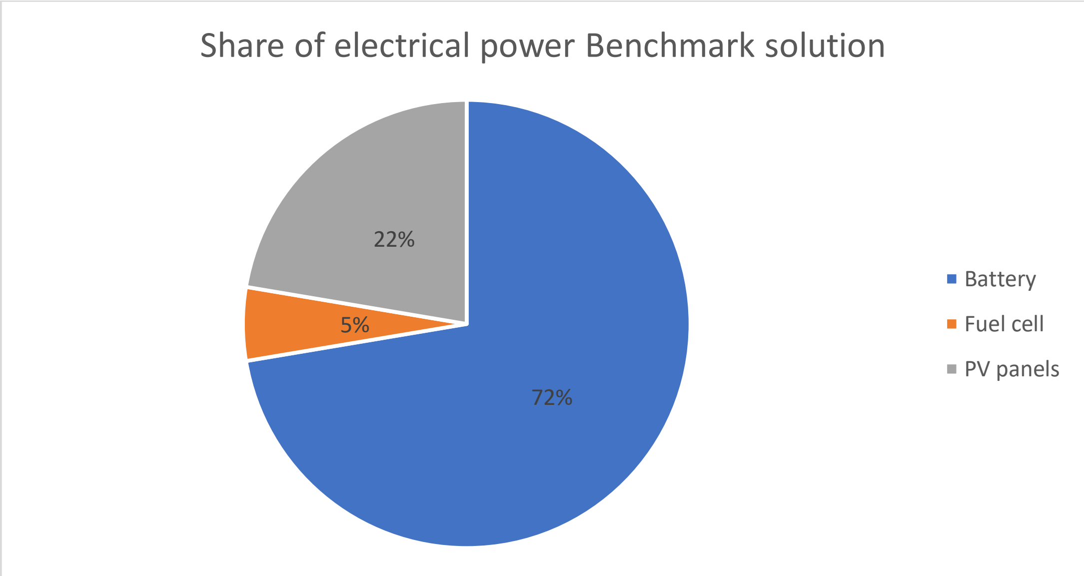

Figure 20 Share of electrical power Benchmark solution

As we can notice from the results above, the 5% of the total power is supplied by the fuel cell and the remaining part from the battery and the photovoltaic panels. Looking also, at the economic table, the cost of the power-to-power system, excluding the battery, is the 26% of the total cost.

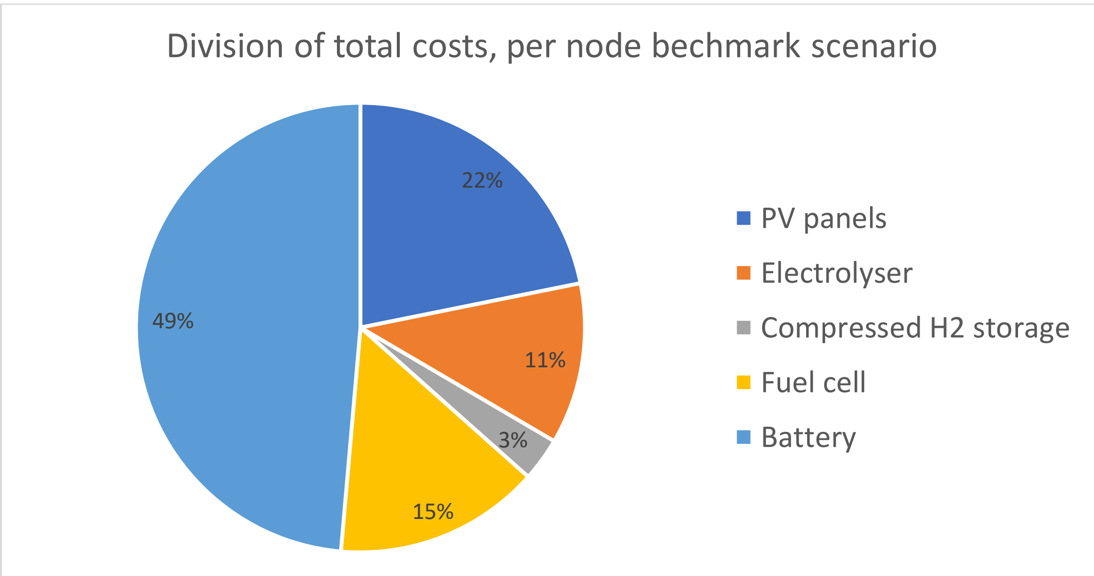

Figure 21 Share of the total cost per node in the benchmark solution

So, it can be useful to investigate if there exist an optimized solution for the size of the different components, in order to reduce the total cost and have a best usage of the different devices.

P2P 2019 optimized solution

The analysis of the optimized solution starts evaluating which could be the best size for the fuel cell.

Four different size of fuel cell have been evaluated: 5 kW, 10 kW, 25 kW, 50 kW.

The prices for the evaluation have been selected according to the following graph[19]:

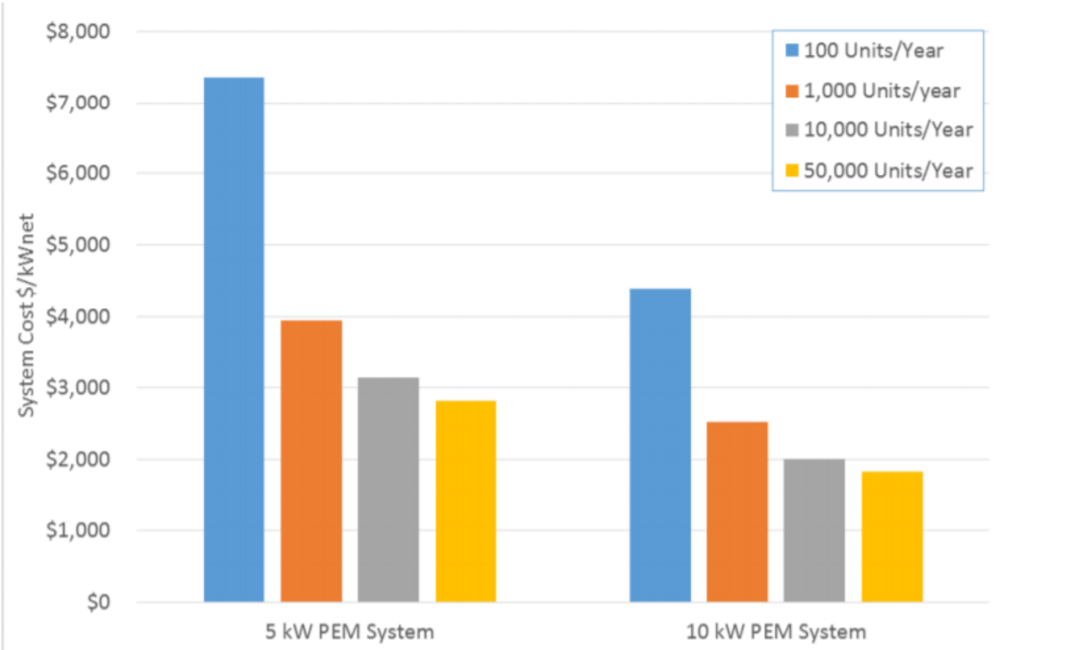

Figure 22 Backup power system installed cost per kW[19]

Table 42 Fuel cell Cost per kw installed: 5kW and 10 kW

	100 units/yr	1000 units/yr	10000 units/yr	50000 units/yr
5 kW	7200 (€/kW)	3900 (€/kW)	3100 (€/kW)	2800 (€/kW)
10 kW	4500 (€/kW)	2300 (€/kW)	2000 (€/kW)	1800 (€/kW)

Since data for the 25 kW and 50 kW has not been found in literature for the specific application, I applied the following formula to estimate the price:

$$C_1 = C_0 * (\frac{S_1}{S_0})^n$$

where:

- C_x is the cost associated to a specific size
- S_x is the specific size
- n is a parameter

So, reversing the equation I found n=0,678072 and after this, I applied the formula for the evaluation of the cost of the 25kW and 50 kW PEMFC.
In the next table are reported the estimated values:

Table 43 Fuel cell Cost per kw installed: 25kW and 50 kW

Size	100 units/yr	1000 units/yr	10000 units/yr	50000 units/yr
25 kW	2500 (€/kW)	1400 (€/kW)	1070 (€/kW)	970 (€/kW)
50 kW	1500 (€/kW)	870 (€/kW)	670 (€/kW)	610 (€/kW)

So, the model has been running with the different sizes of PEMFC and the results show that the optimal one is 25 kW from an economical aspect. In the following figure is shown the electricity generation cost with different fuel cell size:

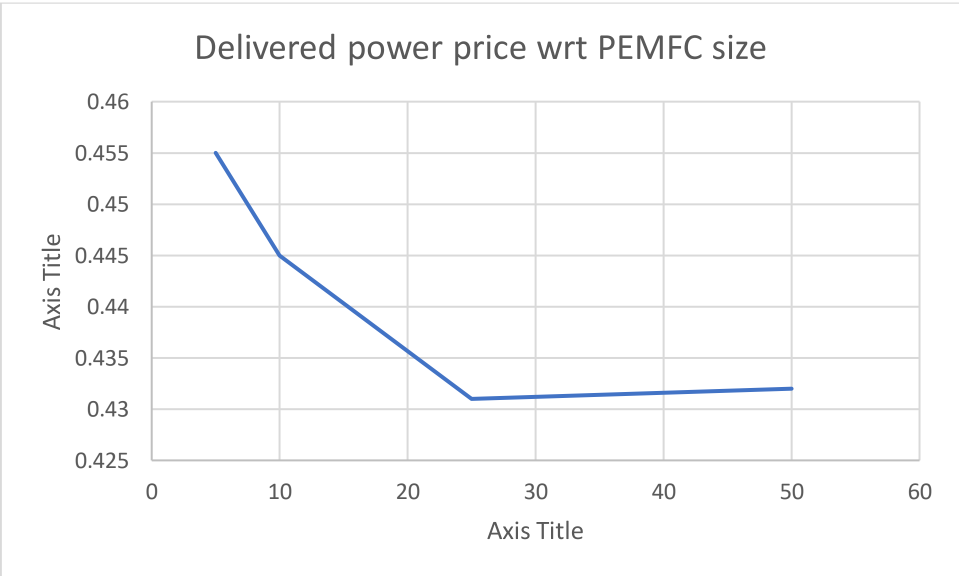

Figure 23 Electricity cost with respect PEMFC size

In the model has been imposed the size of the fuel cell and no other limitations on the size of the other devices has been imposed.
The results of this simulation are listed in tables below:

Table 44 Economic results P2P 2019

Node	Installed Capacity [MW]	Total Capacity [MW]	Total cost [M€]	CAPEX [M€]	Relative OPEX [M€]
PV panels	0,18	0,18	0,278	0,230	0,048
Electrolyser	0,08	0,08	0,232	0,144	0,060
Compressed H2 storage	16,85	16,85	0,013	0,012	0,002
Fuel cell	0,025	0,025	0,080	0,063	0,017
Battery	0,41	0,31	0,372	0,312	0,060
Totals			**0,975**	**0,761**	**0,187**

Table 45 Flow into the nodes [MWh or kg / year] P2P 2019

To	Power	Water	Hydrogen
Battery	72	-	-
Compressed H2 storage	-	-	1 355
Electrolyser	74	12 196	-
Fuel cell	-	-	1 355
Power balance	146	-	-
Power load	168	-	-

Table 46 Flow out of the nodes [MWh or kg / year] P2P 2019

From	Power	Water	Hydrogen
Battery	65	-	-
Compressed H2 storage	-	-	1 355
Electrolyser	-	-	1 355
Fuel cell	25		-
PV panels	225	-	-
Power balance	146	-	-
Water source	-	12 196	-

Table 47 Flow of electrical power [MWh] P2P 2019

From	Electrolyser	Battery	Power balance	Power load
Battery	-	-	-	65
Fuel cell	-	-	-	25
PV panels	-	-	146	78
Power balance	74	72	-	-

Table 48 Main results P2P 2019

Delivered energy price [€/kWh]	0,431
CO_2 [kg/kWh]	0

The simulation of the optimized P2P solution shows that a reduction of the cost of more than 20% can be obtained with a better sizing of the different components.

With this configuration the fuel cell covers more than the 15% of the total power load

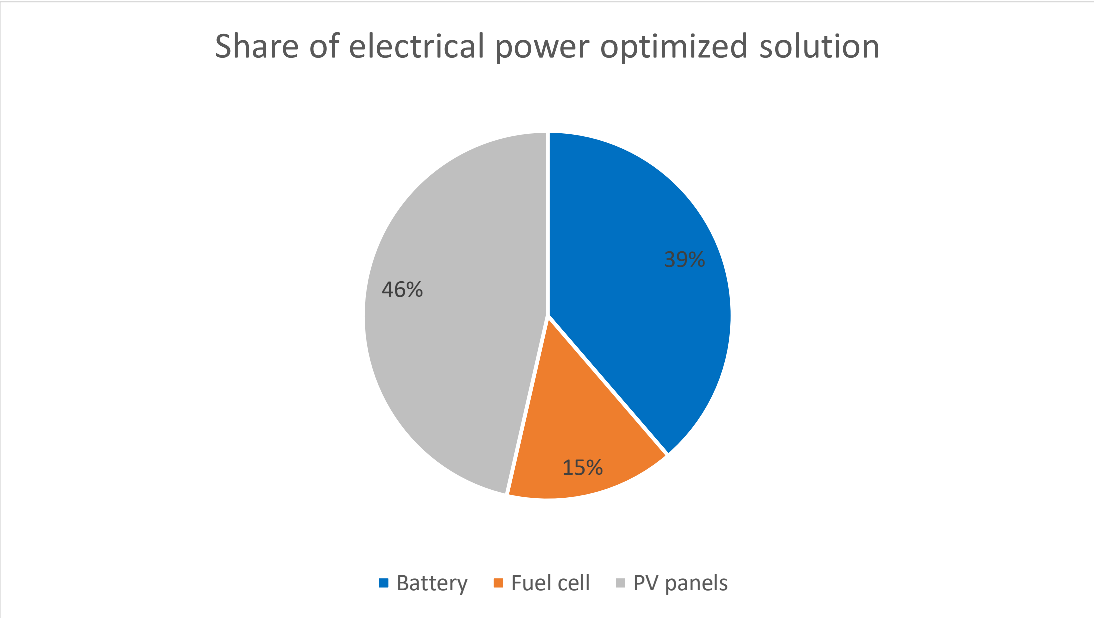

Figure 24 Share of electrical power P2P optimized solution

In the optimized solution the fuel cell supplies the load for more time during the strategic period.

This means the battery would still operate as daily energy buffer, managing smaller power variations and thus reducing the occurrence of deep cycling.

5.1.4. Resume 2019

The main results of the 2019 scenarios are summarized in the next table:

Table 49 Main results 2019 scenarios

Scenario	Total cost [M€]	Delivered energy price [€/kWh]	CO_2 emissions [kg/kWh]
Diesel 2019	1,19	0,521	0,642
Res2019	0,87	0,381	0,375
P2P benchmark	1,18	0,519	0
P2P optimized	0,98	0,431	0

5.2. Scenarios 2030

5.2.1. Diesel 2030

In this scenario the diesel price and diesel generator production characteristics have been set equal to the 2019 case. The fees on the CO2 and NOx emissions have been added for this simulation[20][21].

Table 50 Slack cost for CO2 and NOx production

Plant	Product	Slack cost [€/unit]
Diesel	CO2	0,044
Diesel	NOx	0,109

Table 51 Economic results Diesel 2030

Node	Total cost [M€]	Per capacity OPEX [M€]	Supply cost [M€]	Slack cost [M€]
Diesel	0,345	0,234	0	0,112
Diesel market	0,947	0	0,947	0
Totals	**1,302**	**0,234**	**0,947**	**0,112**

Table 52 Flow out of the nodes [MWh or kg / year] Diesel 2030

From	Power	Diesel
Diesel	168	-
Diesel market	-	34169

Table 53 Main results P2P 2019

Delivered energy price [€/kWh]	0,57
CO2 [kg/kWh]	0,642

5.2.2. RES 2030

For this scenario the future cost of the photovoltaic system has been evaluated according to learning curve effects.

The meaning of 'learning curves' is that the cost of a technology decreases by a constant fraction with every doubling of installed capacity, due to a greater experience, and industrial efficiencies associated with market deployment and research and development.

For PV, the learning rate is historically 18% and it has been expected this to continue and to drive down the cost of new installations[3].

Applying this rate to investment/unit installation costs, with operating costs experiencing a learning rate which is half of that, 9% is obtained.

In the following figure the learning curves for photovoltaic system is shown:

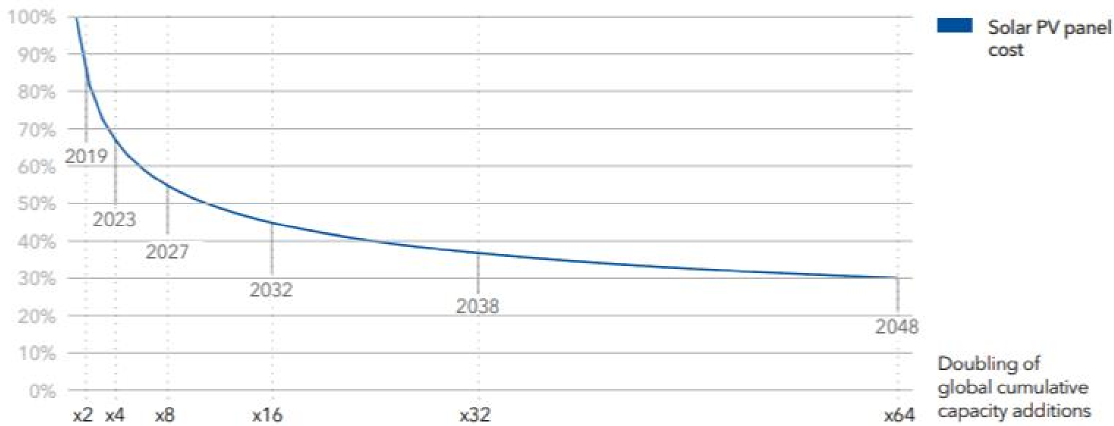

Figure 25 Solar PV learning curve[3]

So, in 2030 we expect the cost will be much lower with respect to the cost in 2019.

Table 54 Photovoltaic cost 2019-2030

Plant	2019 cost	2030 cost
PV	1300 €/kW	900 €/kW

Table 55 Economic results RES 2030-1

Node	Installed Capacity [MW]	Total Capacity [MW]	Total cost [M€]	CAPEX [M€]
PV panels	0,07	0,07	0,075	0,062
Diesel	0	0	0,297	0
Diesel market	0	0	0,541	0
Totals			**0,923**	**0,062**

Table 56 Economic results RES 2030-2

Node	Relative OPEX [M€]	Per capacity OPEX [M€]	Supply cost [M€]	Value of lost load [M€]	Slack cost [M€]
PV panels	0,013	0	0	0	0
Diesel	0	0,234	0	0	0,064
Diesel market	0	0	0,541	0	0

Table 57 Flow into the nodes [MWh or kg / year] RES 2030

To	Power	Diesel
Diesel	-	19521
Power load	168	-

Table 58 Flow out of the nodes [MWh or kg / year] RES 2030

From	Power	Diesel
Diesel	96	-
Diesel market	-	19521
PV panels	72	-

Table 59 Flow of electrical power [MWh] RES 2030

From	Power load
Diesel	96
PV panels	72

Table 60 Main results RES 2030

Power price [€/kWh]	0,404
CO2 [kg/kWh]	0,367

5.2.3. P2P 2030

As it has been done for the photovoltaic, we have to analyze how the different devices can be configured in 2030.

The values adopted for 2030 are not in the lower range of the costs, in order to present an optimistic but conservative scenario for 2030.

For the fuel cell in the following table we have the different costs at different productions per year:

Table 61 Fuel cell cost per unit

	100 units/yr	1000 units/yr	10000 units/yr	50000 units/yr
5 kW	7200 (€/kW)	3900 (€/kW)	3100 (€/kW)	2800 (€/kW)
10 kW	4500 (€/kW)	2300 (€/kW)	2000 (€/kW)	1800 (€/kW)
25 kW	2500 (€/kW)	1400 (€/kW)	**1070 (€/kW)**	970 (€/kW)
50 kW	1500 (€/kW)	870 (€/kW)	670 (€/kW)	610 (€/kW)

In our calculation we analyzed the situation in 2030 with a production of 10000 units/year and also an efficiency of the 60% has been set.

As we have done for the 2019 scenarios, a sensitivity analysis on which size of fuel cell could fit better in our system has been done.

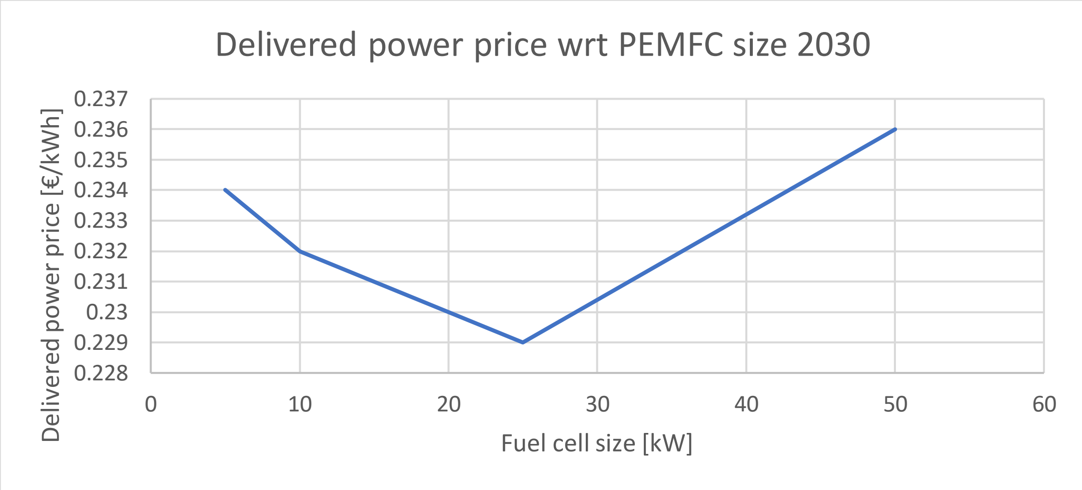

Figure 26 Delivered energyr cost with respect to fuel cell size

The size selected for the fuel cell is 25 kW, because the system presents a low cost of electricity production with respect to the other three cases, as we can appreciate in the figure above.

For the fuel cell the piecewise-linear function has been adopted in this case are assumed the following values[22]:

Table 62 Fuel cell efficiency

Node	Interval	Lambda	Efficiency	Conv. rate
Fuel cell	1	0,55	0,6	0,01998
Fuel cell	2	0,25	0,55	0,018315
Fuel cell	3	0,2	0,45	0,014985

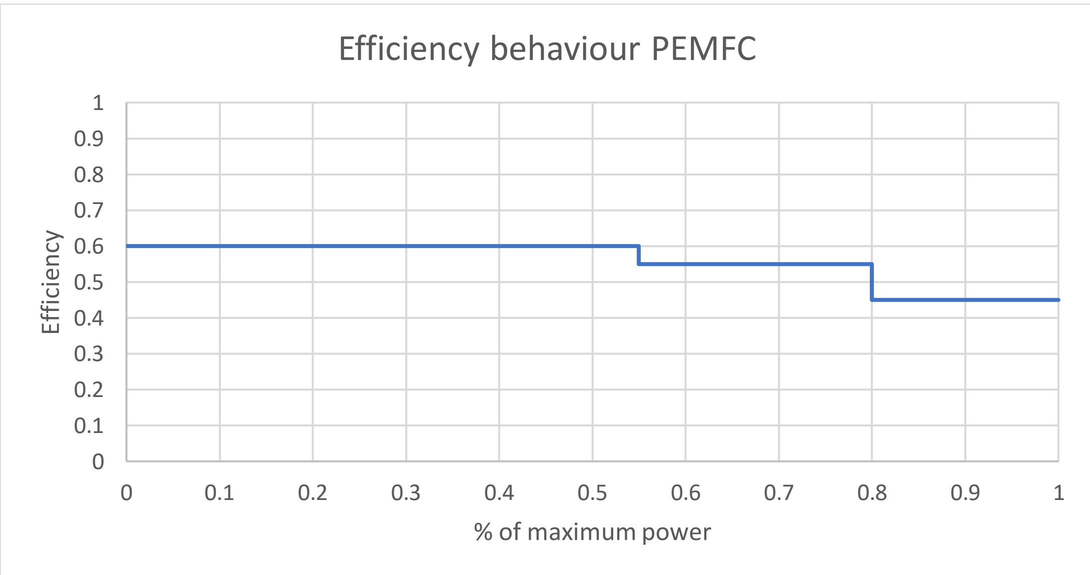

Figure 27 Fuel cell 2030 efficiency with respect to power utilization

For what concern the battery, the growth in intermittent renewables goes hand in hand with growth in stationary battery storage.
For the batteries so, the cost of installation is reduced according to the graph reported in the 2019 scenario.
For the alkaline electrolyser, technology efficiency improvement can be achieved through innovations on the system level as well as optimized system integration due to increase of operational.
The installation cost decreases according to literature starting from the initial value set in the 2019 scenario[18].
In the following table are summarized the main difference in between the 2019 and 2030 scenarios for each different device/plant:

So, once the new values have been set, the model has been run and the result of the P2P 2030 configuration are shown in the next tables:

Table 63 main improvement 2019 vs 2030

Plant/device	Improvement	2019	2030
PV system	Cost of PV decreases due to a greater experience, and industrial efficiencies associated with market deployment and research and development	1300 [€/kW]	900 [€/kW]
Fuel Cell	Increase of maximum efficiency and the values market due to research and development adopted for 2030 are not in the lower range of the costs, in order to present a conservative scenario for 2030	**Efficiency max:** 55% **Cost 25 kW Pemfc:** 2500 [€/kW]	**Efficiency max:** 60% **Cost 25 kW Pemfc:** 1000 [€/kW]

Electrolyser	Efficiency kept constant and reduction of the cost associated with market deployment and research and development and reduction in the cost of the auxiliary system	>1000 [€/kW]	1000 [€/kW]
Battery	cost due to a growth in intermittent renewables deployment	820 [€/kWh]	380 [€/kWh]

Table 64 Economic results P2P 2030

Node	Installed Capacity [MW/MWh/kg]	Total Capacity [MW/MWh/kg]	Total cost [M€]	CAPEX [M€]	Relative OPEX [M€]
PV panels	0,17	0,17	0,182	0,150	0,031
Electrolyser	0,07	0,07	0,110	0,069	0,029
Compressed H2 storage	13,48	13,48	0,011	0,010	0,001
Fuel cell	0,025	0,025	0,032	0,025	0,007
Battery	0,43	0,32	0,178	0,150	0,029
Totals			**0,535**	**0,433**	**0,078**

Table 65 Flow into the nodes [MWh or kg / year] P2P 2030

To	Power	Water	Hydrogen
Battery	74	-	-
Compressed H2 storage	-	-	1 170
Electrolyser	64	10 531	
Fuel cell	-	-	1 170
Power balance	138	-	
Power load	168	-	-

Table 66 Flow out of the nodes [MWh or kg / year] P2P 2030

From	Power	Water	Hydrogen
Battery	67	-	-
Compressed H2 storage	-	-	1 170
Electrolyser	-	-	1 170
Fuel cell	23	-	-
PV panels	216	-	-
Power balance	138	-	
Water source	-	10 531	-

Table 67 Flow of electrical power [MWh] P2P 2030

From	Electrolyser	Battery	Power balance	Power load
Battery	-	-	-	67
Fuel cell	-	-	-	23
PV panels	-	-	138	78
Power balance	64	74	-	-

Table 68 Main results P2P 2030

Delivered energy price [€/kWh]	0,229
CO2 [kg/kWh]	0

5.2.4. P2P 2030 + Hydrogen market

This scenario has been developed in order to decrease the amount of the solar energy curtailed of the previous case since the regulatory framework does not clarify if many fees will be introduced for the energy curtailment.

In the following table the total amount of energy courtailed in the 2030 optimized solution is shown:

Table 69 PV curtailed energy [MWh] P2P 2030

Node	Product	Volume
PV panels	Power	124

In the evaluation of this scenario the cost of hydrogen has been set equal to 5 €/kg, since the cost of hydrogen in Europe nowadays is 9,5€/kg but the objective is to bring it to 5€/kg by 2025-2030[23].

Since there are no cars on Ginostra, we can assume that hydrogen will be sold for a maritime application for instance, to operate a fuel cell fishing vessel.

The results of this configuration are shown in the next tables:

Table 70 Economic results P2P+hydrogen 2030

Node	Installed Capacity	Total Capacity	Total cost	CAPEX	Relative OPEX	Demand income
PV panels	0,17	0,17	0,185	0,153	0,032	0
Electrolyser	0,07	0,07	0,121	0,07	0,028	0
Compressed H2 storage	13,22	13,08	0,010	0,009	0,001	0
Fuel cell	0,025	0,025	0,032	0,025	0,007	0
Battery	0,43	0,32	0,183	0,153	0,029	0
Hydrogen market	0	0	-0,155	0	0	1,55
Totals			**0,398**	**0,410**	**0,099**	**1,54**

Table 71 Flow into the nodes [MWh or kg / year] P2P+hydrogen 2030

To	Power	Water	Hydrogen

Battery	76	-	-
Compressed H_2 storage	-	-	3 308
Electrolyser	181	29 776	-
Fuel cell	-	-	1 096
Hydrogen market	-	-	2 212
Power balance	257	-	-
Power load	168	-	-

Table 72 Flow out of the nodes [MWh or kg / year] P2P 2030

From	Power	Water	Hydrogen
Battery	69	-	-
Compressed H_2 storage	-	-	3 308
Electrolyser	-	-	3 308
Fuel cell	22	-	-
PV panels	334	-	-
Power balance	257	-	-
Water source	-	29 776	-

Table 73 Flow of electrical power [MWh] P2P+hydrogen 2030

From	Electrolyser	Battery	Power balance	Power load
Battery	-	-	-	69
Fuel cell	-	-	-	22
PV panels	-	-	257	78
Power balance	181	76	-	-

Table 74 PV curtailed energy [MWh] P2P+hydrogen 2030

Node	Product	Volume
PV panels	Power	12

Table 75 Main results P2P+hydrogen 2030

Delivered energy price [€/kWh]	0,174
CO_2 [kg/kWh]	0

As we can immediately notice the cost of the delivered power price is reduced due to the sale of the hydrogen produced in excess.

5.2.5. Resume 2030

In the following table the main results of the 2030 scenarios are summarized

Table 76 Main results 2019 scenarios

Scenario	Total cost (M€)	Delivered energy price (€/kWh)	CO2 (kg/kWh)
Diesel 2030	1,302	0,570	0,642
Res 2030	0,923	0,404	0,367
P2P 2030	0,535	0,229	0
P2P + hydrogen market 2030	0,398	0,174	0

6. RESULTS AND CONCLUSIONS

The results of the different scenarios analyzed, both for 2019 and 2030, are summarized in the following tables:

Table 77 Resume of main results

Scenario	Total cost (M€)	Delivered power price (€/kWh)	CO2 (kg/kWh)
Diesel 2019	1,19	0,521	0,642
Res2019	0,87	0,381	0,375
P2P benchmark	1,18	0,519	0
P2P optimized	0,98	0,431	0
Diesel 2030	1,302	0,570	0,642
Res 2030	0,923	0,404	0,367
P2P 2030	0,535	0,229	0
P2P + hydrogen market 2030	0,398	0,174	0

Looking at the table above we can appreciate how the P2P solution represent the best scenario in the 2030 one from a cost and emission point of view.

The installation of only photovoltaic panels with the usage of diesel generators, seems to be the best solution for nowadays from a point of view of the cost of the electricity generations.

The installation of the photovoltaic system will reduce the electricity generation cost and the CO2 emissions compared to the actual situation, but without the energy storage solution, in order to have a feasible solution the usage of diesel generators can't be lower than 58%.

Even introducing just,the battery as storage system, the situation does not change so much, an increment of the cost of the system occurs and a slightly reduction on the CO2 emissions.

So, to have a greater reduction in the CO_2 emissions the P2P solution seems to be the one that fit better in our case of study.

The P2P benchmark solution presents a higher cost with respect to the optimal one, due to a non-optimal sizing of the different subsystems.

The research of the optimal solution from a cost point of view shows a different sizing of the main component of the power-to-power system.

The comparison between the benchmark solution and the optimized one in the 2019 case is shown in the following table:

Table 78 P2P benchmark vs P2P optimized solution

Subsystem	**Benchmark**	**Optimized**
PV plant	170 kW	180 kW
Battery	600 kWh	410 kW
Electrolyser	50 kW	80 kW
Fuel cell	50 kW	25 kW
Hydrogen compressor	1920 kWh	560 kWh

The differences in sizing of these two scenarios can be attributed to the fact that the benchmark solution was not optimized from an economical point of view but from a technological one. From the results shown above we can notice that the fuel cell dimension is reduced from 50 kW to 25 kW mainly due to its high cost. The sizing of the battery and the hydrogen storage has been reduced with respect to the benchmark solution due to economic aspects and also, with the load profile of Ginostra that has been taken into account for the analysis, these devices were found to be oversized. For what concern the electrolyser, it seems to be necessary to install 30 kW more in order to produce the correct amount of hydrogen, that has to be supplied to the fuel cell. It is worth to be noticed that the P2P solution is optimized for a certain profile and it does not take into account possible fluctuations during the day, so from a safety point of view this scenario presents a weaker solution with respect to the benchmark one. The P2P optimized solution lead on a reduction of the electricity generation cost of the 17% in the 2019 with respect to the actual situation in Ginostra. As mentioned before, even if presents a cost higher than the PV scenarios, this case lead to a dramatic reduction on the CO2 emissions, leading Ginostra to be independent from the fossil fuel.

Analyzing in a more detailed way the power-to-power optimal configuration, in 2019 the load is supplied in the following way:

Table 79 Cover of load profile

Plant	Load [%]
PV	46
Battery	39
Fuel cell	15

The load is served for the 46% from the photovoltaic system, the 39% from the Li-ion battery and the remaining part from the fuel cell.

The hourly average load on Ginostra site in a typical summer day is shown:

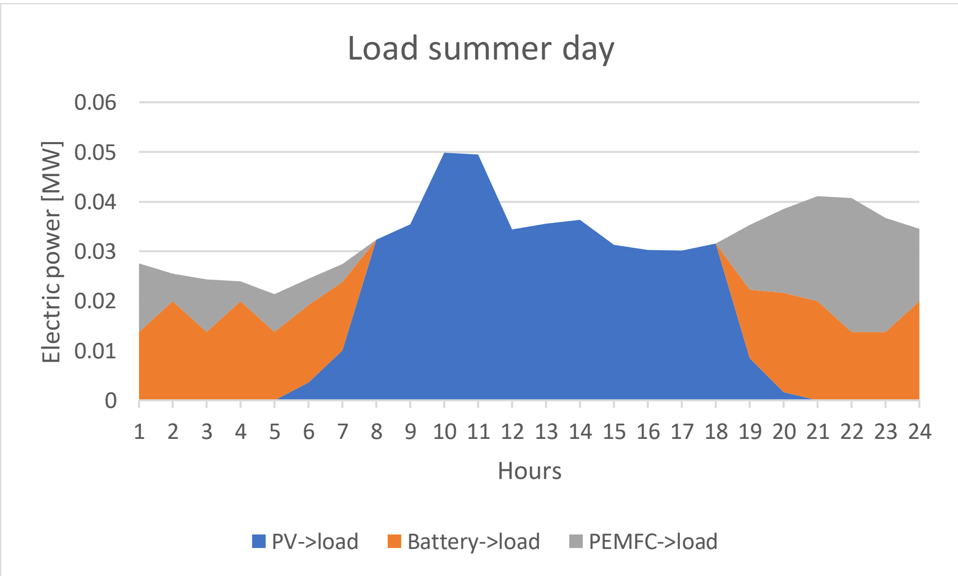

Figure 28 Hourly average load configuration

As seen before the photovoltaic is the main source to cover the load and the battery and fuel cell play have a fundamental role on covering the load during the morning and the night.

The next chart shows the daily average RES distribution in summer:

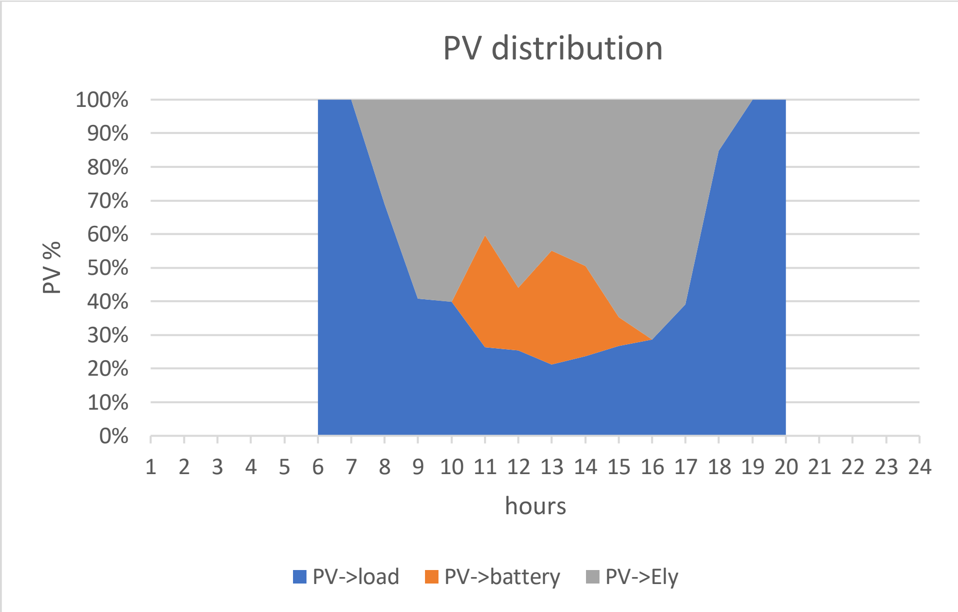

Figure 29 PV management P2P 2019

As we can note a large amount of power is directly send to the load and the remaining part is sent to feed the storage system. In case the storage system is full, and the load fulfilled, the surplus of energy would be curtailed.

Finally, the next graph shows the storage system behaviour:

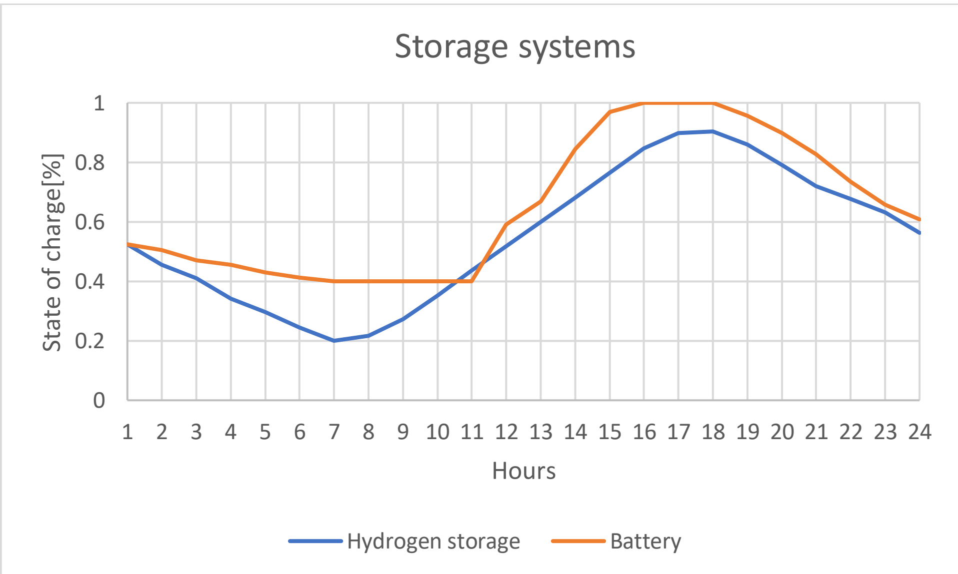

Figure 30 State of charge of hydrogen storage and battery

The optimize P2P solution in 2019 could avoid in Ginostra the use of diesel generators thus ensuring a higher energy efficiency and environment benefits. So, this system will

avoid the use of diesel generators with a fuel saving of approximately 35000 litres per year which corresponds more or less to 70 k€/y due to the high transportation cost of diesel fuel.
For what concern the 2030 scenarios, in the Diesel and RES cases the cost will increase due to the taxes associated to the production of CO_2 and NO_x.
So, in this case the reduction of the CO_2 emission becomes fundamental also from an economical aspect, indeed best solution from an environmental and economical point of view is the P2P solution.
The configuration of the P2P in 2030 is more or less the same of the 2019, but the CAPEX of the different plants has been reduced with respect to the 2019 scenario due to better efficiencies and the volume impact on supply chain and due to a greater number of manufactured units, leading to an electricity generation cost of 0,229€/kWh, which means 56% lower than the actual situation.

In 2030 has been also evaluated the possibility of selling the amount of hydrogen for hydrogen-propelled vessels, in order to reduce the amount of renewable curtailed energy.

Table 80 Slack/emissions [MWh or kg / year] P2P vs P2P+hydrogen 2030

Plant	Curtailed energy (MWh)
PV panels 2030	123
PV panels 2030 + hydrogen	12

This configuration has not been applied to the 2019 due to the high price of the hydrogen in the market.
In this configuration a large amount of power has been recovered and also, we have a decreasing cost in the electricity generation from 0,229 €/kWh to 0,174 €/kWh.
The main drawback of the P2P solution both in 2019 and 2030 is represented by the initial investment cost.

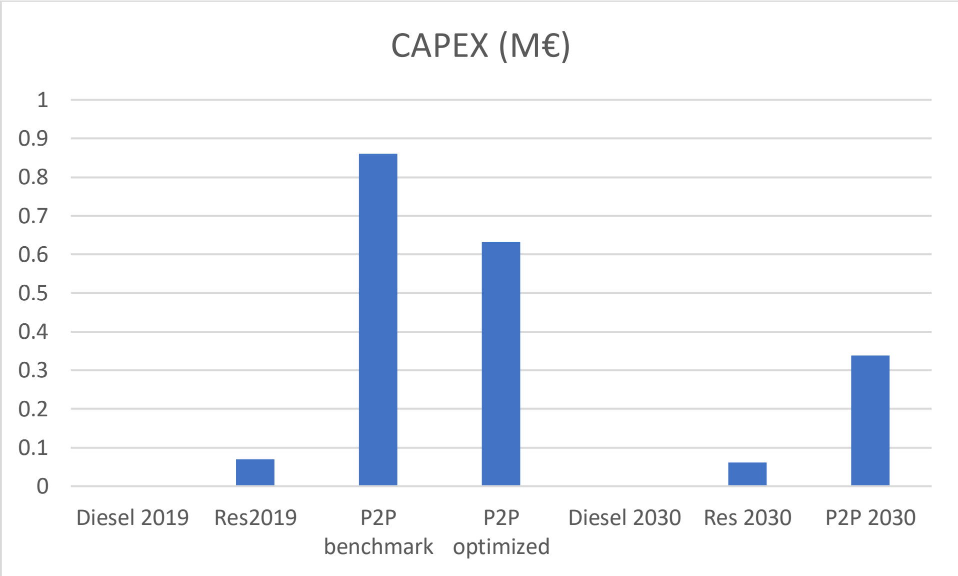

Figure 31 Capex for different scenarios

where for the diesel scenario the cost is null since 0,304 kW are already installed.
But as we have already discussed, even if the initial investment is quite high, after 20 years the power-to-power system, especially in 2030, presents the lower total net system cost.
In the following graph is shown the behavior of the total net cost during the year of plant operation:

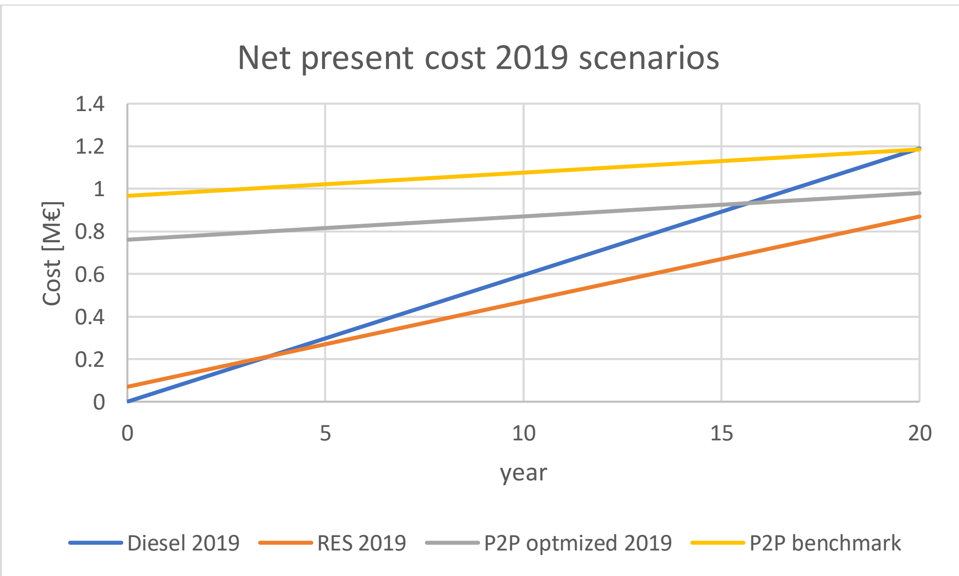

Figure 32 Net present cost for different scenarios 2019

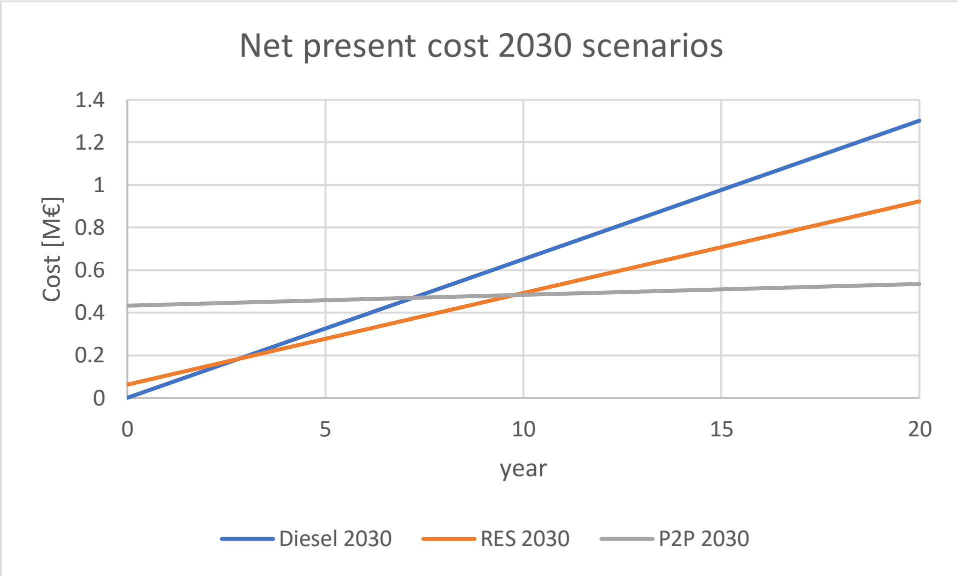

Figure 33 Net present cost for different scenarios 2030

It can be concluded that the main driver for the hydrogen business cases varies from reducing electricity costs and emissions, replacing the existing system improving the quality of the electricity service, reducing costs of electricity supply and reducing local emissions.

In the following tables the different scenarios results are summarized and a final comparison between the different solution analysed for Ginostra and the actual one in terms of delivered power cost end emission reductions.

Table 81 Cost and emission reduction wrt actual situation in Ginostra

Scenario	Cost reduction [%]	CO2 reduction [%]
Diesel 2019	-	-
Res2019	27%	42 %
P2P benchmark	1 %	100 %
P2P optimized	18 %	100 %

Table 82 Cost and emission reduction wrt actual situation in Ginostra 2030

Scenario	Cost reduction [%]	CO2 reduction [%]
Diesel 2030	-	-
Res 2030	29 %	43 %
P2P 2030	60 %	100 %
P2P + hydrogen market 2030	70 %	100 %

So, as we can notice from the previous tables in both 2019 and 2030 the power-to-power solution seems to be the most promising.

Legal-administrative barriers may represent an obstacle to a quick deployment of hydrogen demo installations.
The P2P hydrogen systems are classified as an industrial plant operating inflammable substance. The installation and operation of hydrogen-based systems requires today a significant number of permits and safety precautions, that could mean that to obtain the necessary permits for installation and operation requires additional weeks to several months.
The main obstacle of the current legislation is a lack of storage-specific regulation causing obstacles to storage deployment. To that end, the new regulation should explicitly acknowledge storage as a separate asset class to encourage its differentiated treatment in applicable uses.
Besides removing obstacles resulting from the current regulation, business cases for storage can be improved by considering new regulatory provisions.
In addition to remove obstacles and introduce new regulatory arrangements, deployment of storage technologies can be further supported by other measures with the aim to decrease costs of technologies and accelerate their commercialization, similarly to solar and wind technologies in the past[24].

The main changes that new regulation should address are summarized in the following table[25]:

Table 83 Main regulatory change needed

FROM	TO
Little regulatory acknowledgement of storage and hence a lack of storage-specific rules and insufficient consideration of the impact of new regulation on storage.	Storage acknowledged as a unique and specific component of the energy system and new regulation is explicitly taking impact on storage into account.
Payments for curtailment to RES producers, creating a disincentive to productive use of the curtailed electricity.	Remove price signal distortions caused by compensating curtailment.
Application of final consumption fees to storage, even though storage does not constitute final use of the energy.	Exemption of storage from final consumption fees and double grid fees.

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