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Life Cycle Analysis of hydrogen-based energy storage systems in off-grid areas

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Abstract

Climate change is one of the main problems of the current century: our planet can no longer withstand the emissions of pollutants from the use and combustion of fossil fuels for a long time. Many human activities are the main causes of this climate change: most of the pollutants emitted into the atmosphere derive from the use of fossil fuels for energy for power generation, for industry and in particular for heating. Widespread use of renewable energies has become one of the main objectives for the near future: they are mostly clean, which means that they do not release pollutants into the atmosphere. The main problem of these sources is their intermittence: for this reason, the use of a storage system is of enormous importance in order to better exploit these systems. The use of hydrogen as energy storage system can become an interesting option for the future given its long-term storage, its high energy density and its cleanness in terms of CO_2 emitted. Islands can take advantage of this type of RES-based technologies and P2P systems to achieve energy independence, avoiding solutions that are more expensive or have a greater impact on the environment. In this framework, REMOTE is an EU-funded project, whose main aim is to demonstrate the technical and economic feasibility of hydrogen-based energy storage solutions, designed for four demo cases distributed around Europe. The aim of this thesis is to perform a Life Cycle Assessment for Demo 1 of Remote project (the village of Ginostra, Southern Italy), comparing the current solution used in this location with the Remote one, renewable, based on RES coupled with hydrogen-based energy storage systems, in order to cover the electrical load of the island. The categories of comparison are Climate Change (CC), Particulate Matter (PM), Ozone Depletion (OD) and Terrestrial Acidification (TA). Results obtained, using SimaPro software, show that the emissions in terms of CC for Remote solution are 341.7 kgCO_2eq/MWh, with a great improvement if compared with the current solution based on diesel generators only (10300 kgCO_2eq/MWh); also the other categories exhibit similar advantages. Savings in terms of CO_2eq is huge, about 40000 tons in the total lifetime of the plant (25 years). A comparison with literature is also performed in this thesis, to verify if the results obtained are in the right range with other papers. Moreover, since it is a peculiarity of this demo, the helicopter transport is also analyzed, in order to understand if it can be considered negligible or not.

Keywords: Life Cycle Assessment, P2P storage system, Hydrogen, Remote project, Remote locations, Standalone systems, Off-grid applications, Electrolyzers, Fuel cells

Contents

List of abbreviations

Abbreviations	***Meaning***
RES	Renewable energy systems/sources
P2P	Power-to-Power
CC	Climate Change
PM	Particulate Matter
OD	Ozone Depletion
TA	Terrestrial Acidification
EIA	Energy Information Administration
OECD	Organization for Economic Cooperation and Development
IPCC	Intergovernmental Panel on Climate Change
COP	Conference of the Parties
G2P	Gas-to-Power
SME	Residential and small industrial
EGP	ENEL Green Power
EPS	Engie-Electro Power System
PEM	Proton Exchange/Polymeric Electrolyte Membrane
SOC	State Of Charge
LOH	Level Of Hydrogen
GWP	Global Warming Potential
LCA	Life Cycle Assessment

LCT	Life Cycle Thinking
EOL	End-of-Life
ISO	International Organization for Standardization
GWI	Global Warming Impact
PEMEC	Proton Exchange Membrane Electrolyzer Cell
AEC	Alkaline Electrolyzer Cell
HTE	High-Temperature Electrolyzers
SOEC	Solid Oxide Electrolysis Cell
MCEC	Molten Carbonate Electrolysis Cell
DM	Decreto Ministeriale
ICE	Internal Combustion Engine
PEMFC	Proton Exchange Membrane Fuel Cell
PAFC	Phosphoric Acid Fuel Cell
AFC	Alkaline Fuel Cell
MCFC	Molten Carbonate Fuel Cell
SOFC	Solid Oxide Fuel Cell
MEA	Membrane Electrode Assembly
HOR	Hydrogen Oxidation Reaction
ORR	Oxygen Reduction Reaction
P2H2P	Power-to-Hydrogen-to-Power
P2F2P	Power-to-Fuel-to-Power
DG	Diesel Generators
UPS	Uninterruptible Power Supply

FCH-UPS	Uninterruptible Power Supply system with Fuel Cell (Hydrogen)
ICE-UPS	Uninterruptible Power Supply system with Internal Combustion Engine
BOP	Balance Of Plant
GHG	Greenhouse Gases

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1 Introduction

The world energy consumption is increased during time, in particular in the last century: in the last 50 years it has almost tripled. Figure 1 below represents this trend.

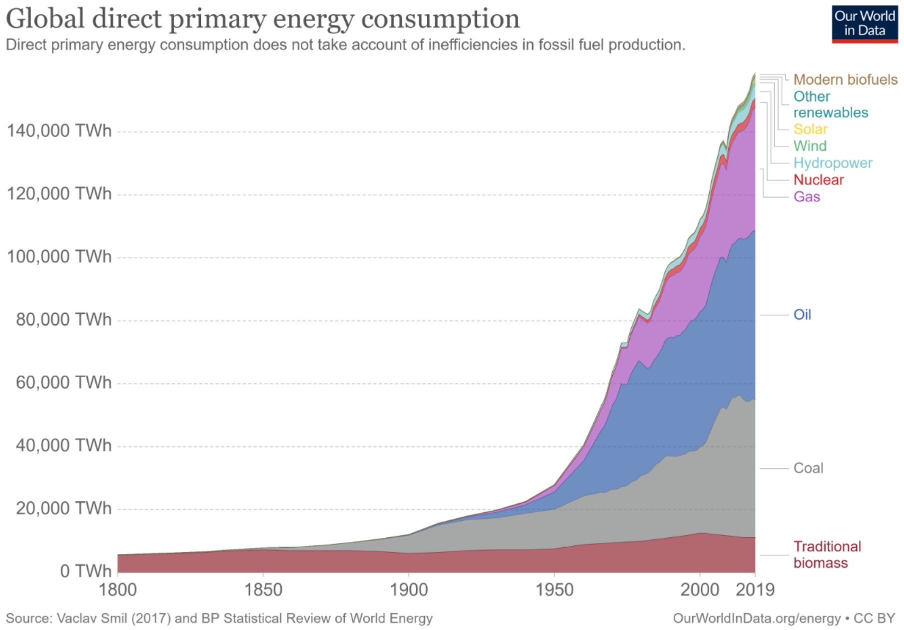

Figure 1: Global direct primary energy consumption during time [1]

According to the United States Energy Information Administration (EIA), world energy consumption will increase by almost 50% between 2019 and 2050 [2]. Most of this growth will comes from countries that are not in the Organization for Economic Cooperation and Development (OECD), and this will be focused in regions where strong economic growth is driving demand, particularly in Asia [3].

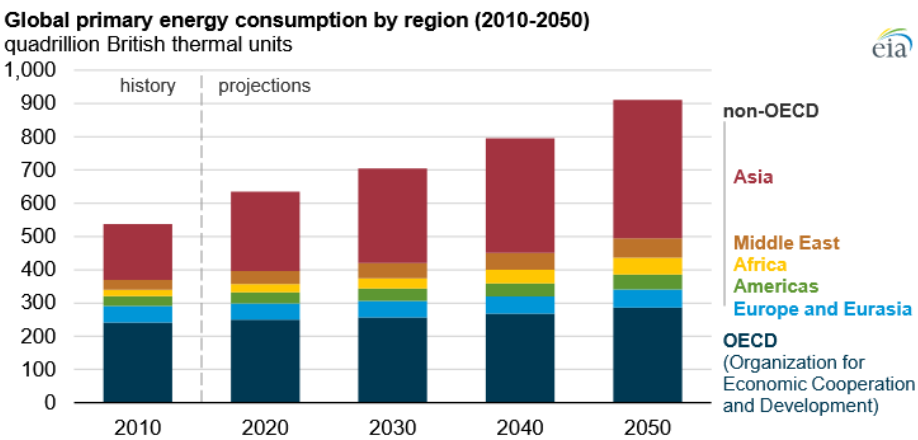

Figure 2: Global primary energy consumption by region (2010-2050) [3]

This development will focus in particular on the industrial sector and consequently there will be an increase in electricity production. The main reason is the population growth, which is expected to increase from the current 7 to 9 billion people, with the increase particularly in emerging countries (i.e. China or India).

Today, fossil fuels, represented by oil, coal and natural gas, are still the main source, providing more than 80% of total energy needs [2]. There are many problems that are associated with these fuels: first, they are not well distributed globally and often it is not the consumer country that have the resources available. However, the main issue with these fossil fuels is that they will not be able to meet future energy needs as they are subject to depletion. Considering the current rates of exploitation, oil, for example, will reach depletion in 50/60 years; for natural gas, reserves should be sufficient for 55 years; for coal, on the other hand, it will occur in about a century. Moreover, the high consumption of fossil fuels has led to increased emissions of pollutants such as CO_2 into the atmosphere. Figure 3 represents the increase of CO_2 in atmosphere during last 30 years.

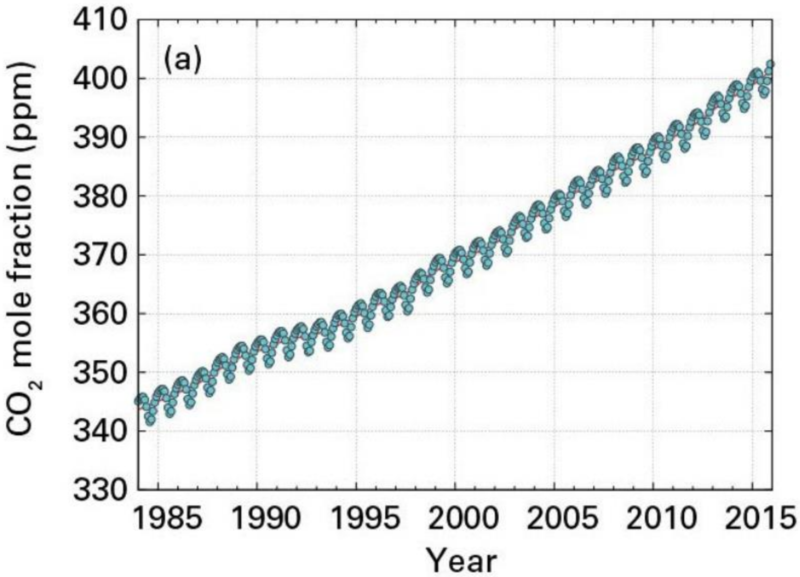

Figure 3: CO_2 world emissions increase in atmosphere during last 30 years [4]

This increasement is concentrated in the principal industrial areas: China, United States and Europe are the most important regions for CO_2 emissions.

The increasement of emission of pollutant is one of the causes of climate change: greenhouse gases in the atmosphere have reached unprecedented levels. Global climate change has already had observable effects on the environment: glaciers have shrunk, ice on rivers and lakes is breaking up earlier, plant and animal ranges have shifted and trees are flowering sooner. Effects that scientists had predicted in the past would result from global climate change are now occurring: loss of sea ice, accelerated sea level rise and longer, more intense heat waves [5].

To this day, the earth's average temperature has risen by about +0.7 °C compared to the pre-industrial era [6].

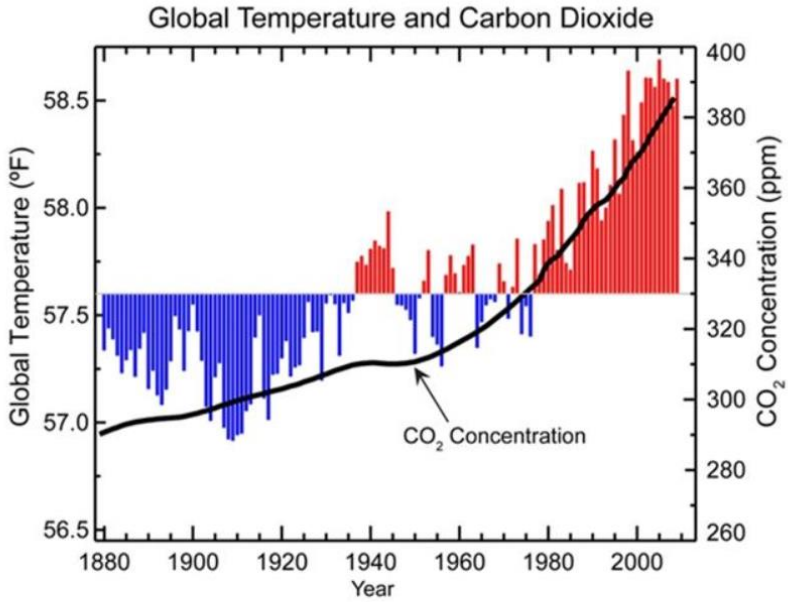

Figure 4: Global temperature and Carbon dioxide increase over time [6]

To prevent the situation from precipitating and the impacts of climate change from becoming even more violent, it is necessary to limit global warming to 1.5°C and to do so we must reduce CO_2 emissions within 450 ppm CO_2eq [6].

Over the years, different agreements have been made between nations to try to mitigate these effects. The most important ones are the Kyoto Protocol of 1997 and the Paris Agreement of 2015. Moreover, the Intergovernmental Panel on Climate Change (IPCC) was founded in order to produce comprehensive assessment reports about the state of scientific, technical and socio-economic knowledge on climate change, its impacts and future risks, and options for reducing the rate at which climate change is taking place [7].

The Kyoto Protocol is an international agreement to combat global warming. It is the first international document that imposed the obligation to reduce emissions, it was signed on December 11, 1997 during the Kyoto Conference of the Parties (COP3) but it entered into force only on February 16, 2005 thanks to the ratification of the Protocol by Russia. The Kyoto Protocol committed the undersigned countries to a quantitative reduction of their greenhouse gas emissions compared to their 1990 emission levels (baseline), in different percentages from state to state. It is divided into two compliance periods and will end in 2020 [8].

“20-20-20” is a set of targets designed by the EU entered into force in June 2009 and will be valid from January 2013 until 2020. It foresees the reduction of greenhouse gas emissions by 20%, the increase of the share of energy produced from renewable sources to 20% and 20% reduction in the primary energy consumption, so increase of energy savings. The goal is to fight climate change [9].

The Paris agreement of 2015 had the merit of being the first global agreement for the climate change mitigation. It entered into force in 2016, following the fulfilment of the conditions for ratification. It is an agreement signed by more than 190 countries that aims to keep the global temperature increase well below 2°C compared to pre-industrial levels and pursue all necessary efforts to limit the increase in temperature to 1.5 degrees as this would significantly reduce the risks and impacts of climate change [10], [11].

Renewable energies are one of the solutions to this important problem. With the rapid growth of electricity generation, renewables, including solar, wind, and hydroelectric power, will be the fastest-growing energy source between 2018 and 2050, surpassing petroleum and other liquids to become the most used energy source [3].

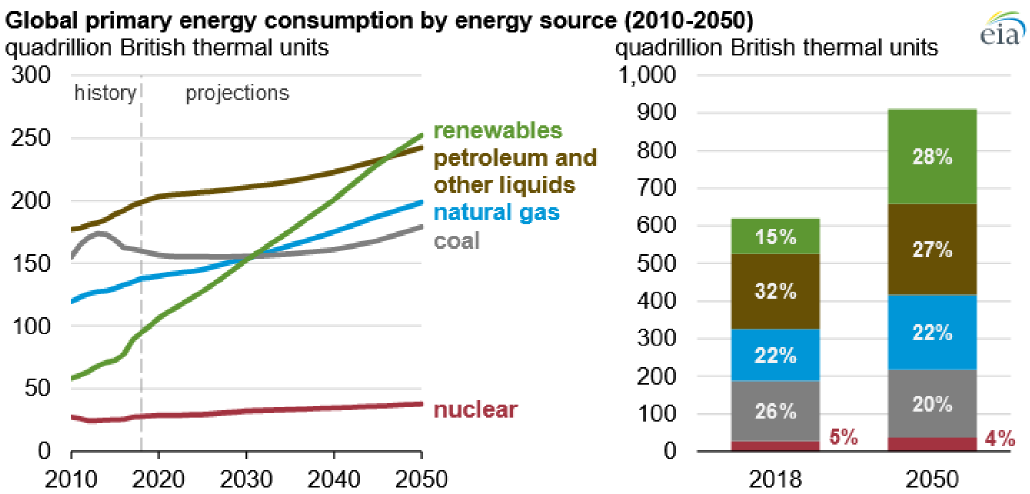

Figure 5: Global primary energy consumption by energy source (2010-2050) [3]

Renewable energies are alternative energies and for the most part they are not polluting for the environment. Their exploitation does not affect the possibility of exploiting the same sources to future generations, and this is the basis of the principle of sustainability. Renewable energies are therefore a possible solution for both the problem of energy supply and climate change, as they do not emit carbon dioxide.

Hydrogen is the key of the future: hydrogen is the fundamental pillar of the energy transition, critically needed to combat global warming and other issues related to traditional energy systems [12]. Figure 6 below represents the predicted evolution of global market shares of different final energy carriers for the period 2000-2100.

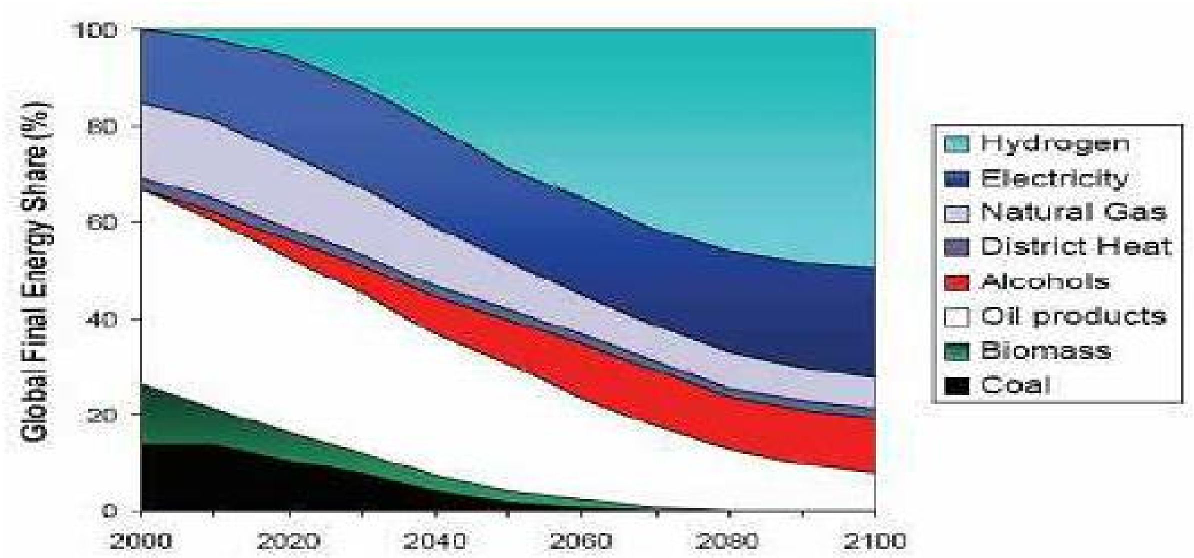

Figure 6: Evolution of global market shares of different final energy carriers (2000-2100) [13]

Renewable energies are characterized by an intermittence in production and, moreover, the demand for energy does not always correspond to the times when it is produced: for this reason, the use of an energy storage system is absolutely necessary. The use of hydrogen as an energy carrier is one of the most interesting solutions: hydrogen allows to store large amounts of energy with low environmental impact. Hydrogen can be coupled with RES (as photovoltaic panels or wind turbines) with very good results: when the renewable energy produced is not needed, it can be used to produce H_2 from water electrolysis, through electrolyzers. When subsequently energy is required, the hydrogen produced can be used in fuel cells to generate the required share. In this way fossil sources are not used and no pollutants are emitted into the atmosphere.

The presented work is performed in the framework of REMOTE (Remote area Energy supply

Multiple Options for integrated hydrogen-based Technologies): this project shall demonstrate the technical and economic feasibility of fuel cells-based H_2 energy storage solutions in isolated and off-grid remote areas. It is an EU-funded 4-year project [14], [15].

In this thesis, a Life Cycle Assessment on the first demo of the project is presented. Firstly, there is a brief description of this European project and in particular of the case under consideration. Then, there is a presentation of the methodology used, followed by a detailed chapter in which the inventory of all the components are listed and described. Subsequently, there is the section of the results, in which the two scenarios considered are compared, for all the categories selected. Finally, a comparison with literature, followed by a specific analysis of the transport contribution is also presented to complete this study.

2 Description of the case study

2.1 REMOTE project

REMOTE (Remote area Energy supply with Multiple Options for integrated hydrogen-based TEchnologies) is an EU-funded aimed to demonstrate the technical and economic feasibility of two fuel cells-based H_2 energy storage solutions (one integrated P2P system, one nonintegrated P2G+G2P system). It is a 4-year project with a budget of EUR 6.76 million. The project coordinated by Politecnico di Torino has the following partners: Ballard Power Systems Europe (DK), Hydrogenics Europe (BE), Powidian (FR), Enel Green Power (IT), Orizwn Anonymh Techniki Etaireia (EL), IRIS (IT), Tronderenergi (NO), EPS ELVI Energy (IT), SINTEF (NO), Ethniko Kentro Erevnas Kai Technologikis Anaptyxis (EL). [15].

Four demos supplied by renewable electricity will be installed in either isolated micro-grids or off-grid remote areas: the aim is to verify the energy self-sustainability of these villages, all without or with the minimum help of fossil fuels with respect to alternative technologies in terms of economics, technical and environmental benefits. This solutions, with supply by renewable energy sources (RES), will be installed in: Ginostra (South Italy), Agkistro (Greece), Ambornetti (North Italy) and Froan Islands (Norway) [14]. In figure 7, the different locations of the four demos are presented.

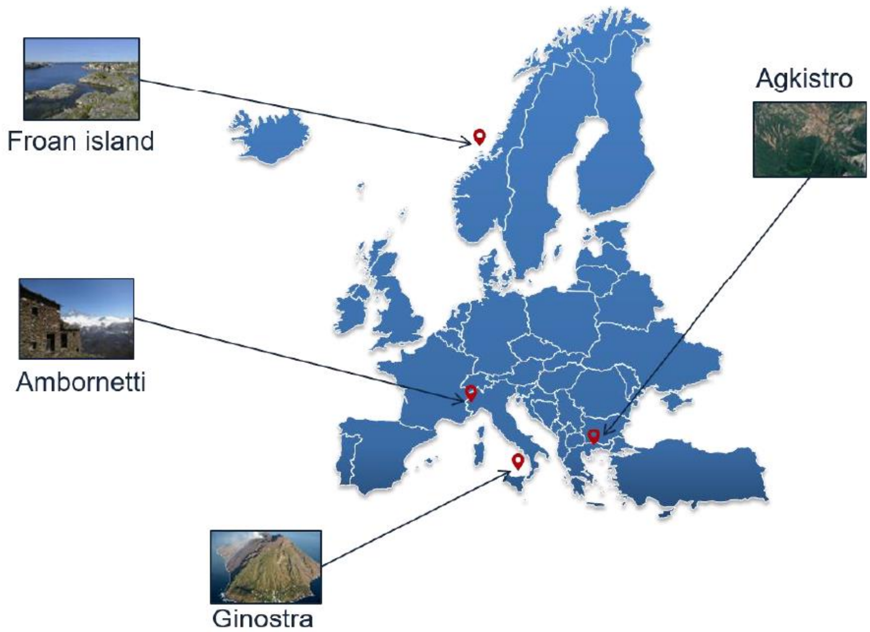

Figure 7: Geographical location of the four DEMOs [16]

These demos comprise two different plant architectures, an integrated P2P system and a non-integrated power-to-gas and gas-to-power (P2G+G2P) system, with different loads to be covered and different types of RES available on-site [14].

The four demos have been chosen in order to obtain a variety of data, so that for future studies there is a basis for comparison. The variety of these cases can help suppliers, end users and general stakeholders to gain experience. It also demonstrates energy and environmental advantages of fuel cells based H_2 energy storage solutions to the broader energy community and to decision makers willing to support more sustainable technologies. This paves way for the deployment of such energy storage solutions at large [14].

The demo cases comprise different typologies of user loads, i.e., residential and small industrial (SME), with different load profiles [14]: this changes affect the phase of design of the P2P energy storage solution but in particular protocols to manage the micro-grids. As expected, this leads to different models of energy management inside the micro-grids and to different models to [14]:

- design hydrogen-based energy storage solutions (size of the electrolyzer, size of the H_2 storage);
- identify methodologies to optimize the design of these typologies of systems;
- design protocols to manage the electric flows inside the micro-grids.

In the following subchapter there will be a brief description of the 4 demos.

2.1.1 Description of the four Demos

The four different solutions and their main technical configuration are explained in the list below, taken from [15]:

- <u>DEMO 1 – Ginostra – (South of Italy):</u> off-grid configuration (island); RES based on PV generators; residential loads available on-site; almost complete substitution of fossil fuels. End-user: ENEL Green Power (EGP), utility.
- <u>DEMO 2 – Agkistro – (Greece):</u> isolated micro-grid application; RES based on hydro generators; industrial (SME) loads available on-site; complete substitution of fossil

fuels; avoided costs for new transmission line. End-user: Horizon SA (HOR), owner of hydro plant.

- DEMO 3 – Ambornetti – (North of Italy): off-grid configuration (remote Alps); RES based on hybrid system with PV-biomass CHP generators; residential loads available on-site; complete substitution of fossil fuels. End-user: IRIS srl (IRIS), stakeholder of the hamlet.
- DEMO 4 – Froan Island – (Norway): isolated micro-grid application; RES based on hybrid system with PV+Wind generators; residential loads + fish industry available on-site; avoided costs for new sub-marine power line; almost complete substitution of fossil fuels (RES > 95%). End-user: Trønder Energi (TE), utility.

The following picture represents the REMOTE concept and innovation potential.

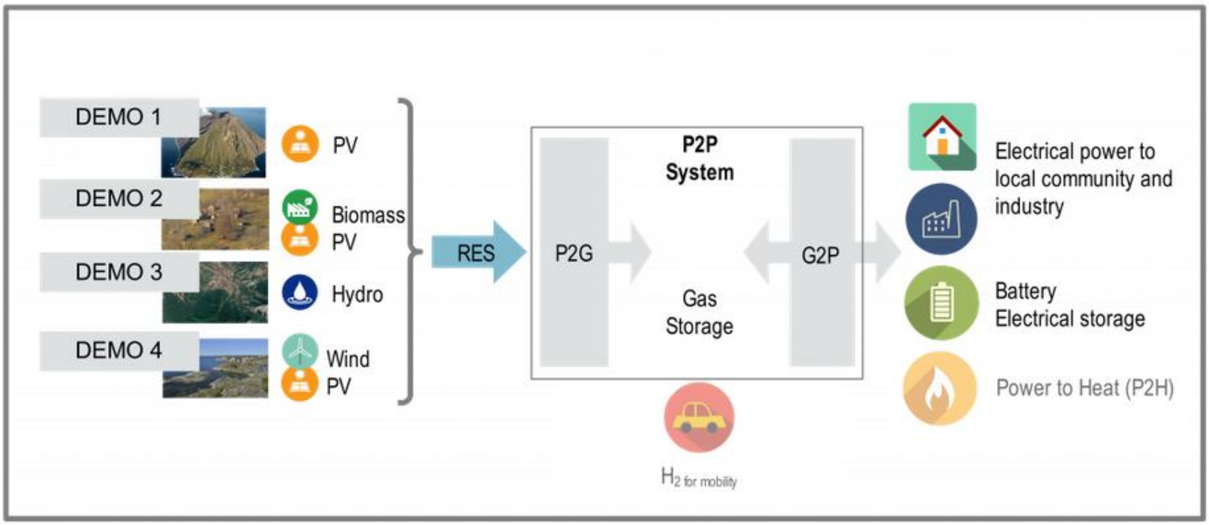

Figure 8: REMOTE concept and innovation potential [15]

A detailed summary of the main technical specifications of the components of the RES + H_2-based storage solution for the REMOTE demo sites, is reported in the figure below.

		1. Ginostra	2. Agkistro	3. Ambornetti	4. Rye/Froan[1]
RES	*Typology*	PV	Hydro	PV + Biomass	PV + Wind
	Size	170 kW	0.9 MW	75 kW PV 49 kW Biomass	250 kW PV 675 kW Wind
P2P	*Typology*	Integrated	Integrated	Non-integrated	Non-integrated
	Supplier	ENGIE-EPS	ENGIE-EPS	BPSE, ENGIE-EPS	HYG, BPSE, POW
	P2G				
	Technology	Alkaline	Alkaline	Alkaline	PEM
	Rated Power	50 kW (2 stacks)	25 kW	18 kW	50 kW
	G2P				
	Technology	PEM (O_2 fed)	PEM (O_2 fed)	PEM	PEM
	Rated Power	50 kW (2 stacks)	50 kW (2 stacks)	85 kW (6 stacks)	100 kW (6 stacks)
	H_2 storage				
	Gross energy (LHV)	1793 kWh	996 kWh	498 kWh	3333 kWh
	Battery				
	Technology	Li-ion	Li-ion	Li-ion	Li-ion
	Rated energy	600 kWh	92 kWh	92 kWh	550 kWh

[1] RES data are specific for Froan, the Norwegian archipelago which was used as case study for the techno-economic analysis.

Figure 9: Technical specifications for all REMOTE demo sites [17]

2.2 Ginostra

Ginostra is a small village located in the island of Stromboli, north of Sicily, Southern Italy, the most northern of the Aeolian archipelago. It is accessible only from the sea. It is about 2 hours and 10 minutes by ferry from Milazzo, far about 70 km.

Until a few years ago the port was considered the smallest in the world as it can accommodate only one boat at a time. There are about 40 residents. [18]

The location of Ginostra and Milazzo is shown in figure below.

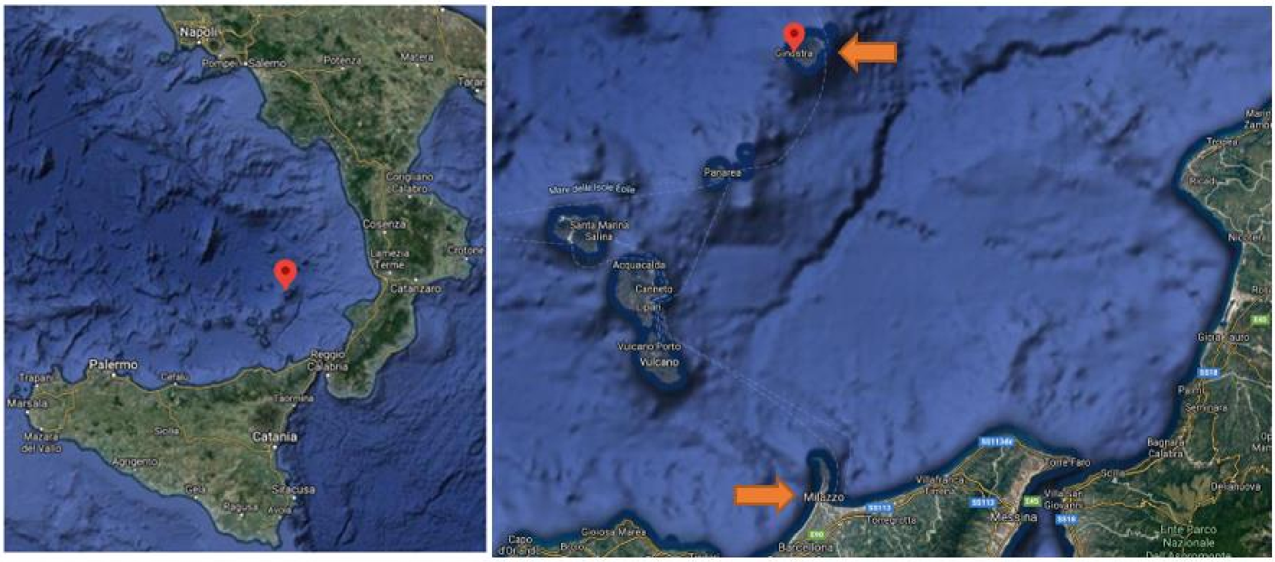

Figure 10: Location of Ginostra and Milazzo

The sustainability of the island, and consequently the electricity consumption is mostly related to the summer tourism: the village is a tourist destination, even if the coast near the village is rocky, there are no real beaches. One of the main attractions of the island is the observation of the volcanic activities of Stromboli.

Figure 11, taken from Google maps, shows the island of Stromboli to see where the village of Ginostra is located, while figure 12 represents a view of the village.

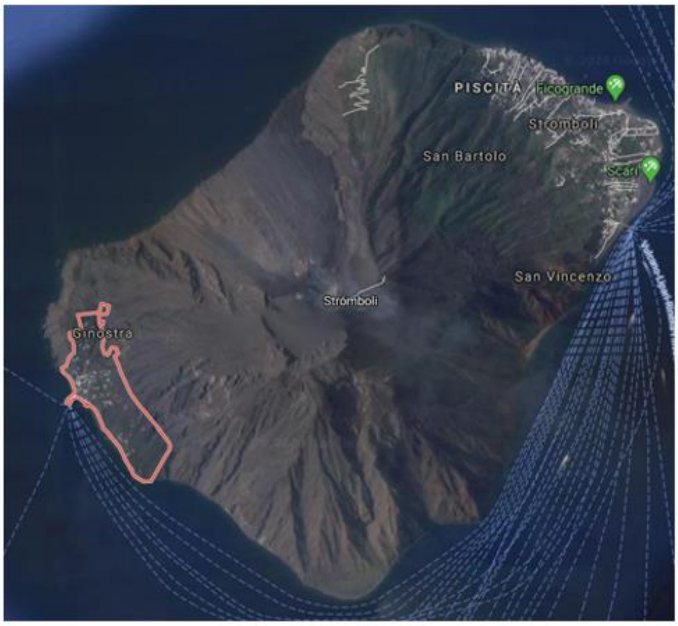

Figure 11: Island of Stromboli

Figure 12: View of the Ginostra village [15]

2.3 Current and future scenario at Ginostra

The site is classified as off-grid since not connected to neither the Italian distribution and transmission grid nor the main Stromboli island micro-grid. All loads are residential and currently satisfied by employing one 160 kW and three 48 kW diesel generators. Because of the remoteness of the area, the fuel must be transported in by helicopter leading to high costs for electricity generation [19]. Enel Green Power (EGP) is the final user of DEMO 1.

For isolated micro-grid or off-grid remote areas, a distribution network is essentially non-existent or there is an interest in managing the local network in an independent way [14]. Main drivers and advantages derived from moving to the new Power to Power (P2P) solution are [16]:

- Increase and optimize the exploitation of local renewable energy sources
- Reduce diesel consumption to decrease local pollution
- Reduce diesel consumption to lower the cost of electricity (related to transportation and logistics issues of fossil fuels due to demo remote location or avoiding the high cost due to grid connection)
- Improve the reliability of the electricity service
- Gain experience from this site improving the P2P concept to subsequently replicate in other European minor islands.

Main technical specifications of the solution proposed by the Remote project are set out below: regarding the RES power plant, a 170 kW PV system from EGP will be installed. The hybrid energy storage system includes a 600 kWh Li-ion battery bank from EGP and an integrated hydrogen-based solution from Engie-Electro Power System (EPS). In particular, the H_2 system is composed of a 50-kW alkaline electrolyzers, a 50 kW PEM fuel cell (i.e., two 25 kW P2P modules) and a hydrogen storage with total capacity of 21.6 m^3. An oxygen storage of 10.8 m^3 is also present since the fuel cell is fed with pure O_2 to avoid to send air rich of marine salts in direct contact with the cathode of the cell. Two 48 kW diesel generators will be maintained as a final back-up system [17].

Table 1 shows the components of analysed scenarios in the carried out LCA.

Components	DEMO 1 solution
PV panels	170 kW
Li-ion batteries	600 kWh
Electrolyzer	50 kW
Hydrogen storage	1793 kWh
Fuel cell	50 kW
Diesel generator	2* 48 kW

Table 1: Specifications of the different components in Ginostra

The total annual electrical load, which is currently covered by diesel generator, is around 172 MWh. The proposed P2P solution aims at reducing the use of diesel generators with consequent advantages from an economic and environmental point of view.

The new PV power plant is estimated to produce about 271 MWh/year: analyzing the hourly PV estimated energy production and the load profiles along the year, it was seen that only slightly less than one third of the overall annual energy from PV, i.e., 82 MWh, can be directly consumed by the load. An energy storage system is therefore necessary to optimize the RES exploitation and store the remaining excess RES energy to use when a renewable energy deficit occurs, thus reducing or even avoiding the intervention of the diesel generator. In case the RES electrical power exceeds the demand of the end-user load, the surplus power is first employed to charge the battery. When the maximum battery SOC is reached, surplus electricity is supplied to the electrolyzers for hydrogen production: this works until the storage tank is completely filled with hydrogen (i.e., a LOH value equal to 1 is reached); whereas the remaining excess RES energy, if present, is curtailed [17].

Simulations show that the proposed hybrid P2P solution enables to drastically decrease the use of current operating diesel generators to a value of around 4% of the total yearly demand. When the RES power is not enough to satisfy the load, the shortage is mainly met by the battery, acting as shorter-term storage. The fuel cell instead only accounts for approximately 3% of the load, but its presence is required due to its longer-term storage capability. The fuel cell is in fact mainly used in the summer period, which is characterized by a higher energy demand because of tourism. [19]

The coverage of the load from different components as described before is summarized in table 2.

Description	Results	Percentage
Load directly covered by RES	81.8 MWh	47.7 %
Load covered by P2P (battery + H_2)	83.1 MWh	48.4 %
Load covered by external source	6.7 MWh	3.9 %
Total load	171.5 MWh	100 %

Table 2: Coverage of the load from different components

3 Life Cycle Assessment

3.1 Methodology

Since the energy effectiveness of the renewable solution in Ginostra is verified, in this thesis it is carried out an environmental analysis. The most important index used in this work is the climate change, or CO_2 equivalent: a carbon dioxide equivalent is a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential [20]. GWP is an index, it is the ratio between the impact caused by a gas in a given period of time (generally 100 years), compared to that caused in the same period by the same amount of carbon dioxide [21]. To evaluate the quantity of CO_2-eq for a given gas, we have to multiply the mass of the gas by the associated GWP:

$$CO_2\ \text{eq} = mass\ of\ the\ gas * GWP\ of\ the\ gas\ [1]$$

For example, GWP for methane is 25: this means that the emission of 1 metric ton of methane is equal to 25 metric tons of carbon dioxide. The carbon dioxide equivalent is not the only index used in this work, there will be a proper section in which all the impact assessment categories are well explained.

In the environmental analysis performed in this thesis, but also in many papers cited during this lecture, it is followed a Life Cycle Assessment (LCA) philosophy.

First of all, we have to focus on the Life Cycle Thinking (LCT): it is an approach, which implies that the environmental assessment should cover the whole life cycle [22]. It starts from the concept of sustainability. The idea of sustainability is based on three pillars: environmental, social and economic. To be sustainable, a process must respect these three pillars, in each phases of its life. A product life cycle can begin with the extraction of raw materials from natural resources in the ground and the energy generation. Materials and energy are then part of production, packaging, distribution, use, maintenance, and eventually recycling, reuse, recovery or final disposal (the so-called End-of-Life, EoL). In each life cycle stages there is the potential to reduce resource consumption and improve the performance of products [23], so there is the potential to be sustainable.

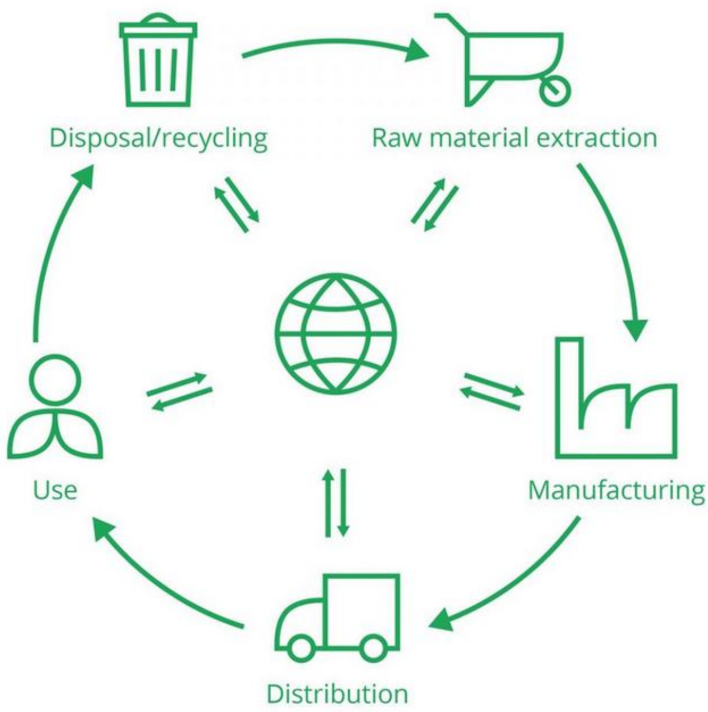

Figure 13: General Life Cycle stages

Life Cycle Assessment (LCA) stands for a quantitative and standardised methodological framework that was developed in the early 1990s (ISO 14040-44). It is an objective tool for analysing and quantifying the environmental consequences of products (services) during all their life cycle [22]. The evaluation is performed by identifying energy and materials consumed and the wastes released in the environment. The evaluation includes all stages of the entire life cycle of the process/activity/product, including extraction and treatment of the raw materials, fabrication, transport, distribution, use, reuse and final disposal [23]: this is called “from-cradle-to-grave”. LCA can assist in identifying opportunities to improve the environmental performance of products at various points in their life cycle, in informing decision-makers in industry, in the selection of relevant indicators of environmental performance, in including measurement techniques, and in marketing [23].

Why using LCA? Because LCA is a standardized and worldwide accepted objective instrument that allows identifying and measuring environmental sustainability [22].

In a company, a LCA is important because it generates detailed and reliable information on its operations, internal use, and it answers questions from customers; moreover it is useful to identify areas of interest, such as the contribution to the greenhouse effect, to provide a sound scientific basis for environmental comparison between its products [23].

A typical LCA is divided in four different phases [24], [25], [26]:

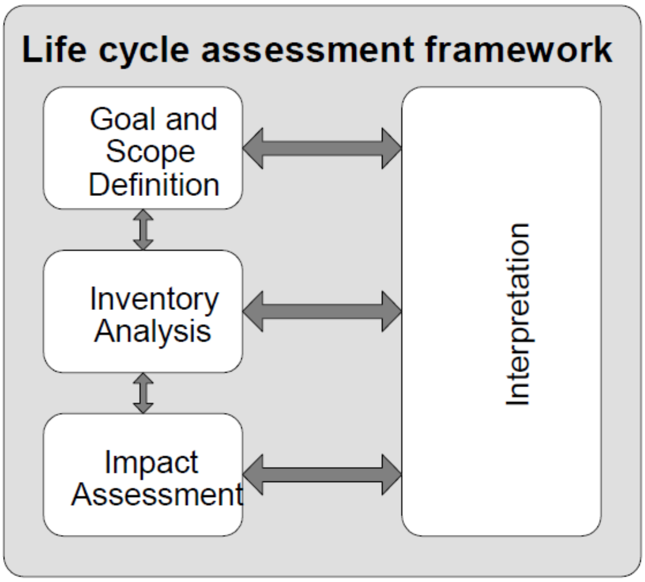

Figure 14: Life cycle assessment framework [22]

1. Goal and scope definition: to define goal, scope function, system boundaries and functional unit of the study;
2. Inventory: to provide a detailed description of the inputs of raw materials and fuels into a system and the output of wastes from it;
3. Impact assessment: to understand and evaluate the magnitude and significance of the potential environmental impacts of a product system;
4. Interpretation and improvements: to reach conclusion and recommendations.

This work is divided in similar parts. Firstly, there is a description of the goal and scope, functional unit, system boundaries and impact assessment categories. Then, there is a section for the inventory, in which there will be a detailed description for each component and the system boundaries more specific for each subsystem, both for the Remote scenario and for the current scenario. After this, there will be the analysis of the results, with a comparison with the two scenario and also with some papers from literature and this, finally, will be the basis of the last part, the conclusion.

3.1.1 Goal and scope definition

The goal of this environmental analysis is to evaluate and compare the difference in the emission between the Remote solution and the current one, in order to understand if the renewable solution will be a valid alternative knowing the effectiveness of its usage from an energetic point of view. The aim of this analysis is also to identify the process or the components that have a bigger environmental burden, in order to understand where the company or the decision maker has to concentrate its possible future improvements. The main index of comparison will be the global warming impact (GWI) or climate change, in terms of CO_2-eq. The results can be useful for future development in the Remote project, but also can be a reliable base to confront for new and different renewable systems in remote locations.

The system to be studied is composed by PV panels, the only energy source of the plant in consideration. There are two different storage systems: the first is the Li-ion battery, useful for the short-term storage of the electricity. Then there is the hydrogen pathway: it is composed by the electrolyser, the hydrogen storage, the oxygen storage and the fuel cell. If the electricity surplus is not directly used or stored in the battery, it is used in the electrolyser in order to produce hydrogen. This production will be useful in case of energy storage for a long period. This hydrogen will be then used in the fuel cell to produce electricity. The gas produced in the electrolyser stack will be stored in hydrogen tanks, and also some oxygen will be stored in order to avoid to send air rich of marine salts in direct contact with the cathode of the fuel cell. Lastly, there are two 48 kW diesel generator, that will be maintained as a final back-up system in case of non-production or problems in production of electricity.

3.1.2 Functional unit

The functional unit considered is 1 MWh of electricity generated from the different components of the Remote and current scenario, and, in order to compare these two, results are expressed in the same unit.

3.1.3 System boundary

This study is performed considering the life cycle of the plant: it is not a “cradle-to-grave” analysis because the End of Life (EOL) is not considered since we don’t have data. For this reason, we decide to call this analysis a “cradle-to-utilization” LCA, because the boundary of the system is placed at the use phase of each components. In this way, this work can be useful for better comparison with other systems, because the EOL can differs depending on the location of the plant in consideration: for example, in some nations, components can be sent to landfill while in others are fully recycled, and this brings to difference in the emissions. This “Cradle-to-utilization” LCA includes the extraction and processing of raw materials, manufacture, installation, transportation to Ginostra and the use phase.

Regarding transport, this is a peculiarity of this Demo: differently from the others, we have to consider the helicopter trips to carry the components in the plant from the mainland. So, one of the aims of this thesis is to evaluate the amount of emission of the transport phase, to understand if it is negligible or not. For this reason, the transport considered is the helicopter round-trip Milazzo-Ginostra, where Milazzo is a city in the mainland in Sicily. All the other transportation from the place of production or extraction of the materials to Milazzo are not considered in this analysis.

Regarding the specific boundaries for each component, these will be defined in the following section, together with the inventory. Everything that is in common with the two scenarios, as the distribution, is not considered.

3.1.4 Impact assessment categories

The categories selected in this analysis are representative of those impacts that are likely to derive from an electricity production. Some categories are not included in the analysis for different reasons: human toxicity is not considered because the way it is calculated is not completely accepted in the scientific world. Another category not studied is the abiotic depletion, for which there is a little agreement.

The following environmental impact categories are evaluated in the LCA:

1. Climate change [kg CO_2-eq]
2. Particulate matter [kg PM2.5-eq]
3. Ozone depletion [kg CFC11-eq]
4. Terrestrial acidification [kg SO_2-eq]

The first three categories are calculated using the European method, “ILCD 2011

Midpoint+", while the fourth is calculated using the method "ReCiPe Midpoint (H)". These categories and these methods are the same of the ones used in [27] and in a thesis about Froan plant, so there is the same approach with the analysis of these two Demos.

3.2 Remote scenario

In the following picture, figure 15, the general configuration of a stand-alone RES/H_2/battery-based hybrid system for this DEMO is shown.

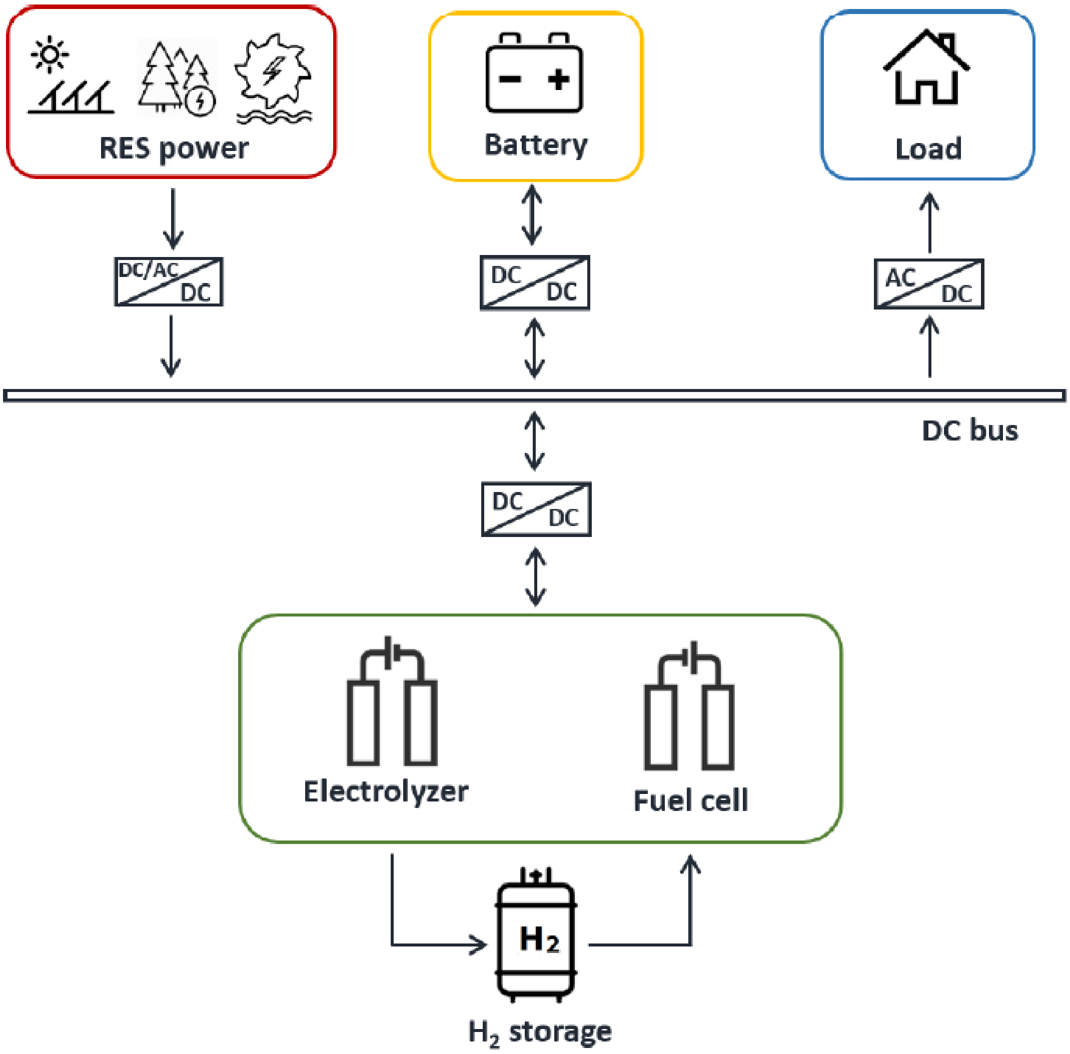

Figure 15: General configuration of a stand-alone RES/H2/battery-based hybrid system [16]

After some preliminary energy simulations, the effectiveness of the hybrid energy storage solution in reducing the usage of external sources is demonstrated [19]. These simulations are useful in order to evaluate the energy exchanges between the load and the components; the part of the load that can't be covered by RES will be supplied using the diesel generators (almost 4% of the total load). These values are reported in the tables 3 and 4 (these data are taken from [17].

RES usage				
RES to load	RES to electrolyser	RES to battery	RES to curtailment	Total RES
MWh/y	MWh/y	MWh/y	MWh/y	MWh/y
88.713	8.442	103.282	70.388	270.826

Table 3: Annual RES usage results

Load coverage				
Load directly covered by RES	Load covered by fuel cell	Load covered by battery	Load covered by external source	Total residential load
MWh/y	MWh/y	MWh/y	MWh/y	MWh/y
81.756	2.398	80.701	6.688	171.543

Table 4: Annual load coverage results

The lifetime of the plant is assumed to be 25 years, as for the Froan plant: so, we can calculate the total energy provided in those years. Results are listed in the next two tables, 5 and 6.

Total RES usage				
RES to load	RES to electrolyser	RES to battery	RES to curtailment	Total RES
MWh	MWh	MWh	MWh	MWh
2217.825	211.05	2582.05	1759.7	6770.65

Table 5: Total RES usage results in 25 years

Total load coverage				
Load directly covered by RES	Load covered by fuel cell	Load covered by battery	Load covered by external source	Total residential load
MWh	MWh	MWh	MWh	MWh
2043.9	59.95	2017.525	167.2	4288.575

Table 6: Total RES coverage results in 25 years

The by-product of the system, heat, is assumed negligible. Concerning the transport, we only consider the helicopter from Milazzo to Ginostra, we do not consider the one to arrive in Sicily. For this helicopter input, in SimaPro®, we have to put the length of the trip in hours: we take the distance from Google Maps and the average helicopter speed (we take the cruising speed) and we calculate the approximate time for the trip. To evaluate the number of trips of the helicopter we start from its maximum capacity data, then we evaluate the weight of each component and we make the division rounding up. The maximum capacity data differs a lot from one helicopter to another, for example from the link [28] there are data of 1400 kg of transport on the hook or 4500 kg of transport on the hook: we choose a middle way, 2000 kg, that is a typical value for cargo helicopter. In the following sections there is a more detailed description of the different components of the plants.

3.2.1 PV panels

The first and only energy source of our plant is the photovoltaic system: a PV power plant of 170 from EGP kW is employed. It consists of 39 strings, each of them composed of 12 modules, which are made of mono-crystalline silicon and characterized by a rated power of 365 W.

Figure 16: Ginostra PV plant [15]

PV panels are estimated to produce on a yearly basis about 270.826 MWh. More in detail, the table 7 below reports the yearly values of the total consumption, RES production, direct RES consumption, surplus and deficit (the sum of the direct RES consumption and the deficit is equal to the total load, while the sum of the direct RES consumption and the RES surplus is the RES production) [16]:

	Energy
Total load	171.543 MWh
RES production	270.826 MWh
Direct RES consumption	81.756 MWh
RES surplus	189.07 MWh
Deficit	89.787 MWh

Table 7: Annual load, RES production, RES consumption, RES surplus and Deficit

Figure 17 below shows the monthly distribution of PV production and load [16]:

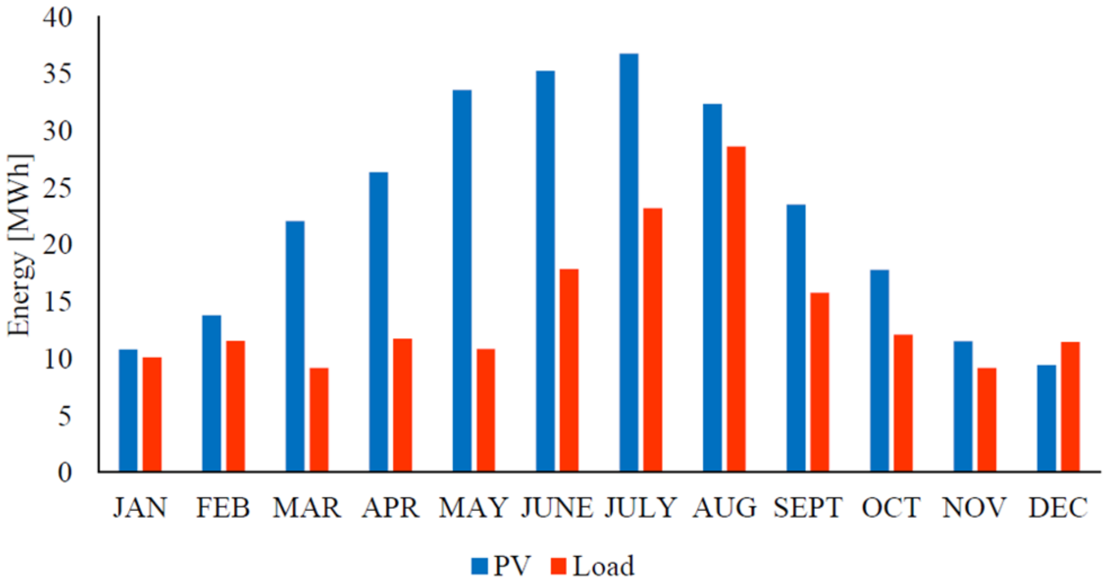

Figure 17: Monthly distribution of PV production and load [16]

We assume to use, for our calculations, the “3S DUAL 72N”: is a type of panel developed by EGP, of last generation. It is characterized by a high efficiency, high durability against harsh environment conditions and higher lifetime power yield [29].

Starting from the main characteristics of the panels, we evaluate the total number of modules and the total PV area of the plant: these values are listed in the tables below, number 8 and 9.

N° of cells	Cell type	Panel dimension	Weight	Product warranty	Module efficiency	Maximum power NOTC
-	-	*mm*	*kg*	*years*	*%*	*W*
6 x 12	Mono-crystalline, n-type	1983 x 998 x 7.5	33	30	18.2	365

Table 8: Main specification of the PV panels

PV plant power capacity	Maximum power NOTC	Number of modules	Area of modules	PV total area
kW	*W/module*	-	*m^2/module*	*m^2*
170	365	466	1,979034	922.23

Table 9: Evaluation of total number of modules and PV total area

The lifetime of the PV panels is assumed to be 30 year: after this period, the power performance is still guaranteed to be at 85%. For this reason, we don't have to consider the replacement in the lifetime of the plant.

Regarding the life cycle stages, the boundaries are specified for a cradle-to-utilization LCA: this includes the extraction of raw materials, the material processing, manufacture, transport to Ginostra, installation and the use stage. Concerning the installation, two components are considered: the electric installations and the photovoltaic mounting system. These two data are taken from SimaPro®. In particular, in the database, the electric installations are based on a 570-kW open ground module: having a PV system in our plant of 170-kW, with a simple proportion we have calculated the required quota for Ginostra: it is an hypothesis, but considering that the environmental burden of this components is negligible, we can consider it suitable. The same idea is applied to the photovoltaic mounting system, also based on a 570-kW PV plant. We don't have data instead for maintenance and for the inverter. The block diagram for PV panels is summarized in figure 18 below.

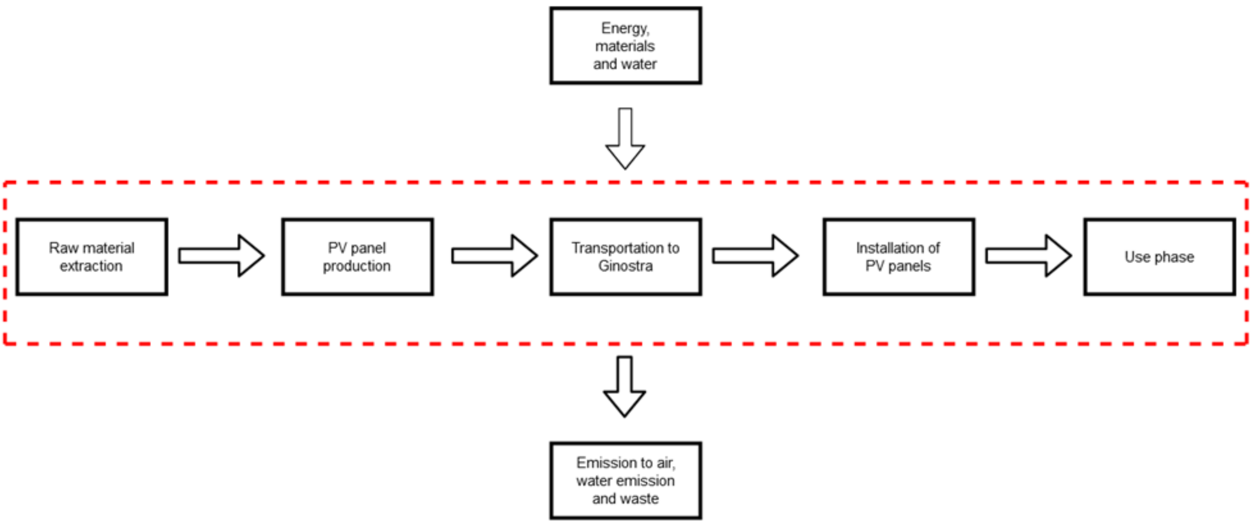

Figure 18: Block diagram for PV panels

Regarding the transport, it is considered only the one with the helicopter, from Milazzo to Ginostra. SimaPro® requires as input the hours of travel: knowing the total weight of the modules and the maximum transport capacity of the helicopter, we obtain the number of trips required and so the number of hours requested. In this case we don't have to replace the PV system since the lifetime of the plant is higher than the warranty of the modules. Tables 10 and 11 summarize the calculation done to obtain these values.

Round-trip distance Milazzo-Ginostra	Average helicopter velocity	Time for round-trip	Maximum transport capacity of the helicopter
km	km/h	h	kg
139.6	250	0.5584	2000

Table 10: Generality about the helicopter trips

Number of modules	Total weight of the modules	Number of helicopter trips	Hours of helicopter trips
-	kg	-	h
466	15378	8	4.47

Table 11: Calculation of hours of helicopter trips for PV panels

In table 12, it is summarized the inventory of the block "PV panels" used in the software SimaPro®, considering the hypothesis listed before:

Known input from Technosphere	Physical quantity	Unit of measurement
Photovoltaic panel, single-Si wafer {GLO}|market for| Alloc Rec, S	922.23	m^2
Transport, helicopter {GLO}| processing | Alloc Rec, S	4.4672	h
Photovoltaic plant, electric installation for 570kWp open ground module {GLO}| market for photovoltaics, electric installation for 570kWp module, open ground | Alloc Rec, S	170/570	p
Photovoltaic mounting system, for 570kWp open ground module {GLO}| market for | Alloc Rec, S	170/570*922.23	m^2

Table 12: Inventory of PV panels used in SimaPro®

The sentences in the column of known input from Technosphere are reported exactly from the software: the first block includes the steps of raw material extraction and manufacturing of PV panels, while third and fourth ones represents respectively the step of installation of these modules in Ginostra plant.

3.2.2 Batteries

An appropriate storage system needs to be designed maximizing the exploitation of RES sources and minimizing the intervention of diesel generators [16]. The first possibility to store surplus energy from PV system is to charge a Li-ion battery bank. During renewable power shortages, the remaining energy fraction to cover the load is supplied by the battery discharging [17]. The other possibility is the storage of energy through the hydrogen, it will be described in the following sections: the battery device has a higher efficiency compared to the hydrogen pathway. The battery is required to provide electricity for the daily operation of the control unit and auxiliary equipment: it also acts as a daily energy buffer, smoothing down the RES power output and avoiding too frequent start-ups and shutdowns of the electrolyzer and fuel cell.

The necessity of battery is increasing in the years, in particular for portable devices but in future also for electric vehicles. As a consequence, the cost in time is reducing. Batteries are characterized by a lower energy density than any other fuels, both in terms of gravimetric and volumetric. Therefore, they are characterized by higher specific energy than capacitors and higher specific power respect to fuel cells. Some peculiarity are: a long life cycle, a fast charge, a wide temperature range, they are safe, recyclable and cheap [30].

There are different types of batteries: Li-ion systems are certainly preferable because of the higher energy densities mainly related to the low weight of the materials. They have been widely used in cell phones, laptops, digital cameras and many other products due to its high energy density, high voltage, low self-discharge, non-memory effect, long cycle life and environmental friendliness [31].

There are different types of Lithium battery systems which differs for the materials: commonly the cathode is an oxide or a phosphate. We can have different kind of anode: we can have metallic lithium or graphite. With this latter, we have a lithium-ion battery.

In Ginostra, a 600 kWh Li-ion battery bank from EGP, with an efficiency of 95%, a charge/discharge rate of 0.5C and a State of Charge (SOC) between 20% and 80% is installed. This device will receive about 103.282 MWh/y from RES and the load covered from it will be about 80.701 MWh/y. In table 13 there are the main characteristics of the battery bank.

Rated energy	Charge/Discharge rate	Efficiency	SOC_{min}	SOC_{max}
kWh	kW/kWh	%	%	%
600	0.5C	95	20	80

Table 13: Main characteristics of the battery bank

Regarding the life cycle stages, the boundaries are specified for a cradle-to-utilization LCA: this includes the raw material extraction, the material processing, the part manufacturing and the battery manufacturing, and last the use phase. We don't have data for the maintenance. In SimaPro® we have directly the data for the Li-ion batteries, the quantity needed is in kg: so, we take the rated energy and we divide it for the energy density of the battery, obtaining the required mass. As energy density, they have one of the highest energy densities of any battery technology today (between 100-265 Wh/kg or 250-670 Wh/L) [32], thus we take a general value from literature of 150 Wh/kg, since we don't have data of the battery used in this demo. The block diagram for batteries is summarized in figure 19 below.

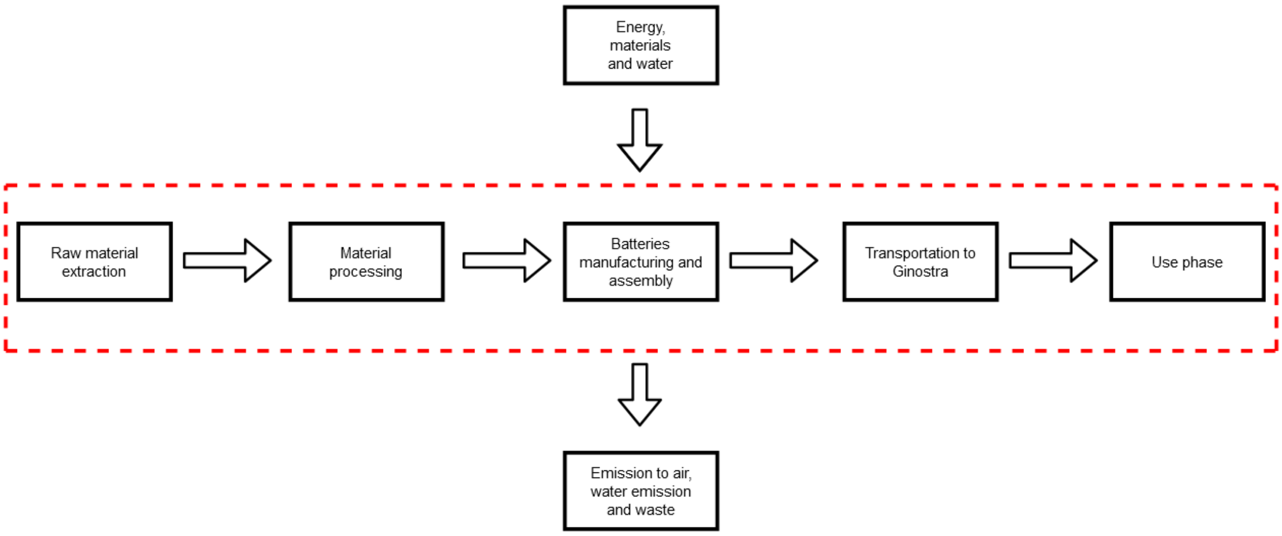

Figure 19: Block diagram for batteries

For the transport, it is considered only the one with the helicopter, from Milazzo to Ginostra. Knowing the total mass of the batteries and the transport capacity of the helicopter (2000 kg [28]), we obtain the total number of travel and so the hour required.

Number of batteries needed	Total weight of the batteries	Number of helicopter trips	Hours of helicopter trips
-	kg	-	hr
3	12000	6	3.3504

Table 14: Calculation of hours of helicopter trips for batteries

In table 15, it is summarized the inventory of the battery stack used in the software SimaPro®, considering the hypothesis listed before (where 3 is the number of batteries needed in the lifetime, 600000 are the Wh and 150 is the energy density):

Known input from Technosphere	Physical quantity	Unit of measurement
Battery, Li-ion, rechargeable, prismatic {GLO}| market for | Alloc Rec, S	$3 * 600000/150$	kg
Transport, helicopter {GLO}| processing | Alloc Rec, S	3.3504	hr

Table 15: Inventory of batteries used in SimaPro®

The sentences in the column of known input from Technosphere are reported exactly from

SimaPro®: the first block includes the steps of raw material extraction, material processing, batteries manufacturing and assembly.

3.2.3 Electrolyzers

The first part of the non-integrated hydrogen storage system is the electrolyzer: when the energy storage is required for a longer period, batteries become expensive and the integration with H_2-P2P systems with medium/long-term capabilities can be a viable and reliable option [17]. This device transforms the surplus energy in hydrogen, that is stored and then used in the fuel cell to produce electricity when needed. In this thesis, both Alkaline and PEM electrolyzers are analyzed in order to see what the difference in the emission for these two technologies are, but the solution used at Ginostra is the Alkaline one.

Electrolyzer is a technology which splits water into hydrogen and oxygen using electricity. It is classified as one of the best ways to produce hydrogen, due to the high efficiency and the low energy needed [33] and if combined with carbon-free electricity coming from RES or nuclear energy, could represent a sustainable pathway for hydrogen production [34]. Even though it is categorized as a good way to produce hydrogen, only a small percentage of the global production is made by electrolysis: this because of the cost, that is still high [35]. In the near future, this technology will improve, and cost will decrease, and consequently it will become one of the most relevant way to produce hydrogen. The basic equipment common to all the electrolysis technologies is the electrochemical cell, constituted basically by two electrodes and an electrolyte. At the electrodes, electrochemical reactions take place, while the delivered ions are transferred through the electrolyte layer and electrons along external conductors. The overall reaction of water electrolysis is the same for all the technologies [34]:

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

The electrolysis of water can either be done at low temperature using liquid water or at high temperature using steam. The categories for low temperature electrolyzers are Proton Exchange Membrane Electrolyzer Cell (PEMEC) and Alkaline Electrolyzer Cell (AEC). High-Temperature Electrolyzers (HTE) is divided into two techniques: Solid Oxide Electrolysis Cell (SOEC), that operates in the range of 700-900 °C, and Molten Carbon Electrolysis Cell

(MCEC) [35]. Figure 20 represents the general configuration of a typical electrolysis cell [35].

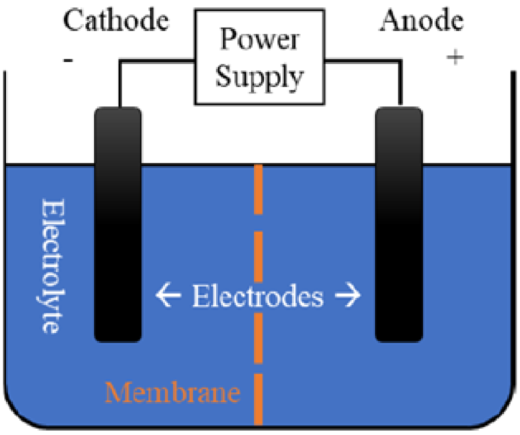

Figure 20: General configuration of a typical electrolysis cell [35]

Alkaline electrolysis has become a well matured technology for hydrogen production up to the megawatt range and it constitutes the most extended electrolytic technology at a commercial level worldwide. It has been used in commercial purposes since the early 1900s, but it is one of the easiest, simplest and suitable methods for hydrogen production: however, this method faces the crisis of relatively high energy consumption, maintenance cost and safety. Alkaline is a low-temperature technique, which operates at a temperature of 40-90ºC; it has a long lifetime and produces hydrogen with high purity [35], [34], [36].

It is characterized by having two electrodes separated by a gas- tight diaphragm which has the function of keeping the product gases apart from one another for the sake of efficiency and safety. This assembly is immersed in a liquid alkaline electrolyte that is usually a highly concentrated aqueous solution of KOH (25–30 wt.%) to maximize its ionic conductivity. Other possible electrolytes solutions of NaOH or NaCl are less commonly used. If a direct current is connected to the electrodes, hydrogen is produced at the cathode and oxygen at the anode [36], [37].

The conversion from water to hydrogen and oxygen in a basic Alkaline electrolysis occurs by following reactions:

$$Anode: \qquad 2OH^- \rightarrow \frac{1}{2}O_2(g) + H_2O + 2e^- \quad [3]$$

$$Cathode: \qquad 2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^- \quad [4]$$

This technology is already implemented and available, and to a relatively low cost: this emanates from the material cost. The main disadvantage of the technology are the slightly lower lifetime and less efficiency [33]. Other issues are: low partial load range, limited current density and low operating pressure and its corrosive character. In this picture, figure 21, the scheme of the operating principle of an Alkaline electrolysis cell is represented [38]:

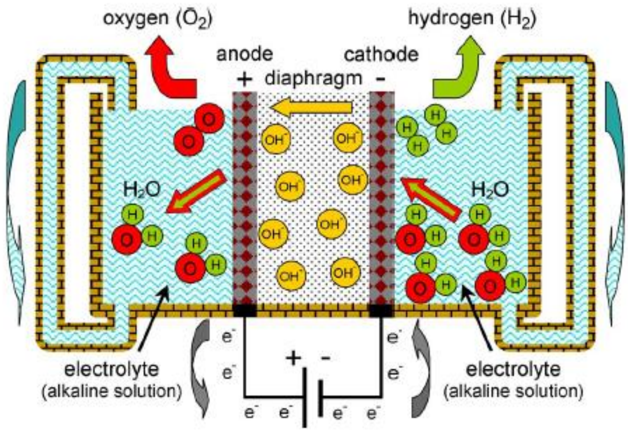

Figure 21: Operating principle of an Alkaline electrolysis cell [38]

PEM electrolyzers produce best alternative for hydrogen production other than alkaline water electrolysis. It is a low-temperature technique, which operates with a pressure up to 15 bar and a temperature around 80ºC. It is characterized by a great hydrogen purity (99.999%) and it is more flexible in terms of easy start and stop [35]. PEM electrolyzers have ability to work under variable power supply: this is due to the fact that the proton transport across the polymeric membrane responds quickly to power fluctuations. This is in contrast with alkaline electrolyzers, where the ionic transport in liquid electrolytes shows a greater inertia [37]. In a PEMEC electrolysis, the electrolyte is not required to be liquid and is commonly a polymer, due to the high proton conductivity in addition to good mechanical and chemical stability. The membrane is thin and conducts protons; the most commonly used membrane is Nafion. The electrodes are Nobel metal-based such as Platinum or Iridium. The conversion from water to hydrogen and oxygen in a basic PEM electrolysis occur by following reactions:

$$Anode: \qquad H_2O \rightarrow \frac{1}{2}O_2(g) + 2H^+(aq.) + 2e^- \quad [5]$$

$$Cathode: \qquad 2H^+(aq.) + 2e^- \rightarrow H_2(g) \quad [6]$$

PEMEC has historically not been the first-hand choice and therefore lack industrial majority: this is due to disadvantages such as the limited lifetime, the high investment cost, associated to the membranes and the noble metal based electrodes and the great sensitivity towards impurities in the water. PEMEC is more expensive then Alkaline, due to the high price for the membrane and the Nobel metal-based electrodes such as platinum or iridium [35]. Advantages are ecological cleanness, small size and mass, high purity of hydrogen gas, lower power consumption, high proton conductivity, control over electrical power variations, high pressure operation, higher safety level, easy handling and maintenance [39]. In the near future, the price is expected to significantly decrease and therefore together with the operational flexibility, the technology is predicted to be more attractive than Alkaline [35]. In this picture, figure 22, the scheme of the operating principle of a proton exchange membrane (PEM) electrolysis cell is represented [38].

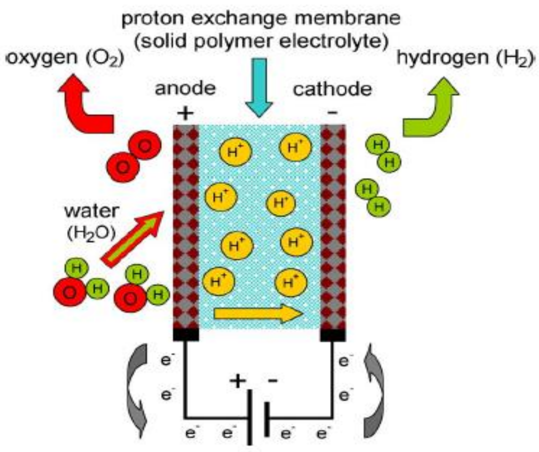

Figure 22: Operating principle of a PEM electrolysis cell [38]

In table 16 below the advantages and disadvantages of these two technologies are summarized [36].

Technology	Advantages	Disadvantages
Alkaline electrolysis	Well established technology	Low current densities
	Non noble catalyst	Crossover of gases
	Long-term durability	Low partial load range
	Relative low cost	Low dynamics
	Stacks in the MW range	Low operational pressures
	Cost effective	Corrosive liquid electrolyte

PEM electrolysis	High current densities	High cost of components
	High voltage efficiency	Acidic corrosive environment
	Good partial load range	Possibly low durability
	Rapid system response	Commercialization
	Compact system design	Stacks below MW range
	High gas purity	
	Dynamic operation	

Table 16: Advantages and disadvantages of Alkaline and PEM electrolysis

Concerning demo 1 in Ginostra, an integrated P2P system supplied by Engie-Electro Power Systems (EPS) has been chosen. In particular, the H2 system is composed of a 50-kW alkaline electrolyser (two 25 kW P2P modules) [17]. According to the simulation, the device should receive about 8.442 MWh/y from RES and produce 5.0036 MWh of hydrogen per year. In table 17, the main technical data of this electrolyzer system are reported (where a: two units of 25 kW, b: referred to the single unit of 25 kW) [17],[16].

Technology	Nominal size	Efficiency	Modulation range	Max operating pressure
-	kW	%	%	barg
Alkaline	50^{a}	70	$10 - 100^{b}$	30

Table 17: Main characteristics of the electrolyzer system.

The lifetime of the electrolyser is assumed to be 9 years for the Alkaline solution and 5 years for the PEM one: we have, so, to consider the replacement in the total lifetime of the plant. The two stacks of 25 kW needs to be substituted after these times, so, for the Alkaline electrolyser, the number of stacks needed in the total lifetime is 6, while for the PEM solution, the amount needed is 10: we must evaluate the environmental burden of all these electrolysis modules.

Regarding the life cycle stages, the boundaries are specified for a cradle-to-utilization LCA: this includes the raw material extraction, the material processing, the manufacturing of the electrolyser system, the transportation to Ginostra and last the use phase, with the hydrogen production. We don't have data for the maintenance. Block diagram for electrolyzers is summarized in figure 23 below.

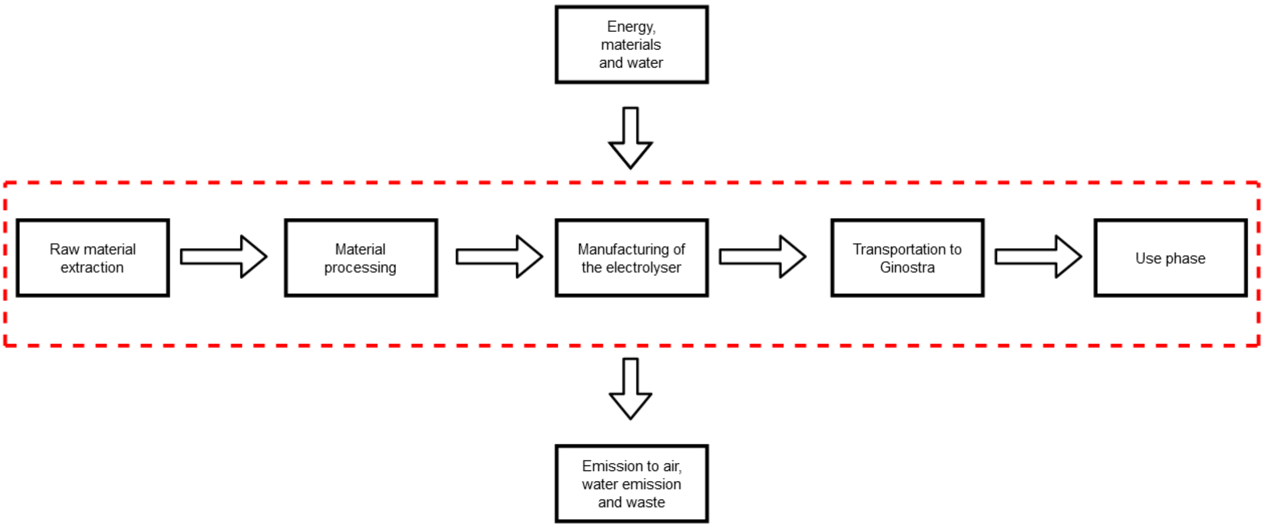

Figure 23: Block diagram for electrolyzers

In SimaPro® we don't have the directly the data for the electrolyser, so we perform two different solution for the two technologies in consideration: both of them start with the hypothesis that we can treat the electrolyser as a fuel cell, because it is almost the same device that works in the opposite way (fuel cell produces electricity starting from hydrogen while the electrolyser produces hydrogen starting from electricity), with only some difference, but we can consider them negligible in our analysis. Moreover, in many papers, in the LCA analysis, the PEM electrolysers, but also the Alkaline ones, are studied as a PEM fuel cell, but with this reasoning we can't see the difference in the emission. Some examples are [40] and [41]. Considering these hypothesis, for the PEM electrolyse we used the data from SimaPro® that describe a fuel cell stack of 2 kW, because is more correct: we assumed that this data is suitable due to the similarity in the size of the cell and with a proportion calculated the required quota for Ginostra. Different is the path we used for the alkaline solution: since that in literature they are considered as a PEM one, and, moreover, in SimaPro® there are no data for the Alkaline solution, we decided to start from an inventory found in literature of a 1 kW stack of an Alkaline fuel cell and we create a new data in the software for a 50 kW of Alkaline electrolyser. The paper in question is [42]. " In the following table 18, the inventory for the 1 kW stack is summarized.

Inventory list for the manufacturing of a 1-kWe stack of an Alkaline fuel cell			
	Material	**Unit**	**Values**
Catalysts	Raney Nickel	kg	0.634 – 0.981
	Silver	kg	0.373 – 0.577
Electrodes	Copper	kg	0.378 – 0.585
	Additives	kg	0.022 – 0.035
	PTFE	kg	0.082 – 0.127
Interconnects	Plastic	kg	0.636 – 1.413
Electrolyte	Potassium Hydroxide	kg	0.423 – 0.792
Frame/Sealing	Plastic	kg	2.086 – 3.503
	Copper	kg	0.399 – 1.091
Electricity	Electricity	kWh	9.8 – 20.3

Table 18: Inventory for the 1-kW stack of an Alkaline fuel cell [42]

For our inventory in the software, we decide to take as amounts of the materials the bigger ones, in order to perform a “safe” analysis: in fact, we are studying the “worst” case in terms of emission, it could happen that in reality the amount of materials needed is lower than what we consider, so the environmental burden will be slightly smaller.

Regarding the transport, we considered only the one with the helicopter, from Milazzo to Ginostra. Knowing the total mass of the electrolyser stacks and the transport capacity of the helicopter (2000 kg [28]), we obtain the total number of travel and so the hour required. For PEM, the total mass is calculated starting from the inventory in the paper [43]: the inventory was referred to a stack of 1 kW, so we made the product to obtain the mass for the 50 kW stack. Instead, for Alkaline, we used the inventory listed before. Next two tables represent the calculation to obtain the hours of helicopter trips needed: table 19 stands for PEM technology while table 20 stands for Alkaline one.

Number of PEM electrolyzers needed	Total weight of the electrolyzers	Number of helicopter trips	Hours of helicopter trips
-	kg	-	h
10	13648	7	3.91

Table 19: Calculation of hours of helicopter trips for PEM electrolyzer

Number of Alkaline electrolyzers needed	Total weight of the electrolyzers	Number of helicopter trips	Hours of helicopter trips
-	kg	-	h
6	1365	1	0.56

Table 20: Calculation of hours of helicopter trips for Alkaline electrolyzer

In this table, number 21, it is summarized the inventory of the electrolyser PEM block used in the software SimaPro®, considering the hypothesis listed before (where 12.5 is the number to be multiplied in order to obtain the electrolyser stack of 25 kW and 10 is the number of electrolyser stacks of 25 kW needed in the total lifetime of the plant):

Known input from Technosphere	Physical quantity	Unit of measurement
Fuel cell, stack polymer electrolyte membrane, 2-kW electrical, future {GLO}| market for | Alloc Rec, S	10*12.5	p
Transport, helicopter {GLO}| processing | Alloc Rec, S	3.91	hr

Table 21: Inventory of PEM electrolyzers used in SimaPro®

The sentences in the column of known input from Technosphere are reported exactly from the software: the first block includes the steps of raw material extraction, material processing and manufacturing of PEM electrolyzers.

Instead, this is the inventory for the Alkaline electrolyser block used in the software (table 22), considering the hypothesis and in particular the inventory of the 1 kW stack of the electrolyser listed before (where 25 is the number to be multiplied in order to obtain the electrolyser stack of 25 kW and 6 is the number of Alkaline electrolyser needed in the total lifetime of the plant). In this table, the block "Alkaline electrolyser of 1 kW" is exactly the inventory listed before (bigger quantity) of the paper [42].

Known input from Technosphere	Physical quantity	Unit of measurement
Alkaline electrolyser of 1 kW	6*25	p
Transport, helicopter {GLO}| processing | Alloc Rec, S	0.56	hr

Table 22: Inventory of Alkaline electrolyzer used in SimaPro®

The sentences in the column of known input from Technosphere are reported exactly from the software: the first block includes the steps of raw material extraction, material processing and manufacturing of Alkaline electrolyzers.

3.2.4 Hydrogen storage

The hydrogen produced by the electrolyzers needs to be stored in tanks, in order to be used when needed by the fuel cell. This is the second part of the non-integrated hydrogen storage system. The proposed hydrogen storage solution for the Remote plant has a total capacity of 21.6 m^3 for 1793 kWh of total gross energy content. The quantities of hydrogen to be stored will be around 60 kg; the defined pressure range will be 3-28 bar and the useful gross energy is estimated at about 1600 kWh.

In table 23 below, the main technical data of the hydrogen storage in Ginostra are listed.

Technical data of the hydrogen storage			
Tank volume	Pressure range	Total gross energy (LHV)	Useful gross energy (LHV)
m^3	bar	kWh	kWh
21.6	3-28	1793 (28-0 bar)	1538 (28-3 bar)

Table 23: Technical data of the hydrogen storage

To evaluate the quantity of hydrogen produced from the electrolyser, we have to start from amount of RES used from that device, the efficiency of the converter (0.965) and the efficiency of the electrolyser itself (0.62). The formula to obtain the result is:

$$Hydrogen\ produced = RES\ to\ electrolyser * efficiency_{converter} * efficiency_{electrolyser} = 125.09 \frac{MWh}{25y} \quad [7]$$

The gas produced by the P2G will be stored in tanks of about 2.7 cubic meters at the same production pressure without intermediate steps for compression. In particular, there are 8 tanks of hydrogen with a volume and pressure respectively equal to 2.7 m^3 and 32 bar: tanks has been designed considering a maximum pressure of about 32 bar. However, the maximum operating pressure is about 28 bar. The size of the tanks has been defined to respect the constraints imposed by Italian law DM 21 August 2006 regarding hydrogen storage. Following figure represents these constraints. In particular, the minimum distance between the hydrogen system and the electrical equipment is equal to 5 m while the minimum distance between the hydrogen system and the neighbouring streets is equal to 20 m.

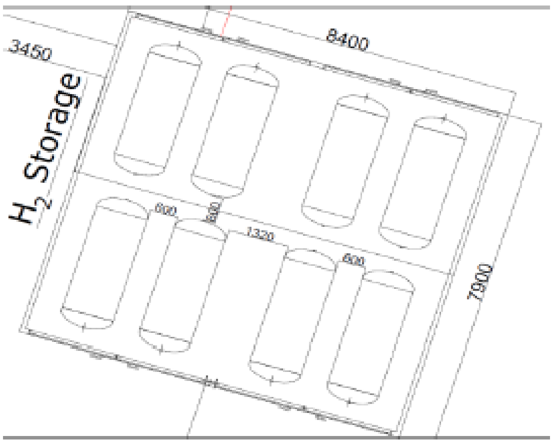

Figure 24: Layout of the H_2 storage

Concerning the material of the storage tank, we assume the stainless-steel: in SimaPro® we use the chromium-steel to analyse the emission of the tank, because there are no data for stainless steel.

To evaluate the weight of the stainless steel tank, we start with the hypothesis that the tank is cylindrical with two half spheres on the sides having the same radius: knowing the H/D ratio from preliminary data of a tank they wanted to install at the Demo 4 at Froan (H=9500mm and D_{ext}=2500mm), knowing the volume of the tank (equal to 2.7 m3) and the thickness of the tank (hypothesized 2 cm, similar to Froan's), we obtain the value of the internal radius through iterations: these ones are reported in table 24.

Iterations to obtain the internal radius						
Internal radius [m]	0.5	0.45	0.48	0.49	0.493	0.4915
Volume of the tank [m^3]	2.84	2.08	2.52	2.68	2.73	2.70

Table 24: Iteration to obtain the internal radius

The ratio H/Dext is equal to 3.8, the external radius is 0.5115 m (internal radius plus the thickness) and the external diameter is 1.023 m. We get so a total length of the tank of 3.877 m. We then obtain the volume of the stainless steel, using the formula:

$$V_{SS} = V_{cyl} + V_{sph} = \pi * (r_{ext}^3 - r^3) * (L - 2 * r_{ext}) + \frac{4}{3}\pi * (r_{ext}^3 - r^3) = 0.243733\ m^3 \quad [8]$$

Once we know the volume of stainless steel, we obtained the mass of SS through the density of SS.

$$Density\ of\ SS = 8027 \frac{kg}{m^3} \quad [9]$$

$$Total\ mass\ of\ the\ stainless - steel\ tanks = 0.243733 * 8027 = 1956.45\ kg \quad [10]$$

The assumed lifetime of the stainless-steel tanks used for hydrogen storage is 25 years: this means that we don't have to consider the replacement in the lifetime of the plant, we evaluate only the environmental burden of the eight initial tanks.

Regarding the life cycle stages, the boundaries are specified for a cradle-to-utilization LCA: this includes the raw material extraction, the material processing, the tank manufacturing and last the use phase. We don't have data for the maintenance. In SimaPro® we used directly the data of the chromium-steel 18/8, with the value in kg of the mass of the tanks. Block diagram for the tanks is summarized in figure 25 below.

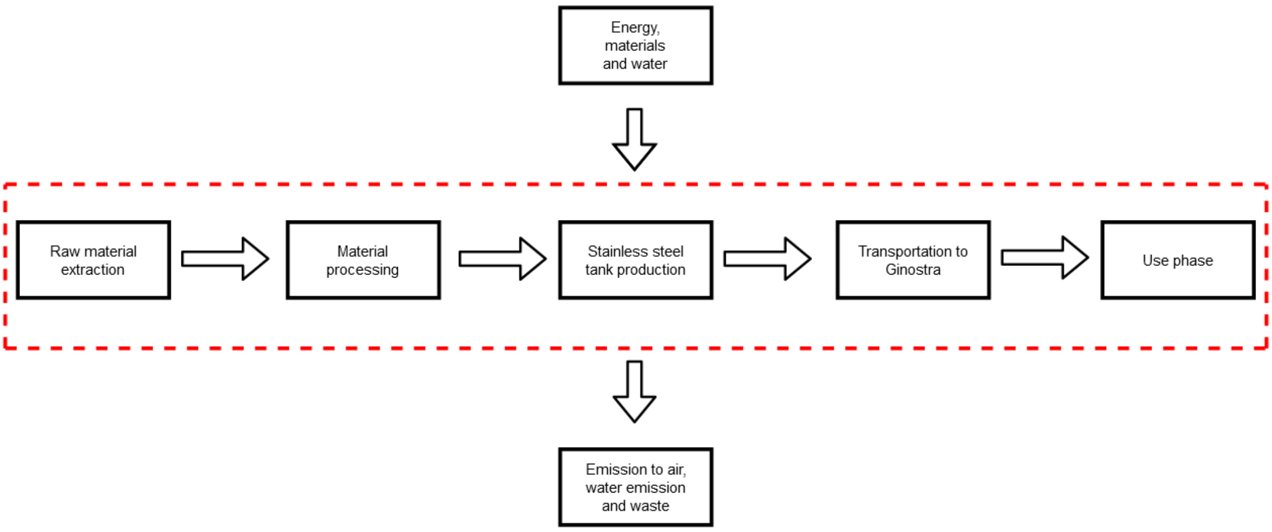

Figure 25: Block diagram for hydrogen tanks

For the transport, we consider only the one with the helicopter, from Milazzo to Ginostra. Knowing the total mass of the tanks and the transport capacity of the helicopter (2000 kg [28]), we obtain the total number of travel and so the hour required.

Number of tanks needed	Total weight of the tanks	Number of helicopter trips	Hours of helicopter trips
-	kg	-	h
8	15651.58	8	4.4672

Table 25: Calculation of hours of helicopter trips for hydrogen storage

In the table below, number 26, it is summarized the inventory used in SimaPro® to calculate the block of the hydrogen storage:

Known input from Technosphere	Physical quantity	Unit of measurement
Steel, chromium steel 18/8 {GLO}| market for | Alloc Rec, S	8*1956.45	kg
Transport, helicopter {GLO}| processing | Alloc Rec, S	4.4672	hr

Table 26: Inventory of hydrogen storage used in SimaPro®

The sentences in the column of known input from Technosphere are reported exactly from the software: the first block includes the steps of raw material extraction, material processing and stainless-steel tank production.

3.2.5 Oxygen storage

Coupled with the hydrogen storage, there is also an oxygen one of 10.8 m^3 is also present since the fuel cell is fed with pure O_2 to avoid sending air rich of marine salts in direct contact with the cathode of the cell. The quantity of oxygen to be stored will be 480 kg (335 Nm^3). In particular, there are 4 tanks with horizontal axis for oxygen with a volume and pressure respectively equal to 2.7 m^3 and 32 bar. As for the hydrogen storage, the size of the tanks has been defined to respect the constraints imposed by Italian law DM 21 August 2006 regarding hydrogen storage. The same limitations regarding the security distances are applied to these tanks too. As for the hydrogen tanks, we have to evaluate again the mass of these ones. For the oxygen storage we don't apply the same calculation as before but, on the other hand, we make a proportion, knowing the ratio between the volumes of the two storage units. In this way the mass of stainless-steel for the oxygen tanks is half of that for the hydrogen tank. In table 27, the main technical data of the oxygen storage in Ginostra are listed.

Data of the oxygen storage			
Hydrogen tanks volume	Oxygen tanks volume	Ratio btw oxygen and hydrogen tanks	Total mass of oxygen tanks
m^3	m^3	-	kg
21.6	10.8	0.5	7825.79

Table 27: Technical data of the hydrogen storage

The assumed lifetime of the stainless-steel tanks used for oxygen storage is 25 years: this means that we don't have to consider the replacement in the lifetime of the plant, we evaluate only the environmental burden of the four initial tanks.

Regarding the life cycle stages, the boundaries are specified for a cradle-to-utilization LCA: this includes the raw material extraction, the material processing, the tank manufacturing and last the use phase. We don't have data for the maintenance. In SimaPro® we used directly the data of the chromium-steel 18/8, with the value in kg of the mass of the tanks. Block diagram for the tanks is summarized in figure 26 below.

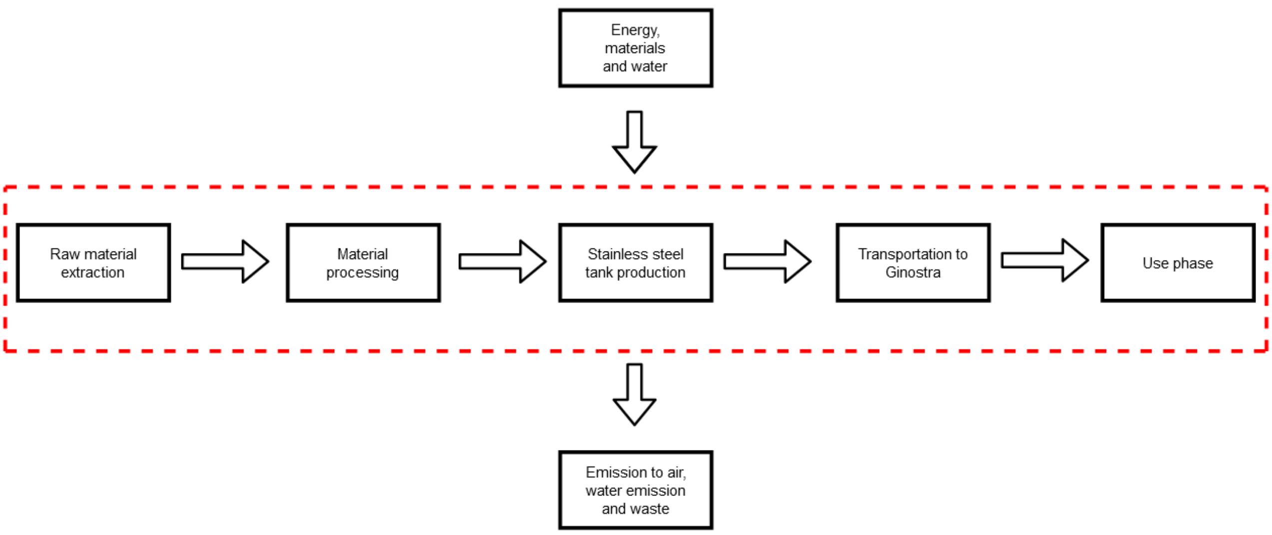

Figure 26: Block diagram for oxygen tanks

For the transport, we considered only the one with the helicopter, from Milazzo to Ginostra. Knowing the total mass of the tanks and the transport capacity of the helicopter (2000 kg [28]), we obtain the total number of travel and so the hour required: this is exactly equal to the half of the amount needed for the hydrogen storage, as hypothesis.

Number of tanks needed	Total weight of the tanks	Number of helicopter trips	Hours of helicopter trips
-	kg	-	h
4	7825.79	4	2.2336

Table 28: Calculation of hours of helicopter trips for oxygen storage

In the following table, number 29, the inventory used in SimaPro® to calculate the block of the oxygen storage is summarized.

Known input from Technosphere	Physical quantity	Unit of measurement
Steel, chromium steel 18/8 {GLO}| market for | Alloc Rec, S	7825.79	kg
Transport, helicopter {GLO}| processing | Alloc Rec, S	2.2336	hr

Table 29: Inventory of oxygen storage used in SimaPro®

The sentences in the column of known input from Technosphere are reported exactly from the software: the first block includes the steps of raw material extraction, material processing and stainless-steel tank production.

3.2.6 Fuel cell

After the electrolyzer, the hydrogen and the oxygen storage, the third part of the non-integrated hydrogen storage system is the fuel cell. A fuel cell is an electrochemical device that converts the chemical energy of a fuel and an oxidant, both externally supplied, to electrical energy and by-products including heat. Fuel cells are generally connected in series to achieve the desired power output: the assembly of several cells together with the necessary equipment (separators, cooling plates, manifolds and supporting structure) is called fuel cell stack [43].

Fuel cell technology is clean, quiet, and flexible one and is already beginning to serve humanity in a variety of useful ways. Nevertheless, production volume is low, and costs are too high. The basic mechanism underlying this conversion is the same as the one for batteries. Unlike a battery, it does not run down or require recharging, and produces energy in the form of electricity and heat as long as fuel is supplied. The fuel cell converts chemical energy directly into electricity without combustion by combining oxygen from the air with hydrogen gas. The only by-products are water and heat. It operates at ambient pressure and no pollutants are produced if pure hydrogen is used. The overall reaction of a fuel cell is the same for all the technologies:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \qquad [11]$$

Fuel cell systems can be used in portable, transport and stationary applications. The main advantage of a fuel cell with respect to a traditional energy converter is its high conversion efficiency. Moreover, the efficiency increases with diminishing load, a very interesting characteristic for the transportation sector where part load operation is the rule and ICEs run at reduced efficiency in low load conditions. The other advantages of fuel cells include very low emission, low noise level, system scalability, simplicity. The fact that hydrogen is the preferred fuel in fuel cells is one of their principal disadvantages, because we have to produce it since it is not present pure in nature in a large quantity [44].

The type of fuel cells is typically distinguished by the electrolyte that is utilized and can be classified into two main categories, based on their operating temperatures, such as low temperature fuel cells (e.g., 60-250°C) and high temperature fuel cells (e.g., 600-1000°C). Low temperature fuel cells have made significant progress in transportation applications due to their quick start times, compact volume and lower weight compared to high temperature fuel cells. The common types of low temperature fuel cells are proton exchange membrane fuel cells (PEMFC), phosphoric acid fuel cells (PAFC), alkaline fuel cells (AFC). The high temperature fuel cells are more efficient than low temperature ones in generating electrical energy. In addition, they provide high temperature waste heat, which is a benefit in stationary cogeneration applications, but presents a problem for transportation applications. Two common ones are molten carbonate fuel cells (MCFC) and solid oxide electrolyte fuel cells (SOFC) [45].

In table 30 below, the typical values for different types of fuel cells are listed [43].

Typical values for different types of fuel cells			
Type	**Transferred ions**	**Average operating temperature [°C]**	**Electrical efficiency [%]**
PEM	H^+	80-120	40
PAFC	H^+	180-200	40
MCFC	$CO_3^=$	630-670	50-55 (60-65)
SOFC	$O^=$	800-1000	50-55 (60-65)

Table 30: Typical values for different types of fuel cells

The solution proposed in the Remote Demo of Ginostra' is a 50-kW PEM fuel cell (two 25-kW P2P modules). According to the simulation, it should receive from the storage tank approximately 160 kg of hydrogen per year and the load covered by the fuel cell should be about 2.398 MWh/y. In the next table, number 31, the main technical data of this fuel cell system are reported (a: two units of 25 kW, b: referred to the single unit of 25 kW) [16], [17].

Technology	Nominal size	Efficiency	Modulation range	Max operating pressure
-	kW	%	%	barg
PEM	50^a	45	$6 - 100^b$	0.5

Table 31: Main characteristics of the fuel cell system.

The Proton Exchange Membrane Fuel Cell (PEMFC) takes its name from the special plastic membrane used as the electrolyte. The most common material for this membrane is Nafion, a per-fluorinated sulphonic acid polymer. The membrane is comprised between the two porous carbon electrodes coated with a minimum amount of platinum catalyst. Platinum is essential for the reaction to take place, due to the low operating temperature of PEMFC, and it is highly sensible to any CO content in the fuel which may poison the catalyst in a short time [43]. Fast start-up times, low temperature operation and high-power densities make them an easy to use technology especially for portable or transport applications. Because the polymer membrane must be kept well humidified for good proton conduction, water management is one of the critical aspects of successfully running a PEMFC [44].

The main components of a PEMFC are the polymer electrolyte membrane (PEM) and two electrodes with an applied catalyst layer. The two electrodes are electrically insulated and separated by the PEM, which also serves as a barrier for the reactant gases but allows the protons to migrate across it. These three components are often referred to together as the membrane electrode assembly (MEA). On the anode side, a hydrogen oxidation reaction (HOR) takes place where the electrons are separated from the protons. The separated electrons travel via the external electron-conductive circuit, through an electrical load, where the generated electrical output of the fuel cell is used, and the protons pass through the PEM to the cathode side of the fuel cell. On the cathode side, where the oxygen reduction reaction (ORR) takes place, the protons and electrons combine with oxygen to produce water. The main electrochemical reactions take place on the triple phase boundary where the electrolyte, the catalyst, and the reactant are all in contact. In this picture, figure 27, the scheme of the operating principle of a proton exchange membrane (PEM) fuel cell is represented [46].

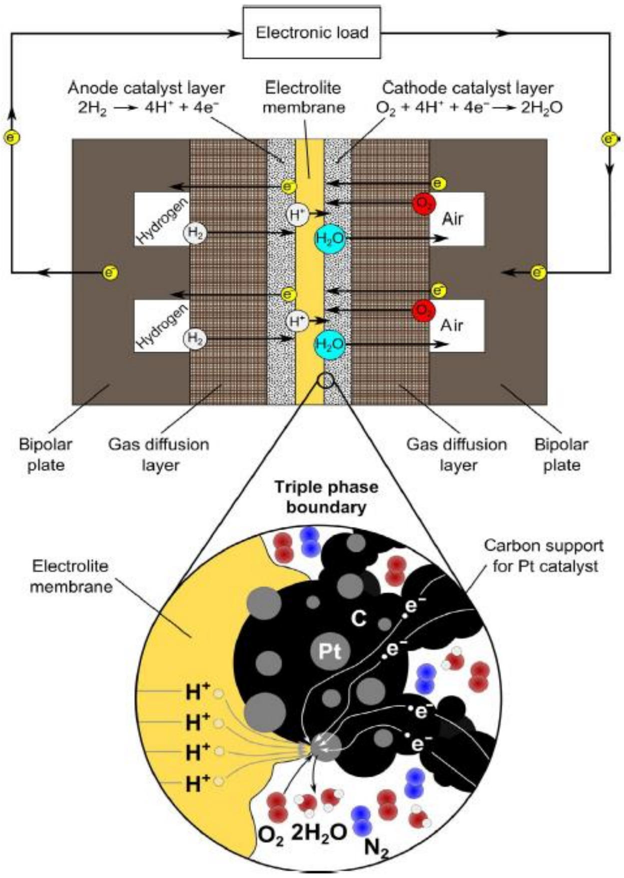

Figure 27: Operating principle of a proton exchange membrane (PEM) fuel cell [46]

The typical operating conditions of a PEMFC are absolute pressure from ambient to 3 bar and temperatures between 45 and 85°C [46]. The reactions involved in a PEMFC are:

$$Anode: H_2 \rightarrow 2H^+ + 2e^- \qquad [12]$$

$$Cathode: \frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \qquad [13]$$

The inventory for the typical manufacturing of a 1-kWe PEMFC system, taken from [46], is enlisted in table 32:

Inventory list for the manufacturing of a 1-kWe PEMFC system			
	Material	**Unit**	**Value**
Stack	Graphite	kg	4.5
	Polyvinylidene chloride (PVdC)	kg	1.1
	Aluminum	kg	0.3
	Chromium steel	kg	0.1
	Glass fibers	kg	0.1
	Perfluorosulfonic acid (PFSA) (Nafion)	kg	0.07
	Carbon black	kg	0.0008
	Platinum	kg	0.00075
BoP	Steel product	kg	3.7
	Polyethylene high density granulate (HDPE)	kg	1.5
	Chromium steel	kg	1.1
	Cast iron component	kg	0.8
	Aluminum	kg	0.75
	Polypropylene granulate (PP)	kg	0.25
System	Electricity	kWh	16.9

Table 32: Inventory for the typical manufacturing of a 1-kWe PEMFC system [46]

The lifetime of the fuel cell is assumed to be 5 years as for the PEM electrolyser solution: we have, so, to consider the replacement in the total lifetime of the plant. The two stacks of 25 kW need to be substituted after this time, so, the total amount needed is 10 (as for the electrolyser): we must evaluate the environmental burden of all these electrolysis modules.

Regarding the life cycle stages, the boundaries are specified for a cradle-to-utilization LCA: this includes the raw material extraction, the material processing, the manufacturing of the fuel cell system and last the use phase, with the electricity production. We don't have data for the maintenance. Block diagram for fuel cells is summarized in figure 28 below.

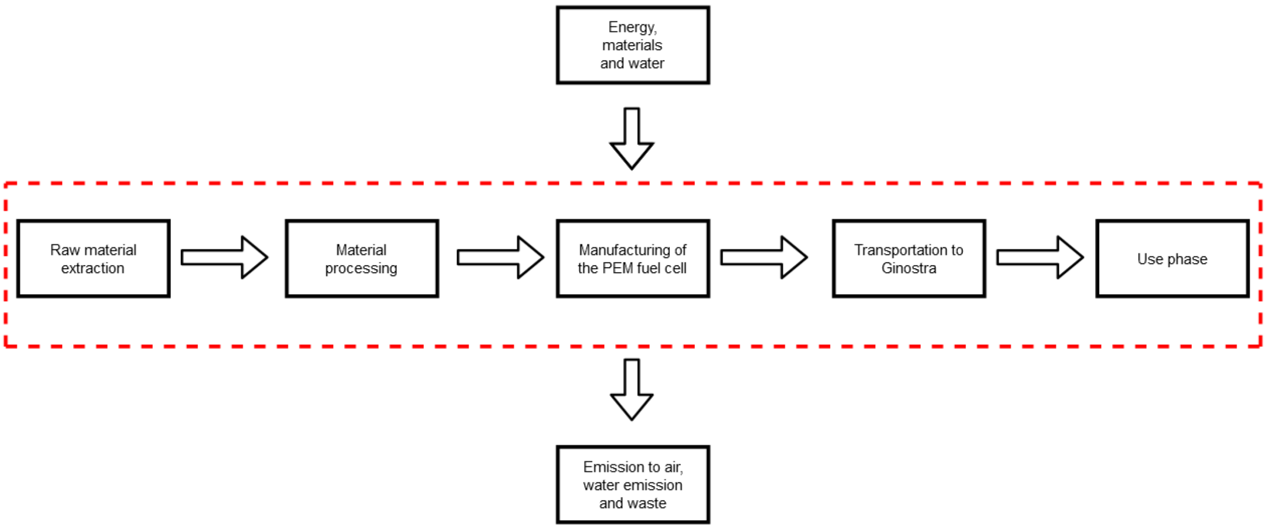

Figure 28: Block diagram for fuel cell

In SimaPro® we have directly the data for the fuel cell stack: we used the data that describe a fuel cell stack of 2 kW: we assumed that this data is suitable due to the similarity in the size of the cell and with a proportion calculated the required quota for Ginostra plant. We decide not to use the inventory listed before because the data on SimaPro® is more accurate, since it is in the database.

Regarding the transport, we considered only the one with the helicopter, from Milazzo to Ginostra: knowing the total mass of the fuel cell stacks and the transport capacity of the helicopter (2000 kg), we obtain the total number of travel and so the hour required. The total mass is calculated starting from the inventory in the paper [43]: the inventory was referred to a stack of 1 kW, so we made a product to obtain the mass for the 50 kW stack. This paper differs in the weight of the materials in the inventory of 1-kWe PEMFC system from the inventory listed before because it includes also the data for the reformer: for the stack and the BOP, instead, the weight is almost the same.

Number of PEM fuel cell needed	Total weight of the fuel cell	Number of helicopter trips	Hours of helicopter trips
-	kg	-	h
10	13648	7	3.9088

Table 33: Calculation of hours of helicopter trips for fuel cells

In the next table, number 34, it is summarized the inventory used in SimaPro® to calculate the block of the fuel cell (where 12.5 is the number to be multiplied in order to obtain the fuel cell stack of 25 kW and 10 is the number of fuel cell stacks of 25 kW needed in the total lifetime of the plant).

Known input from Technosphere	Physical quantity	Unit of measurement
Fuel cell, stack polymer electrolyte membrane, 2kW electrical, future {GLO}| market for | Alloc Rec, S	10*12.5	p
Transport, helicopter {GLO}| processing | Alloc Rec, S	3.9088	hr

Table 34: Inventory of fuel cell used in SimaPro®

The sentences in the column of known input from Technosphere are reported exactly from the software: the first block includes the steps of raw material extraction, material processing and manufacturing of PEM fuel cell.

3.2.7 Diesel generators

The last element of the Remote plant in Ginostra is a diesel generator: it is maintained as final back-up system in order to cover the load when it is impossible with RES and storage system (battery or fuel cell). According to the simulation of Ginostra demo, the diesel generator should cover 6.688 MWh/y that is the 3.9% of the total load. In particular, in our plant, two diesel generators of 48 kW are installed. The average fuel consumption in the

Remote scenario is about 3638.5 liters per year: in this scenario, the operating hours are 504 hours per years. Since we don't have many information about the chosen diesel generators, we assumed as the weight of the diesel generators a value of 1250 kg, from the diesel generator used in Froan plant: this value is in line with other value found in literature so we choose it. In this table, the main specifications of the diesel generator are summarized.

Main specification of the diesel generators					
Size	Number of generators	Weight	Fuel consumption	Operating hours	Total operating hours in 25 years
kW	-	kg	litres/year	hr/y	hr/25y
48	2	1250	3638.5	504	12600

Table 35: Technical specifications of the diesel generator

The fuel consumption, $cons_{DG}$ (in l/h), which depends on the diesel generator output power, was defined as a linear function of its electrical output according to the following equation:

$$cons_{DG} = B_{DG} \cdot P_{DG,N} + A_{DG} \cdot P_{DG} \quad [14]$$

where $P_{DG,N}$ corresponds to the rated power (in kW), P_{DG} is the output power of the diesel generator (in kW), whereas A_{DG} (equal to 0.246 l/kWh) and B_{DG} (equal to 0.08415 l/kWh) are the coefficients of the consumption curve [17].

The lifetime of the diesel generator is assumed to be 16000 hours: considering these operating hours, we don't have to replace this component in the lifetime, so we have to calculate only the emission from these two 48-kW diesel generators.

Regarding the life cycle stages, the boundaries are specified for a cradle-to-utilization LCA: this includes the raw material extraction, the material processing, the manufacturing of the diesel generator system and last the use phase, with the electricity production. We don't have data for the maintenance. Block diagram for diesel generators is summarized in figure 29 below.

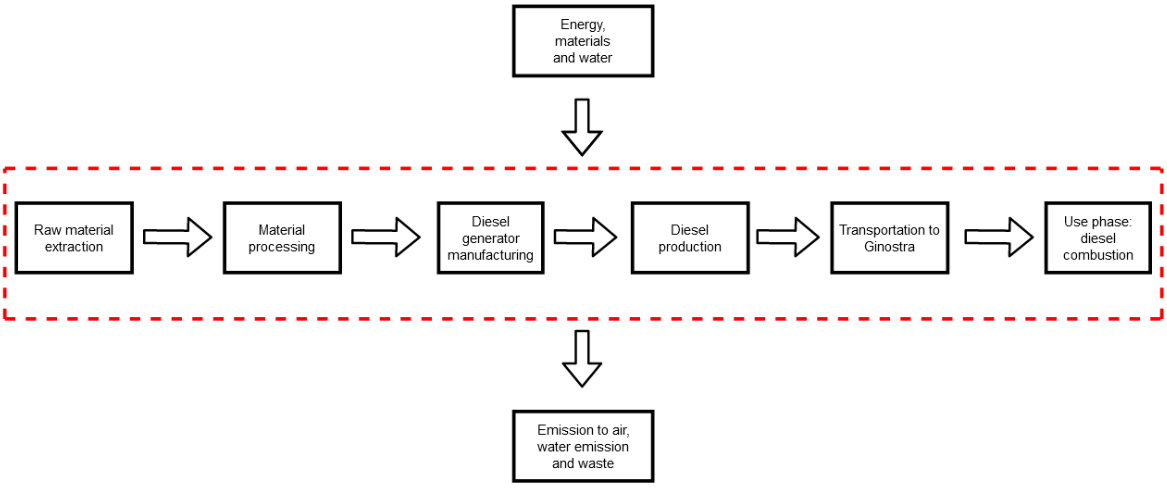

Figure 29: Block diagram for diesel generators

In SimaPro® we have directly the data for this component: we used the one that describe a diesel generator of 18.5 kW: we assumed that this data is suitable due to the similarity in the size of the generator and with a proportion calculated the required quota for Ginostra.

In the following table, number 36, there is an inventory of a diesel generator of 2 kW, taken from [47].

Component	Material	Weight	Units
Engine	Cast-Iron	10.23	kg
	High grade steel	5.35	kg
	Light metal + Alloys	0.16	kg
Steel Frame	Steel	5.56	kg
Generator	Copper Alloys	5.09	kg
	Steel	5.09	kg
Inverter	Aluminum	0.30	kg
	Silica	4	g
	Plastic	0.02	kg
	Copper	6	g
Various peripheral components	Low-alloy steel	3.7	kg
	Steel alloyed	1.1	kg
	Aluminum	1.5	kg

	Cast-Iron	0.8	kg
	Polyethylene	1.5	kg
	Polypropylene	0.25	kg

Table 36: Inventory of a diesel generator of 2 kW [47]

Regarding the transport, we considered only the one with the helicopter, from Milazzo to Ginostra. Starting from the total mass of the diesel generators used in the lifetime of the plant, we have to calculate also the weight of the diesel that will be burn in this component: to do this, knowing the amount of fuel consumed in 25 years, we multiplied that value with the density of diesel (0.835 kg/l [48]), obtaining the weight of the diesel. We sum it at the diesel generator's weight and at the end, knowing the transport capacity of the helicopter (2000 kg [28]), we obtain the total number of travel and so the hour required.

Number of 48-kW diesel generators needed	Total weight of the diesel generators	Total weight of the diesel consumed	Total weight	Number of helicopter trips	Hours of helicopter trips
-	kg	kg	kg	-	h
2	2500 (all)	75953.7	78453.69	40	22.34

Table 37: Calculation of hours of helicopter trips for diesel generators

In table 38 it is summarized the inventory used in SimaPro® to calculate the block of the fuel cell (where 5.189 is the number to be multiplied in order to obtain the two 48-kW diesel generator, 908.11 is the amount of diesel consumed in Remote scenario, transformed thanks to the LHV in MWh).

Known input from Technosphere	Physical quantity	Unit of measurement
Diesel-electric generating set, 18.5kW {GLO}| market for | Alloc Rec, S	5.189189	p
Diesel, burned in diesel-electric generating set, 18.5kW {GLO}| market for | Alloc Rec, S	908.11	MWh
Transport, helicopter {GLO}| processing | Alloc Rec, S	22.34	hr

Table 38: Inventory of diesel generators used in SimaPro®

The sentences in the column of known input from Technosphere are reported exactly from the software: the first block includes the steps of raw material extraction, material processing and diesel generator manufacturing. The second one, instead, accounts for diesel production and the use phase, in which diesel is burned to produce energy.

3.3 Current scenario

When the grid is not reliable in some geographies, the final user seeks for a reliable alternative solution: diesel generators are usually the answer to these needs. They are used mainly as emergency power-supply if the grid falls. Diesel generators are widely utilized in modern industry for high energy density and dynamic stability. They are also used for different configurations such as microgrids. The main characteristics of a diesel generator are: a higher durability which gives it a longer lifetime, compared to the gasoline generator, they can be used on remote sites, they exists in a single phase and three phase, they can be loud due to the vibration [49].

A diesel generator is composed mainly of an internal combustion engine, an electric generator (usually a synchronous type), mechanical coupling, an automatic voltage regulator, a speed regulator, a support chassis, a battery for starting the motor that permits the diesel generator start-up, a fuel tank, and a command panel [50].

Today, in Ginostra, all loads are residential and currently satisfied by employing diesel generators placed on the islands [17]. Two main problems of this solution are the local pollution, due to the high diesel consumption and the high cost for the transport of the fuel to the island. This picture, figure 30, taken from [14], shows a simple scheme of the scenario considered.

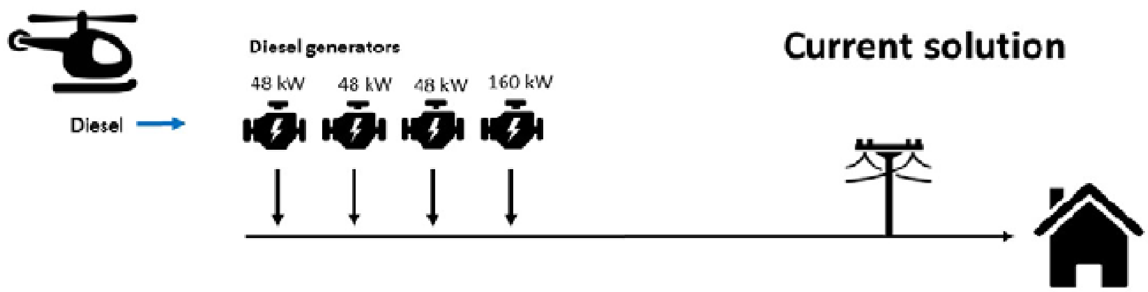

Figure 30: Scheme of the current scenario in Ginostra [14]

It is assumed that the Diesel will cover the total 171.543 MWh/y and for the covering of the demand there are used a diesel generator sized 160 kW and three sized 48 kW. According to the simulations, the total diesel consumption in this scenario is 177259.5 liters per year. Concerning the operating hours, using the model of the paper [17], there are 8758 hours/year of working. In the next table, table 39, the main characteristic of the four diesel generators are listed.

Main specification of the diesel generators					
Size	Number of generators	Weight	Fuel consumption	Operating hours	Total operating hours in 25 years
kW	-	kg	litres/year	hr/y	hr/25y
48 and 160	1 (of 160 kW) and 3 (of 48 kW)	1250 (each one)	177259,5	8758	218950

Table 39: Technical specifications of the diesel generator in current scenario

We made the assumption that all the diesel generators weight the same: this assumption is suitable because the total weight of the generators is negligible in respect of the total weight of the diesel that is burned in the total lifetime of the plant. The lifetime of the diesel generator is assumed to be 16000 hours: differently from Remote scenario, considering these operating hours, we have to replace this component in the lifetime many times.

Regarding the life cycle stages, the boundaries are specified for a cradle-to-utilization LCA: this includes the raw material extraction, the material processing, the manufacturing of the diesel generator system and last the use phase, with the electricity production. We don't have data for the maintenance. Block diagram for diesel generators is summarized in figure 31 below.

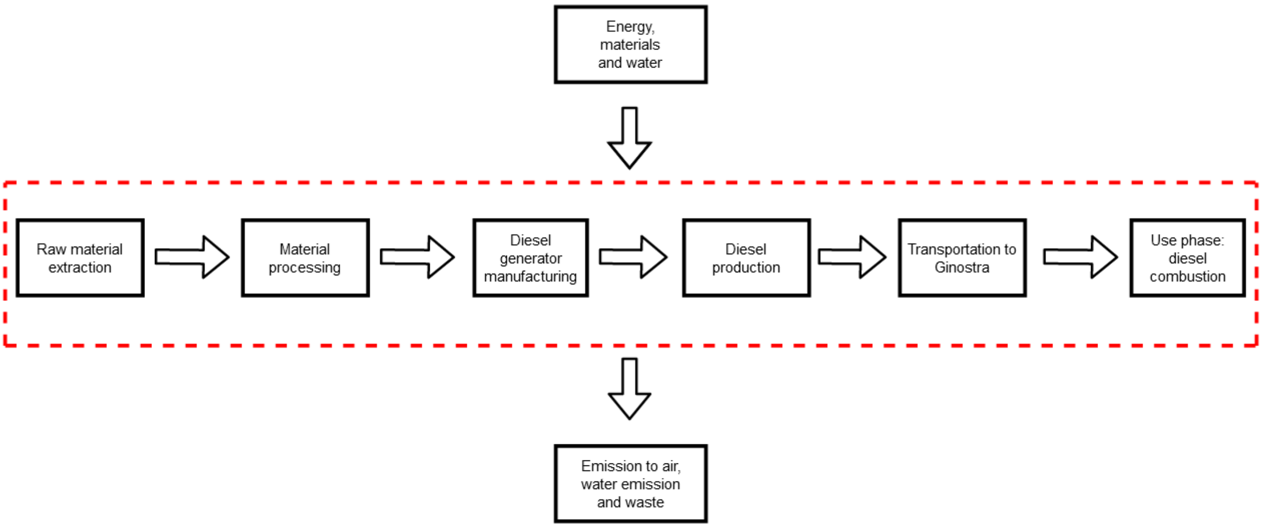

Figure 31: Block diagram for diesel generators in current scenario

In SimaPro® we have directly the data for this component: we used the one that describe a diesel generator of 18.5 kW: we assumed that this data is suitable due to the similarity in the size of the generator and with a proportion calculated the required quota for Ginostra.

Regarding the transport, we considered only the one with the helicopter, from Milazzo to Ginostra. Starting from the total mass of the diesel generators used in the lifetime of the plant, we have to calculate also the weight of the diesel that will be burn in this component: to do this, knowing the amount of fuel consumed in 25 years, we multiplied that value with the density of diesel (0.835 kg/l [48]), obtaining the weight of the diesel. We sum it at the diesel generators' weight and at the end, knowing the transport capacity of the helicopter (2000 kg [28]), we obtain the total number of travel and so the hour required.

Number of 48 and 160-kW diesel generators needed	N° of replace ments	Total weight of the diesel generators	Total weight of the diesel consumed	Total weight	Number of helicopter trips	Hours of helicopter trips
-	-	kg	kg	kg	-	h
56	14	1250 (each one)	3700292,06	3770292.06	1886	1053.14

Table 40: Calculation of hours of helicopter trips for diesel generators in current scenario

This value is very high, but we have to consider that we are talking about 25 years of lifetime: this number means around 75 trips per year, so around 1.5 trips per week: seen in this way, we can conclude that it can be a correct result. This value also depends on the capacity of the helicopter but nevertheless is acceptable considering also the cost of the transport with this vehicle: in fact, if the number of trips was higher, it would not be convenient to supply the island with diesel, due to the high economic cost of supply, without considering the environmental impact of transport itself (but we will see later that, for the emission, transport is negligible respect to the diesel burned in the diesel generator)

In the table 41, the inventory used in SimaPro® to calculate the block of the diesel generator in the current scenario is summarized (where 16.432 is the number to be multiplied in order to obtain the two 48-kW diesel generator, 44241.02 is the amount of diesel consumed in the current scenario, transformed thanks to the LHV in MWh).

Known input from Technosphere	Physical quantity	Unit of measurement
Diesel-electric generating set, 18.5kW {GLO}| market for | Alloc Rec, S	14*16.432	p
Diesel, burned in diesel-electric generating set, 18.5kW {GLO}| market for | Alloc Rec, S	44241.02	MWh
Transport, helicopter {GLO}| processing | Alloc Rec, S	1053.14	hr

Table 41: Inventory of diesel generators used in SimaPro® in current scenario

The sentences in the column of known input from Technosphere are reported exactly from the software: the first block includes the steps of raw material extraction, material processing and diesel generator manufacturing. The second one, instead, accounts for diesel production and the use phase, in which diesel is burned to produce energy.

4 Results

In the following section, the result of the environmental analysis carried out in this thesis are summarized. This chapter will be divided in this way: after a brief introduction, there are three main parts. In the first, the performance of the Remote scenario will be analysed, for the four different impact assessment categories: later, in the same section, there will be some graphs and tables, in particular highlighting the impact of the different contributions for each component (installation, transportation, use phase, manufacture, …). Then, in the second part there will be the analysis of the current scenario, in which there will be graph and tables of the different contribution for the diesel generator use. Lastly, there will be the comparison between the two scenarios, highlighting the advantage/disadvantage of the Remote and current solutions, for each category.

4.1 Remote scenario

The climate change emission (CC) of the Remote scenario, in $kgCO_2eq$, are summarized in the tables and the graphs below. The results obtained are based on the amount of MWh of the load in the 25 years of operation. In this solution, the electrolyzer used is the Alkaline one: in the section dedicated to the electrolyzer results, there will be the comparison between the two technologies analyzed (Alkaline and PEM).

Climate change emission rate for each component							**Total climate change emissions rate**
$kgCO_2eq/MWh$							$kgCO_2eq/$ MWh
PV panels	Batteri es	Electrolyze rs	Hydrogen storage	Oxygen storage	Fuel cells	Diesel generators	Total Remote plant
66.4	23	9.93	16.9	8.47	5	212	341.7

Table 42: Climate change emission rate for each component

The first thing that we can observe from these results is that, even if the diesel generator produces only about 4% of the total energy needed, it is responsible of the biggest impact of the plant, in particular because of the use phase in which there is the diesel combustion.

The second most important component for the environmental burden is the PV panel: it accounts for about 20% of the total emissions of the plant. In the next section, we will highlight per each component the impact for the climate change emission of the different blocks of the inventory.

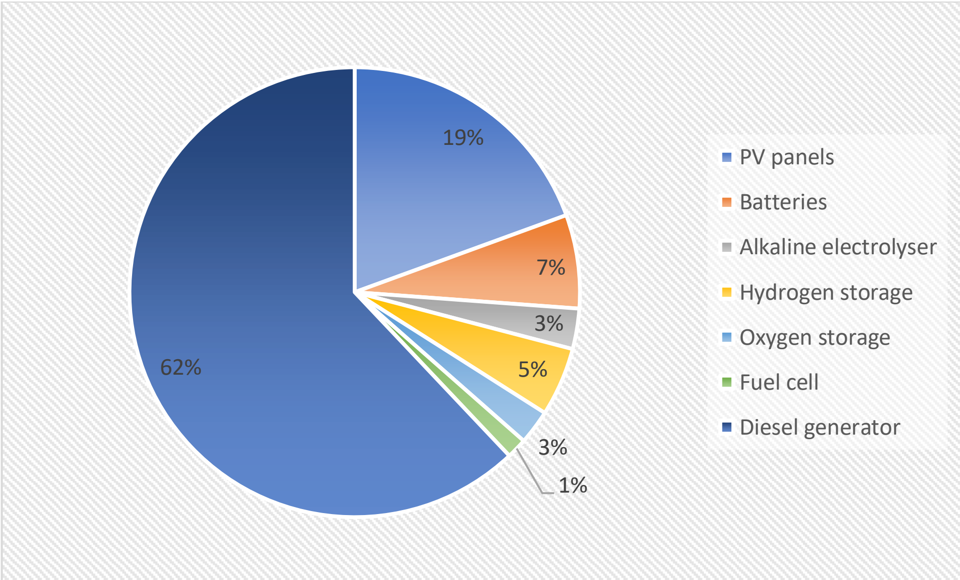

Figure 32: Climate change emission from Ginostra plant

Decreasing with the results, the batteries has a lower environmental impact, with 7%, followed by the hydrogen storage (5%), oxygen storage and alkaline electrolyser (3% each) and the least impactful component is the fuel cell, with only 1% of contribution.

The same graph and tables are proposed for the others impact assessment categories, in order to understand if the general behaviour of the emission changes a lot varying the index of comparison. The first taken into consideration is the particulate matter emission (PM), calculated in kg PM2.5-eq/MWh. We can expect a behaviour similar to the one stated above, because PM is an important index for combustion process or construction sites.

PM emission rate for each component							Total PM emissions rate
$kgPM_{2.5}eq/MWh$							$kgPM_{2.5}eq$ /MWh
PV panels	Batteries	Electrolyzers	Hydrogen storage	Oxygen storage	Fuel cells	Diesel generators	Total Remote plant
0.072	0.037	0.0138	0.0291	0.0146	0.00749	0.212	0.386

Table 43: Particulate Matter emission rate for each component

The diesel generator has again the major contribution (55%), followed by PV panels (19%) and batteries (10%). Again, as for climate change emission, fuel cell has the lower environmental burden, with only 2%. In the next section, we will highlight per each component the impact for particulate matter emission of the different blocks of the inventory.

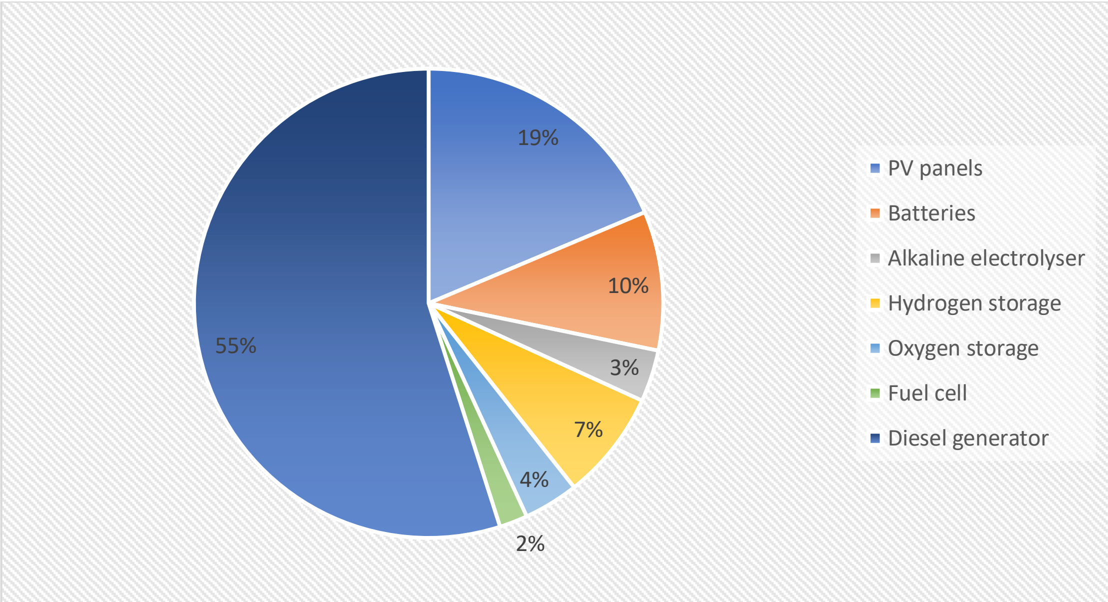

Figure 33: Particulate matter emission from Ginostra plant

The third impact assessment index taken into consideration is the <u>Ozone depletion potential (OD)</u>, calculated in kg CFC-11/MWh. Ozone depletion, gradual thinning of Earth's ozone layer in the upper atmosphere, is caused by the release of chemical compounds containing gaseous chlorine or bromine from industry and other human activities [51].

Ozone depletion emission rate for each component							**Total Ozone depletion emissions rate**
kgCFC-11/MWh							kgCFC-11/MWh
PV panels	Batteries	Electrolyzers	Hydrogen storage	Oxygen storage	Fuel cells	Diesel generators	Total Remote plant
1.01 E-5	1.95 E-6	4.25 E-5	8.37 E-7	4.19 E-7	2.87 E-5	3.61 E-5	1.21 E-4

Table 44: Ozone depletion emission rate for each component

The behaviour in this case is completely different: the component with the biggest burden in terms of ozone depletion is not the diesel generator, even if it has again a very big impact (29.93%), but is the alkaline electrolyser, with 35.24%. Fuel cell has a great contribution too, with 23.8%: these three components accounts for almost 90% of the thinning of Earth's ozone layer caused by our plant. This is due probably to the particular materials used in the P2P technologies that can cause the gradual thinning of Earth's ozone layer in the upper atmosphere. Then there are PV panels (8.37%), batteries (1.62%) and lastly the two storage systems that together accounts for only 1%. In the next section, we will highlight per each component the contribution for ozone depletion potential of the different blocks of the inventory.

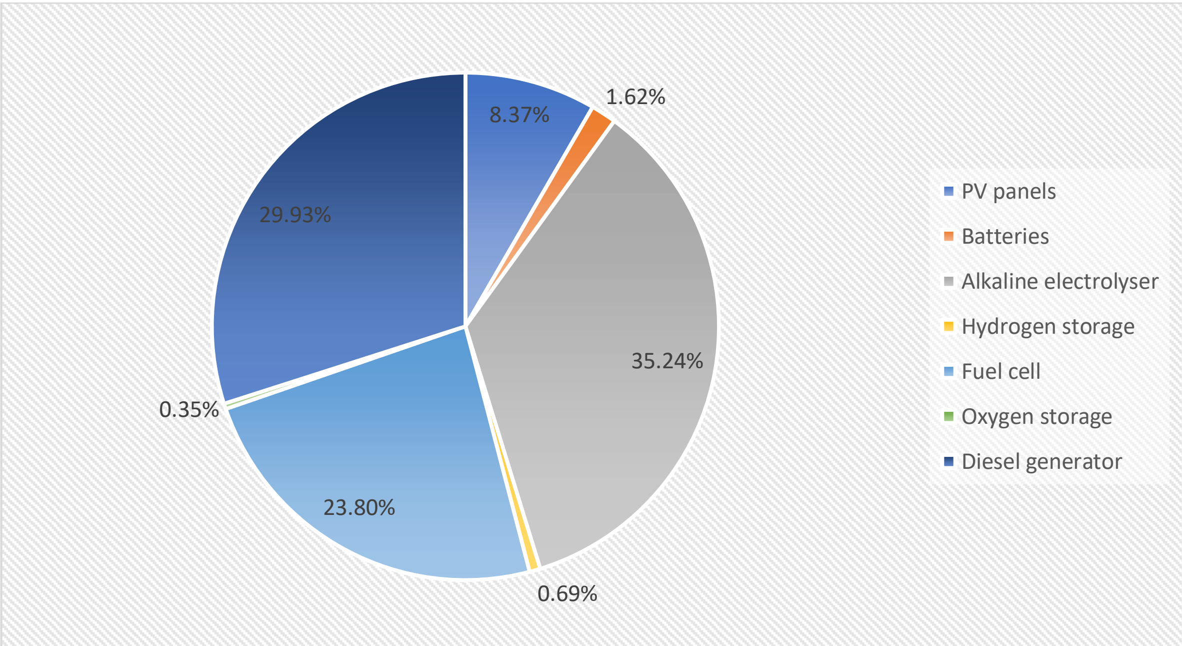

Figure 34: Ozone depletion potential from Ginostra plant

The last category analysed is the Terrestrial acidification potential (TA), expressed in terms of $kgSO_2eq/MWh$. Terrestrial acidification is characterized by changes in soil chemical properties following the deposition of nutrients (namely, nitrogen and sulphur) in acidifying forms [52].

Terrestrial acidification emission rate for each component							Total terrestrial acidification emissions rate
$kgSO_2eq/MWh$							$kgSO_2eq/MWh$
PV panels	Batteri es	Electrol yzers	Hydrogen storage	Oxygen storage	Fuel cells	Diesel generators	Total Remote plant
0.339	0.291	0.136	0.0923	0.0461	0.101	2.19	3.1954

Table 45: Terrestrial acidification emission rate for each component

In this case, the behaviour of the emissions is again similar to the initial one, the diesel generator has the biggest impact (69%). Then, all the other components have a decreasing contribution, starting from PV panels (11%), passing through batteries (9%), alkaline electrolyser (4%), hydrogen storage and fuel cell (3%) and concluding with the oxygen storage (1%). In the next section, we will highlight per each component the contribution for terrestrial acidification potential of the different blocks of the inventory.

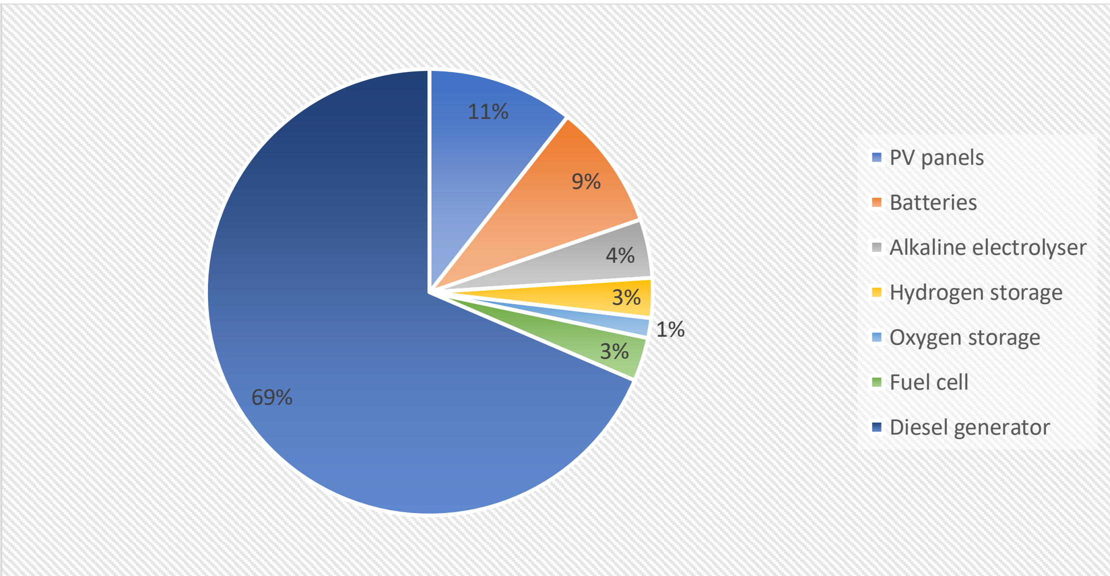

Figure 35: Terrestrial acidification potential from Ginostra plant

Now, before passing to the current scenario, with only diesel generators, there will be a detailed analysis of each component of this scenario: this is important because we can understand, starting from the inventory of the devices, what are the most impacting phases for each one.

4.1.1 PV panels

PV panels are the second source of emission for three out of four categories considered. The inventory is characterized by the panels manufacturing, electric installation, mounting system and the transport. In the following table, number 46, the resulting emission of study, for each LCA phase and for each of the four different categories, are listed:

Resulting emission of PV panels				
	CC [kgCO_2eq/ MWh]	PM [kg$PM_{2.5}$eq/ MWh]	OD [kgCFC-11/MWh]	TA [kgSO_2eq/ MWh]
Raw material extraction and manufacturing of PV panels	59.5	0.0633	9.77E-6	0.286
Transport by helicopter	0.103	2.99E-5	1.89E-8	0.000366
Electric installation for PV plant	0.511	0.00152	1.96E-8	0.0177
PV mounting system	6.28	0.00722	2.51E-7	0.0348
Total	66.4	0.072	1.01E-5	0.339

Table 46: Resulting emission of PV panels

The PV panel manufacture (in blue in the next picture) is responsible of the major impact for each of the four categories, while transport, on the contrary, is almost negligible. The photovoltaic mounting system (yellow) is always higher in value of impact in respect to the electric installation (grey), but in the four categories never accounts more than 10% of the total. The helicopter transport (orange) is always negligible, in particular because the PV panels does not require replacement in the lifetime.

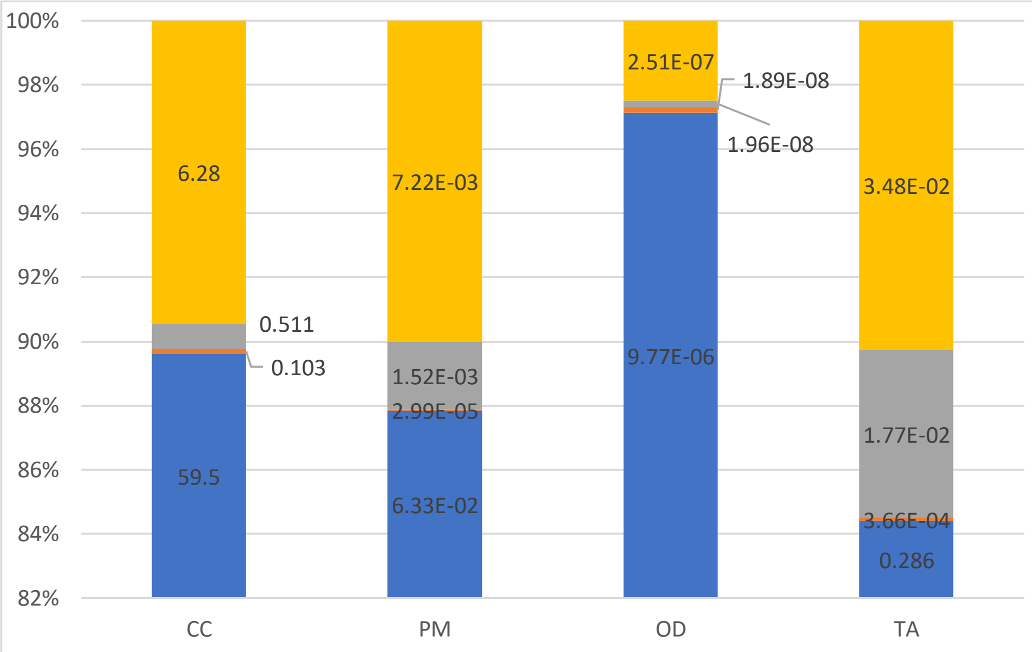

Figure 36: Share of the different emissions from PV panels

4.1.2 Batteries

Batteries represent the second source of emission, not considering the diesel generators, except for the ozone depletion potential where they are almost negligible. In SimaPro® we have the directly the data for the Li-ion battery, so we evaluate the environmental burden of this and of the transport. In table 47, all the values are summarized.

Resulting emission of batteries				
	CC [kgCO_2eq/ MWh]	PM [kg$PM_{2.5}$eq/ MWh]	OD [kgCFC-11/MWh]	TA [kgSO_2eq/ MWh]
Raw material extraction, material processing, batteries manufacturing and assembly	22.9	0.037	1.93E-6	0.29
Transport by helicopter	0.0771	2.24E-5	1.42E-8	0.000274
Total	23	0.037	1.95E-6	0.291

Table 47: Resulting emission of batteries

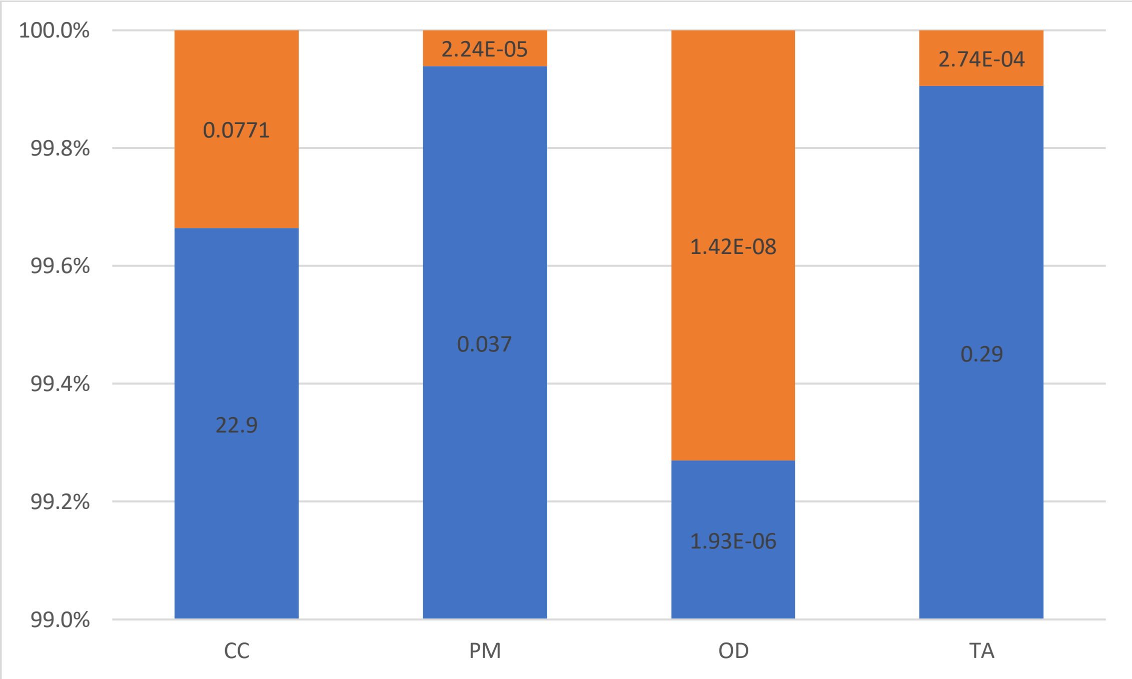

Figure 37: Share of the different emissions from batteries

As expected, the transport (orange) is negligible, even if there is the need of replacement in the lifetime of the plant, for a total of 3 batteries in the 25 years of consideration: in each category it represents less than 1%.

4.1.3 Electrolyzers

Electrolyzers represent 3% of emission of the plant in terms of climate change, particulate matter and terrestrial acidification potential, while for ozone depletion potential they are the most important emission source, with 35.24%. Remote configuration in the plant of Ginostra is characterized by an Alkaline electrolyzer: as explained in the chapter of the inventory, in this thesis it is carried out also a comparison with the technology of PEM electrolyzer, in order to see the difference in the emission in the different categories. The following table n° 48 summarize all these differences between the two technologies. This table consider already the difference in the number of replacements.

Comparison between PEM and Alkaline electrolyser				
	CC [kgCO_2eq/ MWh]	PM [kg$PM_{2.5}$eq/ MWh]	OD [kgCFC-11/MWh]	TA [kgSO_2eq/ MWh]
PEM electrolyser	5	0.00749	2.87E-5	0.101
Alkaline electrolyser	9.93	0.0138	4.25E-5	0.136

Table 48: Comparison between PEM and Alkaline electrolyzer

We can see that the PEM electrolyzer is less impactful in all the four categories. Even if Alkaline solution is the most used technology at a commercial level, it is characterized by a high energy consumption probably due to a less efficiency compared to PEM; at contrary, PEM is characterized by a higher cost of investment, but also an ecological cleanness that can be the cause of this slight difference in the emissions. Moreover, we have to consider the lifetime difference between the two technologies: in environmental terms, PEM is better, but we have to think about more replacement with this solution respect to the Alkaline one. We have to do a trade-off between economy and emissions, and considering the big difference in the investment cost (2000€/kW for the Alkaline electrolyzer, 4600 €/kW for PEM electrolyzer [17]) this is the reason because the PEM technology is not used in the plant. In future, the price is expected to significantly decrease and therefore this technology will become attractive.

As explained in the inventory chapter, we have no data on SimaPro® for Alkaline electrolyzer, so we started from an inventory of a paper found in literature. In table 49, the quota of emission due to electrolyzer and transport are listed.

Figure 38 below presents the share of the different emissions from Alkaline electrolyzers: as expected, transport (orange) is negligible in all the categories. The most impactful material in the inventory of 1-kW Alkaline electrolyzer is the silver for climate change and particulate matter emissions.

Resulting emission of Alkaline electrolyser				
	CC [kgCO_2eq/ MWh]	PM [kg$PM_{2.5}$eq/ MWh]	OD [kgCFC-11/MWh]	TA [kgSO_2eq/ MWh]
Raw material extraction, material processing and manufacturing of the electrolyzers	9.91	0.0138	4.25E-5	0.136
Transport by helicopter	0.0128	3.74E-6	2.37E-9	4.57E-5
Total	9.93	0.0138	4.25E-5	0.136

Table 49: Resulting emission of Alkaline electrolyzer

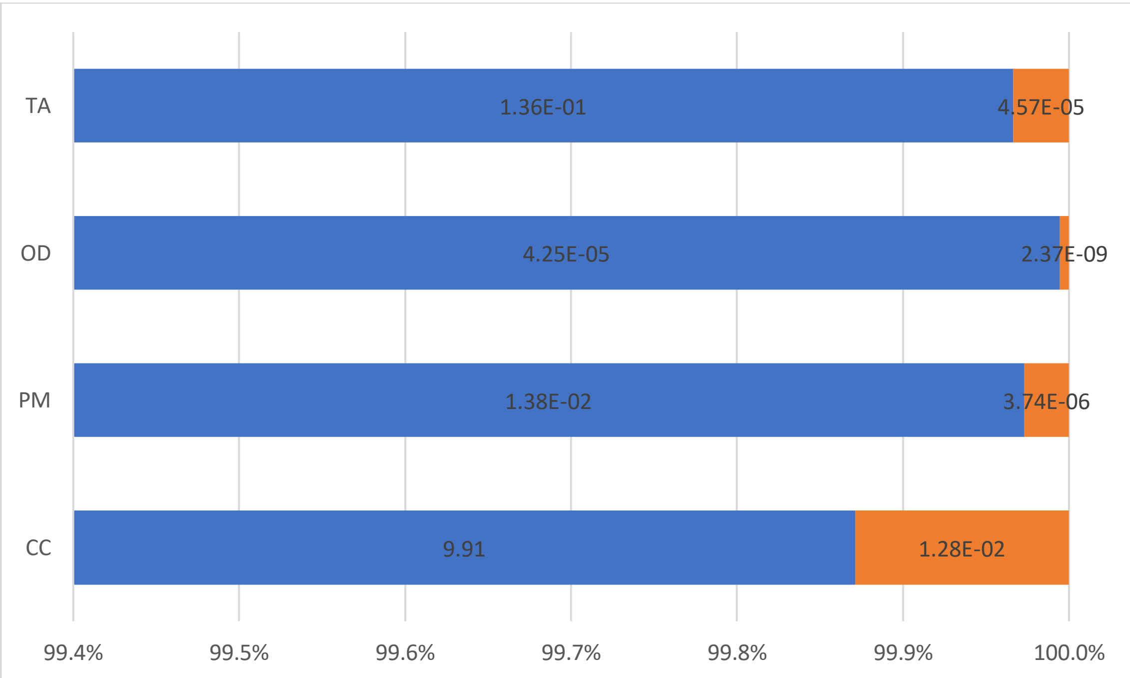

Figure 38: Share of the different emissions from Alkaline electrolyzers

4.1.4 Hydrogen storage

Hydrogen tanks are one of the less important components in terms of emission, in all the categories considered. They are composed only by stainless-steel (in SimaPro® we use chromium-steel to evaluate it, due to lack of data on that) and we have to consider also the transport. In table 50, all the values of emission are summarized. As expected, the transport (orange in figure 39) is negligible, in all the categories.

Resulting emission of hydrogen storage				
	CC [kgCO_2eq/ MWh]	PM [kg$PM_{2.5}$eq/ MWh]	OD [kgCFC-11/MWh]	TA [kgSO_2eq/ MWh]
Raw material extraction, material processing and stainless-steel tank production	16.8	0.0291	8.2E-7	0.0919
Transport by helicopter	0.103	2.99E-5	1.89E-8	0.000366
Total	16.9	0.0291	8.39E-7	0.0923

Table 50: Resulting emission of hydrogen storage

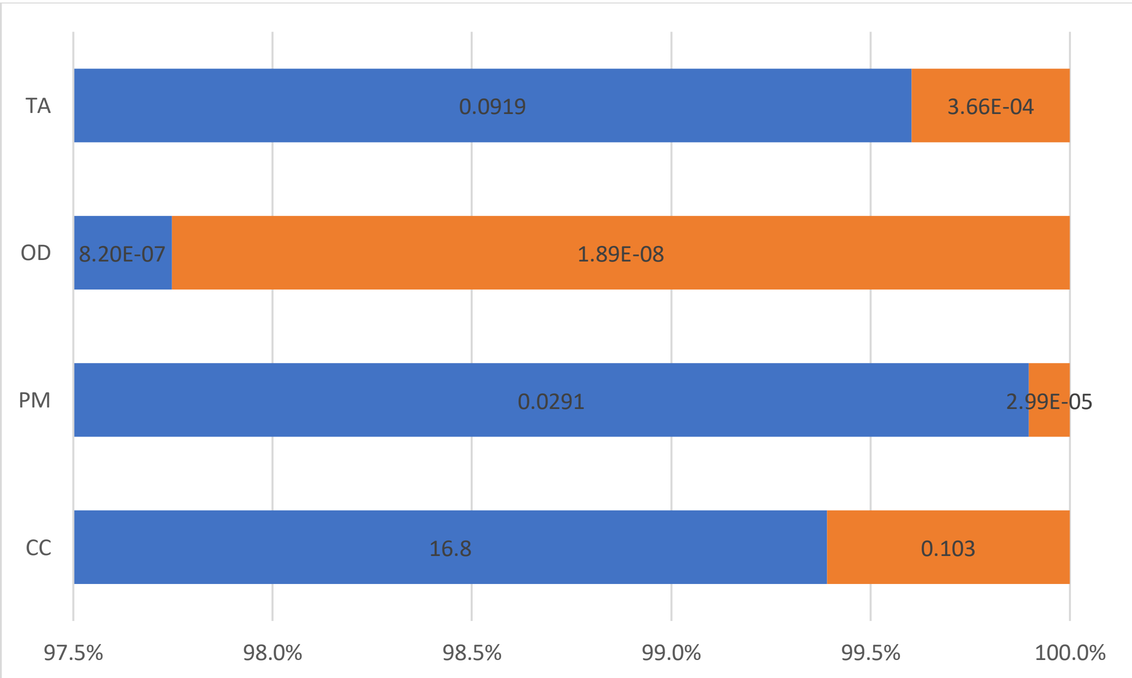

Figure 39: Share of the different emissions from hydrogen storage

4.1.5 Oxygen storage

As for the hydrogen ones, oxygen tanks are low emission components. They are composed only by stainless-steel (in SimaPro® we use chromium-steel to evaluate it) and we have to consider also the transport: since the capacity is exactly the half of the hydrogen tanks, we expected the same results and behavior in all the categories. In the next table, n° 51, all the values are listed.

Resulting emission of oxygen storage				
	CC [kgCO_2eq/ MWh]	PM [kg$PM_{2.5}$eq/ MWh]	OD [kgCFC-11/MWh]	TA [kgSO_2eq/ MWh]
Raw material extraction, material processing and stainless-steel tank production	8.41	0.0146	4.1E-7	0.0459
Transport by helicopter	0.0514	1.5E-5	9.47E-9	0.000183
Total	8.47	0.0146	4.19E-7	0.0461

Table 51: Resulting emission of oxygen storage

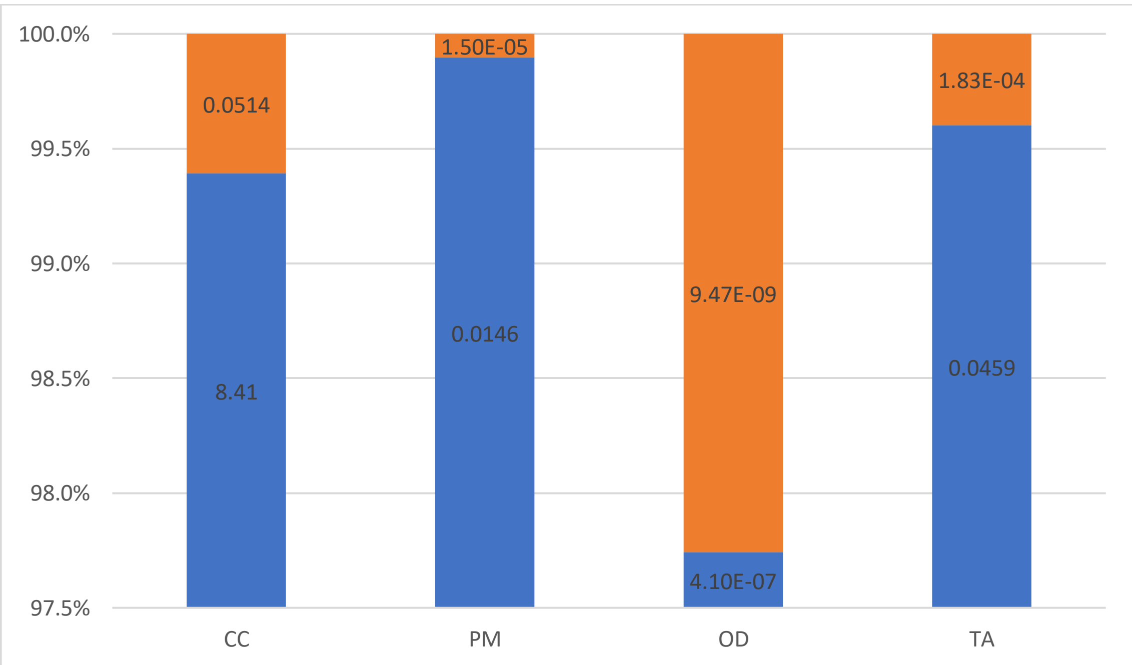

Figure 40: Share of the different emissions from oxygen storage

4.1.6 Fuel cells

Fuel cells are the less impactful components of all the plant, except for ozone depletion potential category. They are PEM solutions, so we can have a reasoning similar to the one stated in the electrolyser section. PEM fuel cell has a high cost of investment but, in this case, it is the chosen solution. The different values of emission are listed in the following table number 52.

Resulting emission of fuel cell				
	CC [kgCO_2eq/MWh]	PM [kg$PM_{2.5}$eq/MWh]	OD [kgCFC-11/MWh]	TA [kgSO_2eq/MWh]
Raw material extraction, material processing and manufacturing of PEM fuel cell	4.91	0.00746	2.87E-5	0.101
Transport by helicopter	0.0899	2.62E-5	1.66E-8	0.00032
Total	5	0.00749	2.87E-5	0.101

Table 52: Resulting emission of fuel cell

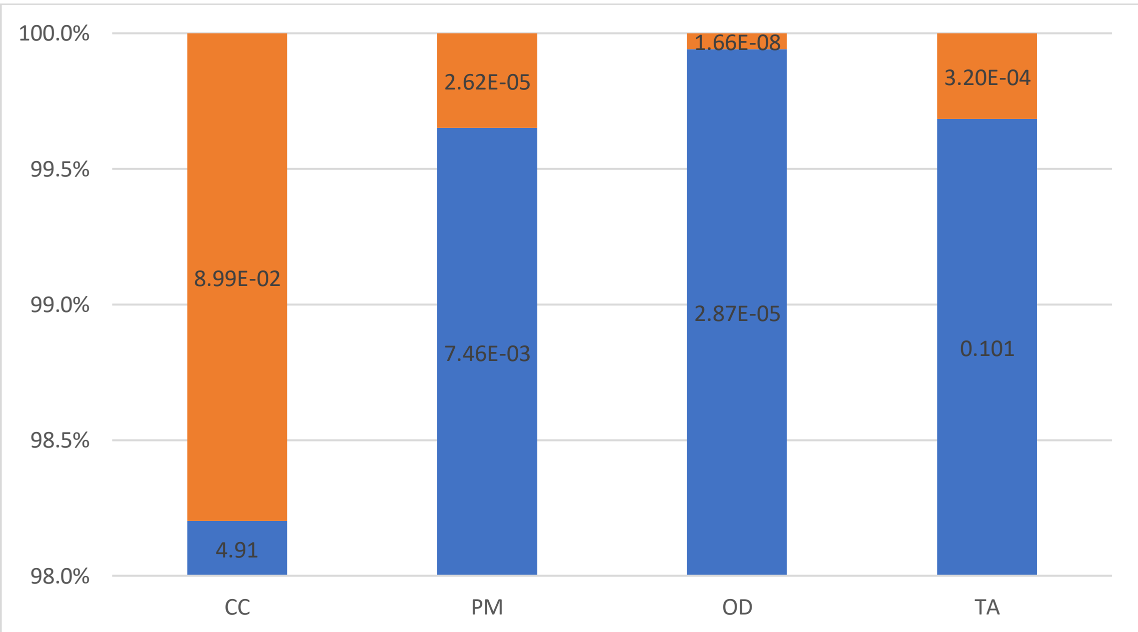

Figure 41: Share of the different emissions from fuel cells

Transport (orange) is again negligible even if we have to consider more than one replacement in the total lifetime of the plant.

4.1.7 Diesel generators

Diesel generators are the main source of emission of the plant: they represent about 70% of emission for terrestrial acidification potential, 62% for climate change, 55% for particulate matter and 30% for ozone depletion, the only category where they aren't the most impactful components.

The main reason, even if they cover a very short part of the total load of Ginostra, is due to the combustion of the diesel, that is the LCA phase with the biggest environmental burden. In table 53, all the values of emission are listed.

Resulting emission of diesel generators				
	CC [kgCO_2eq/ MWh]	PM [kg$PM_{2.5}$eq/ MWh]	OD [kgCFC-11/MWh]	TA [kgSO_2eq/ MWh]
Raw material extraction, material processing and diesel generator manufacturing	11.7	0.014	4.89E-7	0.0683
Diesel production and the use phase	200	0.198	3.55E-5	2.12
Transport by helicopter	0.514	0.00015	9.48E-8	0.00183
Total	212	0.212	3.61E-5	2.19

Table 53: Resulting emission of diesel generators

In this solution, it is not considered the replacement, but we have to remember that the fuel needs to be brought to the island. Even if the number of helicopter trips is higher, compared to the other components, transport (in grey in the figure below) is still negligible, in particular because the fuel burned is responsible of all the emissions. Also, the diesel generators themselves (orange in the picture) have a very low contribution in the emission, not more than about 5% in all the categories.

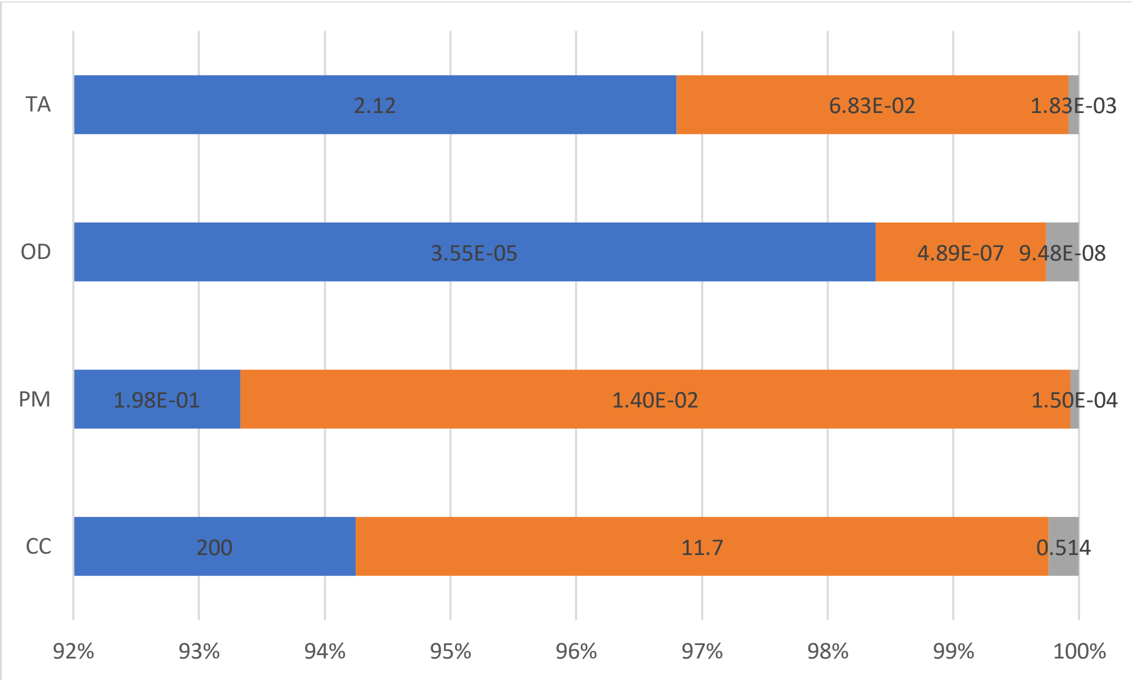

Figure 42: Share of the different emissions from diesel generators

4.2 Current scenario

Current scenario is characterized by the use of three diesel generators of 48 kW and one of 160 kW, in order to cover all the total load of Ginostra. In the current scenario, since the lifetime of each generator is estimated to be 16000 hours, we have to consider the replacement during the lifetime of the plant: for this reason, we can expect that the amount of emission due to the helicopter transport will be higher.

In the following table, number 54, and in the figure 43 below, the values of emission are summarized, splitting the contribution of the generator itself, the burned fuel and the transport.

Looking at them, we can observe that the amount of emission from the transport (grey in the picture) is increased of two order of magnitude, but considering the total emission of the diesel generators it is again negligible, even if the total number of trips is evaluated to be about 1900 in 25 years.

Resulting emission of diesel generators in the current scenario				
	CC [kgCO_2eq/ MWh]	PM [kg$PM_{2.5}$eq/ MWh]	OD [kgCFC-11/MWh]	TA [kgSO_2eq/ MWh]
Raw material extraction, material processing and diesel generator manufacturing	518	0.621	2.17E-5	3.03
Diesel production and the use phase	9.73E3	9.66	0.00173	103
Transport by helicopter	24.2	0.00705	4.47E-6	0.0862
Total	1.03E4	10.3	0.00176	106

Table 54: Resulting emission of diesel generators in the current scenario

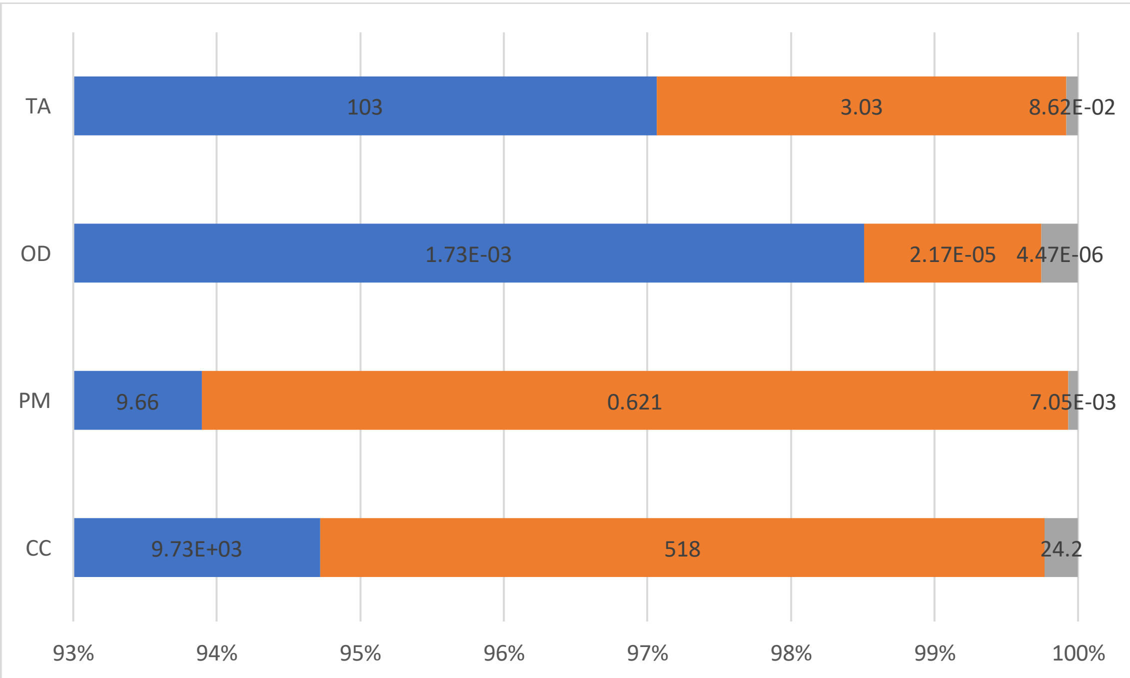

Figure 43: Share of the different emissions from diesel generators in current scenario

The main contribution is, as expected, the one from the diesel burned (in blue), since it has to cover all the load and not only the 4% of the Remote solution. Again, the diesel generators themselves (orange) have a very low contribution in the emission, not more than about 5%

in all the categories exactly as in the new solution. We can also see that, passing from 4% of coverage of the load to the total coverage, the increasement in the emission is similar in all the four categories analysed.

Now, in the next section, there will be a direct comparison of the two scenarios, adding the amount for each component in the Remote solution and comparing with the current one just analysed.

4.3 Comparison of the scenarios results

The results of the two different scenarios are summarized in the next tables, that shows also the difference in percentage with the base case of the current scenario. We start from the climate change emissions and then we will analyze all the categories. There is also, below, a graph of comparison of the two scenarios (figure 44).

Total climate change emission rate of the two scenarios		
Scenario	Total emission rate	Relative variation from the base scenario
-	$kgCO_2eq/MWh$	%
Remote Scenario	341.7	-96.68
Current Scenario	10300	-

Table 55: Total climate change emission rate of the two scenarios

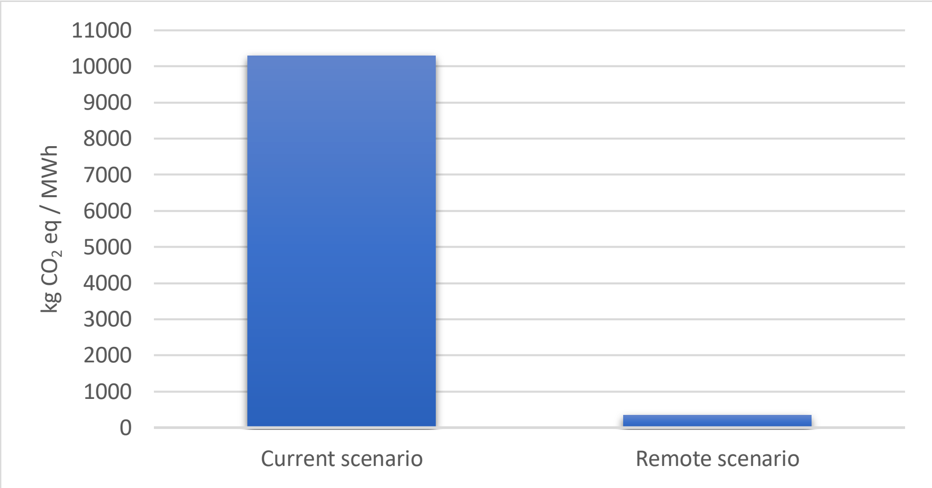

Figure 44: Total climate change emission rate of the two scenarios

The improvement with the new solution will be huge, the actual scenario has a climate change emission equal to about 30 times the emission of the Remote case. In the 25 years of lifetime of the plant the savings in terms of ton of CO_2 emitted in atmosphere will be very high, 42706.92 tons of CO_2 equivalent, as shown in the following table, number 56.

Total lifetime energy to load	Total Remote climate change emissions rate	Total Current climate change emissions rate	Total lifetime climate change emission avoidable Remote vs Current
MWh	tonCO_2eq	tonCO_2eq	tonCO_2eq
4288,575	1465.41	44172.32	42706.92

Table 56: Savings in the lifetime of the plant in terms of ton of CO_2 equivalent

In terms of CO_2 equivalent, there is no possibility of discussion, Remote solution is the best.

The next parameter to compare is the particulate matter emissions: values are reported in table 57 and figure 45.

Total particulate matter emission rate of the two scenarios		
Scenario	Total emission rate	Relative variation from the base scenario
-	$kgPM_{2.5}eq/MWh$	%
Remote Scenario	0,386	-96.25
Current Scenario	10.3	-

Table 57: Total particulate matter emission rate of the two scenarios

The advantage with Remote solution for particulate matter emission is similar in percentage to the improvement of GHG emission, since PM is an index that take into account particularly the combustion process, that is a peculiarity of the actual scenario.

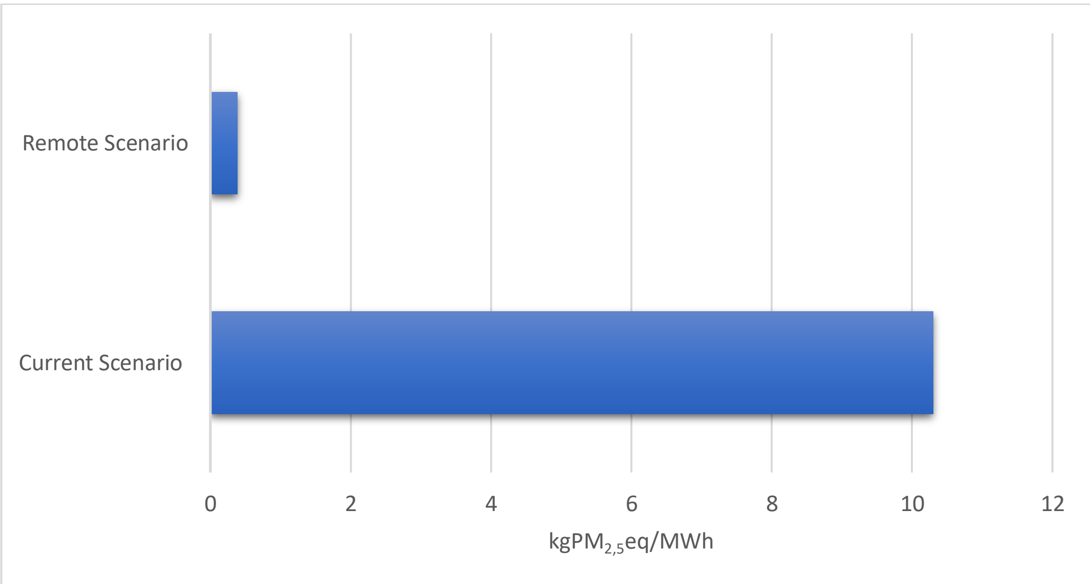

Figure 45: Total particulate matter emission rate of the two scenarios

The savings in the lifetime of the plant in terms of tons $PM_{2.5}$ equivalent will be huge, about 42 tons of $PM_{2.5}$ eq: it is reported in table 58 below.

Total lifetime energy to load	Total Remote PM emissions rate	Total Current PM emissions rate	Total lifetime PM emission avoidable Remote vs Current
MWh	ton $PM_{2.5}$eq	ton $PM_{2.5}$eq	ton $PM_{2.5}$eq
4288,575	1.6553	44.1723	42.517

Table 58: Savings in the lifetime of the plant in terms of tons $PM_{2.5}$ equivalent

The following table and graph are a comparison of the third index, the ozone depletion potential. Since the trend of this category is different from the others, we can expect something different from the results, but always with an improvement with the new solution.

Total ozone depletion potential emission rate of the two scenarios		
Scenario	Total emission rate	Relative variation from the base scenario
-	kgCFC-11eq/MWh	%
Remote Scenario	1.21E-4	-93.125
Current Scenario	0.00176	-

Table 59: Total ozone depletion potential emission rate of the two scenarios

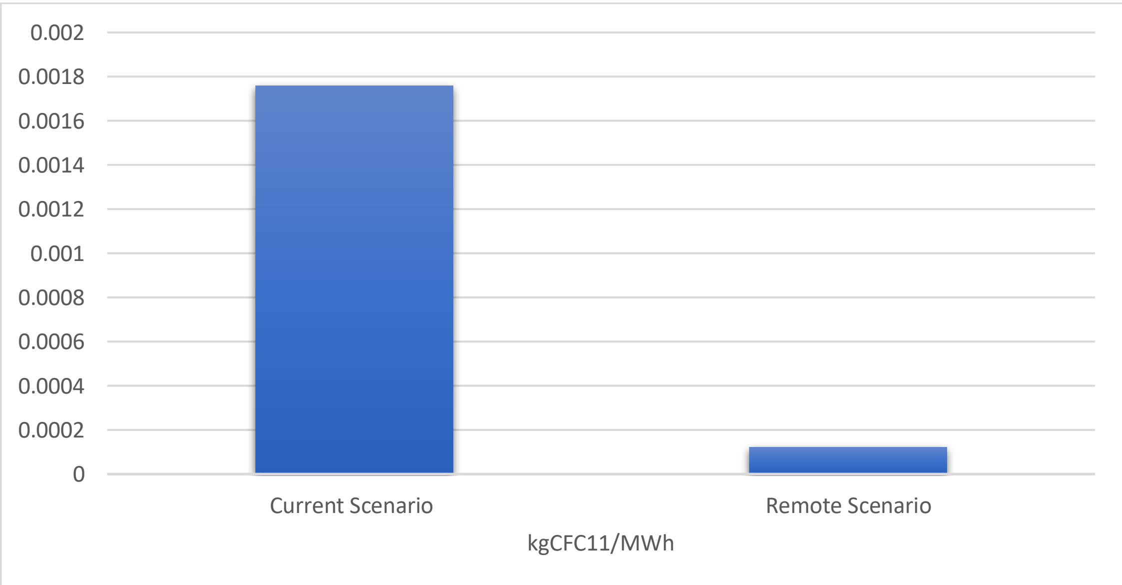

Figure 46: Total ozone depletion potential emission rate of the two scenarios

Even if the performance was different, the improvement with Remote solution is always huge, slightly less in terms of percentage if we want to discover some difference (-93% respect to -96%). In the total lifetime of the plant, the savings in terms of kg CFC11 equivalent is 7.029, a number very low if compared to the first two categories.

Total lifetime energy to load	Total Remote Ozone depletion potential emissions rate	Total Current Ozone depletion potential emissions rate	Total lifetime Ozone depletion potential emission avoidable Remote vs Current
MWh	kg CFC-11eq	kg CFC-11eq	kg CFC-11eq
4288,575	0.5189	7.5479	7.029

Table 60: Savings in the lifetime of the plant in terms of kg CFC11 equivalent

Lastly, there is the terrestrial acidification potential: the values of emission are summarized in table 61.

Total terrestrial acidification potential emission rate of the two scenarios		
Scenario	Total emission rate	Relative variation from the base scenario
-	$kgSO_2eq/MWh$	%
Remote Scenario	3.195	-96.98
Current Scenario	106	-

Table 61: Total terrestrial acidification potential emission rate of the two scenarios

The trend for this index is again similar to the climate change and particulate matter, the improvement is about 96%.

Figure 47 below presents the total terrestrial acidification potential emission rate of the two scenarios.

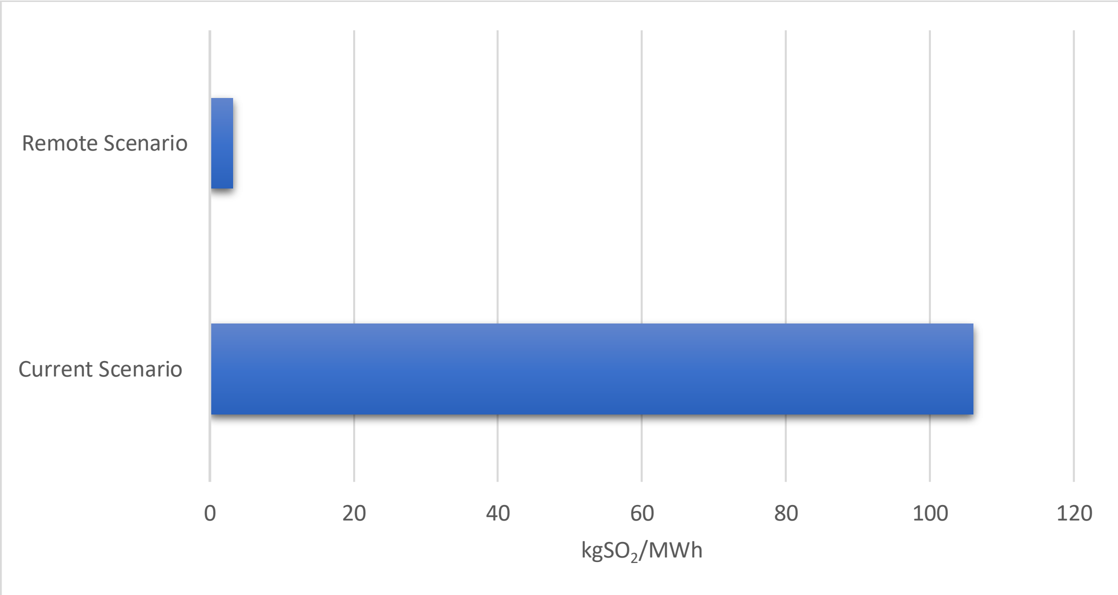

Figure 47: Total terrestrial acidification potential emission rate of the two scenarios

The savings in terms of SO_2 equivalent in the total 25 years of the plant is about 440 tons.

Total lifetime energy to load	Total Remote terrestrial acidification potential emissions rate	Total Current terrestrial acidification potential emissions rate	Total lifetime terrestrial acidification potential emission avoidable Remote vs Current
MWh	ton SO_2eq	ton SO_2eq	ton SO_2eq
4288,575	13.7037	454.589	440.8853

Table 62: Savings in the lifetime of the plant in terms of SO_2 equivalent

5 Comparison with literature

In the literature there are some articles dealing with the analysis of systems similar to the one considered in this thesis. There are articles that introduce the planning or the simulation of these systems, some articles introduce a technical-economic analysis, while others make an environmental analysis as in this study.

However, not many of them consider at the same time both lithium-ion batteries and hydrogen-based energy storage systems, combined with renewable energy sources such as photovoltaic panels: some articles deal only with batteries, others only with electrolyzers, storage tanks and fuel cells and others even with supercapacitors.

Paper [53] refers in particular to the design and simulation of a hybrid PV/fuel cell system. This document does not include a battery bank; the main components of the system are: a polycrystalline PV array, a Unipolar Stuart cell electrolyzer, a hydrogen storage tank, a proton exchange membrane (PEM) fuel cell stack and a control system. No environmental analysis is carried out.

Papers [54] and [55] refer in particular to the techno-economic analysis of P2P systems. [54] presents a case study on a Norwegian island, reporting chronological simulations, sizing and calculation of H_2 cost. System components include a wind turbine, electrolyzer, compressor, storage tank and power converter. Two different configurations are studied: a grid-connected system and an isolated system; in the second case, the system has no ability to interact with the surroundings. In this situation, a diesel power generator is included as backup, that should be sufficient to provide the minimum necessary electrolyzer power at long periods of zero wind power generation. In periods with high wind speeds, any excess wind power is dumped. Unfortunately, this work does not perform an environmental analysis.

[55] presents a detailed overview of the hydrogen-based variable renewable energy systems for the largescale standalone operation. Details of the P2H2P and P2F2P systems are given from technical and economical points of view, providing also an energy management algorithm is also provided for illustrating the operational modes of these systems and the energy balance of various operational modes. The system under consideration consist in an electrolyzer, a compression and storage stage and a fuel cell stack. Even this document does not perform an environmental analysis.

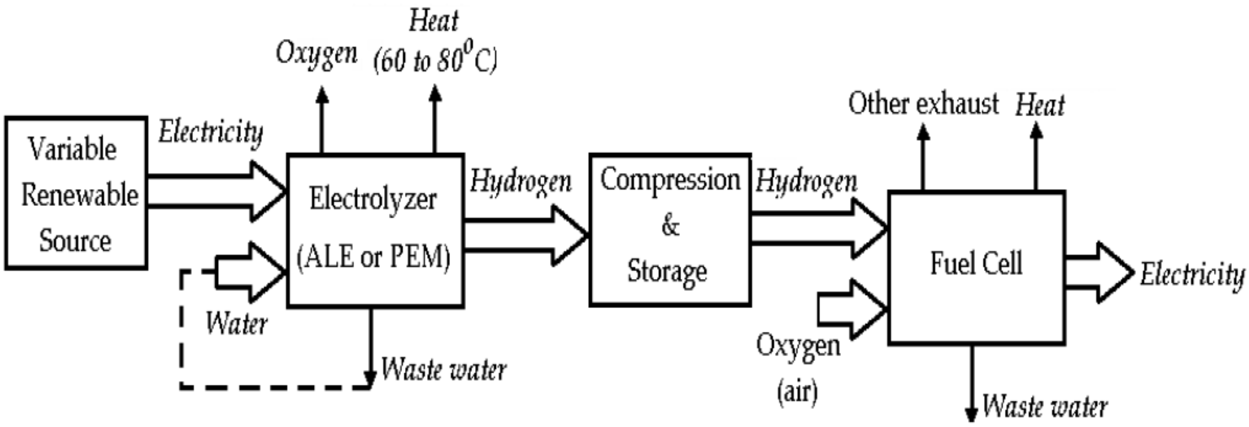

Figure 48: Main processes of the P2H2P conversions in paper [55]

Two works that deal with plants very similar to the one in Ginostra, i.e. PV panels, batteries and especially the components of the hydrogen chain (electrolyzers, storage and fuel cells) are [56] and [57]. These two studies examine plants in particular from the economic point of view: despite the high investment cost, these technologies have a great potential that will be exploited in the coming years.

[56] evaluates the techno-economic feasibility of renewable energy-based systems using hydrogen as energy storage for a stand-alone/off grid microgrid. Three case scenarios, plus a base scenario, were identified and investigated in order to select an optimum solution: the base scenario is a classic trend for a stand-alone microgrid, which comprises two diesel generators (DG), scenario 1 comprises solar PV and Li-ion battery bank, scenario 2 comprises a solar PV, electrolyzer, hydrogen tank and FC while scenario 3 comprises solar PV generation and a hybrid storage system, which comprises P2H2P and a smaller capacity Li-ion battery bank. Unfortunately, in this paper, they do not deal with emissions into the atmosphere for renewable scenarios, there are data only for the base one: it is estimated 610004 kg of CO_2 per year which means more than 15000 tons of CO_2 in 25 years of plant: this number is lower than the current case of Ginostra because they do not consider the replacement and also there are two less diesel generators. The same trend can be seen in the case of Terrestrial Acidification.

[57] investigates the interest of a hybrid solar energy system, including a lithium-based batteries bank and a hydrogen chain (electrolyzer, gas storages and fuel cell), for an off-grid application. This system is compared with two reference cases: PV-diesel generator and PV-Batteries. No environmental analysis is carried out.

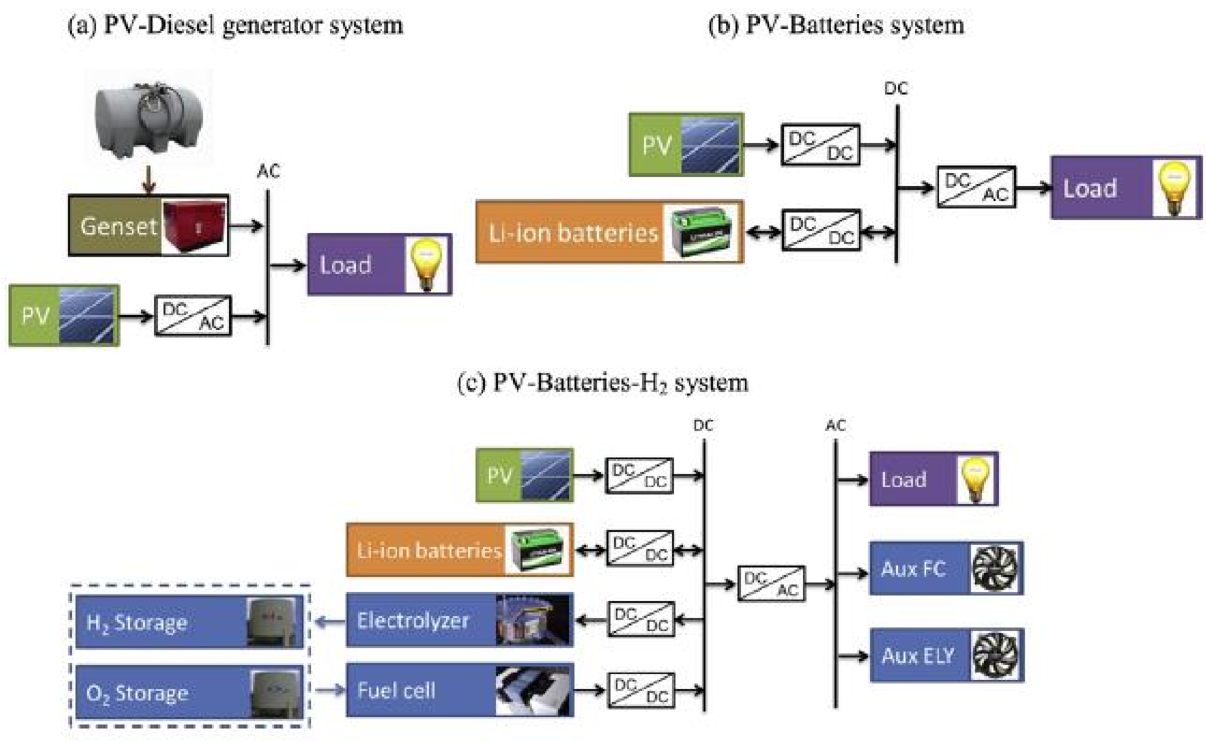

Figure 49: Architectures of the studied systems in paper [57]

All the following papers perform a Life Cycle Assessment on the P2P system under consideration. The first is [58]: the scope is to evaluate an environmental impacts of a 3 kW uninterruptible power supply system with PEM fuel cell (FCH-UPS), focusing on the analysis of the end of life (EOL) scenarios. Results of the study are comparable with Ginostra's one in terms of CC and TA: the emissions evaluated are 2.18 kg CO_2eq/MWh of produced electric energy and 0.0114 kg SO_2eq/MWh. The most impactful component in the system for both categories is the fuel cell stack. These values are in line with the result obtained for our Demo, they are lower because this paper, differently from our, consider the EOL so there are reductions in the emissions.

CC emission in paper [58]	**CC emission in Ginostra**	**TA emission in paper [58]**	**TA emission in Ginostra**
kgCO_2eq/MWh	kgCO_2eq/MWh	kgSO_2eq/MWh	kgSO_2eq/MWh
2.18	5	0.0114	0.101

Table 63: Emissions comparison between Ginostra and paper [58]

[59] conducts a cradle-to-cradle life cycle assessment of a solar panel - battery - supercapacitor configuration for a rural tropical context. The main equipment in this study

were specified as; Monocrystalline Silicon (MC-Si) Solar Panels, Lithium Iron Phosphate (LFP) Batteries and Electronic Double Layer Capacitor (EDLC) Supercapacitors. Differently from the other papers, the most impactful component is the Lithium Iron Phosphate (LFP) Battery Array: the difference is that the technology considered is not the same (LFP respect to Li-Ion battery) and the one considered in this work has a bigger environmental burden. PV panels contributes for about 30% of the emissions and supercapacitors for 10/15%.

[60] performs an investigation of the entire life cycle of the described hydrogen production, transportation, and utilization in isolated territory. In this work the hydrogen is produced by a PEM electrolyzer based on electricity from wind turbines and not from PV panels and then is used by fuel cells. Results are based on 1 kg of hydrogen produced; we can compare Climate Change and Ozone depletion. We start from the emissions from electrolyzer in Ginostra, we multiply it with the total load (4288.575 MWh) in order to obtain the total emissions. We calculate also the hydrogen produced in Ginostra in the lifetime of the plant so we can compare the emissions based on 1 kg of hydrogen produced.

Total CC emissions	Total OD potential	H_2 produced in Ginostra	CC emissions based on H_2 produced	OD potential based on H_2 produced
$kgCO_2eq$	kgCFC-11eq	kg	$kgCO_2eq/kg$	kgCFC-11eq/kg
42585.55	0.182	3752.7	11.35	4.85E-5

Table 64: CC and TA emissions based on kg of hydrogen produced in Ginostra

The values obtained from paper [60] are:

CC emission of electrolyzers	OD potential of the electrolyzers
$kgCO_2eq/kg$	kgCFC-11eq/kg
1.78	1.10E-5

Table 65: CC and TA emissions from paper [60]

Results obtained for Ginostra plant are slightly higher than those of this article, but they are in the same range. This paper does not consider replacement as in our demo, so there is this difference to note. Moreover, we have to remember that the technology used in this plant is PEM and not Alkaline, and this brings to different emissions. Fuel cell, instead, have a negligible impact if compared to electrolyzers' emissions.

The next two papers considered are very similar, they compare the two-pathway considered in Remote project to store electricity. [40] takes into account and compared two alternative integrated power systems for possible appliances in use of a family house: one based on photovoltaic and hydrogen technology (electrolyzer coupled with a fuel cell), the other based on photovoltaic and batteries. The area of Turin was chosen for this study for the multiplicity of scenarios it offers, i.e. grid connected urban area and small villages and remote mountain lodges on the alpine chain that cannot count on a grid connection: for a more detailed study, a family house with 3-4 inhabitants, located in Turin has been chosen The functional unit chosen is equal to 3 kW, as this is the load required from the system by the application. The preliminary LCA results show that both electrolyzer plus fuel cell, and batteries have lower impacts with respect to other components, for example the solar panels: PV modules are the most impactful component for the battery pathway (more than 80% of contribution) while if we consider the hydrogen pathway, the gas tanks are the most impactful (61% of contribution), followed by PV panels (30%). Fuel cell and electrolyzer have a very low impact, but also batteries are negligible.

The same argument is then deepened in [41] in which a mobile system (i.e., an unmanned aerial vehicle) is also investigated. The main drawback of fuel cell-based systems is, at present, represented by their high cost, which is about double that of a battery-based system of the same size and for the same applications: fuel cell-based systems are more complex and require a larger number of auxiliary components for their operation [41].

Another important paper to compare is [61]: it provides an empirical assessment of an uninterruptible power supply (UPS) system based on hydrogen technologies (HT-UPS) using renewable energy sources (RES) with regard to its environmental impacts, using the LCA method; it also compare it to a UPS system based on the internal combustion engine (ICE-UPS). The observed system includes an electrolyzer, H_2 storage tank and a fuel cell stack with relevant support and control equipment. This paper concentrates on the hydrogen technology and does not include PV panels and batteries: the electrical power for the electrolyzer is supplied from the grid, but controlled in a manner that imitates the RES.

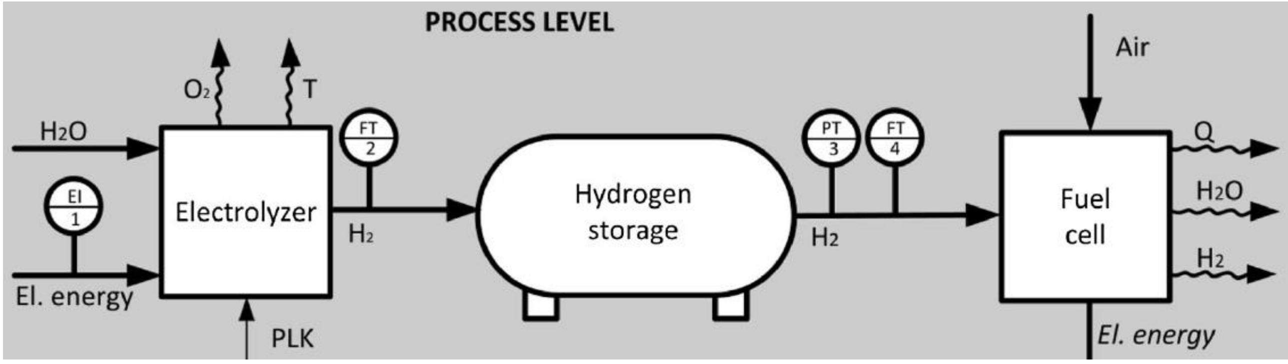

Figure 50: Scheme of the installed HT-UPS system (modified) from paper [41]

The size of the electrolyzer is similar to Ginostra's one (63 kW compared to 50 kW) and it is also an alkaline technology. We can compare the emission of climate change and terrestrial acidification for the three components. For the electrolyzers, in this paper, most of this impact, 97 %, results from components' manufacturing, just 2% from transport and just 1% from operation: this share is very similar to Ginostra's results. A look at the system's components' contribution (electrolyzers plus storage plus fuel cells) reveals that the manufacturing part of the HT-UPS system contributes the most environmental impact both in CC and in TA category (98% of UPS's total), with electrolyzer accounting for the highest contribution (65 % of UPS's total TA, 76% of UPS's total CC). The paper analyses also some categories as abiotic depletion (AD) and eutrophication (E), but the trend is always the same. The results of the comparison with ICE-UPS show that climate change emission for HT-UPS are about one-third compared ICE-UPS while for terrestrial acidification there is only a slightly improvement.

All these documents show something very similar to the system considered in Ginostra, but unfortunately none of them performs an LCA analysis with the same components simultaneously.

Now, in the following paragraphs, there will be a quick comparison with the literature in particular for those device that were found to have the biggest impact in our analysis (diesel generators, PV panels and batteries), in order to verify if the emissions, at least with regard to climate change emissions, are in line with the other articles.

5.1.1 PV panels

PV panels are the second source of emission for climate change, particulate matter and terrestrial acidification in our plant. There are many papers in the literature dealing with the environmental analysis of PV panels. Some of these are:

- [62], that compares the impact of the current Lebanese electricity system with production of electricity from PV, with and without batteries;
- [63], that uses life cycle assessment to estimate the environmental impacts for silicon-based photovoltaic (PV) systems installed in two locations in different years to assess the changes that have occurred in the past decade;
- [64], that compares the potential environmental impact of a 100 kWp photovoltaic plant (PV) with a 100-kW hybrid solar-gas turbine system (SHGT) using a life cycle assessment methodology;
- [65], that investigates the environmental impacts of grid-connected photovoltaic (PV) power generation from crystalline silicon (c-Si) solar modules in China;
- [66], that presents the results of a life cycle assessment (LCA) of the electric generation by means of photovoltaic panels in different countries;
- [67], where the aim of the paper is to review existing energy and CO_2 life cycle analyses of renewable sources-based electricity generation systems;
- [68], that presents a review of life cycle assessment (LCA) of solar PV based electricity generation systems, considering amorphous, mono-crystalline, poly-crystalline and most advanced technologies;
- [69], that review the environmental load of photovoltaic power generation system (PV) during its life cycle by energy payback time (EPT) and Greenhouse Gas emissions through LCA study;
- [70], that presents the energetic and environmental LCA of a 4.2 kWp stand-alone photovoltaic system (SAPV) at the University of Murcia (south-east of Spain);
- [71], that presents a LCA of four commercial PV technologies, i.e., mono-crystalline silicon, multi-crystalline silicon, ribbon-silicon, and cadmium telluride;

- [72], that reviews and analyses LCA studies on solar PV technologies, such as silicon, thin film, dye-sensitized solar cell, perovskite solar cell, and quantum dot-sensitized solar cell.

In particular, paper [63], [64] and [72] are the most recent, of 2018: text [64] is more similar in terms of the size of the system (100 kW compared to 170 kW of Ginostra), while text [72] deals with different photovoltaic technologies, including that of our demo.

General specification of the PV plant presented in paper [64] are listed in the table below:

Size	PV technology	Lifetime	Panel efficiency	Total panel active surface
kW	-	years	%	m^2
100	single-crystalline silicon panel mounted on open ground	30	14	653

Table 66: General specification of the PV plant presented in paper [50]

All these values are values are very similar to the ones of our system. The LCA carried out in this paper is a complete cradle-to-grave: it includes also the end-of-life, in particular landfill or recycling.

This paper includes also results for terrestrial acidification potential. In the next table, the emission results calculated in this paper are listed.

Emissions results of paper [64]		
Climate change	$kgCO_2eq/MWh$	44.3
Terrestrial acidification	$kgSO_2eq/MWh$	19.2

Table 67: Emissions results of paper [64]

Regarding paper [72], in the table below, the values of climate change emission are summarized, in particular the ones from the open-ground mounted, mono-Si PV systems. Value found in our analysis for climate change emission, 66.4 $kgCO_2eq/MWh$, is in line with the values found in the literature. The difference can be different: the most probable is the differences in local energy mix in manufacturing phase, but also the irradiation that changes with the nation in consideration.

Emissions results of paper [58]	
Location	Climate change emission [kgCO_2eq/MWh]
Unites states	280
Italy	200
Europe	36
China	50
Japan	193-500
United States	64.2
South Korea	41.8
Northwest China	65.2
East China	87.3

Table 68: Emissions results of paper [58]

Another important factors can be the technology used but also the base on which these values have been referenced: in our analysis the emission data are referred to the total load of Ginostra in the 25 years of the plant. We can also decide to calculate the emissions of our demo by changing the reference, for example on the basis of the total energy supplied by photovoltaic or on the basis of the total energy delivered by photovoltaic without curtailment, or on the basis of the total load directly covered by RES (therefore non considering the load covered by batteries, fuel cell and diesel generators). In the following table there are the results:

Total RES	Climate change emission rate	Total RES but no curtailment	Climate change emission rate	Load covered directly by RES	Climate change emission rate
MWh	kgCO_2eq/MWh	MWh	kgCO_2eq/MWh	MWh	kgCO_2eq/MWh
6770.65	42.1	5010.95	56.8	2043.9	139.3

Table 69: Climate change emissions referred on different bases

Even if these number are lower or higher than the one calculated before, based on the total load, we respect the range of values found in literature.

5.1.2 Batteries

Batteries are the third source of emission for climate change, particulate matter and terrestrial acidification in our plant while for ozone depletion are almost negligible. Some papers in the literature dealing with the analysis of batteries are:

- [73], that shows a comparative LCA of different types of batteries (Lithium-Ion, PbA, PbA-R, NaS, V-Redox);
- [74], that presents a comparative life cycle assessment of cumulative energy demand (CED) and global warming potential (GWP) of four promising stationary battery technologies: lithium-ion, lead-acid, sodium-sulfur and vanadium-redox-flow;
- [75], that reviews the currently available data and calculated and highlights the impact of the production of several types of battery in terms of energy, raw materials and greenhouse gases in order that future studies may be able to include the impact of batteries more easily within any system;
- [76], that quantified the environmental performance of Lithium Metal Polymer (LMP) stationary batteries through the life cycle assessment methodology and compared to Lithium-ion (Li-ion) units;
- [77], that focuses on the impacts of battery production and builds an energy–environment–economy (3E) evaluation system;
- [78], that estimates, by establishing a life cycle assessment framework, GHG emissions from the production of lithium-ion batteries for electric vehicles in China;
- [79], that discusses what is known about the life-cycle burdens of lithium-ion batteries, with special emphasis placed on constituent-material production and the subsequent manufacturing of batteries; of particular interest is the estimation of the impact of battery-material recycling;
- [80], that provide a transparent inventory for a lithium-ion nickel-cobalt-manganese traction battery based on primary data and report its cradle-to-gate impacts;

- [31], that proposes the optimized design of lithium ion secondary batteries using combination of carbon footprints and life cycle assessment (LCA). Three different batteries were compared in this study: lithium ion secondary battery, nickel metal hydride battery and solar cell;
- [81], that compares the emissions of these two different types of batteries, for many different impact categories;
- [82], that investigate the different processes that are currently used for recycling portable lithium-ion batteries, such as hydrometallurgy, pyrometallurgy, and combinations of processes. The study is a comparison between these recycling processes.

Paper [73] and paper [74] are representative and useful for the comparison with the result obtained in our plant in Ginostra; both of them report data for different type of batteries, in particular for the main technologies: lithium-ion, lead-acid, sodium-sulfur and vanadium-redox-flow.

Table below reports all these values.

Battery type	Climate change emission [60] [$kgCO_2eq/MWh$]	Climate change emission [61] [$kgCO_2eq/MWh$]
Li-ion	20.2	20
PbA	109.9	110
PbA-R	76.9	75
NaS	53.5	55
V-Redox	14.8	15

Table 70: Climate change emissions of papers [60] and [61]

The technology used in Ginostra is the Li-ion one: value obtained (23 $kgCO_2eq/MWh$) is very similar to what is reported from literature, we are in the right range.

5.1.3 Diesel generators

Diesel generators are the main source of emission of the plant: they represent about 70% of emission for terrestrial acidification potential, 62% for climate change, 55% for particulate matter and 30% for ozone depletion, the only category where they aren't the most impactful components. Some papers in the literature dealing with the analysis of diesel generators are:

- [83], that employs a LCA methodology in order to directly compare the environmental impacts, net-energy inputs, and life-cycle cost of two systems: a stand-alone small wind turbine system and a single-home diesel generator system;
- [84], that compare the environmental impacts of a diesel/PV/wind hybrid microgrid on the island of Koh Jig, Thailand with the electrification alternatives of grid extension and home diesel generators;
- [85], that investigates the environmental impact of photovoltaic solar energy systems, comparing it with three alternatives including a diesel generator;
- [86], that estimates the amount of carbon footprints emitted from diesel generators in terms of carbon dioxide;
- [87], that applied a LCA methodology to a 455-kW diesel generator set to quantify the energy demands of each life cycle stage: materials, manufacturing, transportation, use, and end-of-life disposal;
- [88], that describes an application of the Strength Pareto Evolutionary Algorithm to the multi-objective optimization of a stand-alone PV–wind–diesel system with batteries storage with the objective to minimize the levelized cost of energy (LCOE) and the equivalent carbon dioxide (CO_2) life cycle emissions (LCE);
- [89], that focused on the evaluation of the reliability, economic and environmental benefits of renewable energy resources in a microgrid system. The objective of this research work is to minimize the cost of energy, lifecycle cost, the annual cost of load loss and lifecycle greenhouse gas emission.

In particular, with paper [85], we can compare climate change, ozone depletion and terrestrial acidification. In the following table, the results of this article are summarized.

Class	Unit	Total	Diesel Genset	Fuel production	Fuel transport	Fuel combustion
CC	$kgCO_2eq/MWh$	1.27E3	4.4	205	4.62	1.05E3
OD	kgCFC11/MWh	0.00228	2.32E-6	0.00227	5.15E-6	0
TA	$kgSO_2eq/MWh$	16.5	0.0257	1.8	0.0348	14.6

Table 71: Emissions of paper [71]

Ozone depletion potential of the system in this article is almost similar if compared to current scenario in our demo, while the other categories have a lower value. We must remember that in case of CC and TA, the main emission occurs in the fuel combustion phase, so a difference in this stage can bring to very different results.

Paper [84] too, which is newer than the previous one, gives us some values to compare for CC and TA.

Class	Unit	Total
CC	$kgCO_2eq/MWh$	4947
TA	$kgSO_2eq/MWh$	25.22

Table 72: Emissions of paper [72]

In this case, climate change emissions are higher, but are again in the middle between the values obtained in the Remote scenario and current scenario; however, we have to consider that the lifetime of the plant in this paper is lower, only 20 years, the amount of the load to satisfy is much lower than Ginostra and the diesel generator considered is a generic 5-kW model. Terrestrial acidification, instead, is almost the same with the other paper but always lower respect to current scenario in Ginostra.

Now, in the next section, there will be a brief overview also on the comparison with the literature for the other components, but not so detailed because electrolyzers, storage and fuel cells represent only about 10/15% of the emissions of our plant (OD excluded).

5.1.4 Comparison with literature of the other components

Electrolyzers represent 3% of emission of the plant in terms of climate change, particulate matter and terrestrial acidification potential, while for ozone depletion potential they are the most important emission source, with 35.24%: for this reason, there will be only a quick comparison with the literature, reporting only a list of papers that perform a LCA on them, because it is almost negligible for our plant.

In literature, the papers that deal with the LCA of electrolyzers are:

- [33], that evaluate the potential environmental performance of two electrolyzers: PEMEC and SOEC. The result from this study is thereafter compared to a parallel study of one other electrolyzer: Alkaline;
- [35], that perform a comparative life cycle analysis on the alkaline and molten carbonate electrolyzers;
- [90], that evaluates life cycle environmental impacts of renewable hydrogen produced in a proton-exchange membrane electrolyzer using solar energy;
- [91], that present a LCA on this P2G technology;
- [92], that aims to report the environmental performance of hydrogen being produced and compressed for mobility purposes;
- [93], that discusses the potential of H_2 production by proton exchange membrane water electrolysis as an effective option to reduce greenhouse gas emissions in the hydrogen sector. To address this topic, PEM water electrolysis is compared to the reference process - steam methane reforming;
- [94], that presents a comparative Life Cycle Assessment (LCA) using the GaBi software revealing inventory data and environmental impacts for industrial hydrogen production by latest AELs in three different countries (Austria, Germany and Spain) with corresponding grid mixes.

Other articles that examine these components or hydrogen production from different processes are: [95], [96], [34], [97], [36], [98], [99], [100], [39], [38], [101], [102], [37], [103], [104], [105], [106], [107], [12].

Hydrogen and oxygen tanks are some of the less important components in terms of emissions, in all categories considered. In literature, some papers that deal with the environmental analysis of storage system for hydrogen are:

- [108], that evaluates the life cycle GHG Emissions of Various Hydrogen Onboard Storage Options;
- [109], that assess the environmental impacts and the costs of the system developed, a solid-state hydrogen storage tank - fuel cell;
- [110], that enables us to identify the main sources of CO_2 from the production of stainless-steel specifying the extraction and preparation of ores and the production of ferro-alloys, including the electricity needed for these processes, the electricity production needed to produce stainless steel and the production processes at stainless steel sites;
- [61], that provides an empirical assessment of an uninterruptible power supply (UPS) system based on hydrogen technologies (HT-UPS) using renewable energy sources (RES) with regard to its environmental impacts.

Other articles that presents hydrogen storage systems are: [111], [112], [113].

Lastly, there are the fuel cell: they are the less impactful components of all the plant, except for ozone depletion potential category. In literature, there are some papers that perform an LCA on fuel cells; some of them are:

- [47], that compare the environmental impact of diesel generator and PEM fuel cell, especially on remote cell tower applications;
- [46], that performs a LCA study of the whole life cycle for a 1-kW PEMFC system and 20,000 operating hours. In the EoL phase, recycling was used as a primary strategy, with energy extraction and landfill as the second and third;
- [114], that presents an environmental assessment of a recycling process for the platinum catalyst contained in the MEA of a PEM fuel cell;
- [115], that presents an Exploratory Environmental Impact Assessment (EEIA) of the manufacturing process of a PEM fuel cell mounted in a cargo bike from LCA approach;

- [43], that performs life cycle inventory analysis in order to evaluate emissions and land use due to the four phases of the life of a fuel cell system, for PEMFC, SOFC and MCFC technologies;
- [42], that presents a LCA of an alkaline fuel cell based domestic combined heat and power (CHP) system;
- [116], that presents LCAs of fuel cells in mobile and stationary applications with different fuel options and compares them to conventional power train or plant options focusing on different environmental aspects such as use of resources, global warming, acidification and emission of carcinogenic substances;
- [44], that reviews various life cycle analysis studies on fuel cell technology: it also investigates the environmental contributions of various components and materials during the production process of hydrogen fuel;
- [117], that conduces a LCA for two types of a high temperature (HT) PEM FC; The HT PEM FC was adjusted such that it typifies a PEM FC for an electric vehicle (FCEV) or a PEM FC suitable for micro combined heat and power (μ-CHP);
- [118], presents a detailed LCA of the wind–fuel cell integrated system for application in Newfoundland and Labrador;
- [119], that evaluates the environmental impacts of a 3-kW UPS system based on PEM fuel cell in manufacturing and operating stage at operational locations representing renewable (Norway) vs. fossil fuel (Morocco) based energy mix, applying LCA method.

Other articles that presents hydrogen storage systems are: [45] and [120].

For these components, the emissions are in line with literature, since they do not have impacts in operational phase but only in the manufacturing and processing.

6 Transport contribution

One of the peculiarities of the Ginostra site compared to the other demos is the final transport to the use site: since it is located in an island, far from the mainland, our plant needs the use of a helicopter to bring the various component in the site. The transport by ship is not a valid alternative, in particular with regard to the time of travel: if the helicopter is estimated to take a little more than half an hour to make the round trip between Milazzo and Ginostra, by ship the journey time is about two hours for the outward journey only; furthermore, the harbour cannot accommodate large ships so there would be an additional problem.

Figure 51: Helicopter transportation to Ginostra [15]

On the other hand, the helicopter does not bring only advantages: first of all, the transport capacity, which depends on the type of vehicle, is certainly much smaller than that of the ship. So, the number of trips to be considered is much higher, especially for components such as the diesel generator that need refuelling. The problem of this means of transport is therefore the air pollution caused by all those trips.

Even if, in general, in an LCA the transport may not be examined, because in this way the work is more comparable even in different situations and locations, in the case of Ginostra we must consider the helicopter. To do this, we take the share of emissions, for each index considered, of each component, adding it up to the total for the Remote solution. At the end of this analysis we can see which are the most important components for the various impact indices regarding the transport on the island and also, we can obtain a general estimation if this phase is negligible or not in our LCA.

Starting with table below, we will see the transport emission divided component per component; the first is the climate change emission.

As expected, the biggest emission comes from the diesel generator, since the number of trips needed in the total lifetime of the plant is the highest between the components. It represents about 54% of the total transport climate change emissions, followed by PV panels, hydrogen storage and fuel cell (11%, 11% and 10% respectively). Then, there are batteries and oxygen storage that contribute to the total with an 8% and 5%. Finally, there is the Alkaline electrolyser: even if we have to consider the replacement for this device, the number of journeys needed for the transport is very low thanks to the low weight of the stacks.

Transport's climate change emission rate for each component							Total transport's climate change emissions rate
$kgCO_2eq/MWh$							$kgCO_2eq/MWh$
PV panels	Batteries	Electrolyzers	Hydrogen storage	Oxygen storage	Fuel cells	Diesel generators	Total Remote plant
0.103	0.0771	0.0128	0.103	0.0514	0.0899	0.514	0.9512

Table 73: Transport's climate change emission rate for each component

In the following tables, the emission values for the other three indices under consideration are shown.

Transport's particulate matter emission rate for each component							Total transport's particulate matter emissions rate
$kgPM_{2.5}eq/MWh$							$kgPM_{2.5}eq/MWh$
PV panels	Batteries	Electrolyzers	Hydrogen storage	Oxygen storage	Fuel cells	Diesel generators	Total Remote plant
2.99 E-5	2.24 E-5	3.74 E-6	2.99 E-5	1.50 E-5	2.62 E-5	1.50 E-4	2.77 E-4

Table 74: Transport's particulate matter emission rate for each component

Transport's ozone depletion potential for each component							Total transport's ozone depletion potential rate
kgCFC-11/MWh							kgCFC-11/MWh
PV panels	Batteries	Electrolyzers	Hydrogen storage	Oxygen storage	Fuel cells	Diesel generators	Total Remote plant
1.89 E-8	1.42 E-8	2.37 E-9	1.89 E-8	9.47 E-9	1.66 E-8	9.48 E-8	1.75 E-7

Table 75: Transport's ozone depletion potential for each component

Transport's terrestrial acidification potential for each component							Total transport's terrestrial acidification potential rate
$kgSO_2eq/MWh$							$kgSO_2eq/MWh$
PV panels	Batteries	Electrolyzers	Hydrogen storage	Oxygen storage	Fuel cells	Diesel generators	Total Remote plant
3.66 E-4	2.74 E-4	4.57 E-5	3.66 E-4	1.83 E-4	3.2 E-4	1.83E-3	0.0033847

Table 76: Transport's terrestrial acidification potential for each component

The trend is the same in all the categories: this means that, also changing the indexes of comparison, the only parameter that influences these results is the time of trip, calculated in hours and explained in detail in the chapter of the inventory for every component.

The following pie chart is a summary of what has been said so far for the transport, in percentage terms, valid for each impact category.

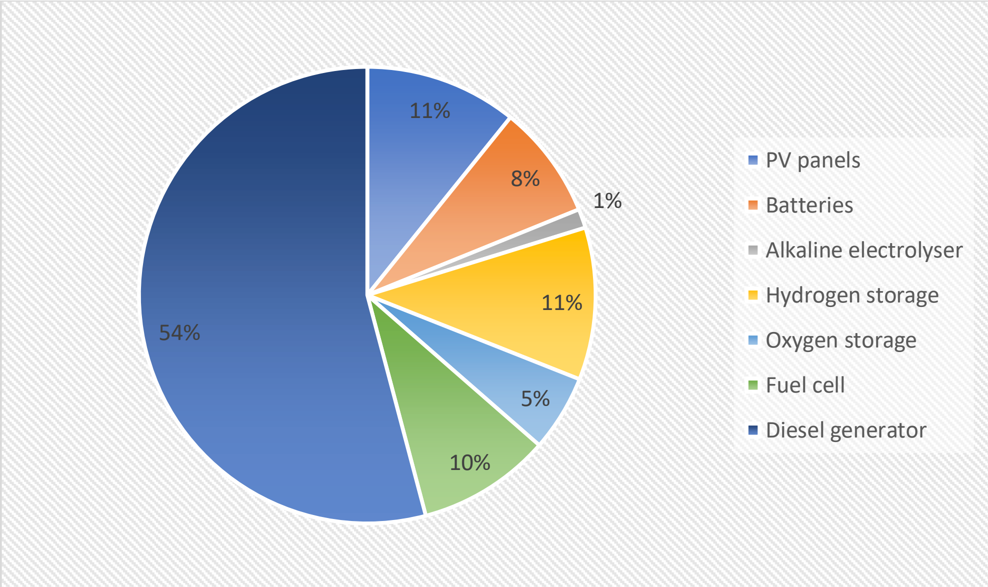

Figure 52: Percentage of the transport emission in Remote configuration

Now is the time to ask ourselves: is helicopter transport, in the total impact analysis, to be considered negligible or not?

To answer to this question, we start calculating the percentage of the transport contribution respect to the total contribution in the emission, for each component and for the total plant. The table below summarizes all these values for climate change emission.

Transport's emission percentage for each component for climate change							Total transport's emission percentage for climate change
%							%
PV panels	Batteries	Electrolyzers	Hydrogen storage	Oxygen storage	Fuel cells	Diesel generators	Total Remote plant
0.155	0.335	0.129	0.609	0.607	1.798	0.242	0.278

Table 77: Transport's emission percentage for each component for climate change

The total contribution of the helicopter transport in terms of CO_2 equivalent is negligible, because represents the 0.278% of the total Remote configuration's emission. The component with the greatest contribution of the transport is the fuel cell with 1.798% (of the total fuel cell climate change emissions): it is always a very low number, but highest if compared to other components. The amount of CO_2 emitted from fuel cell's transport is not the highest in this scenario but, since this is the less impactful component in total, in terms of percentage the transport contributes more.

Particulate matter's results are summarized in the table below.

Transport's emission percentage for each component for particulate matter							**Total transport's emission percentage for particulate matter**
%							%
PV panels	Batteries	Electrolyzers	Hydrogen storage	Oxygen storage	Fuel cells	Diesel generators	Total Remote plant
0.042	0.061	0.027	0.103	0.103	0.350	0.071	0.072

Table 78: Transport's emission percentage for each component for particulate matter

Also, in terms of particulate matter, the results are the same: transport is negligible because it represents 0.072% of the total emission, and the component with the bigger share of contribution of the helicopter is again the fuel cell, for the same reason.

Things change a little if we shift to talk about ozone depletion potential: the table 79 below summarize all the values in percentage.

Transport's emission percentage for each component for ozone depletion							Total transport's emission percentage for ozone depletion
%							%
PV panels	Batteries	Electrolyzers	Hydrogen storage	Oxygen storage	Fuel cells	Diesel generators	Total Remote plant
0.187	0.728	0.006	2.258	2.260	0.058	0.263	0.145

Table 79: Transport's emission percentage for each component for ozone depletion

The components with the greatest impact in percentage for the transport are the two storage systems: if we remember, they are the less impactful devices for this impact assessment category, while fuel cells, alkaline electrolyzers and, as always, diesel generators are the most emissive ones. For this reason, since the tanks have a low impact in total, in terms of percentage the transport contributes more. Generally speaking, instead, transport is negligible also in this category because it represents the 0.145% of the total impact.

Terrestrial acidification's results are summarized in the table below. Again, also in this category, transport represents 0.106% of the total impact, so it is negligible. The most impactful components in percentage for the transport are the two storage systems and the fuel cells, but the number are lower respect to the last category.

Transport's emission percentage for each component for terrestrial acidification							Total transport's emission percentage for terrestrial acidification
%							%
PV panels	Batteries	Electrolyzers	Hydrogen storage	Oxygen storage	Fuel cells	Diesel generators	Total Remote plant
0.108	0.094	0.034	0.397	0.397	0.317	0.084	0.106

Table 80: Transport's emission percentage for each component for terrestrial acidification

Another question to reason is: which scenario is more impactful if we consider only the transport and not all the other phases of the life cycle of the various components? In the next table there is the answer to this doubt, for each category.

Comparison of the transport in the two scenarios				
	Climate change emission	Particulate matter emission	Ozone depletion potential	Terrestrial acidification potential
	$kgCO_2eq/MWh$	$kgPM_{2.5}eq/MWh$	kgCFC-11/MWh	$kgSO_2eq/MWh$
Remote Scenario	0.9512	2.77E-4	1.75E-7	0.00338
Current Scenario	24.2	7.05E-3	4.47E-6	0.0862

Table 81: Comparison of the transport in the two scenarios

The results are very clear: although in the Remote configuration there are many more components to bring to the island, the total number of trips, counting also replacements, is still less than those that are to be considered in the current solution. In fact, the main contribution that makes this number increase considerably is the transport of fuel for the generators. In all categories, switching to the new scenario, there would be an improvement in terms of emissions of about 96% compared to the current scenario.

7 Conclusion

In the world in which we live, with an energy transition in full development, the exploitation of renewable energy sources together with the use of hydrogen as an energy carrier can be the key for the future years. Their use generally does not involve the emission of pollutants; the reductions of CO_2 emissions into the atmosphere could thus be huge.

In this thesis, a Life Cycle Assessment has been performed, in the framework of Remote project, for Demo 1, located in the village of Ginostra, in the island of Stromboli, north of Sicily, Southern Italy. The aim of the current paper was to compare, through an LCA methodology, the current solution used in this location with the Remote one, renewable, based on RES and hydrogen-based energy storage systems, in order to cover the load of the island.

The Remote configuration is composed by PV panels from EGP (170-kW), a lithium-ion battery bank (600 kWh), a 50-kW alkaline electrolyzer, a 50-kW PEM fuel cell (i.e., two 25-kW P2P modules), a hydrogen storage with capacity of 21.6 m^3, an oxygen storage of 10.8 m^3 and, as a final back-up system, two 48 kW diesel generators. On the contrary, concerning the current solution in Ginostra, all loads are satisfied by employing one 160-kW and three 48-kW diesel generators.

The impact assessment categories used for the comparison are Climate Change (CC), Particulate Matter (PM), Ozone Depletion (OD) and Terrestrial Acidification (AD). The methods used are “ILCD 2011 Midpoint+” and “ReCiPe Midpoint (H)”.

From the thesis work and from the analysis carried out, it has emerged that the improvement in the resulting emission with the new solution is very huge: the corresponding values of the different scenarios are summarized in the table below.

	CC	PM	OD	TA
-	[kgCO_2eq/ MWh]	[kg$PM_{2.5}$eq/ MWh]	[kgCFC-11/ MWh]	[kgSO_2eq/ MWh]
Current scenario	10300	10.3	0.00176	106
Remote scenario	341.7	0.386	1.21E-4	3.195

Table 82: Summary of the emissions for the different categories in Ginostra

The enhancement in terms of percentage is around 93/96% for all the categories. The main components responsible for emissions are diesel generators, although they cover only about 4% of the total load: they represent 62% of the total plant emissions for the CC category, 55% for PM, about 30% for OD and 69% for CT. For climate change emissions, the savings in terms of CO_2 equivalent should be about more than 40000 tons in the total lifetime of the plant (25 years). The energy production systems, PV panels and diesel generators, together with batteries accounts for about 90% of the total emissions in three out of four categories. For Ozone Depletion potential, things are different: the three main components with the biggest burden are, in order, the alkaline electrolyzers (35%), diesel generators (30%) and fuel cells (24%).

The most impactful stage for diesel generators is the combustion phase, it contributes for more than 90% of diesel generator emission in all the categories. For all the other components, the manufacturing stage is the responsible of the biggest impact, varying between 90% for photovoltaic panels and 99% for almost all the others. PV mounting system is responsible of the 9/10% of the total PV's impacts.

Even if this demo is characterized by a peculiarity that differentiates it from the others, namely the use of the helicopter to bring the various components on the island, the results obtained show that the share of emissions due to transport can be considered negligible: it represents 0.3% of the total emissions of the Remote plant for climate change emissions, while in other categories the percentage drops to 0.1% of the total emissions. The biggest emission component is again the diesel generator, because it has to consider the fuel transportation: it represents about 54% of the total transport climate change emissions.

A comparison with literature was also carried out: this analysis was useful to demonstrate if the evaluated emission were in the right range with other papers in literature, to have a counterevidence that the work has been done correctly. As expected, the emission values found in literature are mostly in line with those calculated in this document.

This work considers the emission in Ginostra plant without considering the end of life for these components: future work can include this analysis and the value of emissions evaluated will be certainly lower, obtaining in this way a further improvement for the environment.

So, we can say, in conclusion, that the effectiveness of the Remote solution in Ginostra is verified, in environmental terms in addition to energetical ones already evaluated in other documents. The cost of this type of technology, not calculated in this thesis, is very high since there is not a large diffusion on the market: however, the economic feasibility of these systems in remote areas has been verified in other paper, for different investment horizon. In the future, with the development and in-depth study of these technologies, they will surely become very interesting for our society.

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