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ELECTRIFICATION AND HYDROGEN USE IN AVIATION: A SCENARIO-BASED SIMULATION OF TURIN AIRPORT

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ABSTRACT

In the last two centuries, the continuous emissions of CO2 level have brought the greenhouse effect to unimaginable levels, due to an uncontrollable use of fossil fuels. The objective to stay within the 2 °C increase by 2050 is challenging but the continuous development of renewables is year by year most promising. Their intermittency makes them unreliable without proper energy management strategies and efficient storage systems, so far, the use of modern batteries is crucial to store surplus energy from renewables and new storage technologies are in development. Among them, the use of hydrogen as storage has drawn the attention of plenty of researchers. Indeed, it is a clean energy vector with the highest energy density in terms of mass and is already used in different industrial sectors. The employment of hydrogen as storage to cover peaks during low energy production is promising, however, the implementation in modern transportation would be the key to revamping decarbonization in this sector. Indeed, the use of batteries presents different drawbacks, range limit, long recharging time, and low energy density. In this regard, hydrogen presents opposite features. Among the different transportation subsectors, aviation is surely the most difficult to decarbonize, indeed, the specific fuel requirements needed make it very challenging, with hydrogen that could be successfully implemented within the short-medium range segment that is likely to enter operation in the next 15-20 years. However, in this sector, the challenge does not rely only on the airside, but also on the landside, where the hydrogen production, storage, and delivery should happen. It is known that airports are the center of the aviation sector, with energy consumption similar to that of a small city, industries in the surroundings, people working, and many passengers with plenty of commodities available within the airport. The project aims to connect the landside with the airside, trying to simulate the behavior of a typical medium-sized airport as it is the Torino Caselle airport and to imagine how the airport should develop in the next years, to be ready to host future hydrogen-based aircraft. The study analyzes different sensitivities with the development of different scenarios, that could be joined together to create a possible pathway toward complete decarbonization. It is firstly analyzed the Business As Usual (BAU) scenario, where everything remains as it is, then, the implementation of a rooftop solar PV array is studied in the Renewable Development scenario. Continuing towards more green developments, the airport is supposed to employ only green-electric vehicles, in the so-called Electrification scenario. Finally, the use of hydrogen in national and international flights is studied, in the Regional and International scenarios respectively. Results show that the use of renewables such as solar PV, or others available depending on the airport location, can only be beneficial, together with the implementation of green ground vehicles. On the other hand, using green hydrogen would be feasible only if it reaches reasonable prices, in the order of 1-2 €/kg, which is likely to happen if hydrogen mass production will be implemented. In conclusion, even if the use of hydrogen in aviation would be economically feasible only if hydrogen will reach a certain price, this must not frighten airports and airlines owner, as the development of hydrogen production will make it economically affordable.

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1 INTRODUCTION – OVERVIEW OF CLIMATE CHANGE AND COMMITMENT TO DECARBONIZATION: THE TRANSPORTATION SECTOR

The commitment to keep the average world temperature increase within 2°C is nowadays spread worldwide, there are several solutions to reduce greenhouse gases emission, in different fields. The main contributor to the greenhouse effect is CO2, which has a deplorable impact, however, permanence in the atmosphere can perdure many years, differently from other gases. The CO2 in the atmosphere has reached a concentration of more than 400 ppm due to the latest two centuries' anthropological behavior which has experienced an exponential increase in CO2 emissions annually, as highlighted in Figure 1-1 [1].

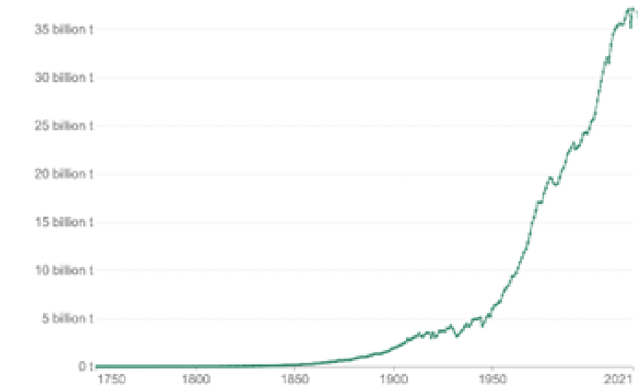


Figure 1-1 - Annual CO2 emissions

Among the different sources of CO2 emission, it is clear how the use of fossil fuels has reached an uncontrollable situation, and only in the last 20-30 years the research has spread toward renewable energies, also investment has increased in this direction, with new renewable capacity installed each year. So basically, the latest increase in CO2 emission has been also accompanied by a relevant increase in installed renewable technologies (Figure 1-2) [1].

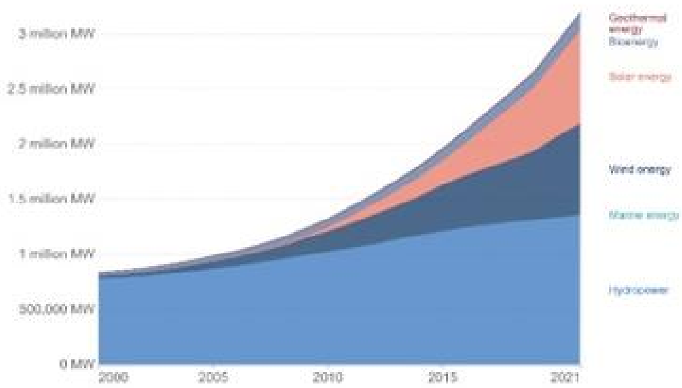


Figure 1-2 - Installed global renewable capacity

However, the continuous increase in energy consumption has not helped the reduction of CO2 emissions, even though the continuous increase of renewable capacity. Indeed, as in some sectors, the transition may appear straightforward, but some other fields are challenging, these are the so-called “hard to abate sectors”, referred to as those fields for which the transition is not nearly so straightforward, because they either lack the technology or its cost remains prohibitive [2]. In these fields, the use of fossils is still widely spread and the challenges towards transition have not been overcome due to the necessity of large investment and customers’ skepticism. One of these fields is the “Energy and Heat” sector and the “Transportation” sector, both together account for about 24 billion tons of CO2 emissions annually (Figure 1-3) [1].

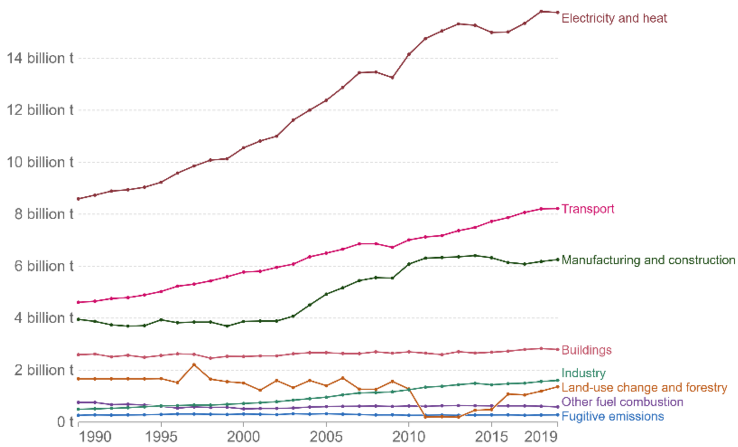


Figure 1-3 - CO2 emissions by sector

Going more in detail in the transport sector it is possible to see how the CO2 emissions are accounted for among the different subsectors (Figure 1-4) [3].

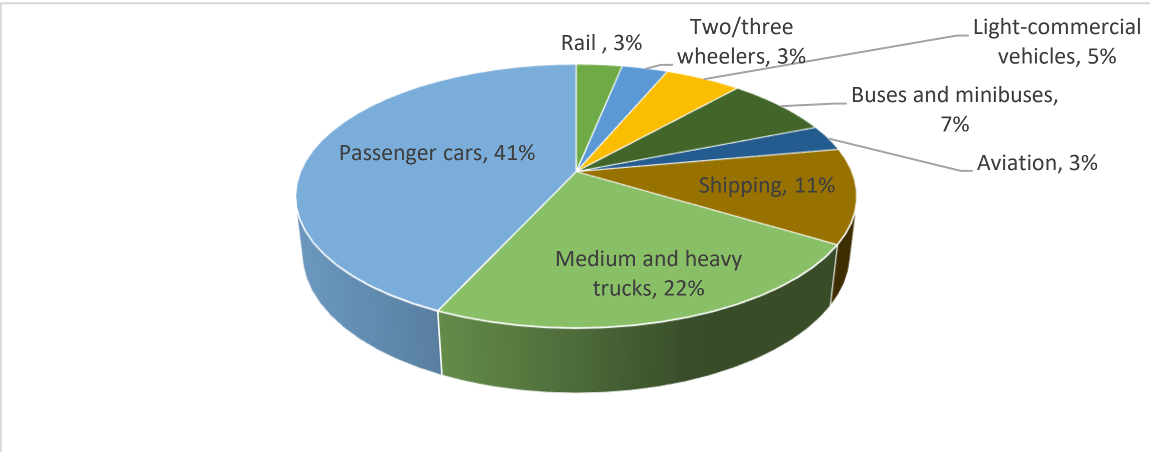


Figure 1-4 - CO2 emission in the different transportation subsectors

As is highlighted, most of the emissions are accounted for by passenger cars, medium and heavy trucks, and shipping. For this reason, the research is strictly focused on overcoming the difficulties that characterize these three main subsectors of transportation. Worldwide it is always more common the utilization of Battery Electric Vehicles (BEV), considered one of the most promising solutions for reducing oil dependency and the environmental impact of road transportation [4]. However, the possibility to see in the future different technologies is strong, the use of alternative fuels, such as Bio-Diesel, is under research, while the use of

Hydrogen as an energy vector is promising, although, it brings different challenges from storage to production. Indeed, hydrogen could be only produced from the scission of the H_2O molecule and it requires energy. The use of excess renewable would be a solution to produce hydrogen with a 0-emission impact, storing the excess energy in the H_2 molecule [5]. This solution will bring to new kind of engine, powered by fuel cells (HFCV). It may be desirable to promote heavy truck transportation well before large amounts of renewable hydrogen are available from surplus [6].

With the continuous increase of policies towards sustainable mobility, the scenario in which Internal Combustion Engines Vehicles (ICEV) will be banned is very strong [5], for this reason, the only way to reach complete sustainable mobility will be the use of BEVs and HFCVs [6].

From this the technology would be extended to other transportation methods, such as shipping, railway, or aviation, that account for fewer CO_2 emissions than road transportation, however, the continuous improvement in sustainability in road transportation would bring to increase in emissions for these other transportation subsectors before cited, that is still in continuous growth.

1.1 Electric drivetrain, Fuel cells, hydrogen, and its production

In the present section, the main ongoing technology towards decarbonization in the transportation sector is discussed, with a particular focus on fuel cells, hydrogen, and its production, highlighting the main characteristics of each, its pros and cons, and future developments in transportation.

1.1.1 Electric drivetrain developments

The concept of electric vehicles is not new, it relies on years and years of research and continuous development by car manufacturers, academic institutions, and private organizations. Indeed, the poor performances and heavy costs of the first electric cars have not made the path towards green mobility easy, only the improvement of battery technology in the last twenty years has made feasible the growth of this technology with accessible prices [5].

Nowadays a good share of road vehicles is a BEV, and the continuous development of the electric drivetrain will let the increase of electric vehicles at the expense of ICE, many manufacturers, indeed, are responding to the policies of European Countries which aim to decarbonize the transportation sector. However, the key to decarbonization still lies in the original electrical source, the vehicles may be considered pollutant-free only if the electricity stored in their battery comes from a renewable source.

Nevertheless, the range limits of BEV and their long recharge time make them less attractive than ICE, despite the continuous limitations imposed by policies and the increase in fuel prices. For this purpose, to facilitate the transition towards electric vehicles, the hybrid solution would be the most appropriate.

So, among the different electric vehicles, it is possible to recognize Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs), and Plug-in Hybrid Electric Vehicles (PHEVs):

- BEVs: as already seen, these are all-electric cars, moved by an electric motor that is powered by a battery, typically of the Li-Ion kind. The main features of these vehicles are the range limit, in the most common vehicles it is around 2-300 km, and the recharge time, however, depends on the charging infrastructure, it could go from several hours to some minutes.

- HEVs: Different from all-electric cars, these vehicles are powered by two kinds of engines, an ICE and an electric motor. The purpose of the electric motor is to take advantage of the Regenerative Breaking and recharge a small battery that could be used to drive the electric motor in a full-electric mode or to support the ICE, with a consequent reduction of consumption and so emission. Even though these vehicles have the same range limit and refilling time as ICE, their weight is augmented due to the presence of two motors (one electric and one thermic) and a small battery to run the electric motor.
- PHEVs: The only difference with the HEVs is the possibility to plug the vehicle into a charging station, taking advantage also of the electricity network [5].

In contrast to vehicles powered by conventional fossil fuel, the energy storage system is of crucial importance for electric vehicles. The use of batteries to store electrical energy is one option, but at the same time, the possibility to use hydrogen as an energy vector is concrete [5]. It is widely recognized that hydrogen will play a fundamental role in the decarbonization of the transportation sector, the use of Fuel Cells (FCs) on board vehicles makes them comparable to ICE. As matter of fact, the refilling time of hydrogen is equivalent to that of petroleum-based fuels and the range limit is the one given by the hydrogen tank. Even so, at present, the use of hydrogen is still challenging due to high costs and a lack of infrastructure, and on the other hand, the production of hydrogen is still widely covered by fossils, making it a not-green resource. Just as batteries, hydrogen could be considered a pollutant-free source only if it is produced without generating emissions, so from renewable sources.

1.1.2 Alternative fuels

Beyond electrical development, another strategy toward decarbonization is the use of green alternative fuels. The use of such fuels could contribute to reducing pollution emissions, indeed, the key is the utilization of bio-extracted fuels, so those chemicals that come from natural resources such as biomasses or recycling of waste materials can come from a variety of sources through thermochemical processes. Their composition is similar to petroleum-derived fuels such as gasoline or diesel and so they could be considered with a similar chemical and physical infrastructure [7].

Biofuels may be of a different kind and could come from different sources, such as biodiesel, methanol, ethanol, butanol, dimethyl ether (DME), diethyl ether, bioethanol, synthetic natural gas (SNG), and so on [8]. For example, DME could be produced from different feedstocks such as coal, natural gas, and biomasses, and its advantage is the higher combustion efficiency, due to its liquid form, indeed it is widely recognized for the higher combustion efficiency of liquid fuels concerning solid fuels.

Alternative fuels are very interesting for those transportation subsectors for which batteries may be of limitation and electric development is very challenging, such as marine and aviation, however, it is true that biodiesel blends are available commercially for road transportation [8]. Nevertheless, the wide use of diesel in marine engines and the continuous development of new technology that could reduce pollutant emissions, has attracted the possibility to engage biodiesel as alternative fuel [9].

Biodiesel has excellent quality and offers different advantages compared with other fuels; indeed, it could be considered a renewable source, processed from plant and animal waste feedstocks, it is versatile as it could be produced from a wide kind of feedstocks, it emits about 78% GHG emissions of conventional diesel, furthermore, it is easy to use, biodegradable and non-toxic. On the other hand, it presents some disadvantages, such as high viscosity, lower energy content than conventional fuels, and higher NOx emissions, moreover, there is the necessity to use compatible materials and special handling in cold weather.

At the same time, there are some criticalities concerning the different biodiesel varieties that could be produced, competition for resources with human food, and costs [9].

Despite this, some marine engine manufacturers as *Caterpillar Incorporated* had extensive experience with biodiesel and stated that it can be used without any short-term problems. Nowadays most of the new and existing Caterpillar marine engines are capable of using up to 30% of biodiesel without any mechanical modification [9].

Another important transportation subsector as aviation is in continuous development and recent studies have shown how biofuels may be a strong candidate to replace fossils, however, it is important to state the compatibility to modern and existing aviation turbines, trying to meet the standards based on engine operation condition, storage, environmental and safety aspects, indeed up to now their poor fuel properties do not make them a feasible solution, but with good possibilities as far the technology is improved [10].

Parallel to these developments, organizations such as IATA and ICAO work towards decarbonization, and the use of waste materials from different feedstocks can contribute [10]. Indeed, large quantities of various waste energy resources could be converted into biofuel. The main advantages are its low cost, easier production than biomass-based biodiesel, better quality, fuel efficiency, lower GHG emission, no need for engine modification, and wide feedstock sources. On the other hand, some of these feedstocks may be of challenging processes, such as plastic waste that could also be a source of toxic gases [7].

In a conclusion, the research of different and more sustainable fuels to replace fossils is in progress, and progress in technology may unlock new and unique fuels such as lately is happening with hydrogen, that present positive but also negative unique features.

1.1.3 Hydrogen: a potential sustainable fuel

Another important alternative fuel that is gaining ground in the energy sector is hydrogen, considered by most as the key to future decarbonization. Hydrogen, indeed, is a very simple molecule with the highest energy density among the known fuel, with a higher heating value three times higher than that of petroleum, of about 120 MJ/kg, it is the lightest element known and carbon-free, it means that its combustion, or in general oxidation, does not release any carbon emission, nor pollutants of any kind [11]. However, in the case of combustion, it releases NOx, but this issue can be easily overcome with the implementation of Fuel Cells (FCs), known also for their higher efficiency than conventional combustion [12].

Unfortunately, hydrogen is not free in nature, and it can be obtained in different ways, it is contained, obviously, in water, and different chemical compounds, such as fossils, biomasses, and so on. For this reason, the production of hydrogen is strictly correlated to the main energy source used and so far, the main sources are fossil fuels that account for 96% of the world's hydrogen production through different processes, such as Steam Methane Reforming (SMR), that are used to produce hydrogen from natural gas, Thermo-chemical conversions starting from sources as coal, oil, biomasses, and wastes, and only 4% of world's hydrogen production comes from water electrolysis [13]. The latter is the only possibility to obtain emission-free hydrogen, electrolysis indeed uses electricity as the main energy source to split H_2O in H_2 and O_2, and if the electricity provided is renewable so it means that also the hydrogen produced can be considered carbon-free, called also green-hydrogen [13]. For this purpose, hydrogen could be considered as energy storage, as well as are considered biofuels and batteries, and among the different solutions hydrogen could be strongly thought to be the key to enabling large-scale renewable storage [13], being batteries not suitable for long-term storage due to their high self-discharge rate, while biofuels struggle to find a suitable use due to different political and land-use related issues [14].

As a fact, the intermittency of renewables and the continuous development worldwide will need a reliable and efficient storage solution strategy, the Hydrogen Council has foreseen a surplus of renewable's electricity of about 250-300 TWh in 2030. Already in 2013 in the Canadian province of Ontario, renewable generation reached a very high level with a surplus of almost 18.3 TWh, at that time the energy was dispatched to the neighboring jurisdiction but if a mature storage strategy would have been implemented so it would have been possible to supply approximately 1,396,000 houses for an entire year [13]. Similarly, the overproduction of renewable has happened 103 times in 2017 in Germany, with consequent losses of energy and negative prices [13]. In this way, it is possible to develop the so-called *Power to X* concept, with hydrogen that could be produced whit renewable's electricity surplus and can be reused when there is low energy production [14].

One of the main uses for hydrogen indeed is in the transportation sector, the continuous development of FCs has made it one of the main alternatives to fossils, it is indeed estimated that the use of H_2 and FCs will be competitive with ICE, due to technological developments but also to increase of fossils' prices [11]. The use of hydrogen in transportation may overcome those problems related to EVs as long recharging times and range limits, however, the EVs infrastructure is already ahead of that of hydrogen vehicles, which is so far almost inexistent [12].

Certainly, the development of a hydrogen infrastructure is an important barrier to the uptake of such technologies, as well the hydrogen production chain must be established. As already cited, so far most of the hydrogen comes from fossils using SMR, however, the implementation of water electrolysis is the key to obtaining green hydrogen. Between the different electrolyzers, it is worth mentioning:

- Alkaline electrolysis cells (AEC) are a mature technology already in use worldwide.
- Proton Exchange Membrane Electrolyzers Cells (PEMEC) are rapidly reaching maturity and are of interest for power-to-gas applications. They have a fast response and start-up, particularly suited for intermittent power supply and mobile applications.
- Solid Oxide Electrolyzers Cells (SOEC) can operate at very high temperatures enabling very high efficiency, but differently from other electrolyzers, they need a long start-up time [12].

To be effective, hydrogen to be stored, among the different solutions, can be compressed at pressures around 20-100 MPa, liquefied at a temperature of nearly -253 °C, cryo-compressed, stored in hybrids, used for solid-state hydrogen storage, or in Liquid Organic Hydrogen Carriers (LOHCs) [15]. Compression of hydrogen is useful to obtain a sufficient energy density, nowadays it is the preferred storage option, nonetheless, the compression consumes about 2.67 kWh/kg of hydrogen, so it means that 7% of the hydrogen energy is lost in compression. In the case of liquefaction, the energy density of hydrogen is greatly increased, allowing large-scale transport, however, it consumes considerably more energy than compression [12].

In conclusion, hydrogen implementation will be the key to future decarbonization with great environmental advantages, exploitation of renewable's surplus, and less fossil dependency. On the other hand, the costs are still too high, and the lack of infrastructure needs high investment costs [13].

1.1.4 Fuel cell: a new electric motor

The concept of the fuel cell is not new, and it has been in development since the 1800s, however, the actual utilization only occurred in the 1950s, whit extensive research from NASA to generate power for space vehicles [5]. FC works in the opposite of electrolyzers, so instead of producing hydrogen, they use it as fuel to produce electricity and heat as a by-product [16]. In general, it is considered an FCs any electro-chemical device that can convert directly the chemical energy of a given substance (or fuel) into electrical energy, the main feature is the possibility to continuously feed the cell with the reactants, as they are an external source, differently from batteries that have their reactants already inside the cell [5]. Usually, the oxidant is O_2 as it is contained in the air, easy and free to use, while depending on the kind of FCs it is possible to use a wide variety of fuel, even if it is recognized that the most suitable and green fuel is hydrogen [17].

As already said the main difference between batteries and FCs is the presence of reactance within the cell or not, as FCs can be fed directly from an external tank. In this way, it is possible to decouple the energy and power of the system, with energy depending on the size of the tank, while power depends on the number of FCs' stacks. However, they also present some similarities, as the working principle is based on anode-cathode electronic transfer and direct chemical energy conversion into electricity, indeed, they both require an electrolyte to perform the reaction [17].

The main classification method of FCs is based on the electrolyte material and the working temperature. So, we can define high-temperature FCs and low-temperature FCs, summarized in Figure 1-5.

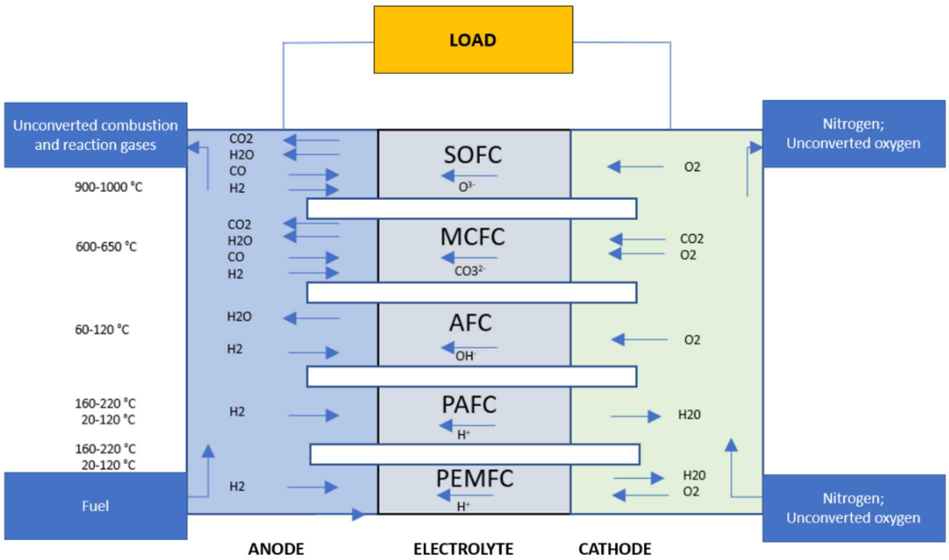


Figure 1-5 - FCs technologies

Among these, the most interesting are SOFC and PEMFC which are respectively high and low-temperature kinds.

SOFC is suitable to use in different kinds of fuels, it works at high temperatures, and it has high efficiency, moreover, due to the high working temperature it does not need a catalyst. On the other hand, it has a slow start-up time, and it is not suitable for those applications in which there is a high fluctuation demand. So, they are most suitable for medium and large power sectors. Typical fuels used in SOFC may be hydrogen, methane, and biofuels. Despite the advantages of such technology, the prohibitive costs make it still not commercialized, due to their precious material that must be able to work at high temperatures. Nowadays research is going toward the reduction of temperature while keeping the same or higher efficiency, to reduce costs and the use of precious materials [18].

Concerning PEMFC, they deliver high-power density while providing low weight. Hydrogen is oxidized in the anode while the reduction of oxygen occurs at the cathode, according to the following reaction: [5]

$$Anode: H_2(g) \rightarrow 2H^+(aq) + 2e^-$$

$$Cathode: \frac{1}{2}O_2(g) + 2H^+ + 2e^- \rightarrow H_2O(l)$$

The main advantage of PEMFC is the low start-up time and the adaptability to dynamic behavior, making it very suitable for the transportation sector in general, mostly for road vehicles. The high efficiency, however, is due to the presence of a catalyst, that in this case is platinum, a very rare material. The use of PEMFC in the automotive sector allows to overcome those issues related to EVs, such as the driving range compared to refilling time, indeed, the autonomy of Fuel Cell Electric Vehicles (FCEV) is in the range of 5-600 km with a refiling time of about 5 min, comparable to ICE. Concerning safety, the high diffusivity of hydrogen allows this technology to be considered safe also in case of a car accident. Said so, it can not be hidden that further developments are needed to make this technology commercial, first of all, the prohibitive costs are one of the main barriers, that could be easily overcome with mass production, secondly, the lack of a hydrogen infrastructure will keep the use of this technology to limited regions such as California and Japan mostly, where the use of FCEV is spreading [19]. Moreover, the hydrogen storage issue is another important barrier that needs to be accomplished, as already discussed.

As well as for passenger cars, lately, also the development of FCs for heavy-duty transportation is under research. The main advantage is the need for fewer infrastructure investments, lower refueling stations due to more predictable routes, and the possibility to take advantage of bigger vehicles and so reduced space restrictions, given the possibility to use the vehicle's roof (as in buses), as a consequence also the tank and compressions costs are reduced, as the hydrogen could be stored ad 350 bar instead of 700 bar as it should be done on passenger vehicles [20] [12].

Concerning other transportation means such as motorbikes, Intelligent Energy has developed a 4 kW FC system in cooperation with Suzuki. The low fuel consumption allows it to be refueled using hydrogen canisters from vending machines. As a result, also FC motorbikes can contribute to reducing emissions and improving air quality [12].

The railway sector is already widely electrified, however, the use of FC trains in those regions for which it is difficult to electrify the network route is a concrete opportunity.

In the marine sector, it is expected to gain traction until 2030, however, some FC deployments are on run, mostly projects concerning ferries' propulsion.

The most difficult to abate sector is aviation, while some hybrid electric concepts are being studied, the use of alternative fuels such as biofuels could be feasible instead of electricity, due to the higher density of liquid fuels, though, they can not be considered emission-free. The use of hydrogen is unlikely to be seen with fuel cells due to the lack of power required for take-off, however, it can be used as propulsion fuel in turbines, instead of kerosene. Nevertheless, the combustion of hydrogen produces more than double the water vapor of kerosene, it contributes to radiative forces at high altitude and so contribute to net warming, despite the short life in the atmosphere. Other aviation-based sectors have more chances to go through decarbonization in the next future, such as Unmanned Aerial Vehicles (UAV) [12].

In other sectors rather than transportation, FCs can contribute to electricity and heat generation, with the development of Fuel Cell CHP with the implementation of high-temperature FCs which are likely to release high-quality waste heat [12].

In the end, it is possible to resume the main advantages of FCs:

- No pollution, being water and heat the only by-product
- Higher thermodynamic efficiency
- Efficiency does not drop with a decrease in power size

- FCs react almost instantly to changes in voltage load, suitable for cogeneration applications
- In the automotive sector the short start-up time makes them very attractive
- Refilling time is comparable to that of conventional systems not necessary to recharge a battery.

On the other hand, it is possible to list the following disadvantages:

- Need for relatively pure fuels
- Development of a more reliable hydrogen storage system is crucial
- PEMFC needs platinum as a catalyst
- Uncontrolled water state changes will negatively affect the FC operation and life
- Efficiency reduced due to the need for compressed air and high-speed compressors
- FCs are overall bulkier and heavier than ICE [17].

Table 1-1- Main fuel cells and their characteristics

FC TYPE	ELECTROLYTE CONDUCTION	OPERATING TEMPERATURE	EFFICIENCY	ADVANTAGES	DISADVANTAGES
Molten Carbonate (MCFC)	Carbonate ions (CO_3^{2-})	High temperature: 600 – 800 °C	50%	High efficiency Generate high-grade waste heat Fast reaction kinetics Catalyst not needed	High-temperature corrosion and intolerance to Sulphur The electrolyte in liquid form Long start-up time
Solid Oxide (SOFC)	Oxide Ions (O^{2-})	High temperature: 1000-1200 °C	60%	High efficiency Generate high-grade waste heat Fast reaction kinetics Catalyst not needed Wide variety of modular configurations	Moderate intolerance to sulfur Lack of practical fabrication processes Technology is not mature yet
Alkaline (AFC)	Hydroxyl ions *(OH-)*	Low temperature: <100 °C	60%	Fast start-up times Easy to operate Lower component cost Platinum catalyst not needed Minimal corrosion Low weight and volume	Extreme intolerant to CO_2 and CO Requires pure oxygen and pure hydrogen The electrolyte in liquid form Relatively short lifetime
Phosphoric acid (PAFC)	Hydrogen ions *(H^+)*	Low temperature: 100-200 °C	40%	Highest temperature among the low-temperature FCs Generate high-grade waste heat Tolerant to CO_2 and minor impurities Stable electrolyte characteristics	Partially intolerant to CO and Sulphur Corrosive liquid electrolyte Large and heavy Long start-up time
Proton Exchange Membrane (PEMFC)	Hydrogen ions *(H^+)*	Low temperature: 60-100 °C	60%	Low temperature, pressure, and start-up time Solid, dry, noncorrosive electrolyte High voltage, current, and power density Tolerant to CO_2 content in the air Compact and solid build	Mid-tolerance to CO and sulfurs Reactant gas needs pre-humification Requires platinum catalyst Fragile and expensive PEM

1.2 HYDROGEN IN TRANSPORTATION

After having analyzed on a high level the main innovative decarbonization solutions in transportation, in the present paragraph the single sub-sector of transportation is discussed, with a focus on the use of hydrogen as the main alternative to fossils.

1.2.1 Automotive transportation

Hydrogen in the automotive sector does not represent a sudden innovation, the development of such technology lies in years and years of research, and only later, with the continuous use of fuel and increase of GHG emissions, the attractiveness of hydrogen reached a sudden improvement. This is also the result of the difficulties that electric vehicles are facing, due to limits in range and long recharge times. However, the improvement of electric cars and their commercialization could be the key to the development of FC cars. As matter of fact, the use of FC will still rely on electricity as an energy source, the only difference is the production of the latter, which will happen using the FC itself, and so stored in a liquid form, into hydrogen rather than in a battery. As previously discussed, the advantage of storing energy in hydrogen is mostly due to the reduction of recharging time of a vehicle and the possibility to decouple energy and power of it [16].

Among the different FCs, the PEMFC is for sure the most promising in the automotive sector as it works at relatively low temperatures, has high dynamicity, high efficiency, and low corrosion compared to other kinds of fuel cells. So far, the main producer of hydrogen vehicles is Toyota, Hyundai, and Honda, with a very niche market enclosed in Japan and California which at the moment are the only region worldwide that ensure a reliable hydrogen infrastructure. However, the Asia-Pacific region is expected to lead the market in the next future, as it can take advantage of the recent growth [17].

On the other hand, the use of hydrogen as fuel brings also different disadvantages. First of all, hydrogen storage still faces some difficulties, and researchers debate the possibility to store hydrogen in a liquid form rather than in a compressed gaseous form [5]. Moreover, the cost of such technology is still prohibitive, with hydrogen vehicles' costs being in the range of $50,000-$60,000, mostly due to the precious material needed to build the catalyst. To be competitive with ICE, FCs must reach $36/kW and one of the possibilities to reduce such cost is mass commercialization. Nevertheless, research is exploiting also different cheaper catalyst solutions, such as liquid polymer cathodes, that could replace platinum. Another aspect to consider is the need to humify the air flowing into the cell, a low level of humidification strongly affects the performance and the durability of the system, corroding the electrodes and the catalyst layers [17].

In general, the automotive sector could be divided into private transport and public transport. Concerning the firsts, the lack of infrastructure is crucial for its commercialization, being it an adding issue to those already discussed previously. In public transport, the problems may be easier to overcome.

The main advantage of using hydrogen in buses is the large space availability, easiness to reach refueling sites that mean fewer investment costs, and FCs on board buses may be 30%-140% more efficient than diesel engines due to a more compact engine and more efficiency the system itself. In the UK there has been already granted 13.8 million euros have to develop a hydrogen infrastructure with relative buses, while the city of Liverpool is ready to be carbon-free by 2040. Also, the major bus company in Europe, Flixbus, is intentioned to deploy FC buses in the next years [17]. Similarly, in the city of Bolzano 12 hydrogen buses have been already inaugurated, to be recharged at their depot, to run in the public transport network of the city. It is so far one of the largest bus fleets in Europe [21].

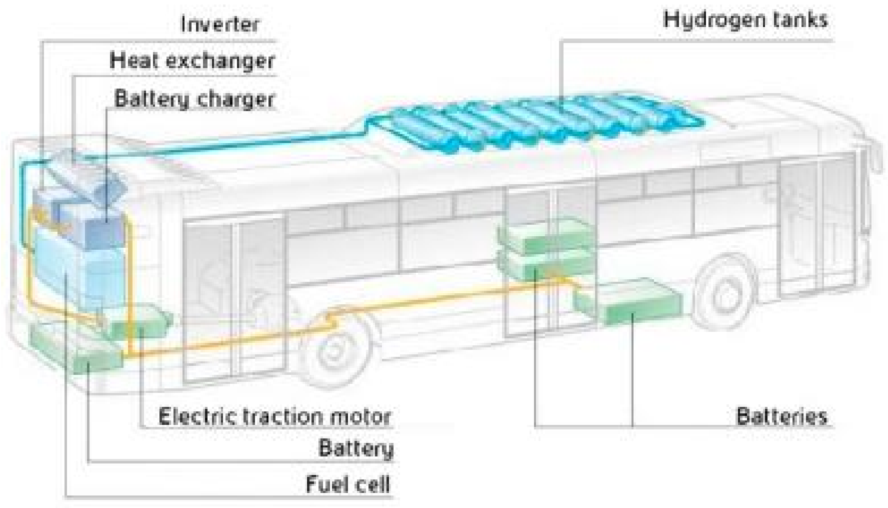


Figure 1-6 - Schematic of a fuel cell bus

In conclusion, the use of hydrogen in the automotive sector is promising, some issues are still to be resolved but the continuous research and development of such technology are positive, with car manufacturers that are moving in this direction. The synergies between manufacturers and countries are the key to enabling this technology, with policies that must play an important role, mostly concerning hydrogen production and delivery, which is still a main issue to let deploying such technology. On the other hand, it is not granted that the development of hydrogen-based public transport will be the gateway to unblocking hydrogen mobility. Indeed, buses present an easier way to overcome those problems that are typical of this field, starting from a less preponderant need for a refueling infrastructure, more space available to store hydrogen, and predictable routes that could help to develop energy management strategies.

1.2.2 Railway transportation

The use of hydrogen in railway transportation could be an opportunity to decarbonize those routes for which the construction of an electrical line would be too much expensive or limited by geographical reasons. Nowadays most of the railway routes are indeed electrified, nonetheless, in some regions or even entire countries, the main fuel used to run locomotives remains diesel. In these systems the diesel engine is one that directly provides electricity to the electric motor, resulting in a diesel-electric motor. The use of hydrogen could be a possibility to avoid the construction of an electrified infrastructure that in this case would be more expensive [22] [23].

Already in 2002, there was the presence of mine locomotives running with hydrogen fuel cells. Other projects in the following years were related to the installation of fuel cells on board locomotives with the assessment of the related issues such as the need to cool down the system, recharging rate, storage, and so on [23]. Another study has presented a simulation tool for the Piedmont corridor in North Carolina, resulting in a feasibility development of a fuel cell or a fuel cell hybrid locomotive to interconnect the two cities of Raleigh and Charlotte [22].

1.2.3 Marine Transportation

Among the different transportation subsectors, also marine ships are widely responsible for pollution and GHG emissions, resulting in not only climate impact, but also marine environmental impact, with the release of huge amounts of toxic gases in the proximity of the sea level. The International Maritime Organization (IMO) forecasted an increase in CO2 emissions in 2050 to be 3 times higher than the 2012 level if no action would be taken. As matter of fact, the propulsion system of marine ships is diesel-based, with engines that are similar to those of land use [9].

Different studies focus on energy management systems to improve marine ships' energy efficiency, acting on different systems such as storage, power management, unconventional propulsion, dual-fuel diesel-electric propulsion, fuel cells, and onboard installed renewables. As for the automotive sector, the development of fuel cell technology is strictly correlated to all-electric ships and several project demonstrations have been carried out in the last decades [24]. It is worth mentioning the following projects and demonstrations cited in [25]:

- FellowSHIP: a 320 kW LNG MCFC registered an efficiency of 44.1% in a test run between 2003 and 2013 with no emission of NOx, SOx, and PM at all.
- FCSHIP: a project regarding operational and safety requirements for a fuel cell applied ship.
- METHAPU: a 20 kW SOFC was installed on a ship, fuelled by MeOH.
- Nemo H2: an interesting project regarding a passenger ship working in the canals of Amsterdam, completely propelled by a PEMFC and a backup battery.
- FELICITAS: realization of a 250 kW LNG SOFC unit for mega yacht purposes with a gas turbine and HVAC system.
- ZEMSHIP: a 4-year project regarding a PEMFC with a backup battery designed for inland passengers to use in Hamburg.

The main challenges concerning this sector regard the volumetric density of hydrogen that is low compared to diesel, resulting in a significantly larger volume of the system, considering also that fuel cells are bulkier than diesel engines [24]. On the other hand, the use of a fuel cell as a propulsion will avoid the combustion of any fuel, with consequently increased efficiency, lower noises, and lower vibrations [25].

1.2.4 Space applications

Hydrogen has been already used in space applications since the 1950s in missions like Apollos, as skyrocket fuel, or even in FCs to supply auxiliary electricity. Lately, with the emersion in other transportation sectors, the use of FCs is studied also for those space applications such as Mars missions or probe explorations. The need for these kinds of missions mostly relies on the capacity of FCs technology to work both as FCs itself and as Electrolyzers, so producing electricity, this kind of machine that can be converted is called Regenerative Fuel Cell (RFC). Indeed, the machines used for such missions usually rely on solar energy, so the possibility to use the surplus of energy during sunlight hours to store energy into hydrogen employing the Electrolyzer mode, and then use it to produce electricity when there is no availability of solar power, through the FC mode of the RFC. The advantage of hydrogen use is the lower weight compared to batteries, due to the high energy density of hydrogen itself. Between the different RCFs, it is possible to recognize the Discrete or United Regenerative Fuel Cells (DRFC or URFC). The first is composed of two machines, an electrolyzer, and an FC, integrated into a single system, allowing the independence of the two machines with the possibility to let them work simultaneously. The URFC, most interesting, is a single machine that could invert its working mode, passing from electrolyzer to FC and vice versa. The main advantage is the lower weight due to the presence of a single machine, but the assessment of similar efficiency must be studied to let this technology more attractive [26].

The use of hydrogen is not only exploited to improve the efficiency of space vehicles, but recent studies exploit also the use of hydrogen for space stationary applications such as [27] in which the researchers have simulated a hybrid system for extraterrestrial habitats capable of using FCs to provide energy during the night while taking advantage of solar energy during sunlight to produce hydrogen.

1.2.5 Aerospace transportation

Of the different transportation subsectors, aerospace is the most difficult to abate in terms of GHGs and pollutants. It is possible to identify two different zones where pollutants and GHGs are emitted, the airports or land emissions, and aircraft with air emissions. The first is responsible for emissions due to different actions happening on land, such as passenger transportation from terminals to airplanes, forklifts, and HVAC systems, but also taxiing of the aircraft itself and landing or taking off. On the other hand, the emissions happening in the air are only coming from cruising airplanes with consequent formation of curtails of water vapor, CO2 emissions, and pollutants. The use of hydrogen in airports and aircraft is widely discussed, presenting at the same time very interesting advantages and at the same time strong barriers to the development of such technology.

Concerning aircraft, the currently available fuel must meet specific requirements, more stringent than land use applications, and they have not to be affected by extreme temperature changes, for instance, flammability, flash point, auto-ignition temperature, and octane number. So far, biofuels, gasoline, Jet A, Jet B, kerosene, and methane are currently available fuels for aircraft use. However, the use of cryogenic fuels such as hydrogen could be a challenging opportunity to decarbonize this sector, it has a relatively high auto-ignition temperature, around 585 °C, high resistance to knock and so a theoretical high-octane number, required for such application. It could be used both in FCs to power auxiliary needs or for low-medium aircraft that could run on electric propulsion or be burned in adjusted turbines. The high energy density by mass of hydrogen is an important factor, as it reduces notably the overall weight of the system, but it has also a lower energy density by volume, making it impossible to store on conventional aircraft. High combustion temperature, lower flame emissivity, higher diffusion rate, no CO2 emissions are only some of the advantages of hydrogen use in aircraft, and on the other hand, the use of a redesign of aircraft to store hydrogen, low boiling point, high production costs, low energy density by volume and large amounts of water vapor emitted are the main barriers to overcome to let hydrogen use be completely advantageous in the aerospace sector as propulsion fuel [28]. Airbus has already announced to launch of its superjumbo jet by 2035, completely hydrogen-based, highlighting how the need for a hydrogen infrastructure will be the key to speeding up the development of hydrogen-based aircraft [29]. The aim is to have FC-powered aircraft able to host about one hundred passengers for a route of approximately 1,000 nautical miles [30].

Concerning the airport infrastructure, the continuous development of air transportation will result in a continuous increase of airports, that have to host more passengers than ever. Already in some countries very jammed airports are similar to small cities, from here the concept of an Aerotropolis, is "*a space that functions as a city itself, with living spaces for workers and their families, factories relying on airborne inputs and service industries located around the airport, with major road and rail infrastructure connected to it.*" [31]. For this purpose, the development of carbon-free technologies such as hydrogen will for sure be one of the main characteristics towards decarbonization of land emissions in the aerospace sector, starting from electric bus shuttle, renewable installation, electric ground support equipment (GSE), possibility to recharge its vehicle. In [32] it is exploited the techno-economic benefit of integrating hydrogen supply and electric auxiliary power units' aircraft with electric vehicle charging stations, solar PVs, and battery storage to reduce the withdrawal of electricity from the grid and improve the electrification of the surrounding systems of the airport. The concept of Aerotropolis is also briefly discussed in [33], where it is highlighted how the use of hydrogen in airports has not to be limited to aircraft but could be enlarged to other systems, creating an airport ecosystem. Airbus has pushed toward the use of hydrogen in airports as an energy vector for land use, it would help the next incoming hydrogen-based aircraft. The airports could be composed of different renewable energy technologies, able to store energy surplus in hydrogen. Logistics will also play a fundamental role, in hydrogen off-site production and delivery (Figure 1-7) [34].

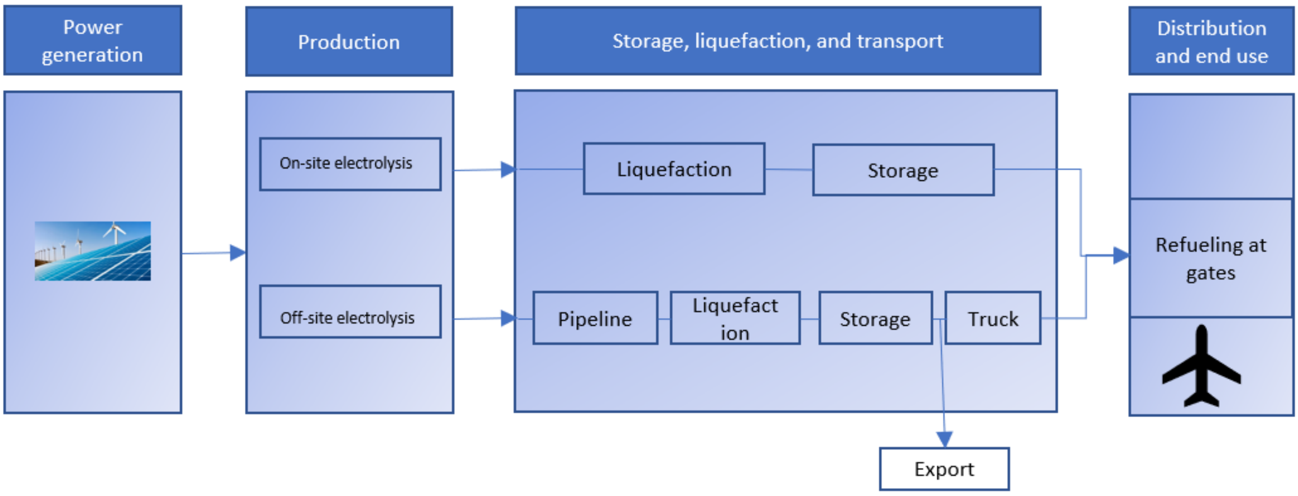


Figure 1-7 - The green hydrogen ecosystem for aviation

1.3 Why Aviation and Airports

As briefly discussed in the previous paragraph, decarbonization of the transportation sector is a very challenging task, with different opportunities, such as biofuels, batteries, and mostly hydrogen. Among the different subsectors, the most challenging remains the aviation sector, with different issues to be overcome to let the use of hydrogen feasible. It is possible to divide the emissions and as well the hydrogen in use in aviation into two zones, land use, so in airports and their surroundings, and air due to cruising of aircraft. In the next two paragraphs, both these aspects will be discussed presenting a brief overview of the main advantages, and disadvantages of hydrogen use in aviation.

1.3.1 Aircrafts

In the prospect of future aviation, the use of hydrogen will play a key role in decarbonization, the different drawbacks of this fuel mostly regards storage, propulsion, and lack of infrastructure on the landside. However, with hydrogen it is possible to use a third of fuel due to hydrogen's high energy density by mass, its environmental impact is zero due to the absence of the pollutant and carbon emissions, despite the huge amount of water vapor formation if burned, which is a GHG. The lifetime of water vapor, however, is nearly zero compared to the one of CO_2, with its lifetime increasing with the altitude until a maximum of nine months at 15 km, as highlighted in Figure 1-8 [28].

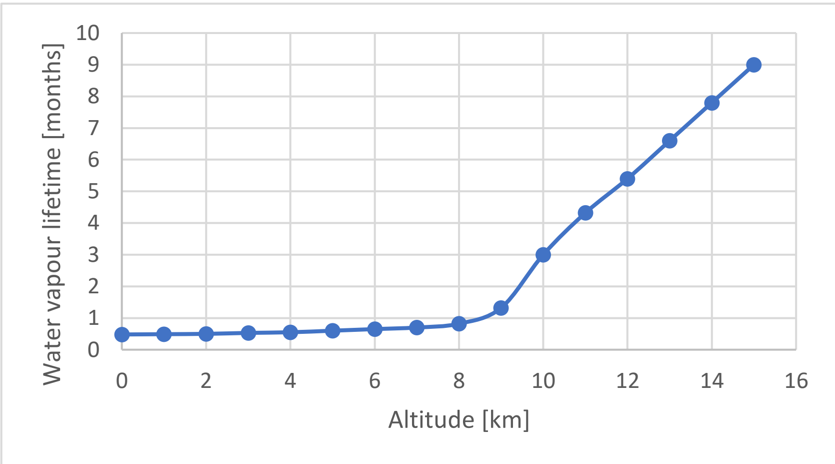


Figure 1-8 - Water vapour lifetime in function of altitude

The use of hydrogen on aircraft may happen in different ways, firstly it is possible to use it in turbines with conventional combustion, so using it as a fuel propeller, secondly, it is possible to use it in FCs and use electrical engines as propulsion, mostly suited for small-medium aircraft, and finally, it could be used always in FCs but to run Auxiliary power units on board of aircraft. The need to store hydrogen on board the aircraft is crucial in all these configurations. If used as fuel propelled in turbines or FCs so it means that a huge amount of fuel must be stored, and if it is true that hydrogen has a very high energy density by mass, making it very advantageous for taking off, reducing the overall fuel weight, it is also true that the energy density by volume is very low, with the necessity to install very bulky and complicated storage systems, with a consequent redesign of the aircraft itself [35].

For this reason, hydrogen must be stored in a different form, usually, in a compressed way, 350-700 bar, to improve its energy density efficiency, or liquid form (LH_2). The latter would be the preferred solution; however, the extremely low boiling point of hydrogen makes it challenging. Different designs have been proposed, both for small-medium and large aircrafts. LH_2 must be stored at very low temperatures, so the storage needs a very complex cryogenic system and good insulation. As matter of fact, the storage on wings, as it happens for kerosene, would be impossible, rather redesign aircraft in such a way they can host storage systems above the passenger's cabin or ahead and behind, as shown in Figure 1-9 [36].

Figure 1-9 - Fuel tank locations for kerosene and future medium or large aircrafts. a) Conventional; b) c) Hydrogen

In [37] two LH_2 combustion designs have been proposed, one for a smaller turboprop aircraft suited for short routes as regionals may be, and another for a narrow-body turbofan aircraft targeting those medium-long flights. The results show the need for an elongated fuselage, gravimetric storage indices in the range of 0.20-0.35, and the possibility to minimize seat space for low-cost airlines, enhancing hydrogen-based aviation. The first aircraft was studied with a capacity of 70 passengers for a 1,400 km flight, while the second aircraft could host up to 165 passengers for a 3,400 km flight. The results shown also how the aircraft would be heavier than fossils based, with lower energy efficiency. However, in 2035, it is expected the launch of the first hydrogen-based aircraft Airbus [30].

Concerning the use of FCs to supply the APU, the main advantage would be the complete elimination of emissions during the stationary time, as the FC would supply the required energy to run the internal power for air conditioning and lighting, as well as for the electronics equipment. The use of APU is employed also during taxiing from the runway to the gate or the parking, and the use of FC would help reduce about 20% of aircraft emissions [36].

Nevertheless, the lack of proper infrastructure, among others, is the main barrier to the development of hydrogen-based aircraft. Indeed, even if all the storage and propulsion issues would be overcome in the next future, the absence of a hydrogen supply chain will make all the researcher efforts useless. The production of green hydrogen is still too much expensive and the need of storage systems is required also on the landside, with dedicated spaces to store the fuel. As well the refilling process of hydrogen is more complex than the one of kerosene, with different safety concerns [36]. For this purpose, the simultaneous development of hydrogen in other sectors rather than transportation would help the mass commercialization of it, but still, the increase of renewable generation is crucial to assess green hydrogen production [38]. Airbus promotes the availability of hydrogen worldwide, to start ensuring a hydrogen infrastructure now, as the next available window for new generation aircraft will be in the next 15-20 years, otherwise there, will be a continuous use of fossil-based aircraft also in the next aircraft generation [39].

So, in conclusion, to assess new hydrogen-based aircraft, it is necessary to overcome some crucial barriers [40]:

- Aircraft and engine redesign, to let the use of hydrogen be feasible both if FCs systems or hydrogen-based turbines are employed.
- Hydrogen storage, to host the fuel onboard the aircraft.

- Assessment of green hydrogen production and reduction of its cost.
- Employment of a safe and reliable hydrogen supply chain and infrastructure in airports, to ensure both on-site production and/or delivery.
- Change of public perception about hydrogen as it is not more dangerous than already used fuels [39].

1.3.2 Airports

As previously discusses, the use of hydrogen on aircraft would be impossible without a reliable hydrogen infrastructure on the landside, and as a constraint, it has to be in airports, where all the operations concerning aircraft happen.

Firstly, it is important to assess the airport infrastructure before going into more detail about its hydrogen use. Airports are the most important feature the aviation, here are where aircraft land, take off, are stored, and where passengers can board them. Different from other transportation sectors, aviation airports are similar to small cities, with shops, living spaces, parks, and all the commodities that may be useful for passengers. With the continuous increase in air travel, the airports will change their face with continuous commodities improvements. Therefore, the energy consumption will increase, not for the terminal building and the surrounding services, such as vehicles, industries, bus shuttles, forklifts, and other ground support equipment [41].

With the commitment to reduce carbon emissions, most airports are accredited under the Airport Carbon Accreditation, from Airports Council International (ACI). The role of this agency is to provide a detailed and multi-step path to carbon neutrality, enabling airport operators to implement best practices in carbon management [41]. The levels, that will be discussed in the next chapters are:

- Mapping.
- Reduction.
- Optimisation.
- Neutrality

As well, emissions in the airport may be divided into three main categories:

- Scope 1: All direct GHG emissions.
- Scope 2: Indirect GHG emissions from consumption of purchased electricity, heat, or other services.
- Scope 3: Other indirect emissions such as extraction, transportation, or production of fuels, waste, and disposal.

For this purpose, airports should identify the main emission sources and determine their control over them, trying as much as possible to build a decarbonization path to be accredited with the highest level of neutrality [41].

Said so, the advent of hydrogen in aviation is not only a matter of accreditation, rather a development of a technology that must travel with aircraft manufacturers, indeed, the connection between aircraft and airports is very close, with airports to be adjusted depending the kind of aircraft that would be host, or vice versa, with airline's operator to buy more suitable aircraft for a given airport. For example, airports should have hangars and terminals that could host both "**Boeing 747"** and "**Airbus A380"** which are slightly different from each other, but differences impact the infrastructure of the airport [35].

The high energy expenditure within airports makes it interesting to exploit new energy efficiency measures, as well installation of renewable sources within the airport framework or in the surroundings. Usually, the electricity consumed in airports is derived from the grid, but lately, other energy sources are exploited, such as cogeneration plants, solar PV, wind, and geothermal energy [42]. Also, the management of ground support equipment would be a key to reducing emissions, it is estimated that the use of green equipment and intelligent management of vehicles to avoid any delay and maximize their use in airports will save about 475,000 tonnes of CO_2 for just one minute saved in the 50 major airports of Europe [43].

In the framework of the airports, the use of hydrogen could be employed in different services, beyond the use in aircraft itself. The airport could be set up to produce hydrogen on-site and supply surrounding vehicle passengers, hydrogen could also be employed in a stationary fuel cell that could provide both heat and electricity, as well supply bus shuttle and ground support equipment at service of aircraft, such as cargo handler, forklifts and so on [44].

In [45] are discussed the main opportunities of hydrogen in aviation, highlighting its use of it in the adjacent airport system. It is assessed how the use of electric and hydrogen ground support equipment will help reduce carbon emission in the surrounding of the airport, with a consequent improvement of the air quality, noise reduction, and costs. The hydrogen should be produced by renewable installed in the proximity of the airport, or by the electricity withdrawn by the grid.

Figure 1-10 - hydrogen applications in airports. a) airside; b) landside

However, to supply hydrogen also to airplanes, the ground infrastructure should be adjusted to be safe and reliable. Indeed, storage, hydrogen handling, and refueling are needed to provide it to airplanes. For this purpose, new regulations for hydrogen handling must be defined, not only in aviation but also in general in other sectors that could be of interest.

Lately, Airbus has signed a partnership agreement with HyPort, a joint venture between Engie and AREC, to support the development of one of the world's first low-carbon hydrogen production and distribution stations at Toulouse airport. The put-in service is forecasted for early 2023 and will be able to produce up to 400 kg of hydrogen daily, to power about 50 ground vehicles [46]. Indeed, the first challenge is the production of hydrogen in a quantity able to meet the prodigious requirements of the aviation sector, and the first step is the initial distribution of it to those technologies more developed, as would be vehicles. In this way, it is possible to start adjusting the airport infrastructure to host hydrogen technologies, while experiencing new logistics and challenges. The commercialization of hydrogen will help reduce costs in the next future, avoiding the increase in ticket prices for flights. In a 2030 scenario, there have been analyzed different hydrogen prices compared to carbon taxes in places to allow better penetration of hydrogen airplanes.

1.4 METHODOLOGY AND RESEARCH OBJECTIVE

1.4.1 Objective

The use of hydrogen is well discussed in the literature, with researchers focusing on the different challenging aspects regarding the aviation sector, both on the landside and the airside, discussed later in Chapter 2 on page 29. In the literature, it is possible to find different studies on hydrogen consumption in airplanes, with different route simulations and theoretical airplane design and layout, at the same time the airport as a hydrogen energy hub and the different aspects regarding refilling, production, delivery, and storage are exchanged topics in different journals. However, to the best of our knowledge, it has been observed a lack of economic assessment concerning the realistic behavior of an airport, with possible hydrogen and electricity consumption and production.

In this project, the main objective is to try to simulate the behavior of a typical middle-sized European airport, with coverage of both the regional and the continental market, as it is the Turin Caselle airport. The simulation to assess the electricity and fuel consumption of the airport, both on the landside and in the airside, also involves the energy consumption of strictly correlated emitting means, such as the bus shuttle linking the airport to the city center, and ground support equipment (GSE) operating within the airport framework.

The development of the project considers four main scenarios, beyond the current behavior of the airport. Firstly, it exploited the possibility to install a wide amount of solar PV, taking advantage of the different available spaces on the top of the airport's buildings, then the indirect emitting systems, as the bus shuttle and the GSE are supposed to be electrified, with consequent reduction of dependency from fossils and reduction of emissions. The use of hydrogen is exploited as a transportation fuel in the third and fourth scenarios, where it is imagined that regional and international segment airplanes, respectively, are hydrogen-based. In all scenarios it is analyzed the use of hydrogen in FCs to further reduces the dependency on the grid, while in the later and the former scenarios only, the production on-site of hydrogen, the delivery from external sources, and a blending system where there is the availability to produce it on-site or buy it, are analyzed, performing an economic evaluation between the feasibility of on-site production or delivery. In the end, it is discussed the possible pathway that modern airports should follow to reach decarbonization.

1.4.2 Project structure

The following paragraph it is described the main software used, while the next chapters are structured in this way:

- Chapter 2: it is analyzed the literature review, with a description of the main challenges investigated, firstly on the airside are described the features and the design that future airplanes may have, then it is reported the main characteristics airport have and should have to follow the decarbonization pathway
- Chapter 3: In this section, it is described the Turin Caselle airport, its location, the electricity, and fuel consumption. Then it is explained how hydrogen and electric consumption in the four scenarios are calculated with the different hypotheses adopted. A detailed description of the scenarios is clarified.
- Chapter 4: In this part, the main results are illustrated, with comparisons between scenarios and graph illustration of the main parameters analyzed.

- Chapter 5: the last section regards the evaluation of the hypothesis done, with a focus on what further study may bring to this work, and what it could be adjusted with deeper research, to optimize the result and have a better overview of the future hydrogen employment in this field.

1.4.3 HOMER Pro

The project has been carried out using Homer Pro software, it is useful to simulate and optimize microgrid design in all sectors, and being an airport similar to a microgrid the use of Homer pro has been successful.

Homer Pro stands for Hybrid Optimization of Multiple Electric Renewables, it can simulate different energy systems and optimize them by cost, also providing sensitivity analysis.

Simulation happens by making an energy balance for each time step comparing the electric and thermal demand with the energy that the system is capable to supply, and calculating the flow of each component of the system. Optimization is possible through the implementation of algorithms, specifically in Homer Pro it is possible to select the Load Following or the Cycle Following configuration. Moreover, it is possible to connect it to a specific optimization algorithm implemented in MATLAB. The definition of sensitivity variables is useful to have different results' cases available, with the opportunity to confront them.

Among the different power sources in Homer Pro, it is possible to recognize: Solar PV, Wind turbine, Conventional fossil generators such as gasoline or diesel, Electric grid, Traditional hydro, Run-of-river hydro, Biomass power, Alternative and custom fuel generator as biogas, Microturbine, and Fuel cell. Moreover, it is possible to define different storage technologies, such as flywheels, batteries, flow batteries, and hydrogen.

In Homer Pro libraries there are already different available sources from U.S. NREL (National Renewable Energy Laboratories), such as solar irradiance per square meter, sunlight hours in a year, and wind availability, each of them for worldwide locations.

The features available in Homer Pro are plenty, for further readings and information it is possible to visit the online manual user [47].

2 LITERATURE REVIEW

2.1 CHALLENGES ON THE AIRCRAFT SIDE

In aviation, it is possible to have different kinds of aircraft, the Unmanned Aerial Vehicles (UAV), and Big-sized aircraft for commercial or cargo flights. As well, as previously discussed, the main barriers concerning hydrogen use in aircraft are related to propulsion, storage, and the weight of the system. In this paragraph, these aspects are discussed with a brief review of the different challenges and solutions proposed in the literature.

2.1.1 UAV

A UAV is a powered vehicle that does not carry any pilot and it is completely controlled using a computer or remote transmitter. The use of these vehicles is lately increased for different objectives, the main area for scientific reasons, use of government in civil or military applications, and commercials [48].

Usually, these vehicles are powered by Li-ion batteries but the limits in terms of energy and power of these systems continue to let the use of ICE, which presents different disadvantages, beyond the emission of pollutants, such as noise and low efficiency. The use of hydrogen can provide a significant benefit given their magnitude increase in mass and volume-specific energy, improving the operating range of these vehicles. The use of hydrogen would be employed in FCs that have higher efficiency concerning ICE, do not emit any pollutant, and is more silent than ICE [49]. However, the use of FCs at the moment results in higher costs than batteries [36].

In the literature, it is possible to find different research projects ongoing to demonstrate the feasibility of such systems. As a matter of fact, in 2018 Intelligent UK developed a UAV which depended entirely on FCs, offering significative improved performances in terms of weight, efficiency, and refueling time [50]. A project called Hydra started on November 2018 to design a hybrid energy management system for a UAV and the vehicle itself which is shown in the next Figure 2-1 [48].

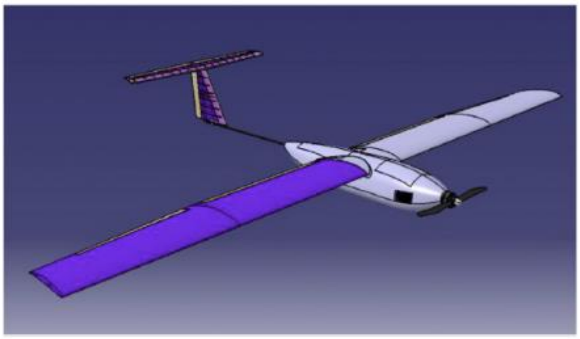


Figure 2-1 - Hydra final design

In [51] the design of a hybrid UAV, the NederDrone, capable of performing a vertical take-off and landing is carried out. The vehicle was equipped with 12 propellers supplied by a hydrogen-based PEMFC and Li-Ion battery for peaks of power. The test flight was performed on the sea, where taking off and landing was performed from a nearby ship, the test lasted more than 3 hours and the weather conditions were not optimal, demonstrating how the NederDrone was designed for real-world conditions.

Figure 2-2 - View of the NederDrone during the test flight

2.1.2 Big size aircrafts

Several experiments are carried out to assess the feasibility of hydrogen and electricity use in aviation. One of the biggest challenges is the use of it on-board commercial and cargo aircraft, as the difficulties coming from the use of hydrogen are not easy to overcome, and as well the use of batteries does not ensure enough power. NASA has already experimented with a solar-powered aircraft that should be able to fly indefinitely, however, the low efficiency of Solar PV and the high-power requirement of airplanes do not make it feasible, but rather use electricity to run the compressors in jet engine airplanes [35].

In [37] a comparison study between the use of e-kerosene and LH_2 in airplanes has been carried out, simulating the use of two different kinds of airplanes, a smaller one, powered by two turboprop engines, and a bigger one, powered by two turbofan engines, both shown in the next figure:

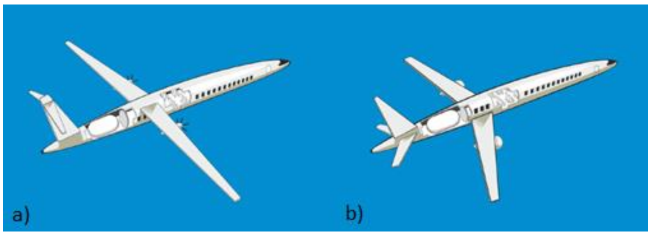


Figure 2-3 - Layout of the a) turboprop; b) turbofan airplane

The results of the study showed a reduction of range that if for the turboprop was negligible, it was almost half for the turbofan aircraft. Moreover, the overall weight is higher due to a very bulky and complicated hydrogen storage system, affecting mostly the Maximum Take Off Mass (MTOM). On the other hand, the emissions of CO_2 were completely called off and lower consumption of hydrogen in terms of mass, by conventional fossil-based aircraft.

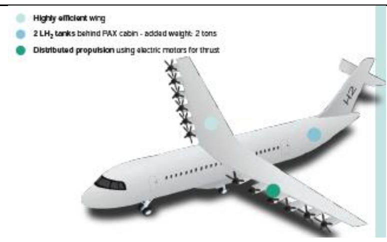
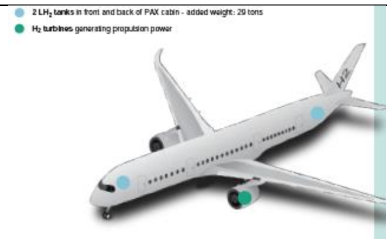
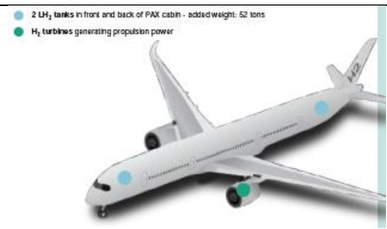
Another study conducted a comparative assessment of two green energy carriers, green hydrogen, and synthetic kerosene, indicating a strong future market potential for the mid-range segment aircraft, that will be likely to run on green fuels in the next future. Results showed high efficiency for the hydrogen engines and a reduction of up to 99% of NO_x. Moreover, the flight at a lower altitude would help the reduction of the

GHG effect of water vapor emissions, with a slight increase in Direct Operating Costs. In conclusion, the researcher state that environmental impact would not be eliminated, but rather drastically reduced if one or both the energy carriers (hydrogen and synthetic kerosene) would be implemented in the next future [52].

In [53] it is possible to consult different ongoing projects regarding hybrid electric aircraft, of different sizes. The review highlights how the use of hybrid solutions would be implemented temporarily to let the use of electricity and hydrogen in airplanes have a start in middle and long-range aircraft, while the use of electricity and hydrogen in UAVs should be easier.

Furtherly, it is assessed how the use of hydrogen would be beneficial for short-range aircraft, the main features for different sizes and flight ranges of aircraft, are expressed in the following Table 2-1 [54].

Table 2-1 Representation and characteristics of the main hydrogen-based conceptual aircraft

SEGMENT	PASSENGERS	RANGE [KM]	PROPULSION	FEATURES	IMAGE
Commuter	19	500	Hydrogen FC	-10% energy demand. 100% reduction of CO_2 and - 90% climate impact reduction. Increase of 5% in costs. +15% MTOM.	
Regional	80	1,000	Hydrogen FC	-8% energy demand. 100% reduction of CO_2 and - 90% climate impact reduction. Increase of 15% in costs. +10% MTOM.	
Short range	165	2,000	Hybrid with hydrogen turbines and FC	-4% energy demand. 100% reduction of CO_2 and - 80% climate impact reduction. Increase of 30% in costs. +14% MTOM.	
Medium range	250	7,000	Hydrogen turbine	+22% energy demand. 100% reduction of CO_2 and - 60% climate impact reduction. Increase of 40% in costs. +12% MTOM.	
Long range	325	10,000	Hydrogen turbine	+42% energy demand. 100% reduction of CO_2 and - 50% climate impact reduction. Increase of 50% in costs. +23% MTOM.	

2.1.3 Propulsion

Hydrogen airplanes could use different kinds of engines, fully electrical airplanes supplied by FCs, hydrogen turbines, and a hybrid solution capable of using both of them.

In the first case, the use of FCs in airplanes is suitable not only for propulsion but also to run the APU while the airplane is on the ground, reducing drastically the pollutant emissions on the landside, moreover, still, on the ground, the electricity produced from the FC could be used for taxiing on the ground, reducing also the fuel consumption, since the jet-fuel turbines are designed to work at high load and are highly inefficient while running on the ground. It may be impossible but due to delays, the time the turbines are running consuming fuel could also reach 10-30% of the total flight time. The use of an all-electrical APU, so, could be useful to reduce landside emissions and save fuel, however, the redesign of airplanes is fundamental to host not only the FCs system that could simply take the place of already used APU but also hydrogen storage [45].

Nevertheless, the use of FCs in airplanes finds its interest in the propulsion system, ZeroAvia is developing a zero-emission hydrogen-fueled electric drivetrain that will be installed on existing short-range airframes, indeed, the use of FCs for long-range aircraft is unlikely to happen, rather the use of hydrogen as a propeller in adjusted turbines [45]. In these systems, the use of a battery would be helpful to ensure faster load following and optimize the peak shaving of the propulsor. In this case, the formation of contrails is unlikely to happen, making it a true zero-emission solution. Unfortunately, FCs can not guarantee the energy necessary to power big aircraft, so they should be used up for regional segment aircraft [55]. Moreover, the use of FCs helps the reduction of the density of nucleation points in water vapor released, with a consequent reduction of environmental impact [40].

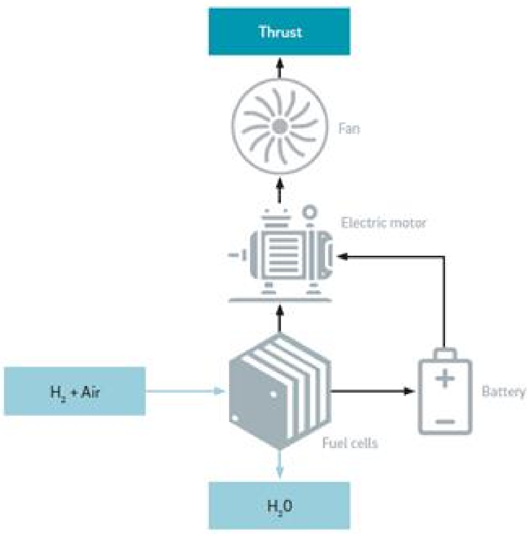


Figure 2-4 - Hydrogen Fuel cell solution

Another solution is the use of hydrogen in turbines. Hydrogen would be burned in turbines as well as it happens with kerosene nowadays, the thrust created by the combustion is necessary to move big-sized aircraft typically used for long-range flights. Differently from FCs, the water vapor formed by the combustion of hydrogen has a radiative effect at high altitudes, and for this reason, the environmental impact will persist with this solution, even if it would be reduced. Moreover, the conversion of hydrogen through combustion has lower efficiency than direct chemical conversion in FCs, it will result in higher fuel consumption and so bigger hydrogen storage and weight added [55].

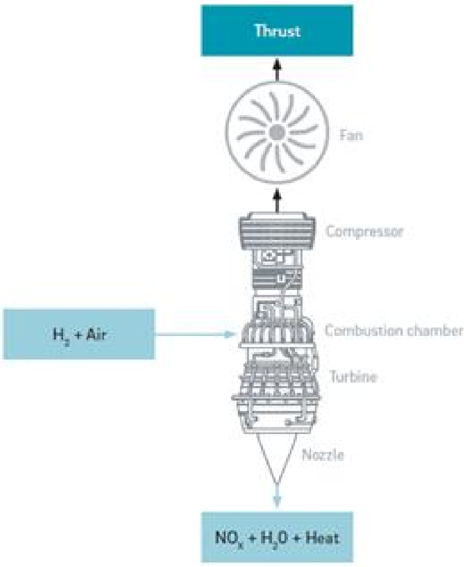


Figure 2-5 - Hydrogen turbine solution

A hybrid solution would overcome the drawback of low thrust during take-off, with the use of hydrogen turbines during this part of the flight, and FCs during the cruise, in this way the water vapor released would be at lower altitudes, making it zero-impacting on the environment [55].

In general, it is possible to compare the two technologies, direct combustion of hydrogen, and chemical conversion in FCs, summarised in the following Table 2-2 [40]:

Table 2-2 - Main characteristics of Hydrogen combustion and FCs use in airplanes

COMBUSTION	FUEL CELLS
Hydrogen burned in a dedicated turbine	Chemical conversion of hydrogen in electricity that runs an electrical motor
30%-40% efficiency	40%-50% efficiency
Elimination of pollution and CO_2 Formation of 2.5 times water vapour contrails than conventional fuels	Elimination of pollution and CO_2 Formation of 2.5 times water vapor contrails than conventional fuels, however, researchers state that the use of fuel cells would help reduce the radiative effect of water vapor
Redesign of engines and aircraft, to store hydrogen	Development of more efficient and powerful FCs, improvement of electric motors, redesign of aircraft to store hydrogen

2.1.4 Storage

The use of hydrogen as fuel in airplanes necessitates storage, the challenges regarding hydrogen storage are different, as well as the way hydrogen could be stored, indeed, the kind of storage used directly affects the design of the aircraft itself and the engines [36].

In general, it is possible to distinguish two hydrogen storage groups, physical-based storage, and chemical-based storage. Physical-based storage could be in turn be categorized in:

- Compressed hydrogen storage: it could be of four types, depending on the working pressure, up to 100MPa for type four vessels, moreover, 10% of the energy content of hydrogen should be used to compress it into vessels.
- Liquid hydrogen storage: due to the extremely low boiling point of hydrogen, the liquid storage must be kept at temperatures of about -250 °C through cryogenic systems. It is shown that 40% of the energy content of hydrogen should be consumed to keep it at low temperatures. This method is mostly suitable for medium and large-scale storage and delivery. Concerning safety, these vessels are equipped with an additional protection layer.
- Cryo-compressed hydrogen storage: in this case hydrogen is compressed in gaseous form at an extremely low temperature, near the liquefaction point. This system ensures high energy density and quick and efficient refueling time due to the existence of a vacuum enclosure [56].

Between the physical storage solution, the use of cryo-compressed hydrogen is the most efficient from the energy density point of view, able to store about 80 kg/m^3 of hydrogen [56], about 10 kg/m^3 more than liquid hydrogen and double the energy density of compressed hydrogen storage [36].

Concerning chemical-based storage instead:

- Chemical sorption: in this case hydrogen molecules are split into atoms and integrated with another molecule structure, among all, metal hydrides to absorb hydrogen. They are directly affected by temperature and can hold 1%-2% up to 7% of hydrogen weight if active heating is provided [57]. However, the use of liquid organic hydrogen carriers (LOHCs) is widely discussed in the literature. Here hydrogen is stored in a liquid molecule structure, bonded chemically, the main advantage is that they are carbon-free, non-toxic, and can be used at relatively low pressures [56].
- Carbon nanotubes: these are tubular carbon structures, able to store hydrogen in the same way metal hybrids do, with the advantage of being able to store a higher amount of hydrogen.
- Glass microsphere: this method is under development and is based on storing hydrogen in hollow glasses spheres, smaller than a salt grain. Hydrogen is stored at high temperatures and high pressure (300 °C and 350-700 bar) [57].

In the literature is possible to find different attempts and studies to simulate the perfect hydrogen tank. In [58] the authors compared different hydrogen tank layouts for three main kinds of aircraft and range segments, Regional, Medium range, and Long range. For each of them, they compared the conventional kerosene storage layout and five different LH_2 storage layouts. Results show that the main parameter affecting hydrogen storage are Maximum Take Off Mass (MTOM), Operating Empty Mass (OEM), and Specific Energy Consumption (SEC), given that these three parameters affect each other. In conclusion, they demonstrated that the optimal hydrogen tank strongly depends on the aircraft range category and design choices.

So far the use of hydrogen in aviation is limited also by the lack of safe and reliable tanks, so far the best result has achieved a 15-20% gravimetric index, while the optimum result would be to achieve 35%-38% [54].

2.2 CHALLENGES ON THE AIRPORT'S SIDE

Beyond the challenges concerning the airside of the aviation sector, the employment of hydrogen is also strictly correlated to landside infrastructure availability and different difficulties have to be overcome in the next future to make hydrogen accessible in airports.

2.2.1 The Airport system and infrastructure

"*An airport is the defined area on land or water intended to be used either wholly or in part for the arrival, departure, and surface movement of aircraft"* is a definition of an airport by [42]. As matter of fact, the airport could be considered a small city, with different services available inside, shops, parking, restaurant, bar, and so on. For this reason, the energy consumed is not negligible, and the structure of the airport itself, as well as the management, can strongly affect the energy consumption. In the airport, the main energy sources are electricity, to power the different systems in the terminal building, fuel, refill airplanes, but also ground vehicles, and heating, if not provided by an electric source [42]. The continuous increase of the aviation sector has made the airport bigger and bigger, with a flow of passengers of about different millions in a year, so thousands of passengers every day, becoming more and more similar to small cities, as it is for Dallas-Fort Worth airport in the U.S. or London's Heathrow, Sao Paulo's International airport and so on worldwide [31].

In general, airports consumption may be divided in:

- Airport infrastructure and ground traffic.
- Aircraft refueling.
- Aircraft movement.
- Operational vehicles in movement [41]

And it is possible to recognize the different forms of emissions, that according to the **Airport Carbon Accreditation** program [59], may be apportioned in:

- Scope 1: All those emissions from airport-controlled sources, such as vehicles, on-site waste, water and power management, boilers, de-icing, and refrigerant losses.
- Scope 2: Regarding off-site electricity generation, that power system as heating, cooling, and lighting.
- Scope 3: Emissions from other sources that are in some way related to the activities of the airport, flights, aircraft ground movement, auxiliary power units, off-site water, waste management, a passenger traveling to the airport, and so on.

The energy consumption of airports could be very high with HVAC systems in terminal buildings as the most responsible, as shown in Figure 2-6. [60].

The main contributions to the energy consumption of terminal buildings regard the shape of the building itself, its orientation, shading effects, windows, and envelope, moreover, the location strongly affects energy needs, with climate variable being one of the most important [42].

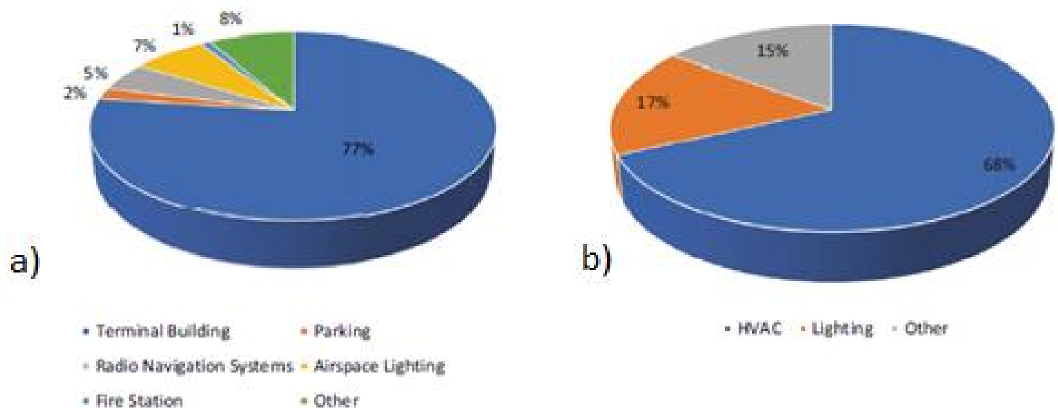


Figure 2-6 - Typical repartition of energy consumption in a) airports; b) terminal building

The complexity of the airport building relies also on its transitional behavior, with different hours in which the occupation level could be very high and as well very low, in this case, the implementation of an intelligent energy management system able to keep the comfort level in the optimal range could save up to 25% of energy. Another important energy-consuming system is lighting, the use of led lamps, and detection systems in certain areas where occupation could be null at some hours, which could be intelligent strategies to save energy. HVAC systems, finally, are the most energy-consuming system in an airport, as the air comfort level must be kept within the optimal range, however, the use of air recovery systems, as well as natural ventilation and other measures, could be an opportunity to perform energy savings [42].To understand the order of magnitude of energy consumption, still, in [42], it is possible to compare different Energy Performance Indicators, for various airports, an example, in Europe in 2009 the highest EPI was registered at Paris Charles De Gaul airport, with 17.93 kWh/pax year.

In the framework of the airport system, a key role is represented by the Airport Carbon Accreditation program, widely cited in this work. Since its creation in 2009, in 2021 there were already 304 accredited airports worldwide, of which 63 that have already reached carbon neutral accreditation and plenty of new accreditation every year. The accreditation is composed of different levels:

- Level 1, Mapping: To be accredited to this level it is necessary to commit to policies regarding emission reduction, and the development of carbon footprint emissions of Scope 1 and 2.
- Level 2, Reduction: To be accredited it is necessary to fulfill all the requirements of level 1 and the development of a Carbon Management Plan to achieve the target of annual reduction of emissions of Scope 1 and 2 types.
- Level 3, Optimisation: It requires all fulfillment of level 2, with a more extensive carbon footprint regarding scope 3 and a formulation of a Stakeholder Engagement Plan to promote wider airport-based emissions ‘reduction.
- Level 3, Transformation: It requires a policy commitment to absolute emission reductions, formulation of a long-term emission reduction target, development of a Carbon management plan, and stakeholder partnership plan to address third-party emissions.

Moreover, it is possible to be accredited at Level 3+ Neutrality, and 4+ Transition, offsetting their residual emissions [60].

Concerning the implementation of hydrogen, it is an added challenge to consider in the airport framework. Indeed, on the one side, it can reduce drastically emissions, if green hydrogen is employed, on the other hand, the complexity of a hydrogen system within the airport is difficult. First of all, the storage issues already discussed in 2.1.4 are valid also on the landside, then, the hydrogen production on-site brings different design challenges, more than an increase in energy demand from the grid, if renewables are not implemented in the airport context, then, its handling comport different safety-related issues that must be overcome due to the importance of security in airports [54].

Concerning safety, the most important measures to adopt should regard the minimization of hydrogen handled time, trying to reduce as much as possible waiting time during the refiling phase of airplanes, allow its handling in open spaces, as it has a very high escape efficiency in air, reducing drastically the probability of self-ignition, use of appropriate equipment from trained personal is strongly important, as well the definition of standards for maintenance, procedures transportation [61].

In [54], it is studied the development of hydrogen use in airports, in two different future scenarios hypotheses, with the implementation of medium and long-range segment airplanes to be hydrogen-based, focusing on infrastructure changes that airports should go through. Results show that smaller and medium airports could lead to decarbonization, as their synergy with few other airports, rather than worldwide ones, and their few congestions could make the introduction and experimenting of hydrogen infrastructure easier than larger airports.

2.2.2 Low carbon energy technologies

The commitment to decarbonization in airports can happen only through the continuous development of low-carbon energy technologies. In [62], the authors highlighted the different possible solutions that could be implemented in airports to reduce carbon emissions, describing not only the technological aspects, but assessing the kind of emissions that could be reduced (Scope 1,2, or 3), the payback of the investment and which could be the kind of airports affected (major airports or regional one)- However, they did not assess how the joint application of more of them could only be synergic, improving their emission reduction impact. The next table resumes the most important initiatives illustrated [62]:

Table 2-3 - Resume of best practice initiative in airports according

INITIATIVE	EMISSIONS REDUCTION [%]	PAYBACK TIME [YEARS]	EMISSIONS SCOPE
Central utility plant	Up to 25%	<20	Scope 1,2
Purchase of renewables	Up to 100%	Variable	Scope 2
On-site solar PV and storage	Up to 100%	<5	Scope 1,2
Electrification of GSE	Up to 100%	>10	Scope 1,2
Sustainable aviation fuel	Up to 40%	>20	Scope 3
Building analytic technologies	Variable	<20	Scope 1,2

In this regard, the most promising employment is the one concerning the installation of solar PV, accompanied by battery or another kind of storage, as the surplus of energy during the day could be used also during the night, exploiting the full advantage of sunlight. The main advantage of Solar panels is their advanced development happened in the last year, with defined established return investment, low maintenance during the whole lifetime of the plant (25+ years), and on the airports specifically it is possible to take advantage of unutilized areas. On the other hand, the problem of solar glare is a serious concern in the airport framework, moreover, the absence of storage strategies may result in energy curtailments. Concerning storage, the use of modern Li-ion batteries is a valid option as they are reliable, efficient, and a widely employed technology, but their low energy storage density and self-discharge rate if not used make them a limited solution. Meanwhile, the possibility to adopt other storage solutions such as hydrogen, flywheels, or the simplest grid energy trade is under development [62].

In [32] it is exploited the benefit of solar panel use integrated with hydrogen supply and auxiliary power unit of aircraft and electric vehicles, focusing on the advantage of FC use to support aircraft in remote stands. The analysis was carried out through five different scenarios based on the airplane's schedule, with an intelligent energy management system. Results show an important energy saving, despite high investment costs, as well the use of hydrogen has shown a more economic and environmental benefit. However, the use of hydrogen in airplanes was not studied.

According to [63] there are three main types of PV installation for airports:

- Land-based solar systems: PV modules are mounted on structures and fixed on the ground. These types are relatively cheap, and their main advantage is the use of unused available land, making it feasible for large–scale installation.
- Building integrated or rooftop: The advantage of using rooftop space is completely exploited in this class of PV systems, however, they can not provide large–scale installation due to limited area available, as usually on the rooftops are also integrated different HVAC systems. Canopy-supported systems: It is well known that the available parking spots in the airport and nearby have to be a lot, to satisfy the huge amount of passenger flow. The installation of solar panels in parking is beneficial not only in terms of energy production but also assessing a major comfort, producing shade for cars.

In Figure 2-7, it is possible to see the above-cited types of airport solar panel installation, taken from [63].

Among the possible hazardous effect of solar panels in airports, solar glare is one of the most dangerous as it affects directly the pilot and the control tower. In [64] It is analyzed the amount of glare from a solar farm installed within the boundaries of a Malaysian airport, is assessed which are the possible solution and how dangerous could be the effect of glare, also considering the Federal Aviation Administration (FAA) regulation on the subject. The highlighted solution comprehends the utilization of solar panels with special anti-reflecting coatings (AR), that could bring the reflectivity down to 10%, also improving the efficiency of the panel as the not-reflected sunlight is absorbed and converted into electricity. Similarly, it is possible to adopt protective glass surfaces, improving the diffusivity of the reflection. Even if not very efficient in terms of energy production, it could be possible to adjust the tilt angle and the orientation of the array or to interact with landing and taking-off operations, as well as with the visibility of the control tower.

Another study [65] focused not only on the solar glare effect but rather identify a series of major accident scenarios concerning the installation of PV arrays in the airport framework. The scenarios analyzed, however, did not result in very probable to happen, making them not less dangerous and to handle with caution. Indeed, they assessed that the use of PV arrays could not be considered still completely safe, and some preventive measures have to be taken into consideration, such as:

- Development of an integrated system, to detect operating panels and possible faults with consequent reduction of electric shock probability.
- Utilization of a frangible support structure, supporting each panel independently.
- Design the array such that it is ensured its integrity and the prevention of debris.

Figure 2-7 - Possible solar panel installation in airports: a) Ground mounted; b) Building integrated; c) Parking canopy

In general, beyond the use of solar panels in airports, which is the most common and easy renewable system to adopt, all sources are limited by constraints, such as the use of wind energy, as these systems must not interfere with airplanes operations, landing and take off, as well as with radio navigation systems, however, some airports have wide available space in the surroundings, as Burlington International Airport, in which it is possible to find a wind farm in operation, as well as in Gran Canarias airport, where the wide sea availability of the island makes it possible to install wind turbines in the nearby of the airport. Similarly, the use of hydroelectric energy is not possible if a large body of water does not surround the airport. At the Juneau airport and Portland Jetport, it is possible to see pilot projects of geothermal use, however, in general, the use of this renewable source is not cost-effective in the airport's framework, as it requires big investments and specific geographic requirements [42].

2.2.3 Airports going towards sustainability

As stated before, the implementation of renewable energy sources in airports is challenging, with most of the technologies under study, however, some airports have already started to realize a new solution to reduce their environmental impact. The recent creation of the Airport Carbon Accreditation program has generated a fast increase in accredited airports worldwide, with new incomes every year and raise of accredited levels already in the program airports. At the end of 2021, there were 304 accredited airports, which covered about 44% of the global passenger share, of these 304, 63 already reached the carbon neutral level. Also in the report, it was highlighted how the most promising energy source to reduce carbon emission is so far solar energy. A commendable example is the **Aereoporti di Roma** which comprehend Fiumicino and Ciampino airports in the Italian Capital city of Rome, as they reached level 4+. The main project going on in **Aereoporti di Roma** concerns the installation of a photovoltaic farm in the airport framework, the use of biofuels to run their plants, electric vehicles fleet, the use of thermal and electric storage to reduce dependency on the grid, as well introduce new sustainable aviation fuels, provide charging point for passengers and personal crew and set up working group and plans with stakeholders, to promote green mobility [59].

Beyond the Accreditation program, different researchers studied the airport framework as an opportunity to develop decarbonization projects, they analyze the already implemented systems, as well as provided new insight. In the case of [43], where it is studied how it could be minimized the waiting time of airplanes in airports, considering the case study of Malpensa airport, the results show that the FIFO (First Input First Output) rule does not guarantee maximum efficiency, rather the implementation of an algorithm to reduce stalling time of airplanes, reducing the useless emissions happening. However, the use of solar energy is widely discussed in the literature, with different examples of solar farms already built, such as it is the case of Indianapolis airport, with an installed capacity of 25 MW, or Kuala Lumpur International airport, with a 19 MW capacity installed between land-based, parking canopy and building integrated systems [63]. Again, Cochin International airport it is installed a total capacity of 30 MW(Figure 2-8 [63]), and in this regard, the study conducted by [66] analyzed the performances of the previous 12 MW capacity of the airport, resulting in a capacity utilization factor of 20.12% and a final yield of 1984h.

Figure 2-8 - Cochin International Airport solar farm: a) Ground mounted; b) Parking canopy; c) Building integrated

Smaller projects concern the performance evaluation of an 830-kW grid-connected PV plant at Kamuzu International Airport in Malawi, with both measured and simulated data obtained in the period from 2013 to 2017, resulting in an average capacity factor of 17.7% [67].

Particular interest in solar panels has been observed in Australia, with plenty of studies and projects ongoing to reduce carbon and grid dependency, mostly due to the abundance of solar energy in the Country. The last report of **CEFC** [62] highlights the possible pathway to reach decarbonization, focusing on airports examples that have developed such technology, to introduce also to the Australian aviation framework such implementation. It follows Table 2-4, which highlights the main results of the report:

Table 2-4 - Worldwide initiative examples of greener airport

INITIATIVE	AIRPORT	CHARACTERISTICS	SAVINGS
Central utility plant	Los Angeles Airport	8.4 MW cogeneration plant with chillers, heat recovery, and storage	25% more efficient 4,890 CO_2/year
Onsite Solar PV and Storage	Darwin International Airport	5.5 MW installed solar capacity	Up to 100% energy covered by RES
Purchasing renewable energy	Sydney Airport	8-year power purchase agreement to power the airport with wind turbines	Up to 75% of energy covered by RES
Electrification of GSE	Brussel airport	Introduction of 30 electric buses	600 tonnes of CO_2 per year
Sustainable aviation fuels (SAF)	Virgin Australia airline and Brisbane airport	Trial of SAF through jet fuel supply infrastructure in Brisbane	Intention to Scope 3 decarbonization
Surface access improvement	Perth airport	A new train station was built near Terminal 1	-
Aircraft and airside upgrades	Brisbane Airport	Changes in the design of aircraft	-
Building analytics technologies	Adelaide airport	Automatic building analytics	More energy efficient
Low-energy baggage handling systems	Rotterdam The Hague airport	Intelligent and autonomous baggage handling system with intelligent vehicles	Up to 50% less energy consumed
Terminal initiatives	San Diego international airport	Construction of a green building terminal	More energy efficient and up to 32% water savings
Airfield lighting upgrades	Dubai International airport	The LED airfield lighting system	$2 million in savings
Ground Source Heat Pumps (HP)	Christchurch International airport	Use of groundwater as a source to provide heating and cooling	31% emission reduction since 2014
Energy from waste	Gatwick airport	Disposition of biosecurity waste management with a new 1 MW waste-to-energy plant	64% recycling rate

Beyond that, plenty of studies are focused on Australian airports ’decarbonization commitment, with Sydney airport’s brief history of how it reached its level 3 accreditation [68], as well as the Adelaide airport environment statement and sustainable policies are discussed in [69], with particular focus on its implementation of an environmental management system, monitor and auditing, engagement with the local community and commitment to continuous improvement approach with the continuous development of solar energy sources. Remaining in Australia, in [70] are discussed the modern environmental development of Brisbane and Melbourne airport, with the first having installed a PV solar system, and the latter taking advantage of a trigeneration energy system beyond the use of solar panels.

Concerning hydrogen, in literature it has not been finding any available sources regarding academic research, however, **VINCI Airports** has launched a partnership with Airbus and Air Liquide to promote the use of hydrogen at airports and build the European airport network to accommodate the future hydrogen-based aircraft, choosing the Lyon-Saint-Exupéry airport as innovation center that will host the hub. The project aims to have a 2023 deployment of a hydrogen gas distribution station to refill land vehicles, while from 2023 and 2030 starting the construction of a hydrogen infrastructure needed for future aircraft, and from 2030 ahead the deployment of such infrastructure [71]. As well in 2022 Airbus signed another collaboration with CAAS (Civil Aviation Authority of Singapore) to carry out a feasibility study for establishing a hydrogen hub at Singapore Changi airport [72].

In this regard, the continuous development of hydrogen worldwide and the latter announcements concerning possible hydrogen hub in airports makes it current the analysis and the forecast of typical airports’ behavior, as is the aim of the present work. The use of renewable in airports is slightly discussed in the literature, with a particular focus on solar energy, as well as other carbon reduction technologies. On the airside, the use of hydrogen as a fuel is under study, with plenty of researchers trying to imagine and design how it could be the future airplane and which technology will be the winner among the different developments. The scope of this work is to simulate a future energy scenario in which hydrogen will be preponderant in airports, as well as zero-carbon technologies, assessing the main parameters useful to let such implementation be feasible, combine, with some limitations, the airside aspects with the landside, with a particular focus on the latter.

3 DESIGN AND SCENARIOS DEVELOPMENT

The present chapter illustrates the main steps followed to develop the project, while in chapter 4 the main conclusions are illustrated and discussed.

Starting from the main objective of evaluating the hydrogen consumption that in the future will characterize worldwide airports, it is evaluated also the economic feasibility of hydrogen use in such framework, and analyzing the main parameters that affect the practicability, such as hydrogen price, grid costs, carbon tax, and others that will be furtherly analyzed.

To obtain a valid model it is necessary to collect useful data to simulate the behavior of the airport and generate a sort of database, that will be the input of our model. Thereafter, it is defined the architecture of the airport, with the main systems such as the grid, solar panels, battery, and so on. Once obtained the complete model, the simulation is carried out, with a series of raw results from it.

Subsequently, the raw results are analyzed, with the useful one collected to better classify the main scenario under development, each one with sensitivity cases, to provide a more extensive study, while useless data are discharged.

Finally, each case is deeply evaluated and compared to each other, to find similarities and dissimilarities. The scope is to highlight the most relevant results and focus on them to have the best understanding. However, the less relevant results are discussed and the main results are assessed, compared with the most relevant ones, for completeness.

In the end, it is briefly discussed the findings achieved and compared, for a better understanding of the analysis carried out, and to evaluate possible flaws and future developments that could take advantage of the present study.

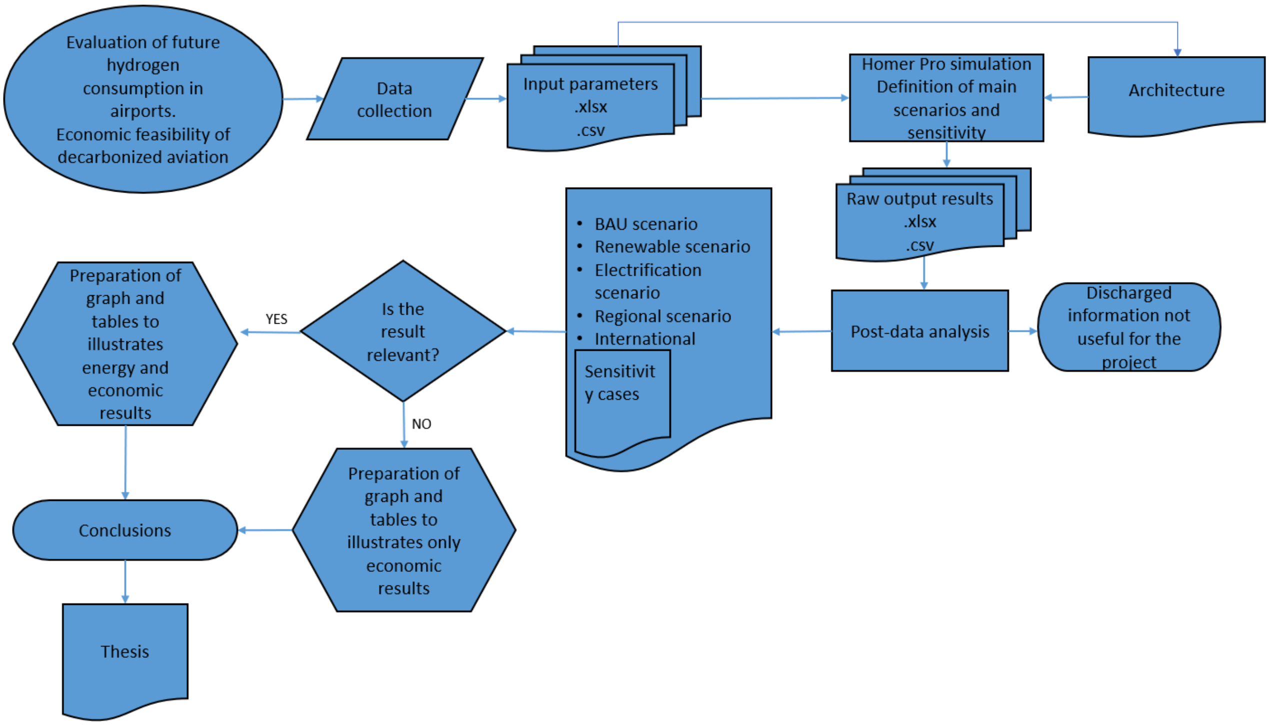


Figure 3-1 - Flowchart of the project

3.1 TORINO CASELLE AIRPORT

3.1.1 Airport location and infrastructure

The airport of Turin (Figure 3-2 [73]), also known as Torino-Caselle airport or "*Sandro Pertini"* is the busiest in the Piedmont region, in Italy. It is located in Caselle, which is part of the metropolitan city of Turin, it was built in 1953 and renewed in 1989 and 2005 in preparation for FIFA World Cup and Winter Olympics. So far, the airport was awarded the *ACI Europe Best Airport Awards* three times, in 2007, 2008, and 2022, in the category of airports that host 1 to 5 million passengers [74]. In 2019, the last year before the pandemic, the number of passengers corresponded to 3,952,158, with 43,655 movements [75].

Figure 3-2 - Airport of Turin

The choice of this airport as a base case for the development of the project relies on different factors. First of all, it is geographically important for the Piedmont region, second of all, the airport of Turin is committed to decarbonization, with different projects concluded and ongoing regarding different fields, it has been accredited level 3 by the Airport Carbon Accreditation program. In the past ten years, there has been a series of interventions aimed to reduce the carbon impact of the airport. Since 2010, indeed, a series of building interventions have been carried out to reduce the energy consumption of the airport, renewal existing systems such as escalators, elevators, and installation of LED systems. Moreover, the intelligent baggage handling system and the intelligent comfort regulation, permit saving over 30% of electricity and gas. Electrification is another solution adopted in the airport, with a new car park with electric charging stations for car sharing opened in 2021, and an electric ambulance in operation since 2022. All of this has brought a continuous reduction in energy consumption over the years, resulting in electricity consumption of 17,000MWh in 2019 (-32% than 2009), about 7,500 MWh of fuels for heating consumed in the same year (-

20% than 2009), and so a reduction of 45% in CO_2 emissions than 2009, resulting in 7,500 tons of CO_2 in 2019 [76].

However, the ongoing projects for the next years state the willingness to purchase 100% of electricity from certified renewable sources and the development of a new car park for end-customer for a total of 16 cars. In 2024 the aim is to create a widely monitored electricity distribution system and to purchase electrical ground support equipment by 2025. The roadmap defined forecasts the installation of different energy renewable sources in the next years such as biogas, hydrogen, photovoltaic and solar thermal, to assess the Smart Grid project ongoing. Moreover, the Aviation contracts recognize the big impact aircraft have on the ambient and so the clauses also concern the use of less polluting aircraft [76].

In collaboration with Politecnico di Torino, the airport aims to create within the airport framework, a test concerning energy smart hubs and carbon offsetting. The use of renewable sources is the key, with the implementation of different systems such as biogas, photovoltaics, energy storage, and hydrogen [76]. Regarding the latter, another reason the Turin airport has been chosen for this work is the imminent installation of the first Fuel cell installed in an Italian airport. The installation is expected in the middle of 2023, due to a partnership between SAGAT (owner of the airport) and SNAM (TSO of gas in Italy). The Fuel cell power will be 1.2 MW and will produce both electricity and heat and be fed with blended natural gas with up to 40% of hydrogen [77].

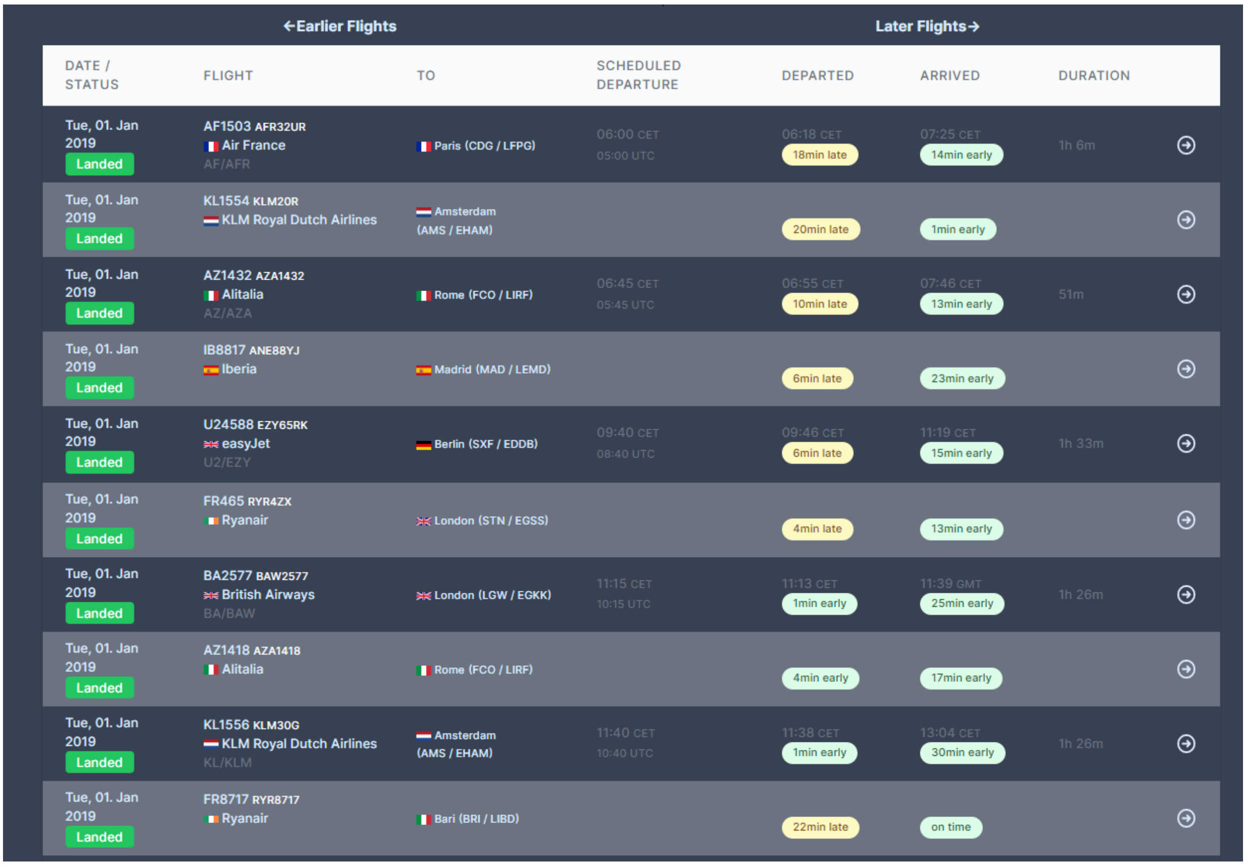
3.1.2 Flights and fuel consumption

To simulate the behavior of the airport it is necessary to evaluate the different parameters needed. The first step is the calculation of the fuel consumption of the aircraft, then, the electricity consumption of the airport, and finally, the diesel consumption of the ground vehicles. In this work, it is not considered the heat commodities and so is the gas consumption of the airport.

As said, the first step is the estimation of the fuel consumption of aircraft. To do so, and in the lack of available official data regarding the airport, it has been used an online source that collects historical data about worldwide airports [78]. Moreover, due to the pandemic in the last years, to have reliable data it has been necessary to adopt pre-pandemic flights, specifically, in 2019.

The construction of the database has followed different stages. Firstly, it has been necessary to transcribe the flight data from the website [78] to a calculation sheet. HOMER Pro needs hourly data, so it has been assumed that all flights happening between *HH: mm and HH: mm + 00:59* were assigned to the hour *HH.* For example, the flight of *06:45* for *Rome* is assigned at the *06:00* timestep, as well as the flight for *London* scheduled at *11:15* is collected at the *11:00* timestep, and so on, without considering any delay. For simplification, only the departures are considered and not the arrivals, as the fuel refilling is based on the journey the airplane has to do. Moreover, a further simplification has regarded the compilation of the database, indeed, only the first week of each month has been completely transcribed, hypothesizing that the following weeks of the month would have been the same, later, the results have been compared with overall available data from official organizations.

Figure 3-3 shows an example of how the collected data appears in the source.



←Earlier Flights						Later Flights→
DATE / STATUS	FLIGHT	TO	SCHEDULED DEPARTURE	DEPARTED	ARRIVED	DURATION
Tue, 01. Jan 2019 Landed	AF1503 AFR32UR Air France AF/AFR	Paris (CDG / LFPG)	06:00 CET 05:00 UTC	06:18 CET 18min late	07:25 CET 14min early	1h 6m
Tue, 01. Jan 2019 Landed	KL1554 KLM20R KLM Royal Dutch Airlines	Amsterdam (AMS / EHAM)		20min late	1min early	
Tue, 01. Jan 2019 Landed	AZ1432 AZA1432 Alitalia AZ/AZA	Rome (FCO / LIRF)	06:45 CET 05:45 UTC	06:55 CET 10min late	07:46 CET 13min early	51m
Tue, 01. Jan 2019 Landed	IB8817 ANE88YJ Iberia	Madrid (MAD / LEMD)		6min late	23min early	
Tue, 01. Jan 2019 Landed	U24588 EZY65RK easyJet U2/EZY	Berlin (SXF / EDDB)	09:40 CET 08:40 UTC	09:46 CET 6min late	11:19 CET 15min early	1h 33m
Tue, 01. Jan 2019 Landed	FR465 RYR4ZX Ryanair	London (STN / EGSS)		4min late	13min early	
Tue, 01. Jan 2019 Landed	BA2577 BAW2577 British Airways BA/BAW	London (LGW / EGKK)	11:15 CET 10:15 UTC	11:13 CET 1min early	11:39 GMT 25min early	1h 26m
Tue, 01. Jan 2019 Landed	AZ1418 AZA1418 Alitalia	Rome (FCO / LIRF)		4min early	17min early	
Tue, 01. Jan 2019 Landed	KL1556 KLM30G KLM Royal Dutch Airlines KL/KLM	Amsterdam (AMS / EHAM)	11:40 CET 10:40 UTC	11:38 CET 1min early	13:04 CET 30min early	1h 26m
Tue, 01. Jan 2019 Landed	FR8717 RYR8717 Ryanair	Bari (BRI / LIBD)		22min late	on time	

Figure 3-3 - Window of the first flight of 2019, as they appear on the website

The main data transcribed are:

- Date
- Day
- Hour
- Destination
- Airlines
- Regional or International flight

The next Table 3-1 shows a small extract of the database built.

Table 3-1 - Extract of the database built

DATE	DAY	HOUR	DESTINATION	AIRLINES	REGIONAL/INTERNATIONAL
2019-02-01	Friday	6:00	Amsterdam	KLM	I
2019-02-01	Friday	6:00	Frankfurt	Lufthansa	I
2019-02-01	Friday	6:00	Munich	Lufthansa	I
2019-02-01	Friday	6:00	Naples	Blue Air	R
2019-02-01	Friday	6:00	Paris	Air France	I
2019-02-01	Friday	7:00	Madrid	Iberia	I
2019-02-01	Friday	7:00	Rome	Blue Panorama	R
2019-02-01	Friday	7:00	Rome	Alitalia	R
2019-02-01	Friday	8:00	Catania	Blue Air	R
2019-02-01	Friday	8:00	Munich	Lufthansa	I
2019-02-01	Friday	8:00	Palermo	Ryanair	R
2019-02-01	Friday	8:00	Paris	Blue air	I
2019-02-01	Friday	10:00	Fes	Ryanair	I
2019-02-01	Friday	10:00	Frankfurt	Lufthansa	I
2019-02-01	Friday	10:00	Paris	Air France	I

DATE	DAY	HOUR	DESTINATION	AIRLINES	REGIONAL/INTERNATIONAL
2019-02-01	Friday	10:00	Stansted	Ryanair	I
2019-02-01	Friday	11:00	Amsterdam	KLM	I
2019-02-01	Friday	11:00	Rome	Alitalia	R
2019-02-01	Friday	12:00	Krakow	Blue Air	I
2019-02-01	Friday	12:00	Stuttgart	Blue Air	I
2019-02-01	Friday	13:00	Barcelona	Ryanair	I
2019-02-01	Friday	13:00	Brindisi	Ryanair	R
2019-02-01	Friday	13:00	Gatwick	British Airways	I

R: Regional, I: International

Once defined the flights for the whole year, are the following steps have been the calculation of the distance between the airport under study and the final destination. For this purpose, it has been used another online tool able to do such tasks [79]. Results are highlighted in the next Table 3-2:

Table 3-2 - Destinations in 2019

DESTINATION	DISTANCE [KM]	DESTINATION	DISTANCE [KM]	DESTINATION	DISTANCE [KM]
Alghero	510.97	Glasgow	1457.26	Nice	174.38
Amsterdam	817.75	Gothenburg	1427.58	Olbia	503.37
Bacau	1494.9	Helsinki	2031.4	Oslo	1644.27
Barcelona	625.96	Heraklion	1841.3	Palermo	901.81
Bari	865.3	Iasi	1548.52	Palma de Mallorca	746.33
Berlin	910.86	Ibiza	873.36	Pantelleria	950.8
Billund	1176.49	Katowice	1033.31	Paris	572.72
Birmingham	1058.14	Krakow	1056.65	Pescara	607.72
Bournemouth	938.66	Lamezia Terme	995.72	Reggio Calabria	1033.86
Brindisi	977.79	Lampedusa	1157.75	Rhodes	1970.64
Bristol	1028.13	Leeds	1172.37	Rome	529.11
Brussels	675.78	Lisbon	1556.28	Seville	1421.48
Bucharest	1453.6	Ljubljana	540.37	Skiathos	1461.43
Budapest	924.79	luqa	1187.54	Stansted	920.97
Cagliari	671.73	Luton	946.92	Stockholm	1746.38
Casablanca	1840.15	Luxembourg	503.43	Stuttgart	405.72
Catania	1058.76	Madrid	1043.6	Tirana	1062.27
Chisinau	1647.91	Mahon	656.8	Trapani	904.9
Cluj	1294.04	Manchester	1155.29	Trieste	458.88
Copenhagen	1210.49	Marrakesh	2030.68	Valencia	921.12
Dublin	1357.08	Memmingen	380.9	Venice	368.91
Edinburgh	1422.37	Moscow	2403.39	Warsaw	368.91
Fes	1652.29	Munich	471.05	Wroclaw	1243.87
Frankfurt	541.57	Naples	731.93		
Gatwick	879.36	Newcastle	1277.92		

After the evaluation of the destinations, the further step towards the evaluation of fuel consumption regards the definition of the kind of airplanes performing the flight. Again, in [78] it is possible to also obtain such data, indeed, as shown in Figure 3-4, with an example of an airplane used for the Turin-Paris route. It is possible to have different data, however, only the kind of airplane and the number of passengers is useful for the present work.

Figure 3-4 - Example of airplane used at Turin airport

For simplification, it is assigned the same airplane for each airline performing the given flight, in this way it has been easy to evaluate the fuel consumption and the number of passengers for each route.

The data regarding the fuel consumption are taken from [80], available in L/100km/seat, for this reason, it has been necessary to convert it to L/100 km using the number of seats of each airplane, as shown in the next Table 3-3:

Table 3-3 - Fuel consumption in liters

AIRPLANE	AIRLINE	SEATS	FUEL CONSUMPTION [L/100 KM]	FUEL CONSUMPTION [L/100 KM/SEAT]
Airbus A319	Adria Airways	124	365.80	2.95
AirbusA320	Aer lingus	150	391.50	2.61
EmbraerE195	Air dolomiti	122	400.16	3.28
EmbraerE170	Air France	88	359.04	4.08
Boeing 737-600	Air Horizont	110	394.90	3.59
Boeing 737 MAX8	Air Italy	166	378.48	2.28
Airbus A319	Air Moldova	124	365.80	2.95
Bombardier CJ1000	Air Nostrum	100	333.00	3.33
Boeing 737-800	Air Explore	166	459.82	2.77
Boeing 737-800	Alba star	166	459.82	2.77
Boeing 737-600	Alba wings	110	304.70	2.77
Airbus A319neo	Alitalia	144	420.48	2.92
Airbus A319	Anda air	124	365.80	2.95
Boeing 737-300	ASL airline	126	435.96	3.46
Boeing 737-300	Austrian airlines	126	435.96	3.46
Boeing 737-700	Bahamasair	126	401.94	3.19
Boeing 737-800	Blue Air	162	448.74	2.77
Boeing 737-800	Blue Panorama	162	448.74	2.77
AirbusA320	British Airways	150	391.50	2.61
Bombardier CJ1000	Brussels Airlines	100	333.00	3.33
EmbraerE170	Cityjet	100	408.00	4.08
McDonnell Douglas MD-83	Danish Air	111	331.87	2.99
AirbusA320Neo	EasyJet	154	346.50	2.25
Boeing 737-800	Enter air	166	459.82	2.77
EmbraerE170	HOP!	88	359.04	4.08

AIRPLANE	AIRLINE	SEATS	FUEL CONSUMPTION [L/100 KM]	FUEL CONSUMPTION [L/100 KM/SEAT]
Bombardier CJ1000	Iberia	100	333.00	3.33
Boeing 737-800	Jet2	162	448.74	2.77
EmbraerE175	KLM	88	349.36	3.97
Boeing 737-800	LOT	166	459.82	2.77
CRJ900	Lufthansa	88	346.72	3.94
Boeing 737-700	Luxair	126	401.94	3.19
Boeing 737-800	Neos	166	459.82	2.77
Boeing 737-800	Norwegian air	166	459.82	2.77
Airbus A321	Redwings	180	450.00	2.5
Boeing 737-800	Royal Air Maroc	166	459.82	2.77
Boeing 737-800	Ryanair	166	459.82	2.77
Boeing 737-700	Sas Scandinavian	126	401.94	3.19
AirbusA320	Siberia Airlines	150	391.50	2.61
Boeing 737-800	Smartwings	166	459.82	2.77
AirbusA320	Titan airways	150	391.50	2.61
AirbusA320	Trade air	150	391.50	2.61
Boeing 737-800	Travel service Hungary	166	459.82	2.77
Boeing 737-800	Travel service Poland	166	459.82	2.77
Boeing 737-700	TUI Airlines	126	401.94	3.19
Boeing 757-200	TUI Airways	200	518.00	2.59
Boeing 737-800	TUIfly	166	459.82	2.77
Airbus A319	Volotea	124	365.80	2.95
AirbusA320	Vueling	150	391.50	2.61
Airbus A321	Wizz air	180	450.00	2.5

In the present work the fuel consumed during take-off and landing has not been analyzed, rather simplified the work considering only the cruise consumption, further analysis could be developed to have a better understanding of fuel consumption during the entire flight in the given route, using statistical analysis. As well, the movement regarding cargo transportation has not been analyzed as no data has been found regarding the hourly traffic.

3.1.3 Electricity consumption

As highlighted in the previous chapters, the Turin airport has been through a decarbonization pathway, increasing its energy efficiency, and resulting in a reduction of 45% in electricity consumed per passenger, allocating its consumption to 4.32 kWh/passenger in 2019, for a total of 17,000 MWh [76].

Starting from this data the aim is to find the hourly electricity consumption of the airport, basing the analysis on the number of passengers flowing in the airport. From paragraph 3.1.2, Table 3-3 it is possible to use the number of passenger seats in airplanes to find out the hourly occupation, it has been hypotheses an average occupation of 80% of available seats for each route, moreover, to rise to electricity consumption it has been considered a specific consumption of $4.32 \times 2 = 8.64$ (Appendix A – Table Conversion) to consider both the departing and the arriving passengers.

Table 3-4 - Number of passengers for each airline

AIRPLANE	AIRLINE	SEATS	PASSENGERS
Airbus A319	Adria Airways	124	99.2
AirbusA320	Aer lingus	150	120
EmbraerE195	Air dolomiti	122	97.6
EmbraerE170	Air France	88	70.4
Boeing 737-600	Air Horizont	110	88
Boeing 737 MAX8	Air Italy	166	132.8
Airbus A319	Air Moldova	124	99.2
Bombardier CJ1000	Air Nostrum	100	80

AIRPLANE	AIRLINE	SEATS	PASSENGERS
Boeing 737-800	Air Explore	166	132.8
Boeing 737-800	Alba star	166	132.8
Boeing 737-600	Alba wings	110	88
Airbus A319neo	Alitalia	144	115.2
Airbus A319	Anda air	124	99.2
Boeing 737-300	ASL airline	126	100.8
Boeing 737-300	Austrian airlines	126	100.8
Boeing 737-700	Bahamasair	126	100.8
Boeing 737-800	Blue Air	162	129.6
Boeing 737-800	Blue Panorama	162	129.6
AirbusA320	British Airways	150	120
Bombardier CJ1000	Brussels Airlines	100	80
EmbraerE170	Cityjet	100	80
McDonnell Douglas MD-83	Danish Air	111	88.8
AirbusA320Neo	EasyJet	154	123.2
Boeing 737-800	Enter air	166	132.8
EmbraerE170	HOP!	88	70.4
Bombardier CJ1000	Iberia	100	80
Boeing 737-800	Jet2	162	129.6
EmbraerE175	KLM	88	70.4
Boeing 737-800	LOT	166	132.8
CRJ900	Lufthansa	88	70.4
Boeing 737-700	Luxair	126	100.8
Boeing 737-800	Neos	166	132.8
Boeing 737-800	Norwegian air	166	132.8
Airbus A321	Redwings	180	144
Boeing 737-800	Royal Air Maroc	166	132.8
Boeing 737-800	Ryanair	166	132.8
Boeing 737-700	Sas Scandinavian	126	100.8
AirbusA320	Siberia Airlines	150	120
Boeing 737-800	Smartwings	166	132.8
AirbusA320	Titan airways	150	120
AirbusA320	Trade air	150	120
Boeing 737-800	Travel service Hungary	166	132.8
Boeing 737-800	Travel service Poland	166	132.8
Boeing 737-700	TUI Airlines	126	100.8
Boeing 757-200	TUI Airways	200	160
Boeing 737-800	TUIfly	166	132.8
Airbus A319	Volotea	124	99.2
AirbusA320	Vueling	150	120
Airbus A321	Wizz air	180	144

To accomplish a reliable behavior of the airport, it has been supposed a base load fixed consumption of 42.7 kWh that is summed to the variable consumption depending on the occupation. Doing this, the results show a total electricity consumption of 17,326 MWh, which is about 2% higher than the declared consumption.

3.1.4 Bus shuttle and ground support equipment

The last step to have all loads needed to carry out the analysis regards the evaluation of fuel consumed by the ground vehicles assumed to be diesel. In the present work, only ground vehicle operating within the airport and the bus shuttle linking it to the city center has been analyzed, and no charging station and gasoline consumption concerning private vehicles have been considered.

BUS SHUTTLE

The airport connection with the city center is performed by the "**Arriva"** bus company, which route schedule has been obtained on its website on *24/05/2022* [81]. In this way it has been possible to create a realistic simulation of bus routes, resulting in a total employment of 11 different buses throughout the entire day. Using the tool available in google maps [73], it has been possible to evaluate the distance traveled by bus, equal to 20 km one way, and so 40 km round trip.

The average diesel consumption of buses is assumed to be equal to 0.24 l/km [82] which for the given route results in an average consumption of 8.16 kg/route. Results are shown in the next Table 3-5, after the conversion from liter to kg (Appendix A – Table Conversion):

Table 3-5 - Diesel consumption of buses

HOUR [HH]	DIESEL CONSUMPTION [KG] WEEKDAYS	DIESEL CONSUMPTION [KG] SATURDAY	DIESEL CONSUMPTION [KG] SUNDAY
00	16.32	8.16	0.00
01	0.00	0.00	0.00
02	0.00	0.00	0.00
03	0.00	0.00	0.00
04	0.00	0.00	0.00
05	8.16	0.00	0.00
06	24.48	24.48	16.32
07	40.80	16.32	16.32
08	48.96	16.32	16.32
09	32.64	16.32	16.32
10	32.64	16.32	16.32
11	32.64	16.32	16.32
12	32.64	16.32	16.32
13	32.64	16.32	16.32
14	32.64	16.32	16.32
15	32.64	16.32	16.32
16	32.64	16.32	16.32
17	32.64	16.32	16.32
18	32.64	16.32	16.32
19	32.64	16.32	16.32
20	32.64	16.32	16.32
21	32.64	16.32	16.32
22	32.64	16.32	16.32
23	32.64	16.32	16.32
Total daily consumption [kg]	**628.32**	**310.08**	**293.76**

GROUND SUPPORT EQUIPMENT

The GSE is useful for the correct operation of the airport, as they fulfill all those tasks needed to ensure comfort, safety, and reliability in air travel. In the present work, due to a lack of data, the number of ground vehicles and their consumption has been estimated. Firstly, according to [83] ground vehicles may be divided into three main categories:

- Type A: these vehicles are typically on-road vehicles, used to transport fuel, food, and people around the airport.
- Type C: high-powered tug tractors responsible for pushing the plane back from the gate.
- Type C: these vehicles are small and have low power, used to handle cargo.

Usually, for each airplane, it is necessary the operation 3 to 5 vehicles of type A, one vehicle of type B, and three vehicles of type C [83]. In the present work, it has been assumed adopt the following vehicles for each airplane:

Table 3-6 - Diesel consumption of GSE for each flight

CATEGORY	VEHICLE	DIESEL CONSUMPTION [KG]	MINUTES OF WORK FOR EACH AIRPLANE	TASK JOB
A	Fuel transporter	3.67	45	Fuel transportation to the aircraft for refilling
A	Catering truck	3.67	45	Transportation of food to the aircraft
A	Bus shuttle	4.9	60	Transportation of passengers to stand-alone aircraft
B	Tug truck	1.61	20	Pushing of the aircraft from the terminal
C	Cargo 1	2.45	30	Transportation of commodities or passenger baggage
C	Cargo 2	2.45	30	Transportation of commodities or passenger baggage
C	Belt transporter	2.45	30	Filling of the aircraft's belly of baggage
	Total diesel consumption [kg]	**21.23**		

The previous estimation has been done considering a specific diesel consumption of 1.5 gallons/hour [84], and the relative unit of conversions (Appendix A – Table Conversion). As previously said, the results are only an estimation of the order of magnitude of the diesel consumption of the GSE, analyzed in the lack of further available data. In conclusion, it is possible to evaluate the yearly diesel consumption by taking advantage of the database built previously in paragraph 3.1.2, where it is shown an extract of diesel consumption in the next Table 3-7:

Table 3-7 Extract of the database concerning GSE diesel consumption

DATE	DAY	HOUR	DESTINATION	AIRLINES	GSE DIESEL CONSUMPTION [KG]
2019-01-16	Wednesday	10:00	Stansted	Ryanair	21.23
2019-01-16	Wednesday	11:00	Amsterdam	KLM	21.23
2019-01-16	Wednesday	11:00	Rome	Alitalia	21.23
2019-01-16	Wednesday	11:00	Rome	Alitalia	21.23
2019-01-16	Wednesday	12:00	Brindisi	Ryanair	21.23
2019-01-16	Wednesday	12:00	Krakow	Blue air	21.23
2019-01-16	Wednesday	12:00	Marrakesh	TUI airlines	21.23
2019-01-16	Wednesday	13:00	Lamezia Terme	Blue air	21.23
2019-01-16	Wednesday	13:00	Madrid	Iberia	21.23
2019-01-16	Wednesday	13:00	Munich	Lufthansa	21.23
2019-01-16	Wednesday	13:00	Naples	Blue air	21.23
2019-01-16	Wednesday	14:00	Brussels	Ryanair	21.23

3.2 Scenarios

In the present chapter, the main scenarios are described, highlighting their meaning, the main assumptions, input, and architecture considered to run the simulation.

Firstly, it is assessed the Business As Usual scenario, which identifies the base loads of the airport, in such a way the other scenarios are developed as an improvement of it, reaching step by step the complete decarbonization in the last scenario.

For each of them, moreover, is carried out a sensitivity analysis to exploit the possible cases that could help or not the use of hydrogen in airports, stressing the importance of hydrogen price reduction as soon as the continuous development of hydrogen technologies also in other sectors is established. Moreover, other parameters may play a key role in the settlement of hydrogen use, such as an increase in fuel costs, and taxes that could be determined through policies, as will be discussed in Chapters 4, and 5.

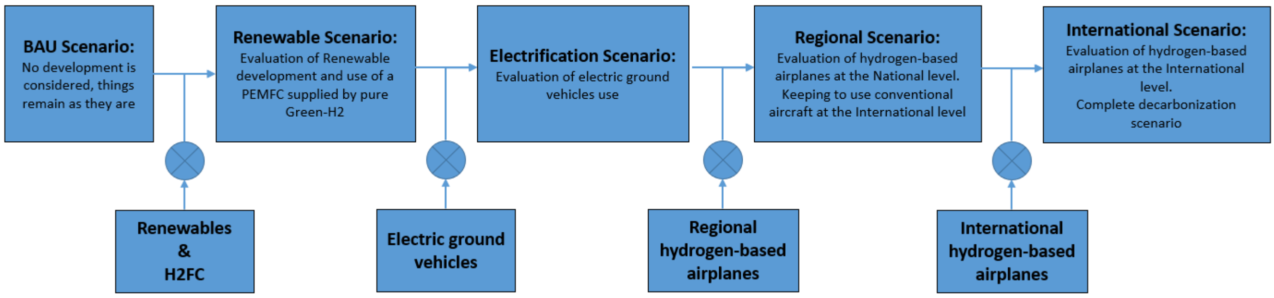


Figure 3-5 - Flowchart of scenarios

3.2.1 Scenarios definition

Once obtained the main energy and fuel consumption, it is necessary to carry on the simulation by developing different possible future scenarios of the airport. For simplification and software limitations, it has not been considered a further growth of loads, however, in the next years, it is likely to happen.

For each scenario, where applicable, it has been defined different sensitivity parameters, summarized in the next Table 3-8 (all conversion parameters are summarised in Appendix A – Table Conversion):

Table 3-8 - Sensitivity variables

SENSITIVITY	VALUE	ASSUMPTION AND REFERENCE
Grid costs	0.167 €/kWh 0.184 €/kWh	[85] Non-Household consumer up to 19.000 MWh/year in 2019 +10%
FC capital cost	2,231.46 €/kW 1,785.17 €/kW 1.153.73 €/kW	[86] -20% -50%
Hydrogen price	7.09 €/kg 4.73 €/kg 1.51 €/kg	[87] [88] forecast in 2030 [88] pessimistic forecast in 2050
Diesel price	1.82 €/L 2.60 €/L	[89] [90] Based on crude oil prices projections
Jet fuel price	1.06 €/L 1.51 €/L	[91] [90] Based on crude oil prices projections
Carbon tax	0.00 €/tonCO2 42.7 €/tonCO2	[92] average carbon tax in European Countries

Given that, for each scenario, among all possible sensitivity cases, it has been decided to analyze the following cases:

Table 3-9 - Sensitivity cases

	CASE	GRID COSTS [€/KWH]	FC CAPITAL COSTS [€/KW]	HYDROGEN PRICE [€/KG]	DIESEL PRICE [€/L]	JET FUEL PRICE [€/L]	CARBON TAX [€/TONCO2]
Base	1	0.167	2231.46	7.09	1.82	1.06	0.00
Grid cost increase	2	0.184	2231.46	7.09	1.82	1.06	0.00
	3	0.184	1775.17	4.73	1.82	1.06	0.00
	4	0.184	1115.73	1.51	1.82	1.06	0.00
Carbon tax	5	0.167	2231.46	7.09	1.82	1.06	42.7
	6	0.167	1775.17	4.73	1.82	1.06	42.7
	7	0.167	1115.73	1.51	1.82	1.06	42.7
Fuel cost increase	8	0.167	2231.46	7.09	2.6	1.51	0.00
	9	0.167	1775.17	4.73	2.6	1.51	0.00
	10	0.167	1115.73	1.51	2.6	1.51	0.00

BUSINESS AS USUAL (BAU)

In this scenario, there is no further development, with bus shuttles and airplanes to continue to be supplied by diesel and jet fuel, while the electricity consumption is directly withdrawn from the grid. In this case, the aim is to analyze how the airport behaves in the current situation and how it will do in the following years without taking any other action.

RENEWABLE

In the renewable scenario it is exploited the possibility to install renewable power sources in the airport framework, however, the limited renewable availability in the geographical region surrounding the airport, as well as the present technology limitations already discussed in paragraph 2.2.2, leave as the only opportunity the exploitation of solar PV in the airport framework. Moreover, since in 2023, the airport aims to install the first hydrogen fuel cell in an Italian airport, it has been necessary to exploit also the use of such technology, evaluating the economic feasibility of a PEMFC of different sizes. The aim of this scenario is the reduction of dependency on the grid, as well as the exploitation of unused parts of the airport, moreover, the increase in self-production lay the foundations for further green technology employment.

ELECTRIFICATION

In this scenario, all the ground vehicles, so comprehending the one operating within the airport and the bus shuttle linking it with the city center, are assumed to be electrified, eliminating the diesel dependency of the airport. As consequence, there is an increase in electricity consumption, but also a reduction in direct emissions and derived emissions, as the diesel supply is usually done employing trucks. However, in this analysis, only direct consumption is considered.

REGIONAL DEVELOPMENT

The regional development exploits the first use of hydrogen in airplanes, simulating the overnight development of hydrogen hubs in nationwide airports. In this way, it would be possible to assess how much would be the hydrogen demand in a typical medium-sized airport if only national flights would adopt such technology. The aim is to simulate the first hydrogen milestone in aviation. Such a big investment could not happen suddenly, rather deferred in different years, however, for simplification it is assumed the sudden switch to hydrogen airplanes operating at the national level, this is valid also for the International development scenario, while it is most likely to happen a short transition toward renewables and electric vehicles, in the previous scenarios.

INTERNATIONAL DEVELOPMENT

The final scenario regards the implementation of hydrogen airplanes at the international level, making the airport completely carbon-free in all kinds of emissions. The technology challenges regarding storage, transportation, off-site hydrogen production, and ancillary requirements regarding on-site hydrogen production are not treated in the present work, as there is no standard concerning hydrogen use and handling so far, as well there is still a debate regarding the kind of storages available, this is valid also for the Regional development scenario

3.2.2 BAU

As said before, the Business As Usual scenario aims to address the continuous use of fossils in the following years. In Homer Pro the airport has been simulated using the following loads as input, evaluated in the previous paragraphs, and reported in the next figures:

- Electricity load (Figure 3-6)
- Diesel load (Figure 3-7)
- Jet fuel load (Figure 3-8)

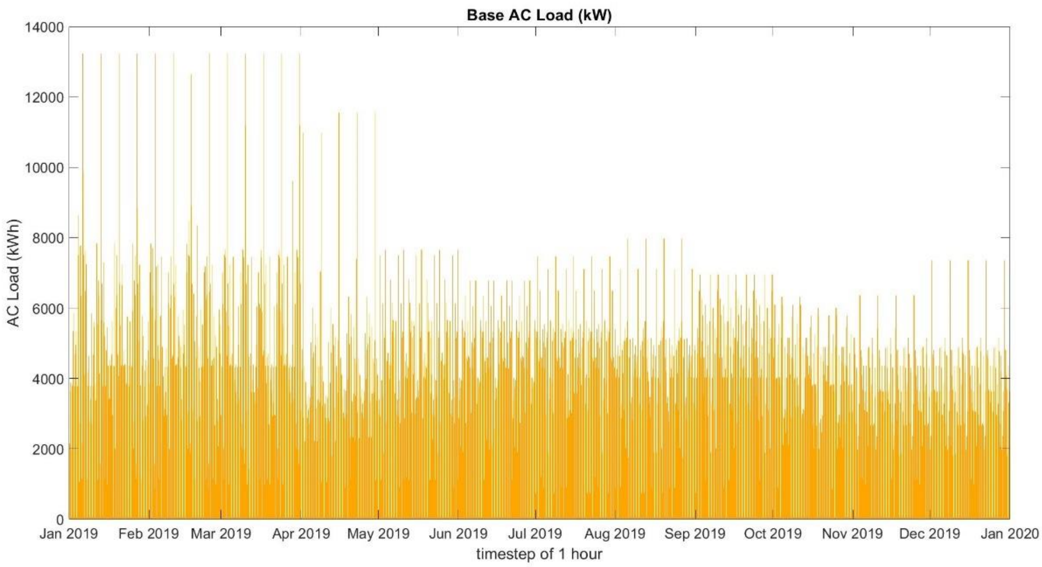


Figure 3-6 - BAU hourly electricity load

As it is possible to notice, the electricity consumption is not linear, with different peaks during the year, mostly due to the busiest hours in the airport which makes it very energy-consuming. However, given the predictability of electricity consumption, due to a fixed flight schedule, it is possible to employ an intelligent energy management system to flatten the behavior, through the use of energy storage.

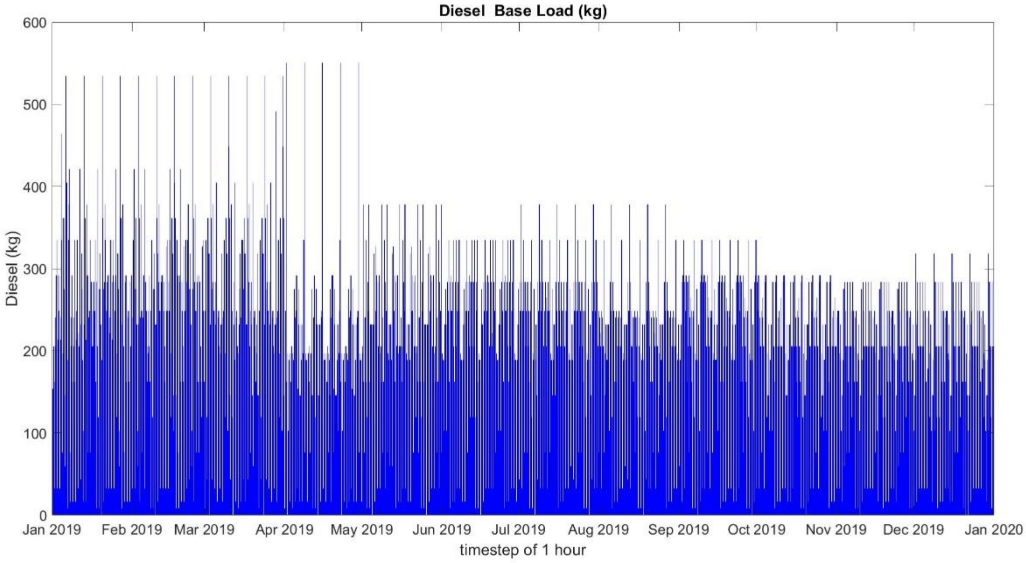


Figure 3-7 - BAU hourly diesel load

Regarding diesel consumption, the high GSE diesel consumption makes it strictly correlated to flight schedule, as other loads. So, also in this case, there is high predictability of consumption, with a large margin of management.

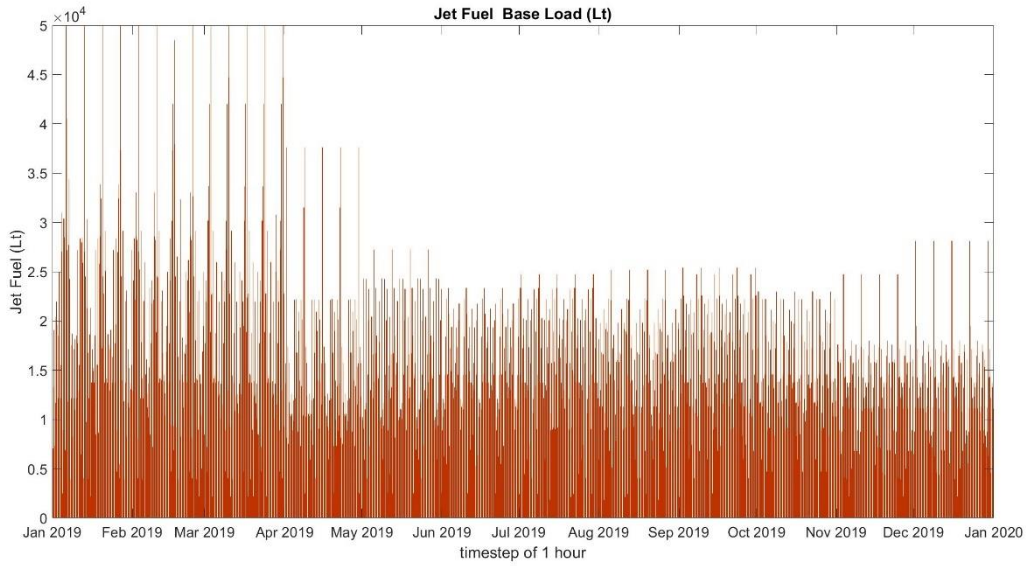


Figure 3-8 - BAU hourly jet fuel load

Similarly to electricity consumption, jet fuel consumption is strictly correlated to a scheduled flight, indeed, it is possible to notice how the pattern is analogous to the one of electricity. This is helpful to address fuel consumption and hydrogen consumption once it will be implemented, however, the necessity of hydrogen storage is essential to overcome any unexpected event that could affect the flight schedule and create annoyance.

Starting from this it has been developed the next scenarios, adding the different features already discussed.

3.2.3 Renewable development

In renewable development, the aim is the exploitation of green energy sources, in particular, two different technologies have been analyzed, solar panels and PEMFCs.

SOLAR PANELS

The big space availability in airports makes them appetible regarding the installation of solar panels, as already discussed in paragraph 2.2.2 there are different installation solutions. In this analysis, only parking canopy and rooftop mounted have been considered, individuating different available spaces.

Table 3-10 - Data regarding the installation of solar panels

LAYER	BUILDING	AREA [M²]	NUMBER OF PANELS	POWER [KW]	REFERENCE NUMBER IN Figure 3-9
Airport terminal and south buildings	MainBuildingNorth	503	231	99.33	1
	MainBuildingSouth	525	241	103.63	2
	TerminalsNorth	1600	737	316.91	3
	TerminalsSouth	1613	743	319.49	4
	MainBuildingEast	1654	762	327.66	5
	BuildingSouth1	1927	888	381.84	6
	MainBuildingWest	2281	1051	451.93	7
	BuildingSouth2	3834	1766	759.38	8
	HangarSouth	3934	1812	779.16	9
	MainBuilding	4425	2039	876.77	10
	Terminals	6104	2812	1209.16	11
				5625.26	
Parking spot	ParkSouth	1738	800	344	1
	ParkMall	1180	543	233.49	2
	ParkExternal	2363	1088	467.84	3
	MainParkingNorth	4352	2005	862.15	4
	MainParkSouth	4553	2098	902.14	5
				2809.62	
North building and hangars	HangarNorth7	123	56	24.08	1
	HangarNorth3	472	217	93.31	2
	HangarNorth8	702	323	138.89	3
	HangarNorth9	751	346	148.78	4
	HangarNorth5	841	387	166.41	5
	HangarNorth2	851	392	168.56	6
	HangarNorth4	903	416	178.88	7
	HangarNorth1	1191	548	235.64	8
	HangarNorth6	1226	564	242.52	9
	BuildingNorthSmall	1307	602	258.86	10
	HangarEast	1320	608	261.44	11
	BuildingNorthEast	1707	786	337.98	12
	BuildingNorth	2228	1026	441.18	13
				2696.53	

Figure 3-9 - Individuation of the chosen space for solar panel installation

The number and the total installed capacity on each space have been evaluated using the technical datasheet of an Italian manufacturer, using a 72-cell monocrystalline panel with the following characteristics:

- PV size: 2.17 m^2 [93]
- PV capacity: 0.43 kW [93]
- PV cost: 781.63 €/kWh [86] (after conversion from $/kWh to €/kWh)
- O&M PV cost: 13.36 €/kWh/year [86] (after conversion from $/kWh to €/kWh)

Due to a lack of further data in the present work the possible interference with other already existing systems on the roof of the buildings has not been considered, assuming that the whole space could be available for solar panel installation. The lifetime of the battery it has supposed to be 25 years, while O&M costs are 10% of the capital costs.

PEMFC

Even if the future installation of the fuel cell will be fed by hydrogen blended with natural gas, in this analysis it has been supposed to use pure green hydrogen in a PEMFC, that better respond to dynamic load as it could happen in an airport, in Homer Pro it has been analyzed the use of different size, 1200 kW, 1800 kW, 2400 kW. The capital cost of the fuel cell has been already discussed in paragraph 3.2.1 while the main characteristics declared by the manufacturer, and referred to the single module of 200 kW as bigger sized are not available, are referred to [94]:

- Rated Power: 200 kW
- Minimum power: 55 kW
- Peak fuel efficiency: 53.5%
- Fuel: gaseous hydrogen

The lifetime of the battery it has supposed to be 15 years, while O&M costs are 10% of the capital costs.

BATTERY STORAGE:

To complete the analysis, the installation of a battery storage system has been considered, to evaluate the possibility to store PV surplus energy and use it when there is no PV production, rather than selling it to the grid. From the manufacturer, the big-size battery solution has an average cost of 300,000 €/MW [95]. Without any further knowledge of the energy surplus/needs, it has been decided to let the software decide the best size of the battery, through the use of the "search optimizer" that allows the evaluation of the best solution for the given application. The lifetime of the battery it has supposed to be 15 years, while O&M costs are 10% of the capital costs.

LOADS

Once defined all the energy sources, to complete the design in Homer Pro, it is necessary to upload the loads calculated in 3.1.2,3.1.3,3.1.4, however, within the software, there is no such tool able to simulate the diesel and jet fuel consumption. For this reason, it has been necessary to take advantage of other kinds of loads, such as "*hydrogen load*" and "*thermal load*" available in Homer Pro.

- *Hydrogen load*: This load is used to simulate the diesel consumption of the airport. In Homer Pro, it is strictly linked to a "*reformer*" that has been designed to work with 100% efficiency and simulate the supply of diesel. This passage is fundamental to have the same results as the one calculated previously, without affecting the analysis. However, to do so the load had to be converted from L to kg (Appendix A – Table).
- *Thermal load*: In this case, it simulates the jet fuel load. The concept is the same as hydrogen load, with the "*boiler*" working as a jet fuel supply with an efficiency of 100%. Similarly, the thermal load is calculated in kWh, so it has been necessary to convert the liter of jet fuel into kWh (Appendix A – Table Conversion).

This is valid for all application scenarios.

Concerning the grid instead, since the airport purchases 100% electricity from certified renewable energy, it does not emit any CO2. The surplus of energy could be inserted again in the grid at the same price of purchase (minus taxes and network costs) equal to 0.092€/kWh. In the next Figure 3-10, it is represented the final design of the Renewable scenario in Homer Pro.

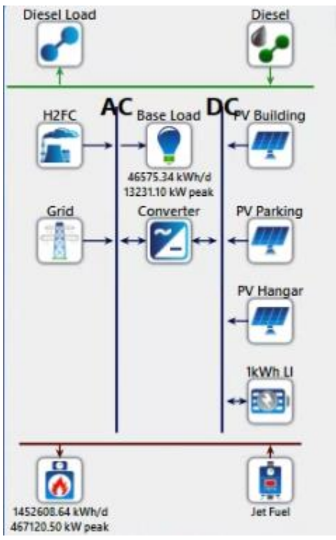


Figure 3-10 - Renewable Homer Pro design

The converter added is considered with an efficiency of 95% and infinite capacity, to not affect the analysis, as it is considered to be an integrated part of the PV system.

3.2.4 Electrification development

In the Electrification scenario, beyond the use of renewables, it is assessed the employment of electric ground vehicles operating within the airport and outside the airport (without considering private vehicles).

BUS SHUTTLE

Starting from the schedule of the bus shuttle [81], the easier way to rise electricity consumption is through the knowledge of the specific consumption of an electric bus. In [96] it is evaluated the average consumption of an electric bus operating in Amsterdam, results show that the average consumption is about 0.99 kWh/km at the ambient temperature, while during winter and summer seasons it increases by +14% and +9%. In this way it is possible to design the charging station at the airport and the battery of the bus, to select the right model.

Table 3-11 - Overall energy consumption of the bus shuttle in different seasons

	WINTER	SUMMER	SPRING/FALL
ROUND TRIP [KM]	40	40	40
ELECTRICITY CONSUMPTION [KWH/KM]	1.13	1.08	0.99
ELECTRICITY CONSUMPTION [KWH]	45.14	43.16	39.60

From the schedule of the bus [81] it is possible to evaluate the time the bus is stationary at the airport and the energy consumed during the journey. Simulating the daily bus route, it is also possible to evaluate the battery level, to design the battery capacity and the charging station power such that the battery level does not fall under a certain level, for reliability reasons but also to ensure a longer life of the battery.

The process is iterative, fixing the size of the charging station, and varying the battery capacity of the bus, then it is fixed the battery capacity of the bus and varied the size of charging station at the airport. Afterwhile, data are collected, and the best solution is adopted, considering economical and technological results, and selecting the available on-the-market solution that satisfies the minimal requirements. Finally, the simulation is run with the right parameters, to confirm the optimal functioning. It has been supposed that the first run would start from the city center with the battery at full capacity, so it is needed half of the round-trip electricity for the first daily run.

Table 3-12 - Simulation of energy consumption of one bus during the winter season

	CENTER->AIRPORT		AIRPORT->CENTER					
	DEPARTURE [HH: MM]	ARRIVAL [HH: MM]	DEPARTURE [HH: MM]	ARRIVAL [HH: MM]	STOP AT THE AIRPORT	ENERGY [KWH]	BATTERY LEVEL [KWH]	BATTERY LEVEL [%]
Week days	4:45	5:30	6:10	6:55	0.53	22.572	88.00	100%
	7:15	8:05	8:15	9:05	0.13	40.00	82.86	94%
	9:15	10:05	10:15	11:05	0.13	40.00	77.71	88%
	11:15	12:05	12:15	13:05	0.13	40.00	72.57	82%
	13:15	14:05	14:15	15:05	0.13	40.00	67.42	77%
	15:15	16:05	16:15	17:05	0.13	40.00	62.28	71%
	17:15	18:05	18:15	19:05	0.13	40.00	57.14	65%
	19:15	20:05	20:15	21:05	0.13	40.00	51.99	59%
	21:15	22:05	22:15	23:05	0.13	40.00	46.85	53%
	23:15	0:05	0:30	1:15	0.33	45.14	88.00	100%

The electric bus chosen is the IVECO E-way full electric with an 88 kWh battery, suitable for fast recharging through a pantograph [97]. The latter has been chosen in order with a charging power from 150 to 450 kW [98].

The cost of a single bus is equal to €300,000 [99], for a total investment of €3,300,000 considering 11 buses needed to fulfill the timesheet, while there is a need for a single pantograph to install at the airport, for a total cost of €145,405 [98]

In this way, it is obtained the hourly electricity consumption of the bus shuttle is, and an example of summer consumption is shown in the next Table 3-13.

Table 3-13 - Summer electricity consumption of bus shuttle

HOUR [HH]	ELECTRICITY CONSUMPTION [KWH] WEEKDAYS	ELECTRICITY CONSUMPTION [KWH] SATURDAY	ELECTRICITY CONSUMPTION [KWH] SUNDAY
00	83.16	40.00	0.00
01	0.00	0.00	0.00
02	0.00	0.00	0.00
03	0.00	0.00	0.00
04	0.00	0.00	0.00
05	21.58	0.00	0.00
06	64.70	63.16	43.16
07	106.33	61.58	43.16
08	204.75	80.00	80.00
09	163.16	80.00	80.00
10	160.00	80.00	80.00
11	160.00	80.00	80.00
12	160.00	80.00	80.00
13	160.00	80.00	80.00
14	160.00	80.00	80.00
15	160.00	80.00	80.00
16	160.00	80.00	80.00
17	160.00	80.00	80.00
18	160.00	80.00	80.00
19	160.00	80.00	80.00
20	160.00	80.00	80.00
21	160.00	80.00	80.00
22	160.00	83.16	83.16
23	166.33	83.16	83.16
Total daily consumption [kWh]	**628.32**	**310.08**	**293.76**

GROUND SUPPORT EQUIPMENT

As said before, it is needed a total of 7 ground vehicles operate in the system. Concerning the vehicles of type A, it has been assumed the same electricity consumption, supposing an average distance traveled of 10 km for each flight. Regarding vehicles of type C, their average electricity consumption could be assumed to be around 30 kWh/3.5 hours of work [100], and assumed to operate for half an hour for each flight, as previously analyzed in 3.1.4. A different analysis has been carried out for the tug truck, type B, as it needs high power to move an airplane, for a short time. The study [101] conducted on the **Tesla CyberTruck** regarding the electricity consumed to tow different cargos of different weights has been useful to perform a linear interpolation to find the energy consumed to tow an airplane. Indeed, from the result of the study it has been found that the energy consumed is almost linearly correlated to the weight of the cargo towed, assuming that the truck would tow the airplane for 1 mile (1.6 km).

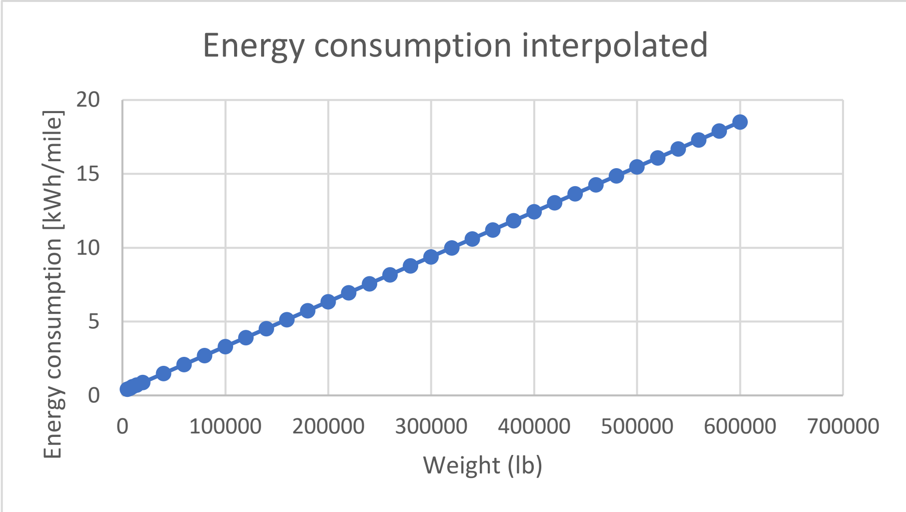


Figure 3-11 - Electricity consumption of a tug truck

Considering the average weight of an Airbus 737-800, among the most used in the airport, is equal to 79 tons [102], but for sake of security, it has been considered a weight of 100 tons (about 220,000 lb). As a result, the energy consumption of the tug truck is equal to about 7.00 kWh/mile.

The total capital cost considered has been assumed to be 35% [103] more than classical fossil-based GSE [104]. Moreover, the peak of flights in a year is equal to 12/hour so it is necessary to purchase at least 15 of each vehicle's kind. In the next table the summary of the total capital cost:

Table 3-14 – The capital cost of GSE

CATEGORY	VEHICLE	DIESEL-BASED COST [€]	ELECTRIC-BASED COST [€]	NUMBER OF NEEDED VEHICLES
A	Fuel transporter	24,573.51	33,174.24	15
A	Catering truck	24,573.51	33,174.24	15
A	Bus shuttle	28,3540.5	300,000	15
B	Tug truck	81,281.6	108,510.9	15
C	Cargo 1	24,573.51	60,000	15
C	Cargo 2	31,189.45	42,105.76	15
C	Belt transporter	24,573.51	60,000	15
-	**Fast charging station 22 kW**	-	2,000 [105]	15
	Total capital costs	**494,305.56**	9.058.624.43	

The converter added is considered with an efficiency of 95% and infinite capacity, to not affect the analysis, as it is considered to be an integrated part of the PV system. However, in this scenario, the cost associated with the investment (Bus shuttle, GSE, charging station, and pantograph), has been allocated in the converter, as it is not possible to associate a cost to the electric load.

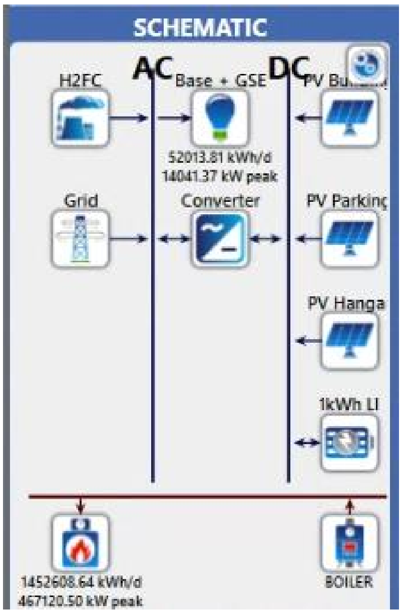


Figure 3-12 - Electrification Homer Pro design

3.2.5 Regional flights development

In the Regional scenario, the aim is to substitute part of the jet fuel load with hydrogen. For simplification and since a defined technology is not already known, it is supposed to use conventional aircraft with adjusted turbines to burn hydrogen and as well to host hydrogen storage. However, in the present work, the issue related to hydrogen safety handling, storage on board aircraft, and the cost of airplanes is not considered. The conversion is supposed to be easy, with hydrogen turbines working with the same efficiency as conventional turbines, it is only needed to convert the jet fuel into hydrogen by using gravimetric energy density. Indeed, the energy density of Jet fuel is equal to 43 MJ/kg, while the one of hydrogen is 120 MJ/kg, so to produce 1 MJ with 1kg of hydrogen it is ${}^{43}/_{120}$ kilograms of jet fuel (Appendix A – Table):

$$m_{H2} = m_{JetFuel} \times 0.35$$

So, it means that the unit of conversion to have a rough estimate of hydrogen consumption is 0.35 [106].

In this way, it is possible to convert the jet fuel consumption for all flights to hydrogen consumption, and for this specific scenario use only the Regional flight as input for Homer Pro as hydrogen load, while the International flights will continue to be fossil-based.

To have hydrogen in the airport has been analyzed different solutions, indeed, hydrogen could be produced both on-site and off-site. A blending of both has been analyzed, considering 4 different solutions:

- 100% on-site production
- 50% on-site production 50% off-site production
- 100% off-site production
- Design of the electrolyzer to work with surplus energy, avoiding selling it to the grid (from now one referred to as *Regional Design*

The selected electrolyzer is a PEMFC scalable for different sizes, with a plant efficiency higher than 75.5% [107] with a cost of 793.91 €/kWh [108]. Even if the use of hydrogen should happen upon its production or delivery to reduce leakages due to storage, in the present work it has been considered to adopt a general compression hydrogen storage capable to store hydrogen up to 700 bar with a cost of 141.77 €/kg [109].

To evaluate the size of the electrolyzer and of the hydrogen storage it has proceeded in this way:

- Electrolyzer: starting from the energy content of hydrogen, 33.34 kWh/kg [110], and considering the efficiency of the electrolyzer being 75.5%, it is straightforward that the energy consumption is equal to:

$$E_{el} = {e_{H2}}/{\eta_{el}}$$

  where E_{el} is the overall electricity consumption of the electrolyzer, e_{H2} is the gravimetric energy content of hydrogen, and η_{el} is the efficiency of the electrolyzer. Moreover, it has been considered a value of 3.3 kWh/kg_{H2} to compress it up to 700 bar [111]. Overall, the energy consumption of the electrolyzer is equal to 47.45 kWh/kg_{H2}. Unfortunately in Homer Pro, it is not possible to model an electrolyzer that could work with the electricity withdrawn from the grid, but only with the surplus produced from renewables. For this reason, to model the energy consumption for the first three regional solutions, it has been added a new electric load that concerns only the electrolyzer consumption, based on the hydrogen needed.

- Hydrogen storage: the size of the storage has been designed considering the day with the highest hydrogen consumption, multiplied by a safety factor of 10%. The final hydrogen storage size for the regional development is 29,000 kg.

The overall costs of the system are reported in the next table, considering also the cost of GSE, Bus shuttle, and charging station obtained in the previous scenario. Similarly, in Homer Pro, the cost of the electrolyzer is hidden in the one of the hydrogen storage, as it is not possible to allocate a cost for the electric load, while in the *Regional Design,* it is possible to directly model the electrolyzer such artifice has not been performed. O&M costs have been supposed to be 10% of the capital cost. The lifetime of all systems is assumed to be 15 years.

Table 3-15 - Total capital cost of Regional scenario

SOLUTION	H2 TANK COSTS [€]	ELECTROLYZER CAPACITY [KW]	ELECTRIFICATION COSTS [€]	ELECTROLYZER COSTS [€]	TOTAL CAPITAL COSTS [€]	O&M COSTS [€/YEAR]
100% on-site production	4,111,336.89	367,500	12,504,029.66	291,763,149.19	308,378,515.74	30,837,851.57
50% on-site production	4,111,336.89	175,000	12,504,029.66	138,934,832.95	155,550,199.50	15,555,019.95
0% on-site production	4,111,336.89	0	12,504,029.66	0	16,615,366.55	1,661,536.66
Regional Design	4,111,336.89	17,500	12,504,029.66	13,893,483.29	30,508,849.84	3,050,884.99

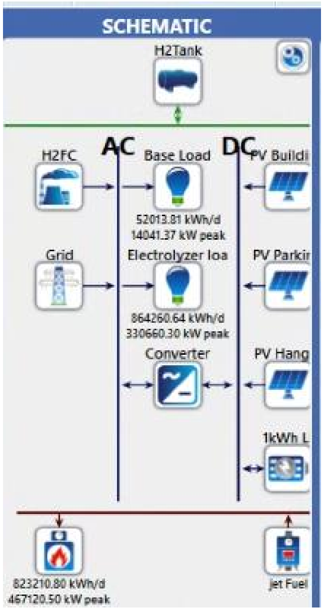


Figure 3-14 - Design of Regional scenario, 100% on-site production

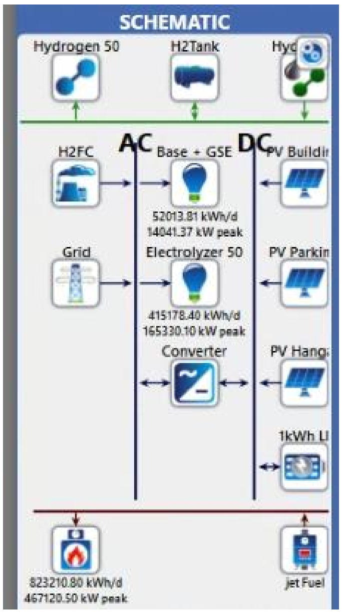


Figure 3-13 - Design of Regional scenario, 50% on-site production

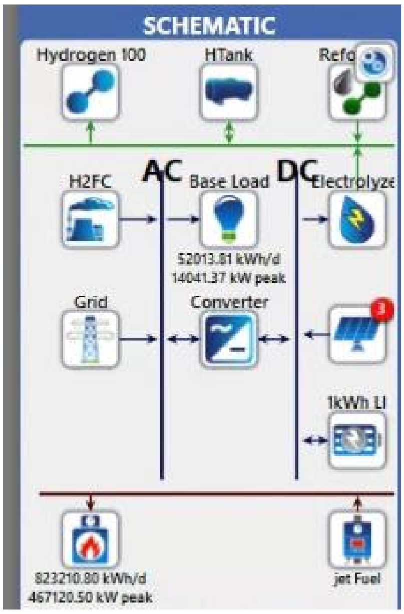


Figure 3-16 - Design of Regional scenario, 0% on-site production

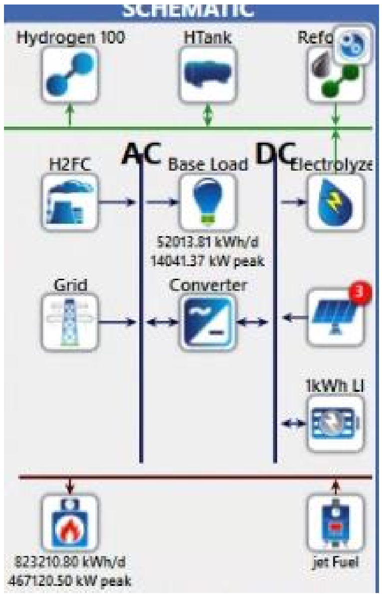


Figure 3-15 - Design of Regional scenario, Regional Design

3.2.6 International flights development

All the assumptions made in the Regional development scenario are valid also for the International development scenario, the only change regards the size of the hydrogen tank storage, that in this case is 90,000 kg. So, to not be repetitive only results are reported in this paragraph.

Table 3-16 - Total capital cost of the International scenario

SOLUTION	H2 TANK COSTS [€]	ELECTROLYZER CAPACITY [KW]	ELECTRIFICATION COSTS [€]	ELECTROLYZER COSTS [€]	TOTAL CAPITAL COSTS [€]	O&M COSTS [€/YEAR]
100% on-site production	12,759,321.39	700,000	12,504,029.66	555,739,331.79	581,002,682.84	58,100,268.28
50% on-site production	12,759,321.39	350,000	12,504,029.66	277,869,665.89	303,133,016.94	30,313,301.69
0% on-site production	12,759,321.39	0	12,504,029.66	0	25,263,351.05	2,526,335.10
Regional Design	12,759,321.39	17,500	12,504,029.66	13,893,483.29	39,156,834.34	3,915,683.43

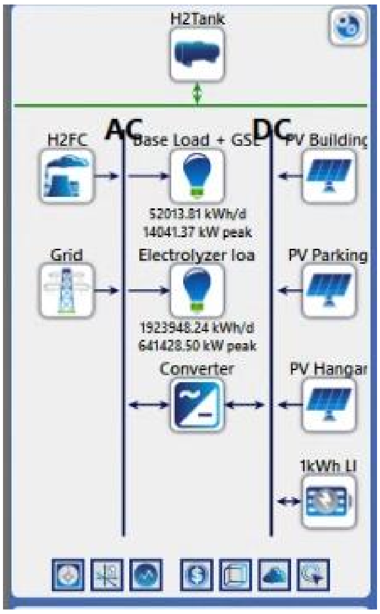


Figure 3-18 - Design International scenario, 100% on-site production

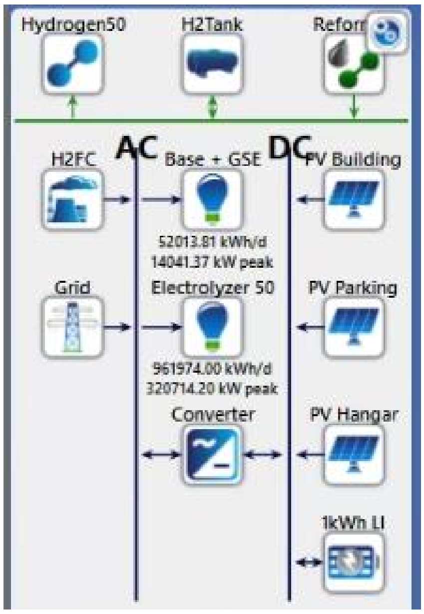


Figure 3-17 - Design International scenario, 50% on-site production

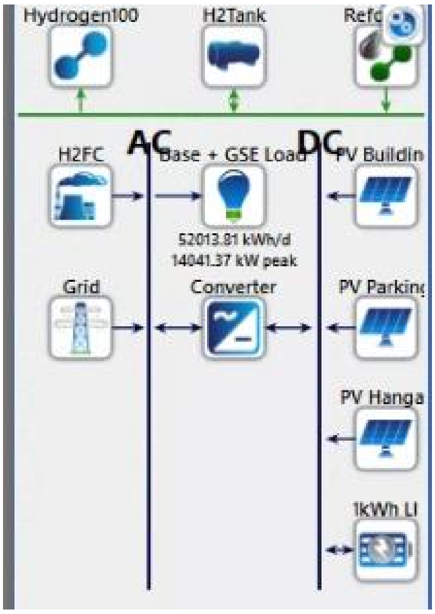


Figure 3-20 -Design International scenario, 0% on-site production

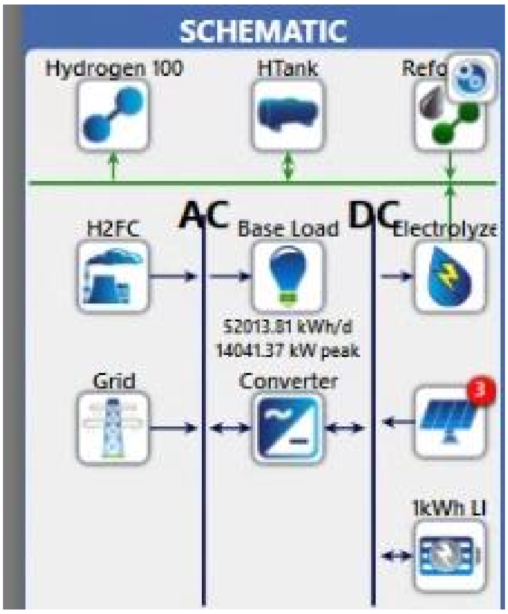


Figure 3-19 -Design International scenario, International Design

4 TECHNO-ECONOMIC ANALYSIS

4.1 SCENARIOS PRELIMINARY ANALYSIS

Before discussing the main results, it is necessary to make an initial selection of the best sensitivity cases for each scenario.

RENEWABLE

In the Renewable scenario, the employment of hydrogen for aviation is not considered, but rather the use of it in a PEMFC. However, the installation of it is economically sustainable only if the cost of the PEMFC and of the hydrogen fall below a certain level, which is the instance of sensitivity cases 4, 7, and 10.

- Sensitivity case 4: It is considered the installation of a 2400 kW PEMFC
- Sensitivity case 7: It is considered the installation of a 1200 kW PEMFC
- Sensitivity case 10: It is considered the installation of a 1200 kW PEMFC

The difference in size is because in case 4 the increase in grid price makes the installation of a larger-size PEMFC economically feasible. The main results are reported in Table 4-1, where it is possible also to notice how the influence of the PEMFC in a 50 years analysis does not weigh too much. Given that, the similarities between cases in the same macro-areas make it redundant to analyze all cases and to focus on cases 1, 4, 7, and 10.

ELECTRIFICATION

Similarly, as for the Renewable scenario, the employment of a PEMFC is economically feasible for the same sensitivity cases. As well, results reported in

Table *4-2* show how the installation of a PEMFC does not weigh much compared to the total initial capital cost, making it redundant to further analyze the other cases, but rather focus on sensitivity cases 1, 4, 7, and 10.

REGIONAL

Regarding the Regional scenario, different hydrogen supply solutions have been analyzed, with different on-site hydrogen production shares. From a preliminary analysis concerning the Net Present Cost (NPC) of the solutions, it has been assessed how the on-site hydrogen production is less feasible than off-site production, as the electricity price from the grid is too high. However, the exploitation of surplus energy from renewables and the design of an electrolyzer able to fulfill all renewable production peaks is a valid solution. The key concept relies on the possibility to store the surplus energy in hydrogen rather than a battery or selling electricity to the grid. As a result, among the different solutions, the latter is the most feasible, with a comparable NPC to complete off-site production, for this reason, it has proceeded with this solution. In Table 4-3 it is reported a comparison among the solutions for sensitivity case 1 (base case), the other cases follow the same trend, and simplification is not reported in this work.

Said so, and choosing the best hydrogen supply solution, it is possible to follow the same line of thinking as the other scenarios.

Table 4-4 illustrates the results of the ten sensitivity cases analyzed. Differently from the Renewable and Electrification scenarios, the reduction of PEMFC and hydrogen costs make the NPC difference more pronounced, due to a higher hydrogen utilization. For this reason in the present work, only cases 1, 4, 7, and

10 are reported, which present the lower NPC, and, as for previous scenarios, the best architecture involves the use of the PEMFC.

INTERNATIONAL

Similar reasoning as for the Regional scenario is valid for the International scenario, with on-site production being economically feasible only with the utilization of a surplus of renewable energy, storing hydrogen, as reported in Table 4-5**,** where it is reported only the base case sensitivity for simplification.

Said so, it is clear how the best solution considers the installation of a small electrolyzer able to produce hydrogen from the surplus of energy from renewables, as for the Regional scenario.

Moreover, Table 4-6, reports the results for all the sensitivity cases, that for this scenario are reduced to 4, as the sensitivities concerning the carbon tax and the fuel cost increase are not valid, due to 0 CO2 emissions and fossil fuel used. For this reason, only sensitivity cases 1, and 4 are analyzed in this report, which involves also the installation of a PEMFC.

PRELIMINARY ANALYSIS CONCLUSIONS

In conclusion, it is possible to assess how for all scenarios the most interesting cases regard the use of a PEMFC, which is economically feasible only if its costs and hydrogen are low enough. Moreover, in all cases, the use of the battery is not the best option, as the investment needed and the degradation of it is less efficient than the sale of electricity in the grid, which does not need any investment. However, the overall NPC with the battery use is just slightly higher, so a further and more precise analysis, with the implementation of a more efficient and intelligent energy management system, could reduce the total NPC, making this solution more feasible than the one without the battery. However, such a study lies in the present work.

In the next paragraphs, the main results for sensitivity cases 1, 4, 7, and 10 are highlighted.

Table 4-1 - Renewable scenario, sensitivity cases results

AREA	CASE	POWER PRICE [€/KWH]	CO2 PENALTY [€/TONNE]	H2FC CAPITAL COST[€/KW]	DIESEL FUEL PRICE [€/L]	HYDROGEN PRICE [€/KG]	JET FUEL PRICE [€/L]	H2FC [KW]	LI-ION [KW]	NPC [M€]	OPERATING COST [M€/YEAR]	INITIAL CAPITAL [M€]
Base	**1**	0.17	0.00	2,231.46	1.82	7.09	1.06	0	0	814.70	64.60	8.70
Grid costs increase	**2**	0.18	0.00	2,231.46	1.82	7.09	1.06	0	0	816.87	64.77	8.70
	3	0.18	0.00	1,775.17	1.82	4.73	1.06	0	0	816.87	64.77	8.70
	4	0.18	0.00	1,115.73	1.82	1.51	1.06	1800	0	815.46	64.26	10.71
Carbon tax	**5**	0.17	42.70	2,231.46	1.82	7.09	1.06	0	0	885.08	70.24	8.70
	6	0.17	42.70	1,775.17	1.82	4.73	1.06	0	0	885.08	70.24	8.70
	7	0.17	42.70	1,115.73	1.82	1.51	1.06	1200	0	884.70	69.94	10.04
Fuel cost increase	**8**	0.17	0.00	2,231.46	2.60	7.09	1.51	0	0	1,150.14	91.52	8.70
	9	0.17	0.00	1,775.17	2.60	4.73	1.51	0	0	1,150.14	91.52	8.70
	10	0.17	0.00	1,115.73	2.60	1.51	1.51	1200	0	1,149.76	91.22	10.04

Table 4-2 - Electrification scenario, sensitivity cases results

AREA	CASE	POWER PRICE [€/KWH]	CO2 PENALTY [€/TONNE]	H2FC CAPITAL COST [€/KW]	HYDROGEN PRICE [€/KG]	JET FUEL PRICE [€/L]	H2FC [KW]	LI-ION [KW]	NPC [M€]	OPERATING COST [M€/YEAR]	INITIAL CAPITAL [M€]
Base	**1**	0.17	0.00	2,231.46	7.09	1.06	0	0	810.34	62.80	21.20
Grid costs increase	**2**	0.18	0.00	2,231.46	7.09	1.06	0	0	812.79	63.00	21.20
	3	0.18	0.00	1,775.17	4.73	1.06	0	0	812.79	63.00	21.20
	4	0.18	0.00	1,115.73	1.51	1.06	1800	0	811.14	62.45	23.21
Carbon tax	**5**	0.17	42.70	2,231.46	7.09	1.06	0	0	880.01	68.39	21.20
	6	0.17	42.70	1,775.17	4.73	1.06	0	0	880.01	68.39	21.20
	7	0.17	42.70	1,115.73	1.51	1.06	1200	0	879.47	68.07	22.54
Fuel cost increase	**8**	0.17	0.00	2,231.46	7.09	1.51	0	0	1,128.12	88.30	21.20
	9	0.17	0.00	1,775.17	4.73	1.51	0	0	1,128.12	88.30	21.20
	10	0.17	0.00	1,115.73	1.51	1.51	1200	0	1,127.58	87.98	22.54

Table 4-3 - Regional scenario best H2 supply solution – case 1

ON-SITE PRODUCTION	POWER PRICE [€/KWH]	CO2 PENALTY [€/TONNE]	H2FC CAPITAL COST [€/KW]	HYDROGEN PRICE [€/KG]	JET FUEL PRICE [€/L]	H2FC [KW]	1KWH LI-ION [KW]	NPC [M€]	OPERATING COST [M€/YEAR]	INITIAL CAPITAL [M€]
0%	0.17	0	2,231.46	7.09	1.06	0	0	1,084.25	84.30	25.32
50%	0.17	0	2,231.46	7.09	1.06	0	0	1,463.65	98.65	164.25
100%	0.17	0	2,231.46	7.09	1.06	0	0	1,931.24	118.47	317.08
Design	0.17	0	2,231.46	7.09	1.06	0	0	1,119.05	88.30	21.20

Table 4-4 - Regional design scenario, sensitivity cases results

AREA	CASE	POWER PRICE [€/KWH]	CO2 PENALTY [€/TONNE]	H2FC CAPITAL COST [€/KW]	HYDROGEN PRICE [€/KG]	JET FUEL PRICE [€/L]	H2FC [KW]	1KWH LI-ION [KW]	NPC [M€]	OPERATING COST [M€/YEAR]	INITIAL CAPITAL [M€]
Base	**1**	0.17	0.00	2,231.46	7.09	1.06	0	0	1,119.05	85.49	39.21
Grid costs increase	**2**	0.18	0.00	2,231.46	7.09	1.06	0	0	1,121.51	85.68	39.21
	3	0.18	0.00	1,775.17	4.73	1.06	0	0	928.89	70.22	41.57
	4	0.18	0.00	1,115.73	1.51	1.06	1200	0	664.74	48.73	43.57
Carbon tax	**5**	0.17	42.70	2,231.46	7.09	1.06	0	0	1,158.54	88.66	41.57
	6	0.17	42.70	1,775.17	4.73	1.06	0	0	965.89	73.19	41.57
	7	0.17	42.70	1,115.73	1.51	1.06	1200	0	702.54	51.78	43.57
Fuel cost increase	**8**	0.17	0.00	2,231.46	7.09	1.51	0	0	1,299.14	99.94	41.57
	9	0.17	0.00	1,775.17	4.73	1.51	0	0	1,106.49	84.48	41.57
	10	0.17	0.00	1,115.73	1.51	1.51	1200	0	843.15	63.07	43.57

Table 4-5 – International scenario best H2 supply solution – case 1

ON-SITE PRODUCTION	POWER PRICE [€/KWH]	CO2 PENALTY [€/TONNE]	H2FC CAPITAL COST [€/KW]	HYDROGEN PRICE [€/KG]	JET FUEL PRICE [€/L]	H2FC [KW]	1KWH LI-ION [KW]	NPC [M€]	OPERATING COST [M€/YEAR]	INITIAL CAPITAL [M€]
0%	0.17	0	2,231.46	7.09	1.06	0	4.85	1,45.32	33.96	112.77
50%	0.17	0	2,231.46	7.09	1.06	0	0.49	2,309.65	311.83	149.46
100%	0.17	0	2,231.46	7.09	1.06	0	0.33	3,039.38	175.82	589.70
Design	0.17	0	2,231.46	7.09	1.06	0	4.81	1,486.12	113.95	47.86

Table 4-6 - International design scenario, sensitivity cases results

AREA	CASE	POWER PRICE [€/KWH]	CO2 PENALTY [€/TONNE]	H2FC CAPITAL COST [€/KW]	HYDROGEN PRICE [€/KG]	JET FUEL PRICE [€/L]	H2FC [KW]	1KWH LI-ION [KW]	NPC [M€]	OPERATING COST [M€/YEAR]	INITIAL CAPITAL [M€]
Base	**1**	0.17	0.00	2,231.46	7.09	1.06	0	0	1,486.12	113.95	47.86
Grid costs increase	**2**	0.18	0.00	2,231.46	7.09	1.06	0	0	1,488.57	114.15	47.86
	3	0.18	0.00	1,775.17	4.73	1.06	0	0	1,040.28	78.16	47.86
	4	0.18	0.00	1,115.73	1.51	1.06	1200	0	427.36	28.67	49.19
Carbon tax	**5**	0.17	42.70	2,231.46	7.09	1.06	0	0	1,486.12	113.95	47.86
	6	0.17	42.70	1,775.17	4.73	1.06	0	0	1,037.82	77.96	47.86
	7	0.17	42.70	1,115.73	1.51	1.06	1200	0	425.68	28.55	49.20
Fuel cost increase	**8**	0.17	0.00	2,231.46	7.09	1.51	0	0	1,486.12	113.95	47.86
	9	0.17	0.00	1,775.17	4.73	1.51	0	0	1,037.82	77.86	47.86
	10	0.17	0.00	1,115.73	1.51	1.51	1200	0	425.68	28.55	49.20

For every scenario, it has considered a Discounted rate of 10%, an average of Public Transport, Power Generation, and Industry Sector rates used in the PRIMES model [112], while the inflation rate for Italy in 2021 is equal to about 2% [113]. Resulting in a Real Discount rate of 7.843%, used in the software to evaluate the NPC, while the NPV and the economic indices have been evaluated through a calculation sheet, considering the cash flow obtained by the difference between the given scenario and the BAU scenario. The main formulas are reported below [114]:

- NPV: $\sum_{t=0}^{n} \frac{R_t}{(1+i)^t} - R_0$ where $\mathbf{R_t}$ are te net cash flow, $\mathbf{R_0}$ is the initial capital cost, **i** is the real discount rate, and **n** are the number of time periods
- IRR: is the **i** at which the NPV=0, calculated through the default formula integrated into the calculation sheet software.
- ROI: $Current\ value\ of\ investment - Cost\ of\ investment \Big/ Cost\ of\ investment$
- IP: $NPV\ of\ future\ cash\ flow \Big/ Initial\ investment$
- SPBT: $|Initial\ investment| \Big/ Cash\ flow$
- DPBT: $Log_{10}(1 - SPBT * 0.08) \Big/ Log_{10}(1 + 0.08)$

Moreover, since HomerPro is not able to calculate emissions from Reformer, and given the necessity to evaluate Diesel load using this instrument, the CO2 emissions coming from this source have been evaluated in a separate section and added the cost due to them (only in the Carbon tax case). The parameters considered for Diesel emissions are reported in Appendix A – Table Conversion.

4.2 BASE CASE

In the base sensitivity case it is exploited the base parameters adopted in the analysis, resumed as follows:

Table 4-7 - Base case sensitivity variables

POWER PRICE [€/KWH]	CO2 PENALTY [€/TONNE]	H2FC CAPITAL COST [€/KW]	DIESEL FUEL PRICE [€/L]	HYDROGEN PRICE [€/KG]	JET FUEL PRICE [€/L]
0.17	0.00	2,231.46	1.82	7.09	1.06

4.2.1 Renewable development

In the Renewable development scenario, the aim is to exploit the feasibility of renewable energy installation in the airport framework. Specifically, in Turin airport, the best solution is the installation of solar panels to reduce dependency on the grid and to sell the surplus to it rather than the use of a battery.

The main loads, that concern electricity (Figure 3-6), diesel (Figure 3-7), and jet fuel (Figure 3-8) are the same as the business as usual. The only difference is the electricity sold to the grid, which represents the surplus generated by solar panels. In Figure 4-1, it is possible to see the hourly electricity consumption of the airport compared with the renewable output and the electricity sold to the grid.

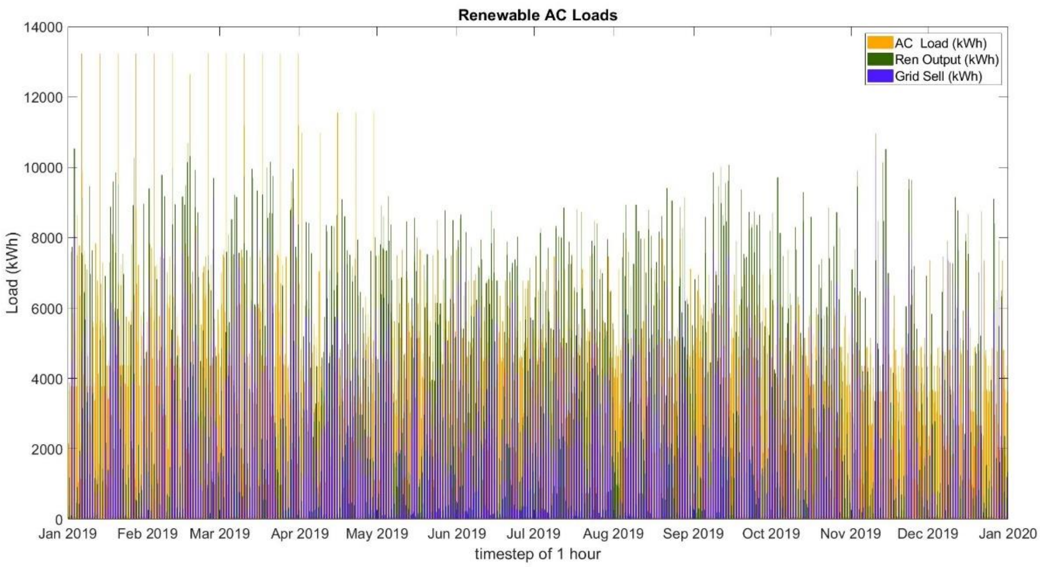


Figure 4-1 - Comparisons among electricity input/output, Renewable scenario, Base case

The use of renewable energy, such as solar panels, is a valid solution to reduce energy purchased from the grid, with a reduction of -45% with a consequent economic saving, as highlighted in Figure 4-3 and Figure 4-4, where it is compared the NPC of the BAU scenario and the Renewable scenario.

The following Figure 4-2 represents the schematic of the electricity consumption and supply of the airport, while Table 4-8 shows the yearly overall consumption of the main systems of the airport (Electricity, Diesel, and Jet fuel).

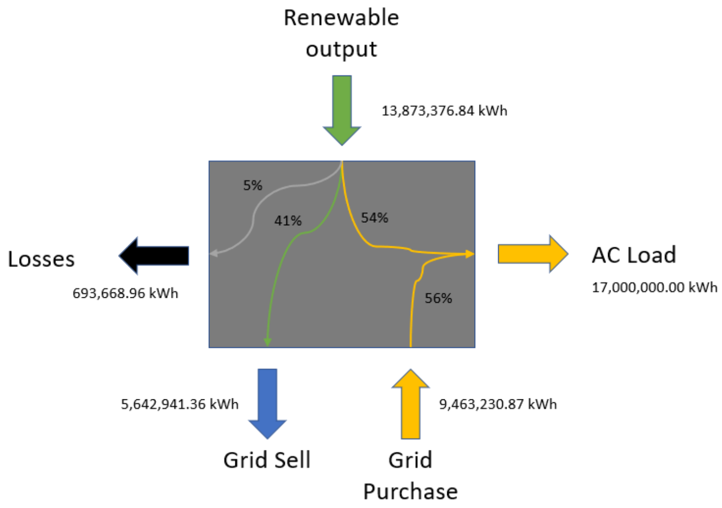


Figure 4-2 - Airport electricity supply/consumption scheme, Renewable scenario, Base case

Table 4-8 – Consumption, Renewable scenario, Base case

AC PRIMARY LOAD (MWH)	DIESEL LOAD (KG)	GRID PURCHASES (MWH)	GRID SELL (MWH)	RENEWABLE OUTPUT (MWH)	JET FUEL (LT)	CO2 EMISSIONS (TON)
17,326.00	552,697.00	9,463.23	5,642.94	13,873.38	56,686,173.00	132,248.15

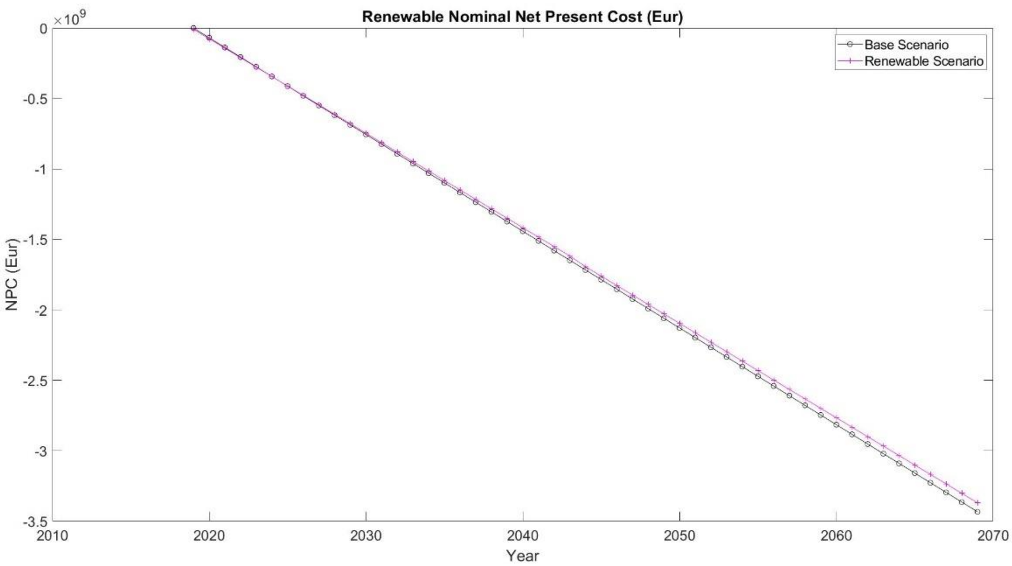


Figure 4-3 - Nominal NPC, Renewable scenario, Base case

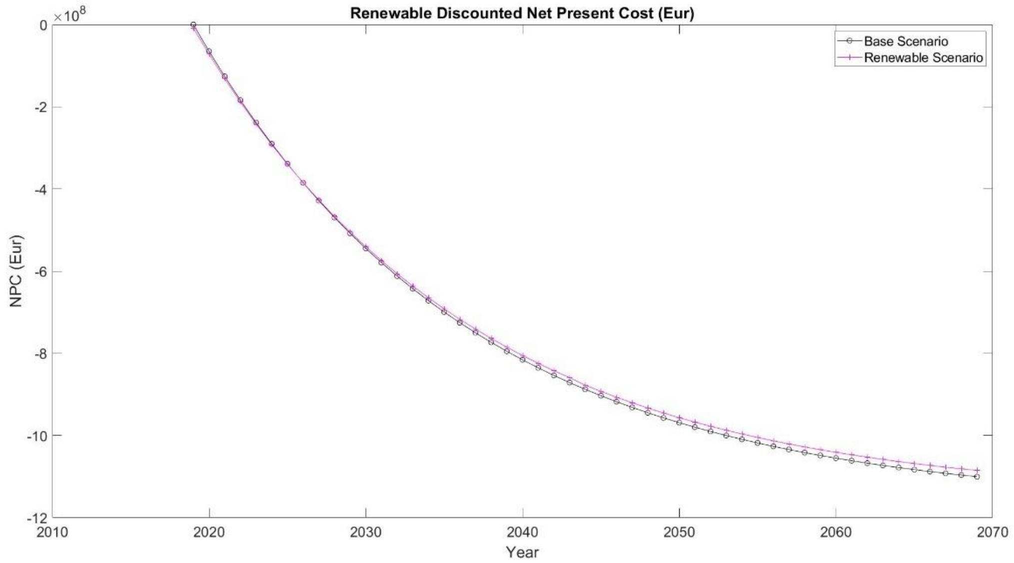


Figure 4-4 - Discounted NPC, Renewable scenario, Base case

Regarding the economic results, the next Table 4-9 highlights the main index taken into consideration in this analysis where:

- IRR: the Internal rate of Return is a discount rate that makes the net present value (NPV) of all cash flows equal to zero.
- ROI: The Return Of Investment represents how well an investment has performed and is calculated by dividing an investment's net profit by its initial cost
- SPbT: The Standard Payback Time is the period at the end of which an investment has produced sufficient net revenue to recover its investment costs. In the case of the discounted cash flows, it is called Discounted Payback Time (DPbT)
- NPV: the Net Present Value is the worth of an investment at the end of the period considered, discounted to today's value. In this analysis, the investment considered has a life of 50 years, but it is considered also the NPV after 25 years (NPV25).
- PI: The Profitability Index represents the project attractiveness and is calculated by dividing the NPV by the initial investment. This analysis is considered also the PI at 2 years (PI25)

Table 4-9 - Economic results, Renewable scenario, Base case

IRR	ROI	SPBT [YEARS]	DPBT [YEARS]	NPV [M€]	PI	NPV25 [M€]	PI25
18%	15%	5.37	7.29	27.57	3.17	24.92	2.86

As it is possible to see, and In line with other studies cited in the literature, the installation of renewables is a key factor in airports, with a double vantage, the reduction of dependency from the grid, and the possibility to insert electricity in the grid, becoming a prosumer and contribute to renewable development by taking advantage of the available space in the airport.

4.2.2 Electrification development

In the Electrification development scenario, the aim is to exploit the feasibility to adopt electric ground vehicles instead of diesel-based ones in the airport framework. Differently from the base case, so, the electricity load is higher as there is the necessity to supply power to the bus shuttle service and the GSE. It results in an increase in energy purchased, while the electricity sold to the network remains about the same. In Figure 4-5**,** it is illustrated the total electricity load compared to the renewable output and the electricity sold.

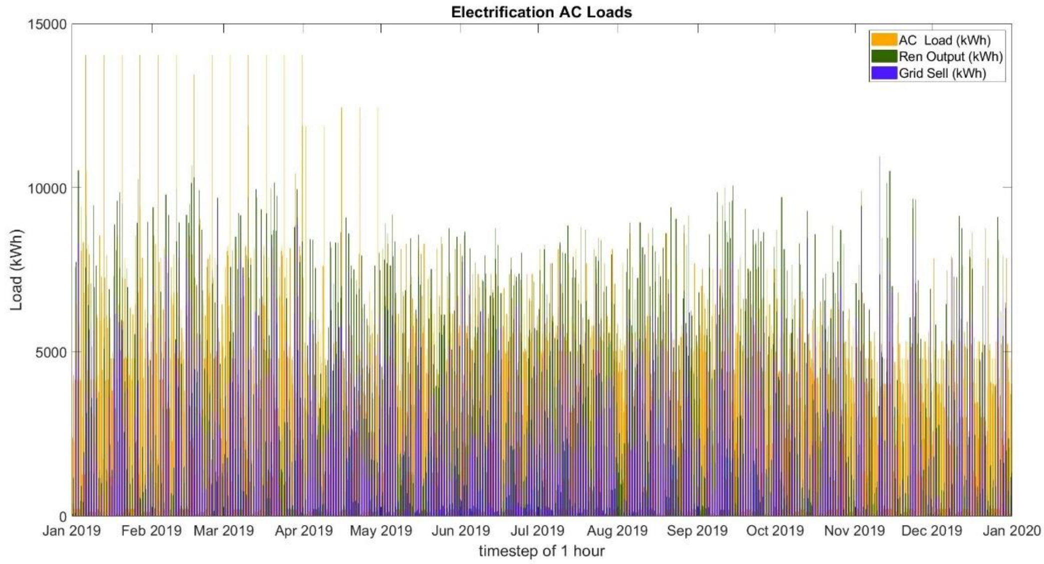


Figure 4-5 - Comparisons among electricity input/output, Electrification scenario, Base case

The following Figure 4-6, represents the schematic of the electricity consumption and supply of the airport, while Table 4-10**,** shows the yearly overall consumption of the main systems of the airport compared also with the Renewable scenario and highlights the overall increase/decrease.

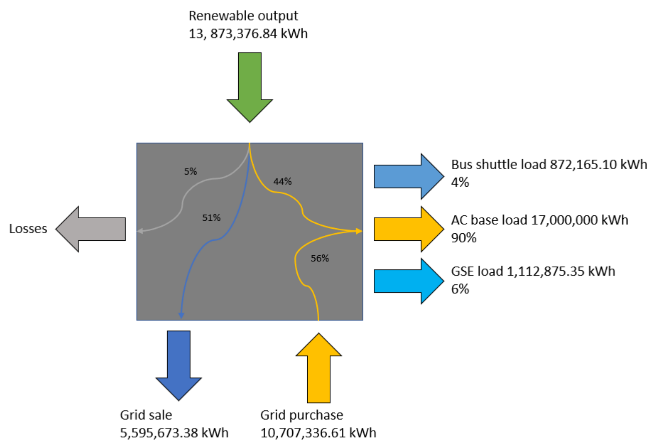


Figure 4-6 - Airport electricity supply/consumption scheme, Electrification scenario, Base case

Table 4-10 - Consumption, Electrification scenario, Base case

	AC PRIMARY LOAD (MWH)	GRID PURCHASES (MWH)	GRID SELL (MWH)	RENEWABLE OUTPUT (MWH)	JET FUEL (LT)	CO2 EMISSIONS (TON)
Renewable	17,326.00	9,463.23	5,642.94	13,873.38	56,686,173.00	132,248.15
Variation (%)	+8%	+13%	-9%	0%	0%	-1%
Electrification	18,782.00	10,712.40	5,110.10	13,873.38	56,686,173.00	130,982.47

As could be seen the implementation of electric ground vehicles follows an increase in total electricity consumption, and also in grid purchase. On the other hand, there is a better exploitation of renewable energies, with a reduction of electricity sold to the grid. Finally, there is a slight reduction in CO_2 emissions, that in this scenario regards only jet fuel consumption.

Concerning economic results, in Figure 4-7 and Figure 4-8, it is possible to see the Net Present Cost of the Electrification scenario, compared with the Business As usual.

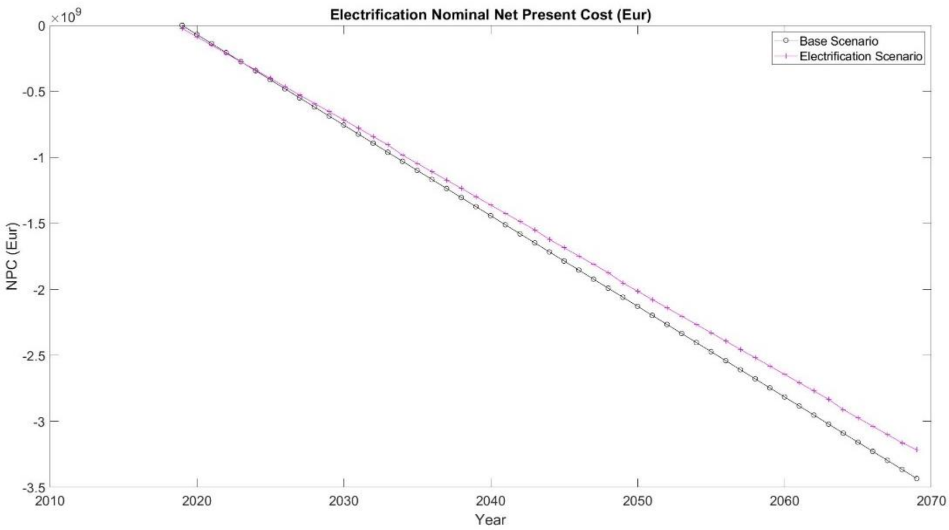


Figure 4-7 - Nominal NPC, Electrification scenario, Base case

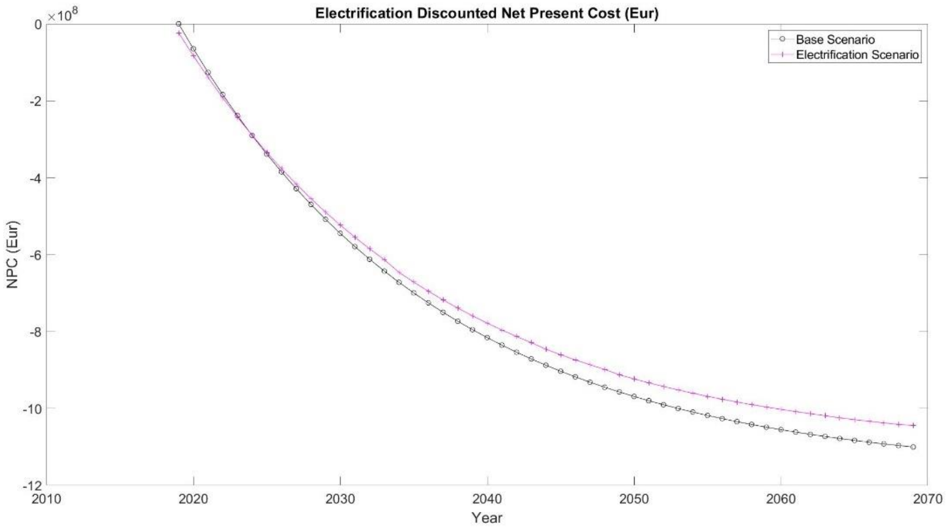


Figure 4-8 - Discounted NPC, Electrification scenario, Base case

In Table 4-11, instead, the main economic indices are illustrated, resulting in a more convenient NPV in this scenario, affirming how the investment in electric ground vehicles may be not only an economic opportunity but also an environmental opportunity.

Table 4-11 - Economic results, Electrification scenario, Base case

IRR	ROI	SPBT [YEARS]	DPBT [YEARS]	NPV [M€]	PI	NPV25 [M€]	PI25
15%	11%	6.2	8.9	56.95	2.69	52.87	2.49

4.2.3 Regional flights development

In the Regional development scenario, the aim is to exploit the feasibility to start adopting hydrogen-based airplanes, operating at the National level. As previously said, in the present work it is shown the solution with the hydrogen produced mostly off-site, with a small share produced on-site taking advantage of the electricity surplus from renewables, instead of selling it in the grid. In Figure 4-9**,** it is illustrated the total electricity load compared to the renewable output and the electricity absorbed by the electrolyzer.

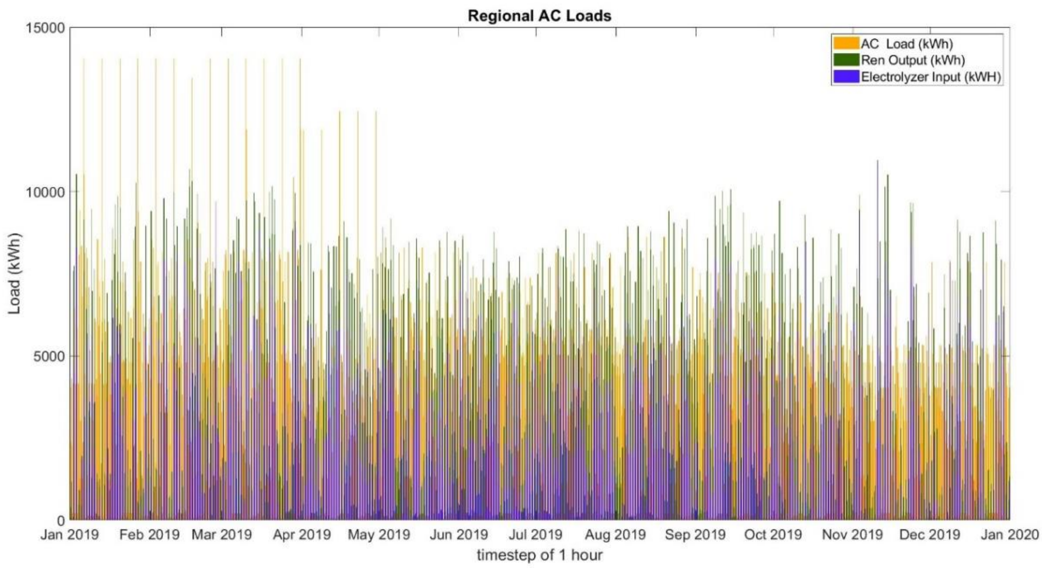


Figure 4-9 - Comparisons among electricity input/output, Regional scenario, Base case

Similarly, in the next Table 4-12, and, it is illustrated the overall hydrogen consumption and the share of electrolyzer and delivery, also highlighted as hourly supply in Figure 4-10, while in Figure 4-11 it is shown a schematic representation of the electricity loads of the airport.

Table 4-12 - Hydrogen consumption, Regional scenario, Base case

	DELIVERY	ELECTROLYZER	TOTAL CONSUMPTION
Hydrogen supply (kg)	6,648,141.66	107,105.92	6,755,247.58
Hydrogen share (kg)	98%	2%	100%

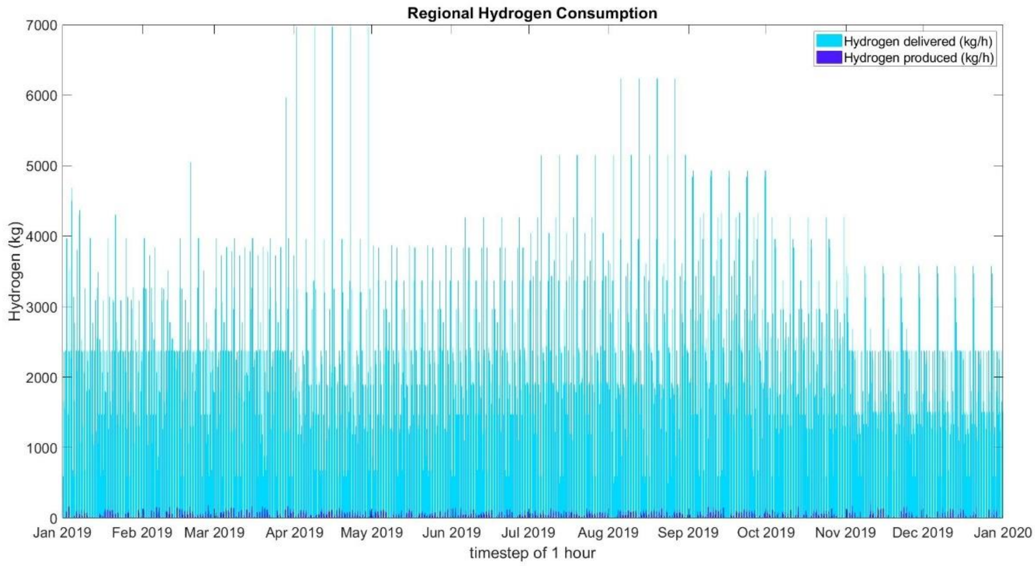


Figure 4-10 - Comparisons between hydrogen supply solutions, Regional scenario, Base case

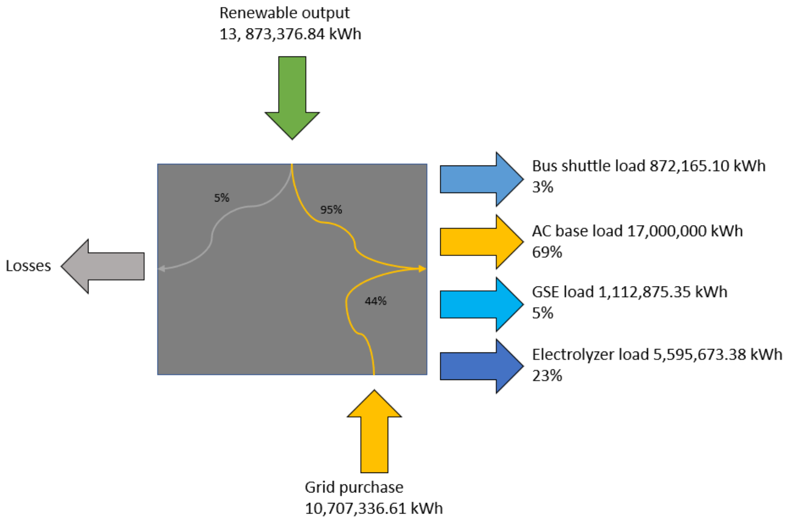


Figure 4-11 - Airport electricity supply/consumption scheme, Regional scenario, Base case

As it is possible to notice also in Table 4-13**,** the total electricity consumption does not change, as the surplus of energy produced from renewable is completely used by the electrolyzer to produce hydrogen, acting as energy storage. However, the hydrogen produced by the electrolyzer covers a small share of the total consumption, about 1%. Moreover, the use of green hydrogen in regional flights allows reducing yearly CO2 emissions by 43% with respect to the Business As Usual (such emissions are equal to the Renewable scenario), due to a reduction of 43% in Jet fuel.

Table 4-13 - Consumption, Regional scenario, Base case

	AC PRIMARY LOAD (MWH)	GRID PURCHASES (MWH)	GRID SELL (MWH)	RENEWABLE OUTPUT (MWH)	JET FUEL (LT)	CO2 EMISSIONS (TON)
Renewable	17,326.00	9,463.23	5,642.94	13,873.38	56,686,173.00	132,248.15
Variation (%)	+8%	+13%	-9%	0%	0%	-1%
Electrification	18,782.00	10,712.40	5,110.10	13,873.38	56,686,173.00	130,982.47
Variation (%)	0%	0%	-100%	0%	-43%	-43%
Regional	18,782.00	10,712.40	0	13,873.38	32,124,736	74,229.35
		ELECTROLYZER INPUT (MWH)	5,379.10			
		ELECTROLYZER OPERATION (H)	2,681			

Concerning economic results, the nominal and discounted NPC are illustrated in Figure 4-12 and Figure 4-13. As it is possible to notice the high hydrogen cost of the Base case (Sensitivity case 1) does not allow to have positive cash flows with respect to the Business As Usual scenario. It is affirmed how the use of hydrogen is still economically prohibitive with present costs, making this technology development strictly correlated to the reduction in hydrogen price, as it should happen in the following years.

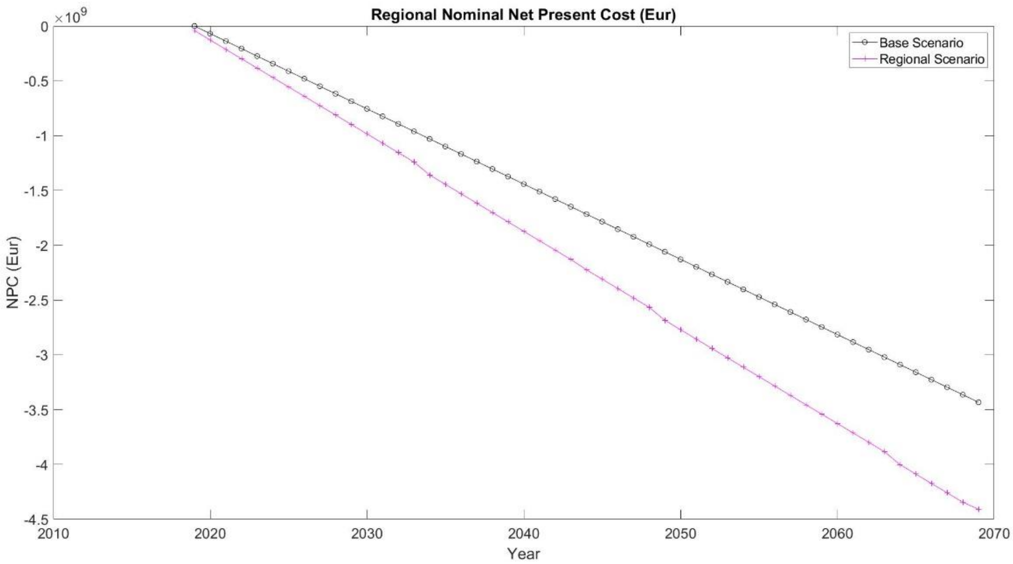


Figure 4-12 - Nominal NPC, Regional scenario, Base case

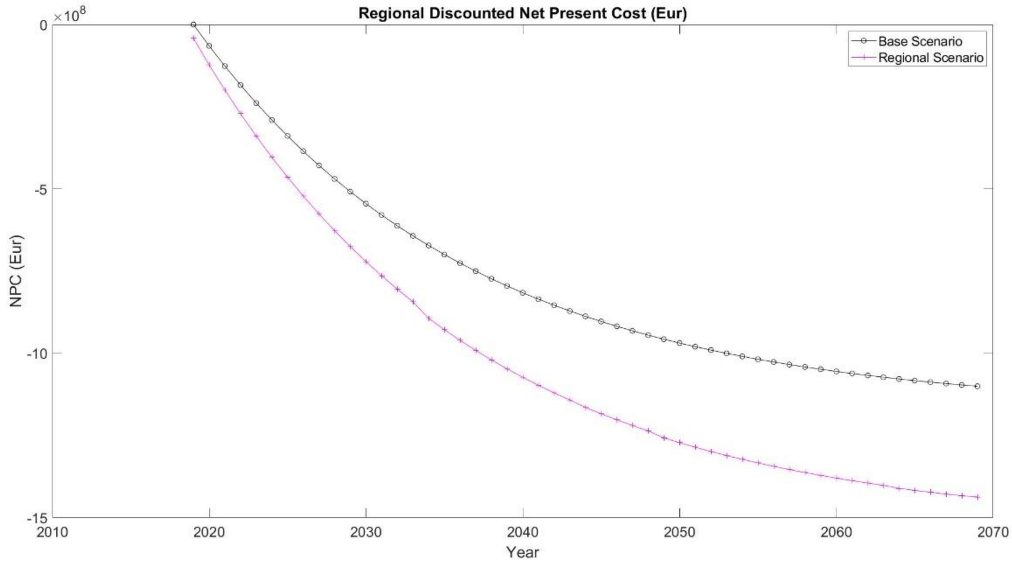


Figure 4-13 - Discounted NPC, Regional scenario, Base case

Table 4-14 - Economic results, Regional scenario, Base case

IRR	ROI	SPbT [years]	DPbT [years]	NPV [M€]	PI	NPV25 [M€]	PI25
N/A	-55%	-2	-2	-249.18	-5.50	-180.46	4.60

4.2.4 International flights development

Finally, in the International development scenario, the aim is to exploit the feasibility of completely adopting hydrogen-based airplanes, operating at the whole level. As previously said, in the present work it is shown the solution with the hydrogen produced mostly off-site, with a small share produced on-site taking advantage of the electricity surplus from renewables, instead of selling it in the grid. Results concerning electricity consumption are similar to the Regional development scenario, as all energy resources have been already exploited in that scenario. The only difference regards the hydrogen consumption and share of on-site production, resumed in Figure 4-14 and Table 4-15

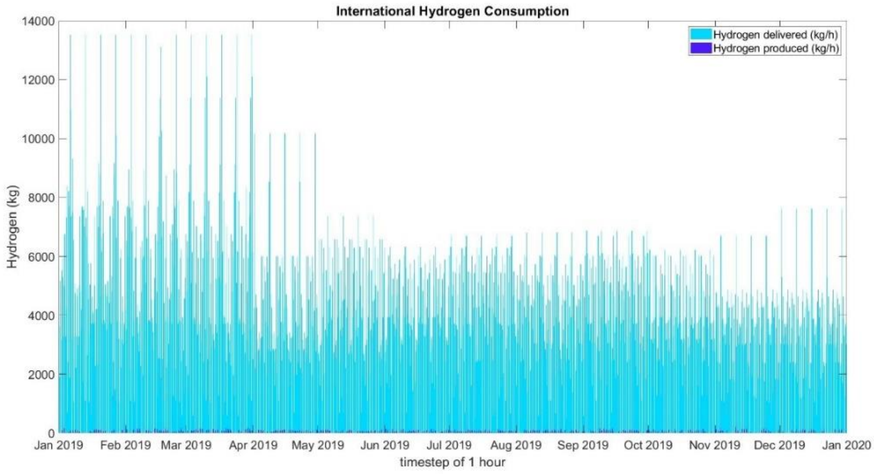


Figure 4-14 - Comparisons between hydrogen supply solutions, International scenario, Base case

Table 4-15 - Hydrogen consumption, International scenario, Base case

	DELIVERY	ELECTROLYZER	TOTAL CONSUMPTION
Hydrogen supply (kg)	15,343,472.86	107,105.92	15,450,578.78
Hydrogen share (kg)	99.3%	0.7%	100%

As well, the main consumption is, however, resumed in the next Table 4-16

Table 4-16 - Consumption, International scenario, Base case

	AC PRIMARY LOAD (MWH)	GRID PURCHASES (MWH)	GRID SELL (MWH)	RENEWABLE OUTPUT (MWH)	JET FUEL (LT)	CO2 EMISSIONS (TON)
Renewable	17,326.00	9,463.23	5,642.94	13,873.38	56,686,173.00	132,248.15
Variation (%)	+8%	+13%	-9%	0%	0%	-1%
Electrification	18,782.00	10,712.40	5,110.10	13,873.38	56,686,173.00	130,982.47
Variation (%)	0%	0%	-100%	0%	-43%	-43%
Regional	18,782.00	10,712.40	0	13,873.38	32,124,736	74,229.35
Variation (%)	0%	0%	0%	0%	-100%%	-100%
International	18,782.00	10,712.40	0	13,873.38	0	0
		ELECTROLYZER INPUT (MWH)	5,595.67			
		ELECTROLYZER OPERATION (H)	2,681			

Concerning economic results, analysis has carried out similar outcomes of the Regional scenario, with an NPC too much higher than the Business as Usual scenario due to a too much high hydrogen price.

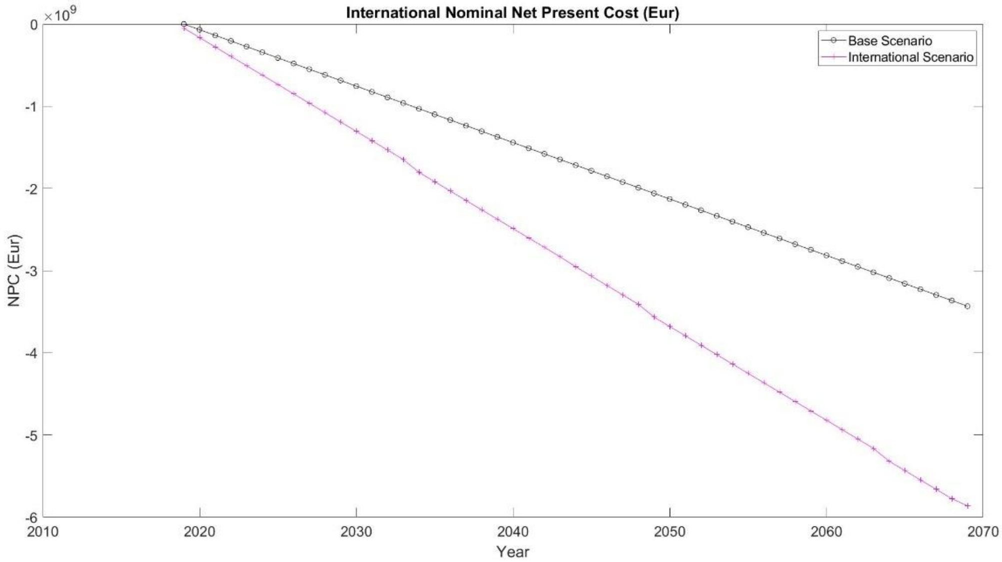


Figure 4-15- Nominal NPC, International scenario, Base case

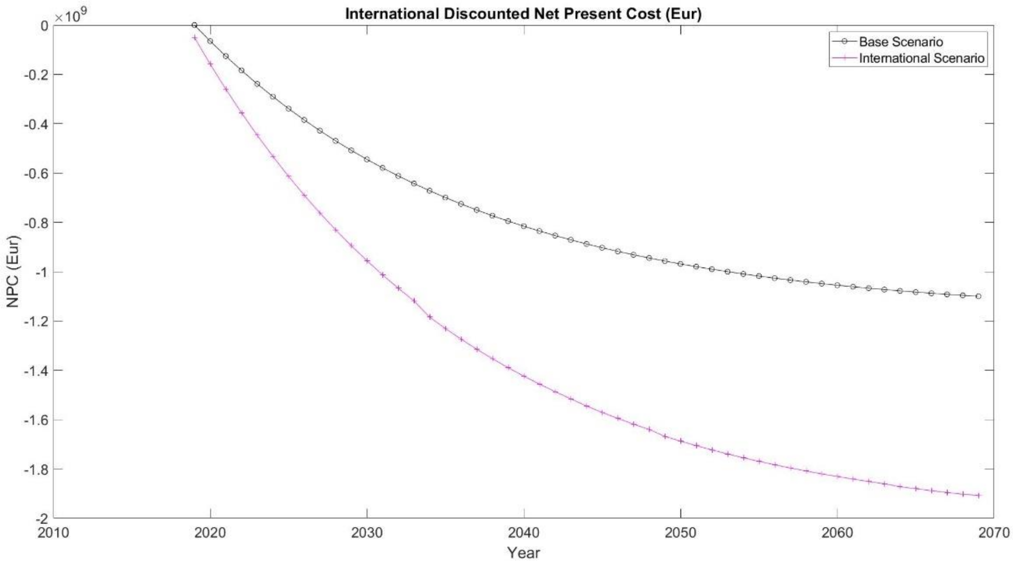


Figure 4-16 - Discounted NPC, International scenario, Base case

Table 4-17 - Economic results, International scenario, Base case

IRR	ROI	SPBT [YEARS]	DPBT [YEARS]	NPV [M€]	PI	NPV25 [M€]	PI25
N/A	-106%	-1	-1	-661.24	-11.82	-482.55	-10.08

4.3 GRID COSTS INCREASE

In the base sensitivity case it is exploited the base parameters adopted in the analysis, resumed as follows:

Table 4-18 - Grid cost case sensitivity variables

	CASE	GRID COSTS [€/KWH]	FC CAPITAL COSTS [€/KW]	HYDROGEN PRICE [€/KG]	DIESEL PRICE [€/L]	JET FUEL PRICE [€/L]	CARBON TAX [€/TONCO2]
Grid cost increase	2	0.184	2231.46	7.09	1.82	1.06	0.00
	3	0.184	1775.17	4.73	1.82	1.06	0.00
	4	0.184	1115.73	1.51	1.82	1.06	0.00

However, in paragraph 4.1 it has been assessed how cases 2 and 3 are not economically interesting and economically feasible, due to a high hydrogen price, as it has been already proved in the Base case (paragraph 0) for Regional and International scenario, while for Renewable and Electrification the use of hydrogen is limited and it is not much influential.

4.3.1 Renewable development

The main loads, that concern electricity (Figure 3-6) diesel (Figure 3-7), and jet fuel (Figure 3-8) are the same as the business as usual. The difference with the other scenarios is the electricity sold to the grid and the use of a hydrogen-based fuel cell, which helps in the reduction of dependency on the grid, together with the installation of solar panels. In Figure 4-17, it is possible to see the hourly electricity consumption of the airport compared with the renewable output, the electricity sold to the grid, and the electricity produced by the fuel cell

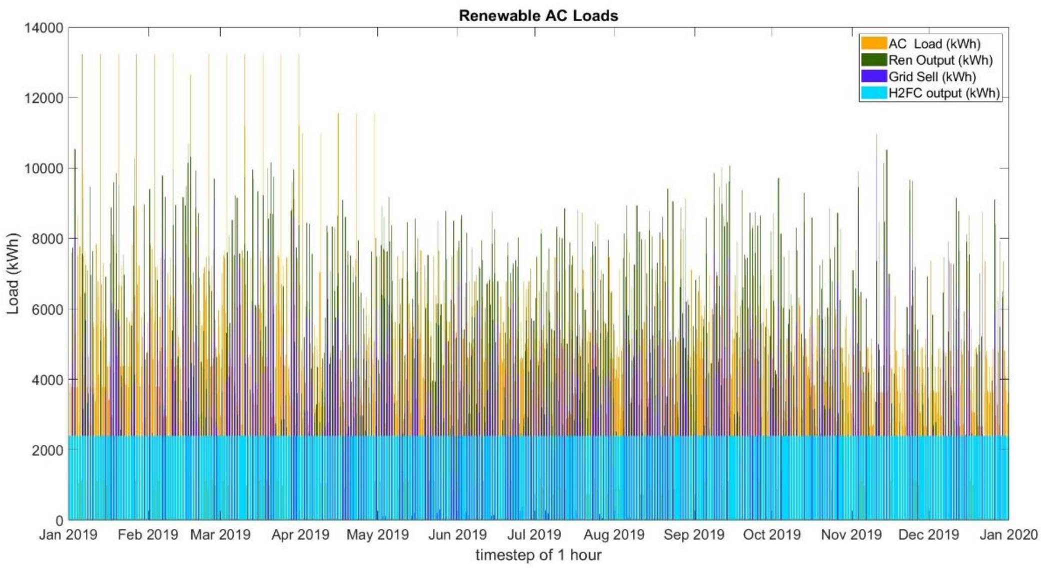


Figure 4-17 - Comparisons among electricity input/output, Renewable scenario, Grid costs increase case

The use of renewable energy, such as solar panels and fuel cells (considered a renewable technology only if the hydrogen used is produced by renewables), is a valid solution to reduce energy purchased from the grid, with a reduction of -75% with a consequent economic saving, as highlighted in Figure 4-18 and Figure 4-19, where it is compared the NPC of the BAU scenario and the Renewable scenario.

The following Table 4-19 shows the yearly overall consumption of the main systems of the airport (Electricity, Diesel, and Jet fuel). It is possible to notice how the implementation of an H2FC could make the airport independent from the grid, as the grid sold is higher than the one purchased. It means that the development of an intelligent energy management system and the continuous development of storage technology could help the reduction of grid dependency, promoting energy communities and microgrids.

Table 4-19 – Consumption, Renewable scenario, Grid costs increase case

AC PRIMARY LOAD (MWH)	DIESEL LOAD (KG)	GRID PURCHASES (MWH)	GRID SELL (MWH)	RENEWABLE OUTPUT (MWH)	H2FC OUTPUT (MWH)	JET FUEL (LT)	CO2 EMISSIONS (TON)
17,326.00	552,697.00	4,398.27	6,024.78	13,873.38	5,446.80	56,686,173.00	132,248.15

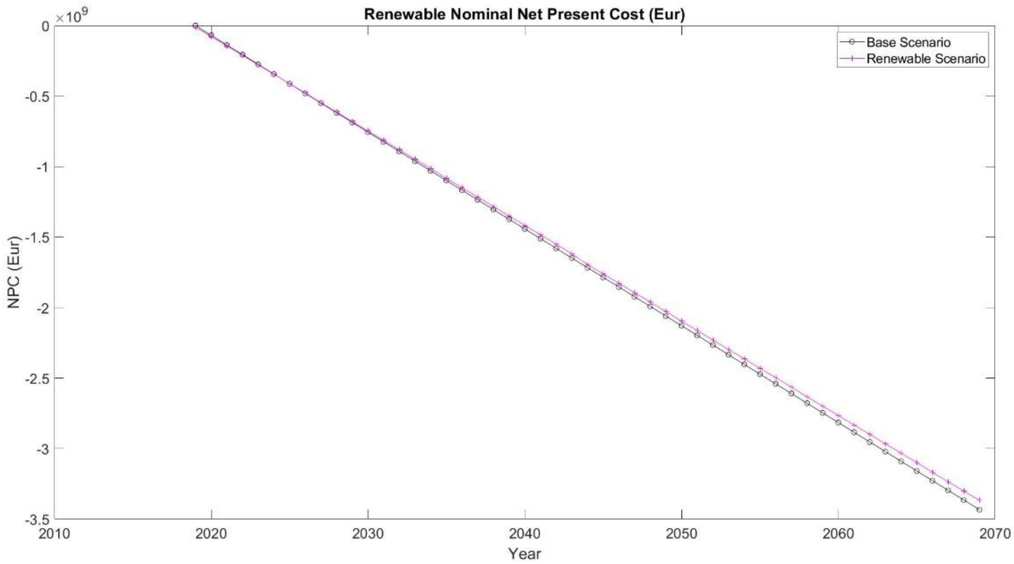


Figure 4-18 - Nominal NPC, Renewable scenario, Grid costs increase case

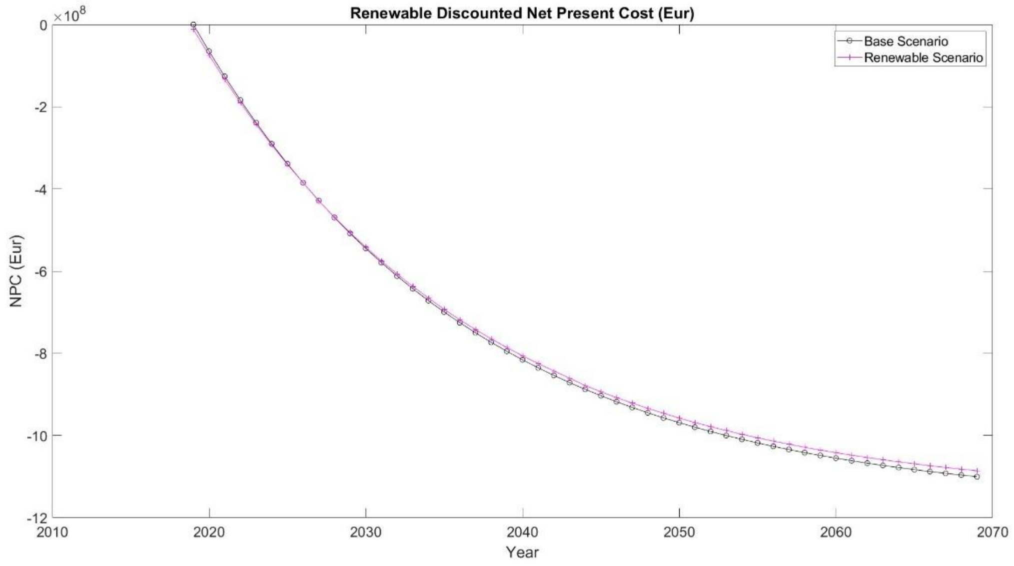


Figure 4-19 - Discounted NPC, Renewable scenario, Grid costs increase case

Regarding the economic results, in the next Table 4-20 are highlighted the main index taken into consideration in this analysis:

Table 4-20 - Economic results, Renewable scenario, Grid costs increase case

IRR	ROI	SPBT [YEARS]	DPBT [YEARS]	NPV [M€]	PI	NPV25 [M€]	PI25
19%	15%	4.7	6.2	34.73	3.24	31.57	2.95

As it is possible to see, and In line with other studies cited in the literature, the installation of renewables is a key factor in airports, with a double vantage, the reduction of dependency from the grid, and the possibility to insert electricity in the grid, becoming a prosumer and contribute to renewable development by taking advantage of the available space in the airport. Moreover, in this case, the installation of a hydrogen fuel cell and the accessible hydrogen price makes the investment convenient, even if the economic indices are less performant than the base case.

4.3.2 Electrification development

In the Electrification development scenario, the aim is to exploit the feasibility to adopt electric ground vehicles instead of diesel-based ones in the airport framework. Differently from the base case, so, the electricity load is higher as there is the necessity to supply power to the bus shuttle service and the GSE. It results in a slight increase in energy purchased, with part of the added electricity consumption covered by a larger size in H2FC than the Renewable scenario. In Figure 4-20**,** it is illustrated the total electricity load compared to the renewable output, the H2FC output, and the electricity sold.

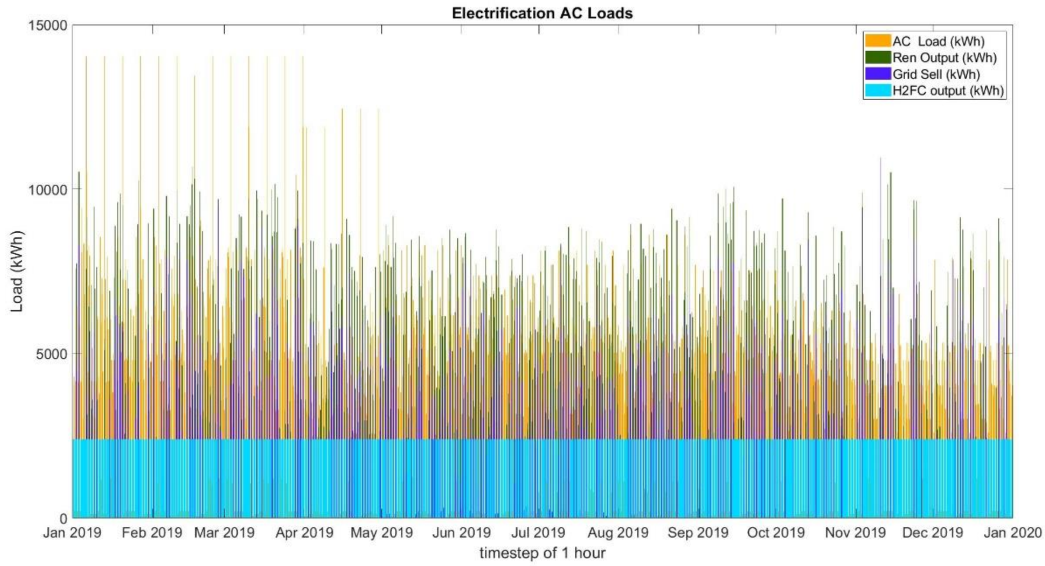


Figure 4-20 - Comparisons among electricity input/output, Electrification scenario, Grid costs increase case

The following Table 4-21, shows the yearly overall consumption of the main systems of the airport compared also with the Renewable scenario and highlights the overall increase/decrease.

Table 4-21 - Consumption, Electrification scenario, Grid costs increase case

	AC PRIMARY LOAD (MWH)	DIESEL LOAD (KG)	GRID PURCHASES (MWH)	GRID SELL (MWH)	RENEWABLE OUTPUT (MWH)	H2FC OUTPUT (MWH)	JET FUEL (LT)	CO2 EMISSIONS (TON)
Renewable	17,326.00	552,697.00	4,398.27	6,024.78	13,873.38	5,446.80	56,686,173.00	132,248.15
Variation	+8%	-100%	+20%	-9%	0%	+5%	0%	-1%
Electrification	18,782.00	0	5,268.44	5,485.55	13,873.38	5,819.40	56,686,173.00	130,975.99

As could be seen the implementation of electric ground vehicles follows an increase in total electricity consumption, and also in grid purchase. On the other hand, there is better exploitation of renewable energies, while the use of H2FC generates a slight increase in sold to the grid. Finally, there is a slight reduction in CO2 emissions, that in this scenario regards only jet fuel consumption.

Concerning economic results, in Figure 4-21, and Figure 4-22 it is possible to see the Net Present Cost of the Electrification scenario, compared with the Business As usual.

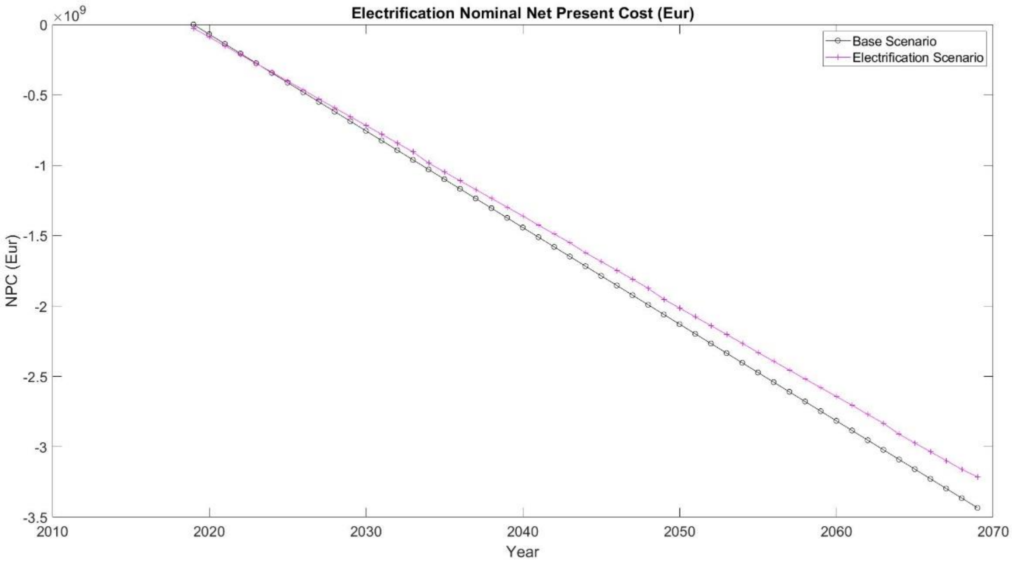


Figure 4-21 – Nominal NPC, Electrification scenario, Grid costs increase case

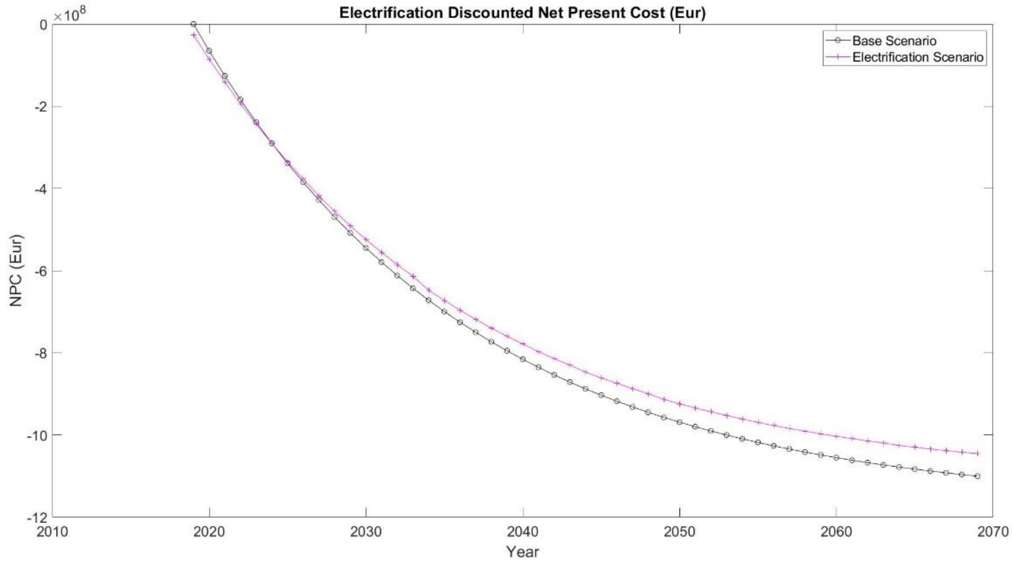


Figure 4-22 – Discounted NPC, Electrification scenario, Grid costs increase case

In Table 4-22, instead, the main economic indices are illustrated, resulting in a more convenient NPV in this scenario, affirming how the investment in electric ground vehicles may be not only an economic opportunity but also an environmental opportunity.

Table 4-22 - Economic results, Electrification scenario, Grid costs increase case

IRR	ROI	SPBT [YEARS]	DPBT [YEARS]	NPV [M€]	PI	NPV25 [M€]	PI25
15%	11%	5.7	7.9	64.06	2.76	59.29	2.55

4.3.3 Regional flights development

In the Regional development scenario, the aim is to exploit the feasibility to start adopting hydrogen-based airplanes, operating at the National level. As previously said, in the present work it is shown the solution with the hydrogen produced mostly off-site, with a small share produced on-site taking advantage of the electricity surplus from renewables, instead of selling it in the grid. In Figure 4-23**,** it is illustrated the total electricity load compared to the renewable output, the electricity absorbed by the electrolyzer, and the one produced by the hydrogen fuel cell.

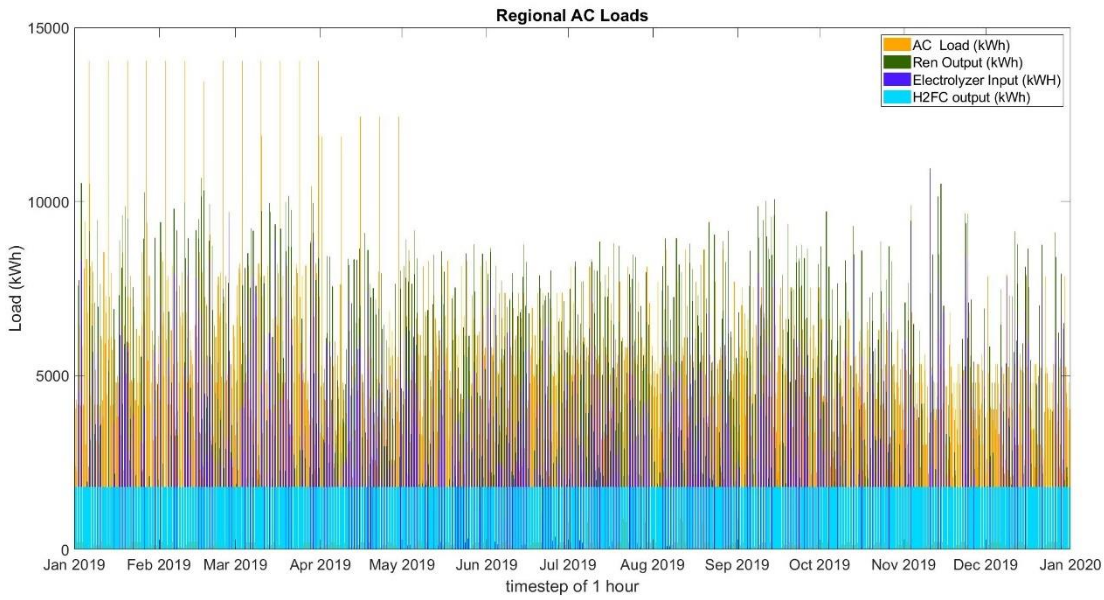


Figure 4-23 - Comparisons among electricity input/output, Regional scenario, Grid costs increase case

Similarly, in the next Table 4-23Figure 4-24, it is illustrated the overall hydrogen consumption and the share of the electrolyzer and delivered. In Figure 4-24, it is illustrated the hourly hydrogen consumption with respect to the total supply, highlighting how the consumption coming from the fuel cell is minimal with respect to airplane consumption.

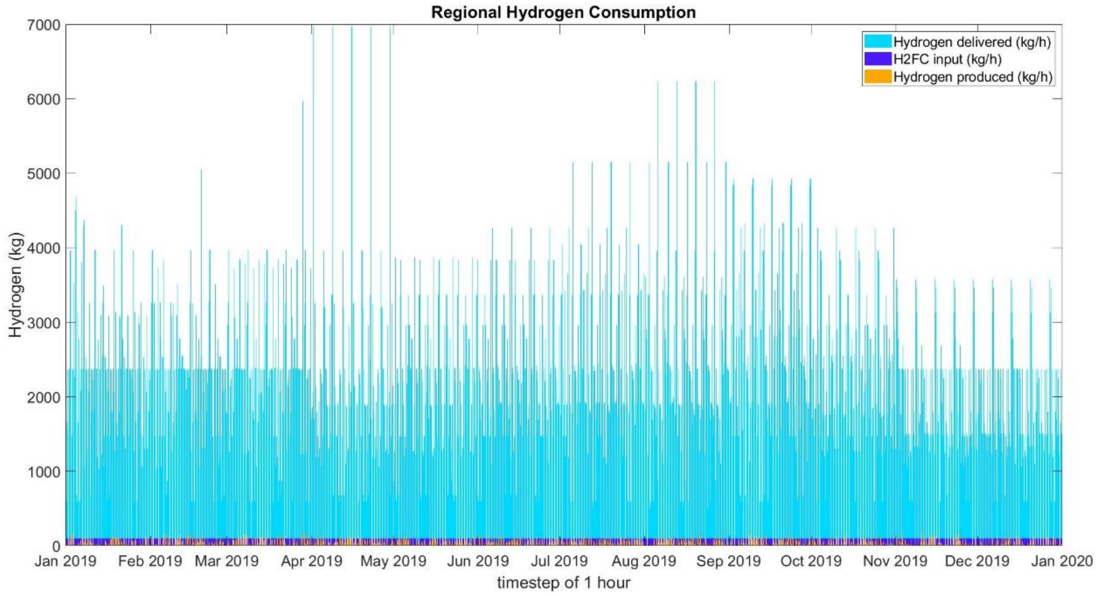


Figure 4-24 - Hydrogen consumption, Regional scenario, Grid costs increase case

Table 4-23 – Hydrogen consumption, Regional scenario, Grid costs increase case

	DELIVERY	ELECTROLYZER	TOTAL CONSUMPTION
Hydrogen supply (kg)	6,648,141.66	107,105.92	6,762,436.13
Hydrogen share (kg)	98%	2%	100%

As it is possible to notice also in Table 4-24**,** the total electricity consumption does not change, as the surplus of energy produced from renewable is completely used by the electrolyzer to produce hydrogen, acting as energy storage. However, the hydrogen produced by the electrolyzer covers a small share of the total consumption, about 1%. Moreover, the use of green hydrogen in regional flights allows for a reduction of yearly CO2 emissions by 43% with respect to Electrification, due to a reduction of 43% in Jet fuel.

Table 4-24 – Consumption, Regional scenario, Grid costs increase case

	AC PRIMARY LOAD (MWH)	GRID PURCHASES (MWH)	GRID SELL (MWH)	RENEWABLE OUTPUT (MWH)	H2FC OUTPUT (MWH)	JET FUEL (LT)	CO2 EMISSIONS (TON)
Renewable	17,326.00	4,398.27	6,024.78	13,873.38	5,446.80	56,686,173.00	132,248.15
Variation	+8%	+20%	-9%	0%	+5%	0%	-1%
Electrification	18,782.00	5,268.44	5,485.55	13,873.38	5,819.40	56,686,173.00	130,975.99
Variation (%)	0%	+26%	-100%	0%	-30%	-43%	-43%
Regional	18,782.00	6,700.88	0	13,873.00	4,120.80	32,124.74	74,224
		ELECTROLYZER INPUT (MWH)	5,491.60				
		ELECTROLYZER OPERATION (H)	3,163				

Concerning economic results, the nominal and discounted NPC are illustrated in Figure 4-25 and Figure 4-26. Differently, from the Base case sensitivity, the low hydrogen price allows having positive cash flows, making the investment more convenient. This is one of the key parameters of the analysis, the economic feasibility of hydrogen use in aviation and the exploitation of accessible prices for hydrogen use.

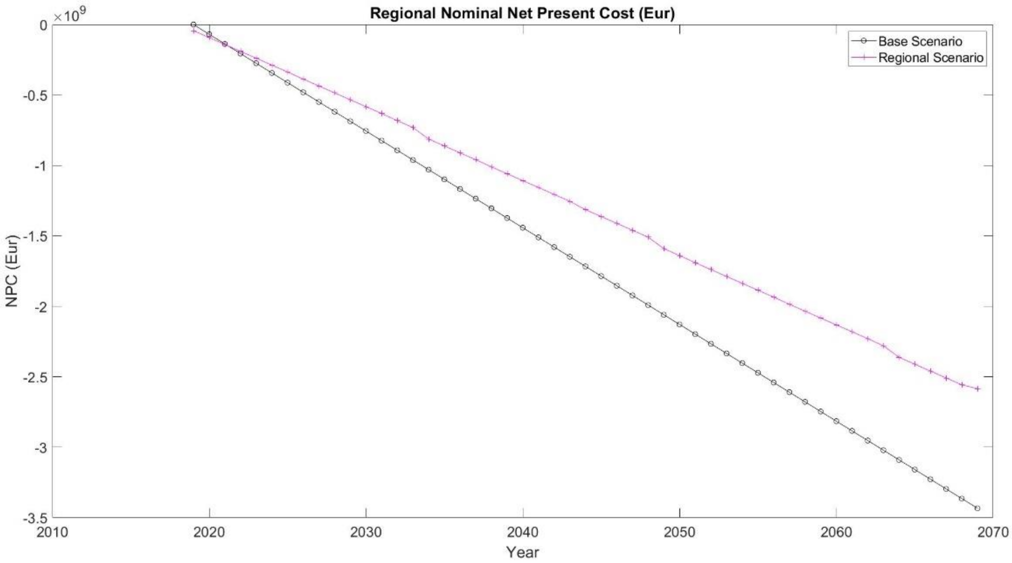


Figure 4-25 - Nominal NPC, Regional scenario, Grid costs increase case

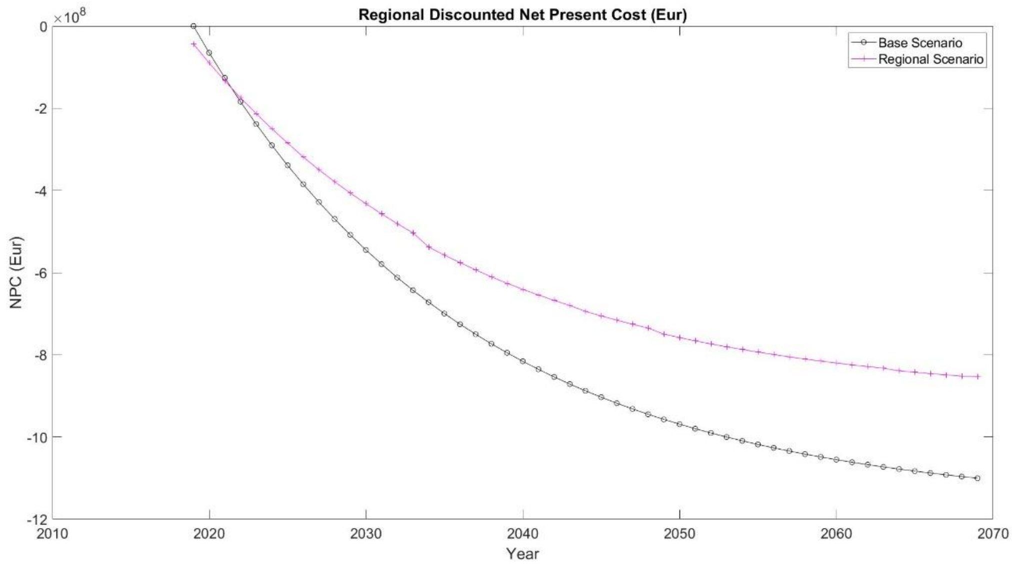


Figure 4-26 - Discounted NPC, Regional scenario, Grid costs increase case

Table 4-25 – Economic results, Regional scenario, Grid costs increase case

IRR	ROI	SPBT [YEARS]	DPBT [YEARS]	NPV [M€]	PI	NPV25 [M€]	PI25
45%	37%	2.3	2.6	245.13	6.05	220.01	5.43

4.3.4 International flights development

Finally, in the International development scenario, the aim is to exploit the feasibility of completely adopting hydrogen-based airplanes, operating at the whole level. As previously said, in the present work it is shown the solution with the hydrogen produced mostly off-site, with a small share produced on-site taking advantage of the electricity surplus from renewables, instead of selling it in the grid. Results concerning electricity consumption are similar to the Regional development scenario, as all energy resources have been already exploited in that scenario. The only difference regards the hydrogen consumption and share of on-site production, moreover, the influence of hydrogen consumed in the hydrogen fuel cell is lower than the Regional scenario, meaning that most of the hydrogen supplied and produced is consumed by airplanes. Hourly results are resumed in Figure 4-27, and Table 4-26.

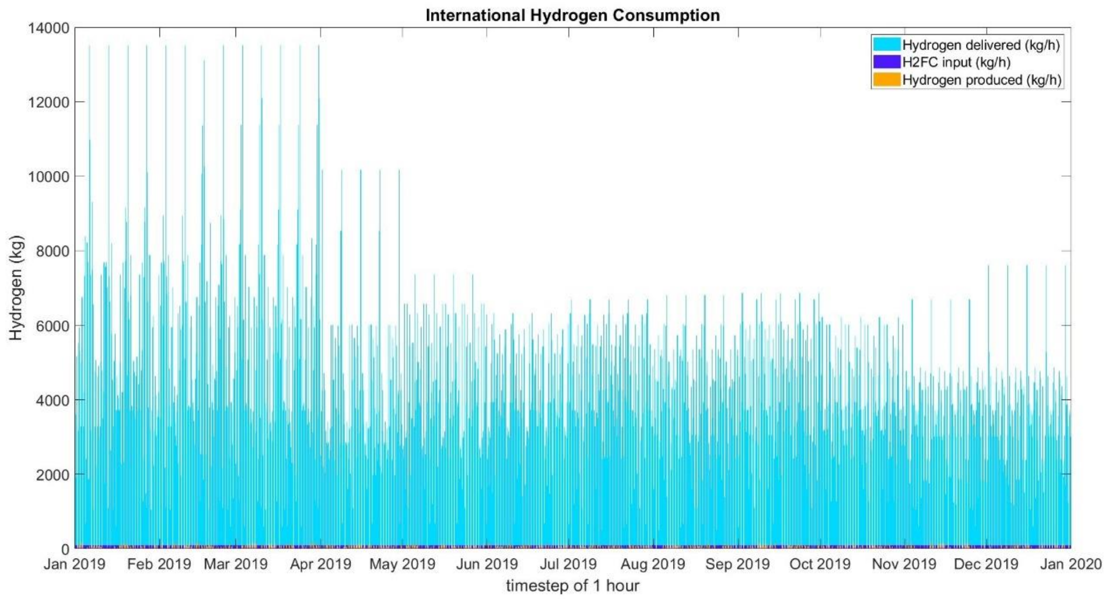


Figure 4-27 - Comparisons between hydrogen supply solutions, International scenario, Grid costs increase case

Table 4-26 – Hydrogen consumption, International scenario, Grid costs increase case

	DELIVERY	ELECTROLYZER	TOTAL CONSUMPTION
Hydrogen supply (kg)	15,343,472.86	107,105.92	15,450,578.78
Hydrogen share (kg)	99.3%	0.7%	100%

As well, the main consumption is, however, resumed in the next Table 4-27. The electricity output of the hydrogen fuel cell is unchanged, as the larger size assumed is already analyzed in the regional scenario, exploiting the highest electricity that could be produced by the fuel cell.

Table 4-27 – Consumption, International scenario, Grid costs increase case

	AC PRIMARY LOAD (MWH)	GRID PURCHASES (MWH)	GRID SELL (MWH)	RENEWABLE OUTPUT (MWH)	H2FC OUTPUT (MWH)	JET FUEL (LT)	CO2 EMISSIONS (TON)
Renewable	17,326.00	4,398.27	6,024.78	13,873.38	5,446.80	56,686,173.00	132,248.15
Variation	+8%	+20%	-9%	0%	+5%	0%	-2%
Electrification	18,782.00	5,268.44	5,485.55	13,873.38	5,819.40	56,686,173.00	130,975.99
Variation (%)	0%	0%	-100%	0%	-30%	-43%	-43%
Regional	18,782.00	6,700.88	0	13,873.00	4,120.80	32,124.74	74,224
Variation (%)	0%	0%	0%	0%	0%%	-100%	-100%
International	18,782.00	6,700.88	0	13,873.00	4,120.80	0%	0
		ELECTROLYZER INPUT (MWH)	5,971.23				
		ELECTROLYZER OPERATION (H)	2,681				

Concerning economic results, analysis has carried out similar outcomes of the Regional scenario, with a lower NPC than the Business As Usual scenario. The main reason relies on the low hydrogen price.

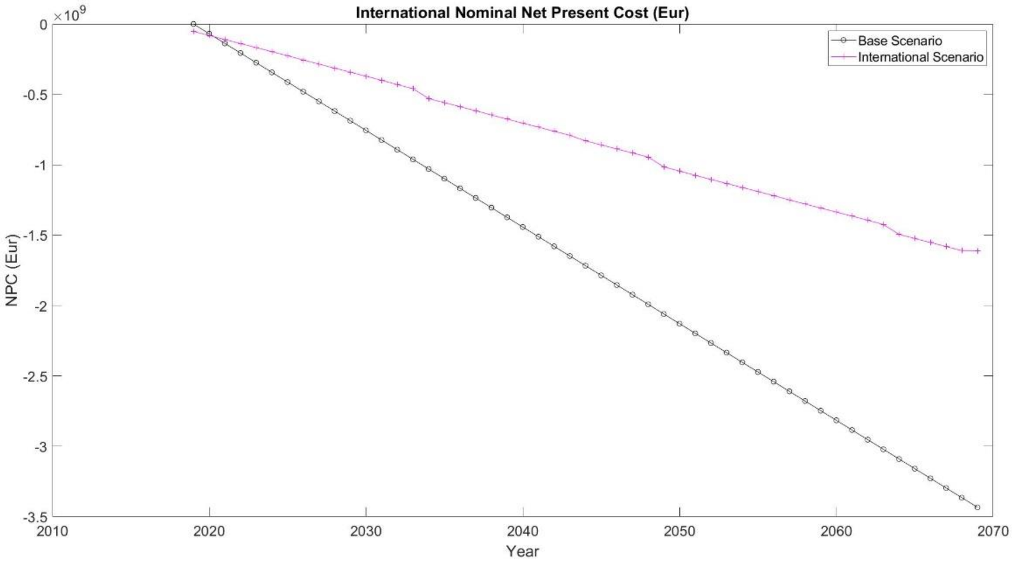


Figure 4-28- Nominal NPC, International scenario, Grid costs increase case

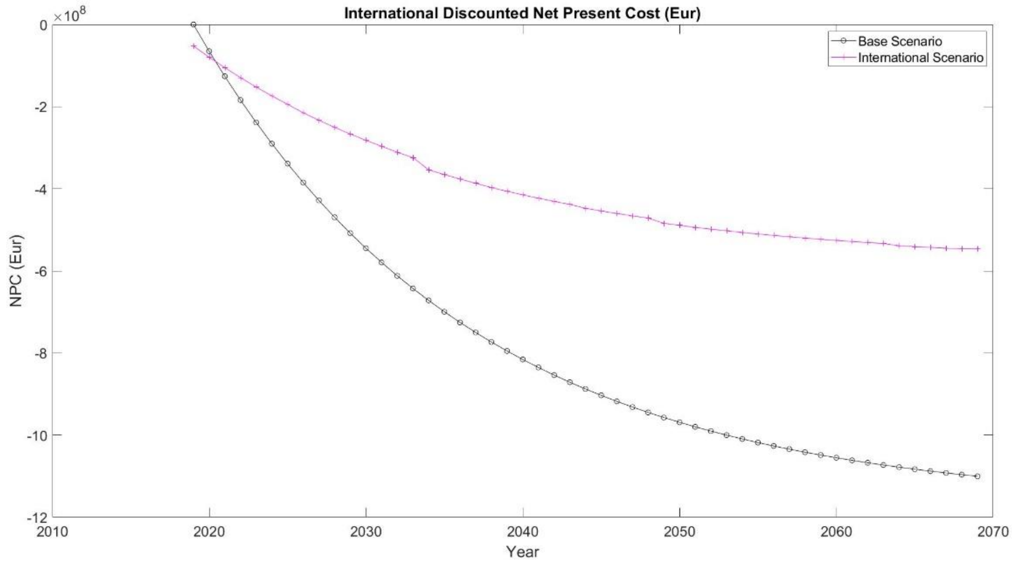


Figure 4-29 – Discounted NPC, International scenario, Grid costs increase case

Table 4-28 - Economic results, International scenario, Grid costs increase case

IRR	ROI	SPBT [YEARS]	DPBT [YEARS]	NPV [€]	PI	NPV25 [€]	PI25
7%	70%	1.3	1.4	499.81	10.16	442.89	9

4.4 Carbon tax

In the base sensitivity case it is exploited the base parameters adopted in the analysis, resumed as follows:

Table 4-29 – Carbon tax sensitivity variables

	CASE	GRID COSTS [€/KWH]	FC CAPITAL COSTS [€/KW]	HYDROGEN PRICE [€/KG]	DIESEL PRICE [€/L]	JET FUEL PRICE [€/L]	CARBON TAX [€/TONCO2]
Carbon tax	5	0.17	2,231.46	7.09	1.82	1.06	42.7
	6	0.17	1,775.17	4.73	1.82	1.06	42.7
	7	0.17	1,115.73	1.51	1.82	1.06	42.7

However, in paragraph 4.1 it has been assessed how cases 5 and 6 are not economically interesting and economically feasible, due to a high hydrogen price, as has been already proved in the Base case for the Regional and International scenarios, while for Renewable and Electrification the use of hydrogen is limited and it is not much influential.

Moreover in this scenario, the International scenario does not have any meaning, since the carbon tax must be applied to CO2 emissions, and in such a scenario, the emissions are equal to 0. For this reason, the results are not reported as they are completely similar to the previous sensitivity case (Grid costs increase).

For a similar reason, it is assessed a strong resemblance in energy consumption and loads. The only difference regards the size of the H2FC which is equal to 1200 kW instead of larger capacities. The main reasons rely on the lower grid costs that justify the smaller fuel cell size, being economically more convenient. To not be redundant, in this section, the electric loads and hydrogen consumption are not reported in graphs as for the previous cases, but only numeric results are illustrated. Regarding economic results, instead, they have meaning also in this case and differ from the previous one, so they are shown and discussed.

4.4.1 Renewable development

In the next table, the main consumptions are illustrated. Differently from the previous case, the smaller H2FC size allows the purchase of more electricity, it becomes a cheaper solution due to a lower electricity cost from the grid.

Table 4-30 – Consumption, Renewable scenario, Carbon tax case

AC PRIMARY LOAD (MWH)	DIESEL LOAD (KG)	GRID PURCHASES (MWH)	GRID SELL (MWH)	RENEWABLE OUTPUT (MWH)	H2FC OUTPUT (MWH)	JET FUEL (LT)	CO2 EMISSIONS (TON)
17,326.00	552,697.00	5,745.58	5,740.58	13,873.38	3,814.80	56,686,173.00	132,248.15

Regarding economic results, in the next figures, it is possible to see the slight convenience in the investment, due to the accessible hydrogen price that allows the use of hydrogen fuel cells. In the next table, instead, the main economic indices analyzed are illustrated, affirming how the investment is economically feasible, with a net advantage.

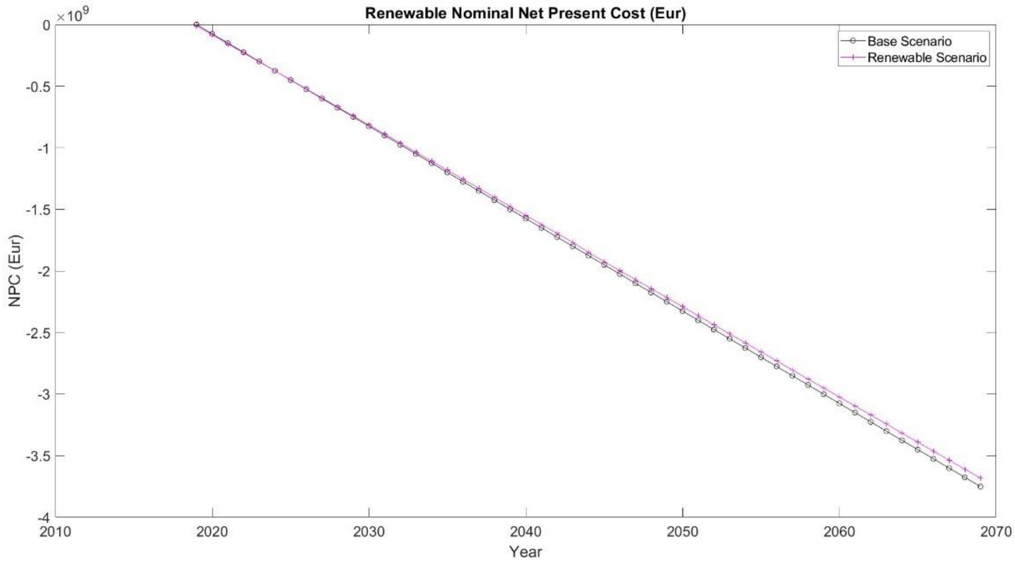


Figure 4-31 - Nominal NPC, Renewable scenario, Carbon tax case

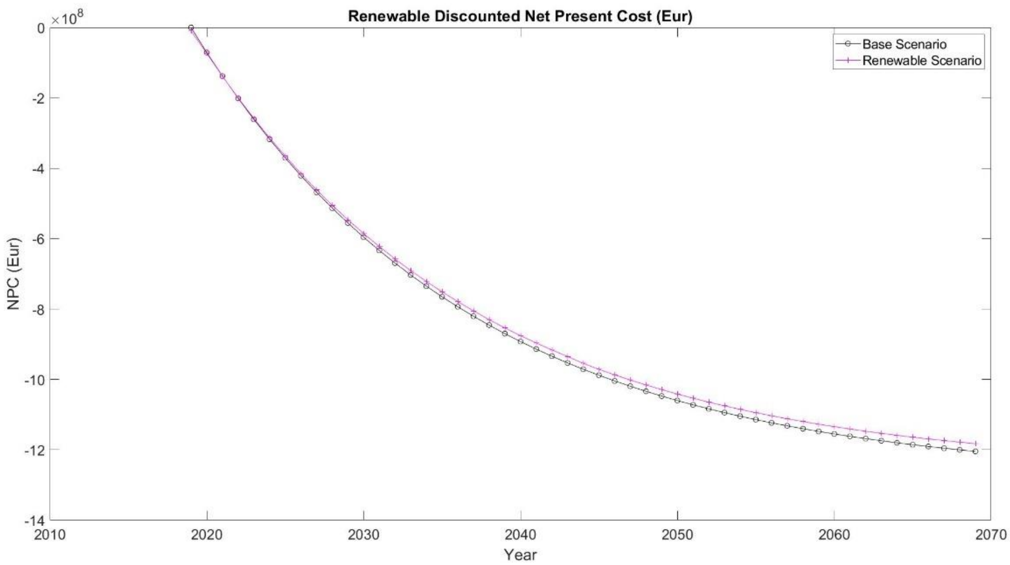


Figure 4-30 - Discounted NPC, Renewable scenario, Carbon tax case

T*able 4-31 - Economic results, Renewable scenario, Carbon tax case*

IRR	ROI	SPBT [YEARS]	DPBT [YEARS]	NPV [M€]	PI	NPV25 [M€]	PI25
18%	14%	5.2	7.0	30.63	3.05	27.91	2.78

4.4.2 Electrification development

In the present scenario, given the introduction of a carbon tax, the avoided emissions play a significant role, with a reduction by 1% of emission, and consequently of costs. However, the electricity consumption is higher than in the Renewable scenario, with a consequent increase in grid purchases.

Table 4-32 - Consumption, Electrification scenario, Carbon tax case

	AC PRIMARY LOAD (MWH)	DIESEL LOAD (KG)	GRID PURCHASES (MWH)	GRID SELL (MWH)	RENEWABLE OUTPUT (MWH)	H2FC OUTPUT (MWH)	JET FUEL (LT)	CO2 EMISSIONS (TON)
Renewable	17,326.00	552,697.00	5,745.58	5,740.58	13,873.38	3,814.80	56,686,173.00	132,248.15
Variation	+8%	-100%	+17%	-9%	0%	+5%	0%	-2%
Electrification	18,782.04	0	6,780.77	5,167.28	13,873.38	3,988.80	56,686,173.00	130,975.99

Concerning economic results the investment needed to electrify ground vehicles is repaid in about 4-5 years, resulting in very efficient venture capital. This is also due to the implementation of the carbon tax, which increases the overall net present cost of the BAU scenario, resulting in money savings due to a reduction in CO2 emissions.

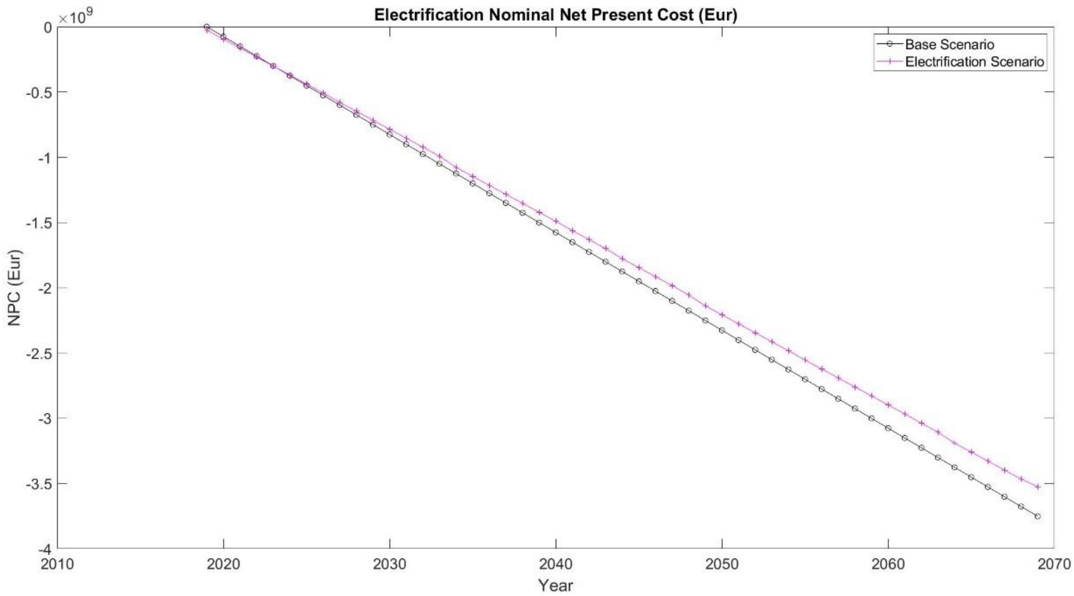


Figure 4-32 - Nominal NPC, Electrification scenario, Carbon tax case

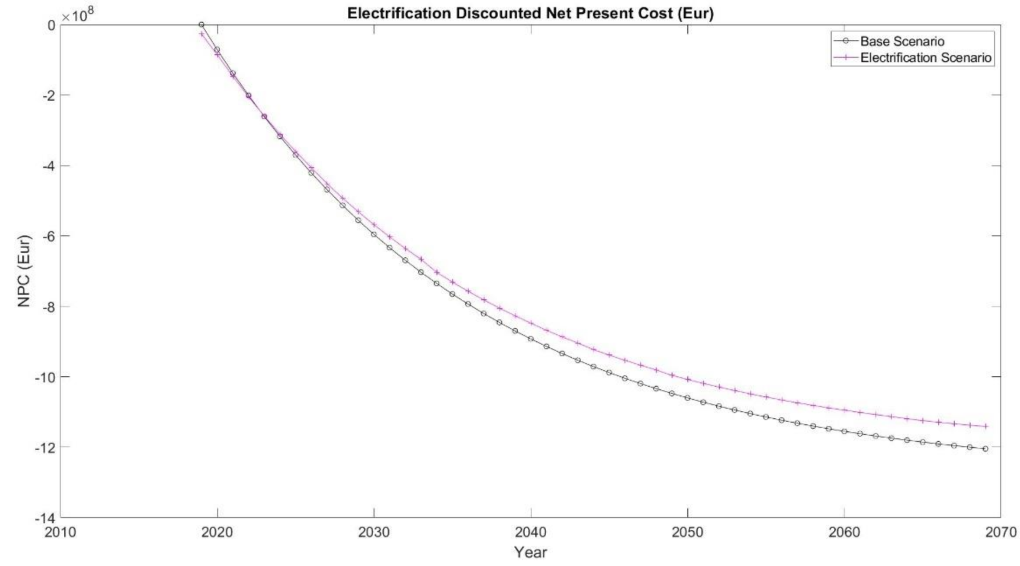


Figure 4-33 - Discounted NPC, Electrification scenario, Carbon tax case

Table 4-33 - Economic results, Electrification scenario, Carbon tax case

IRR	ROI	SPBT [YEARS]	DPBT [YEARS]	NPV [M€]	PI	NPV25 [M€]	PI25
15%	11%	5.9	8.4	60.87	2.7	56.45	2.5

4.4.3 Regional flights development

In the next table, the main energy results are illustrated, which do not differ much from the Grid cost sensitivity case. As for the other sensitivity cases, the surplus electricity is completely used in the electrolyzer to produce hydrogen, instead of selling it to the grid.

Table 4-34 - Consumption, Regional scenario, Carbon tax case

	AC PRIMARY LOAD (MWH)	GRID PURCHASES (MWH)	GRID SELL (MWH)	RENEWABLE OUTPUT (MWH)	H2FC OUTPUT (MWH)	JET FUEL (LT)	CO2 EMISSIONS (TON)	
Renewable	17,326.00	5,745.58	5,740.58	13,873.38	3,814.80	56,686,173.00	132,248.15	
Variation	+8%	+20%	-9%	0%	+5%	0%	-2%	
Electrification	18,782.04	6,780.77	5,167.28	13,873.38	3,988.80	56,686,173.00	130,975.99	
Variation (%)	0%	+0%	-100%	0%	+0%	-43%	-43%	
Regional	18,782.04	6,780.76	0	13,873.00	3,988.80	32,124,736	74,224.84	
		ELECTROLYZER INPUT (MWH)	5,437.62					
		ELECTROLYZER OPERATION (H)	3,054					

Concerning economic results, the avoided CO2 emissions represent a positive cash flow, as those are costs avoided. In conclusion, the carbon tax sensitivity case aims to assess how the use of policies is a key action that could push stakeholders to invest in green technologies, as their development could bring lower operating costs.

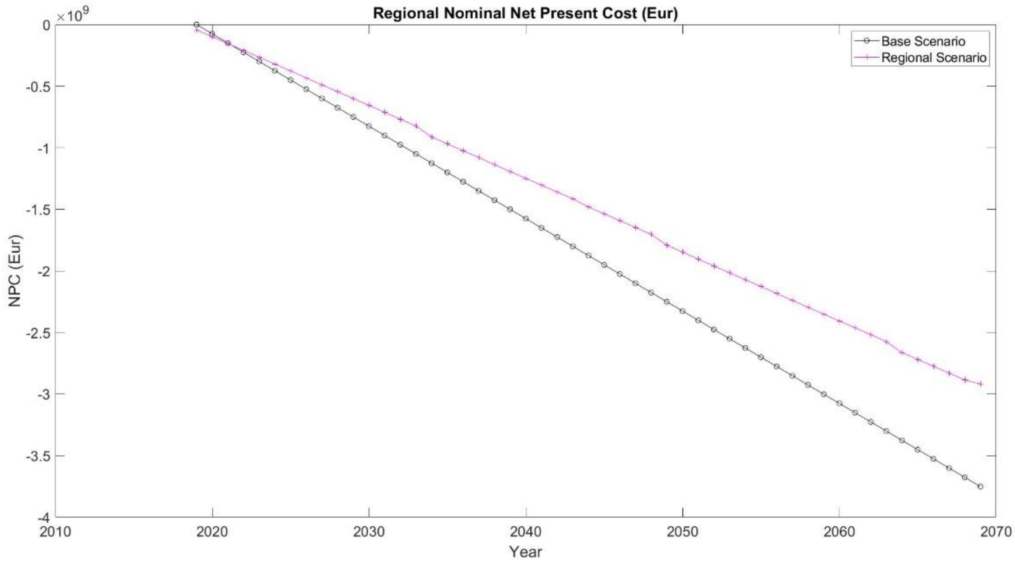


Figure 4-34 - Nominal NPC, Regional scenario, Carbon tax case

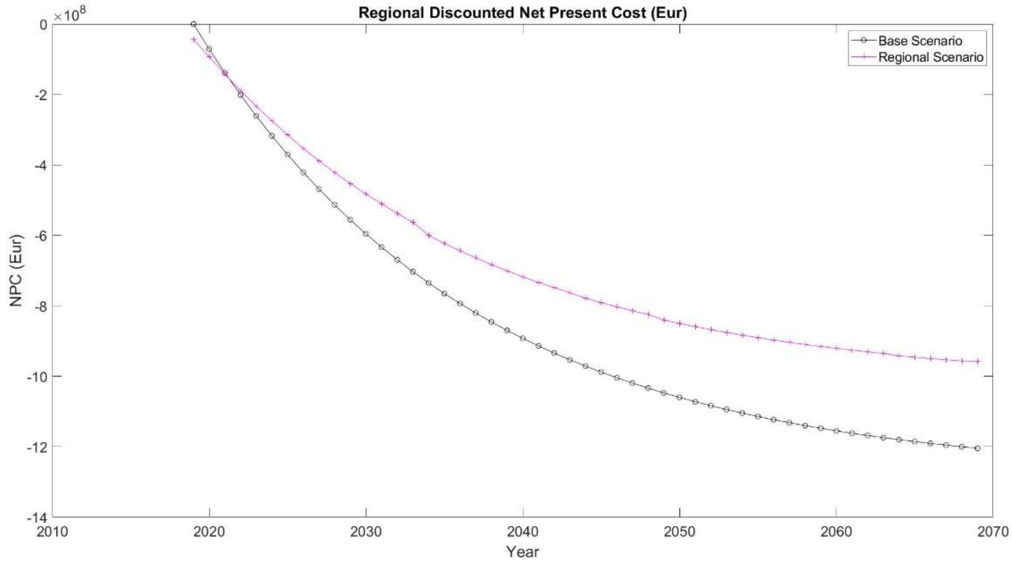


Figure 4-35 - Discounted NPC, Regional scenario, Carbon tax case

Table 4-35 - Economic results, Regional scenario, Carbon tax case

IRR	ROI	SPBT [YEARS]	DPBT [YEARS]	NPV [M€]	PI	NPV25 [M€]	PI25
88%	82%	1.1	1.2	567.97	11.54	502.06	10.21

4.5 FUEL COSTS INCREASE

In the base sensitivity case it is exploited the base parameters adopted in the analysis, resumed as follows:

Table 4-36 - Fuel costs increase sensitivity variables

	CASE	GRID COSTS [€/KWH]	FC CAPITAL COSTS [€/KW]	HYDROGEN PRICE [€/KG]	DIESEL PRICE [€/L]	JET FUEL PRICE [€/L]	CARBON TAX [€/TONCO2]
Fuel cost increase	**8**	0.17	2,231.46	7.09	2.60	1.51	0.00
	9	0.17	1,775.17	4.73	2.60	1.51	0.00
	10	0.17	1,115.73	1.51	2.60	1.51	0.00

However, in paragraph 4.1 it has been assessed how cases 8 and 9 are not economically interesting and economically feasible, due to a high hydrogen price, as has been already proved in the Base case for the Regional and International scenario, while for Renewable and Electrification the use of hydrogen is limited and it is not much influential.

Moreover in this scenario, the International scenario does not have any meaning, since the carbon tax must be applied to CO2 emissions, and in such a scenario, the emissions are equal to 0. For this reason, the results are not reported as they are similar to the previous sensitivity case (Grid costs increase).

Similarly, the increase in the price of fossils is not evaluated in the international scenario, since the aim of it is the complete elimination of fossil fuels. Said so, in the present paragraph the results are not reported as they are completely similar to the Grid costs increase sensitivity case.

For a similar reason, it is assessed a strong resemblance in energy consumption and loads. The main reasons rely on the lower grid costs that justify the smaller fuel cell size, being economically more convenient. To not be redundant, in this section, the electric loads and hydrogen consumption are not reported in graphs as for the previous cases, but only numeric results are illustrated. Regarding economic results, instead, they have meaning also in this case and differ from the previous one, so they are shown and discussed.

4.5.1 Renewable development

In the next table, the main consumption is illustrated. Similarly to the previous case, the H2FC size allows the purchase of more electricity than Grid costs increase as it becomes a cheaper solution due to a lower electricity cost from the grid.

Table 4-37 - Consumption, Renewable scenario, Fuel costs increase case

AC PRIMARY LOAD (MWH)	DIESEL LOAD (KG)	GRID PURCHASES (MWH)	GRID SELL (MWH)	RENEWABLE OUTPUT (MWH)	H2FC OUTPUT (MWH)	JET FUEL (LT)	CO2 EMISSIONS (TON)
17,326.00	552,697.00	5,745.58	5,740.09	13,873.38	3,814.80	56,686,173.00	132,248.15

Regarding economic results, in the next figures, it is possible to see the slight convenience in the investment, due to the accessible hydrogen price that allows the use of hydrogen fuel cells. In the next table, instead, the main economic indices analyzed are illustrated, affirming how the investment is economically feasible, with a net advantage.

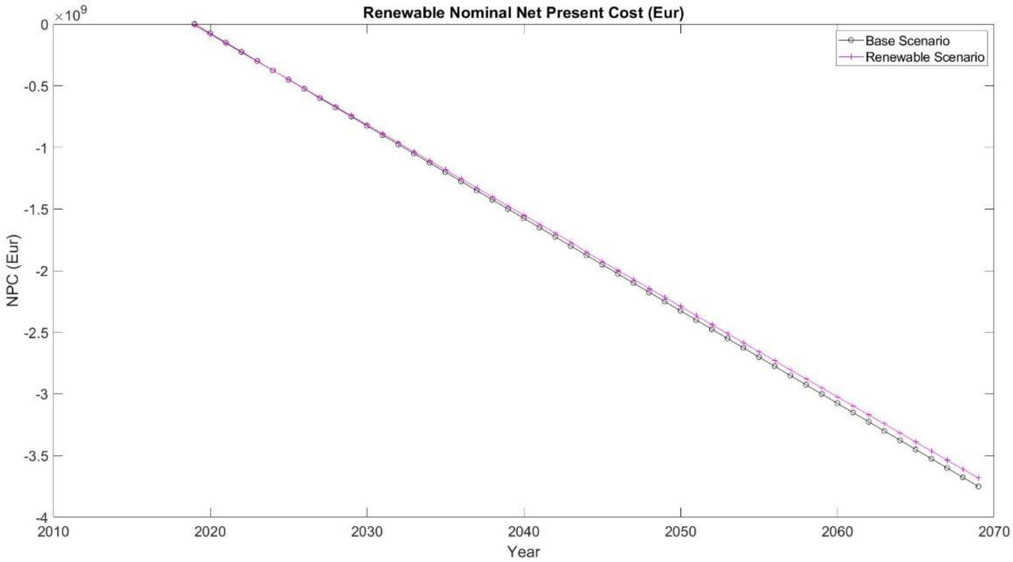


Figure 4-36 - Nominal NPC, Renewable scenario, Fuel costs increase case

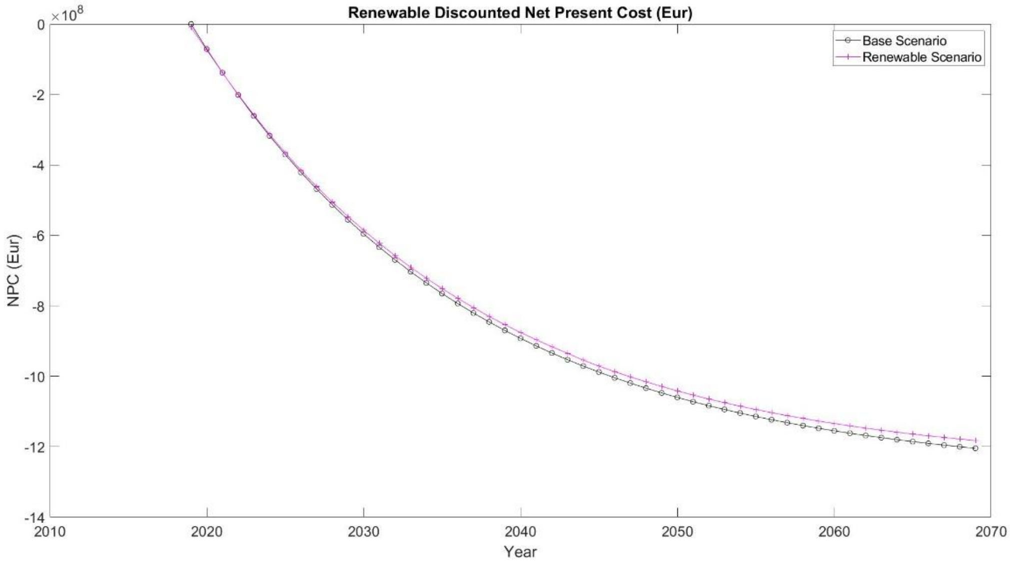


Figure 4-37 - Discounted NPC, Renewable scenario, Fuel costs increase case

Table 4-38 - Economic results, Renewable scenario, Fuel costs increase case

IRR	ROI	SPBT [YEARS]	DPBT [YEARS]	NPV [M€]	PI	NPV25 [M€]	PI25
18%	14%	5.2	7	30.63	3.05	27.91	2.78

4.5.2 Electrification development

In the present scenario, given the increase in fossil fuel costs, the complete elimination of diesel plays a significant role, as the use of electricity would be even more convenient. However, it results in an increase in electricity consumption concerning the Renewable scenario.

Table 4-39 - Consumption, Electrification scenario, Fuel costs increase case

	AC PRIMARY LOAD (MWH)	DIESEL LOAD (KG)	GRID PURCHASES (MWH)	GRID SELL (MWH)	RENEWABLE OUTPUT (MWH)	H2FC OUTPUT (MWH)	JET FUEL (LT)	CO2 EMISSIONS (TON)
Renewable	17,326.00	552,697.00	5,745.58	5,740.09	13,873.38	3,814.80	56,686,173.00	132,248.15
Variation	+8%	-100%	+17%	+6%	0%	+5%	0%	-2%
Electrification	18,782.00	0	6,781.57	5,166.87	13,873.38	3,987.60	56,686,173.00	130,977.97

Concerning economic results the investment needed to electrify ground vehicles is repaid in about 4-5 years, resulting in more efficient venture capital than the introduction of a carbon tax, meaning the continuous and natural increase in fossil fuel costs will automatically generate a sudden opportuneness in electrification. This effect will be much higher with the development of hydrogen use in airplanes.

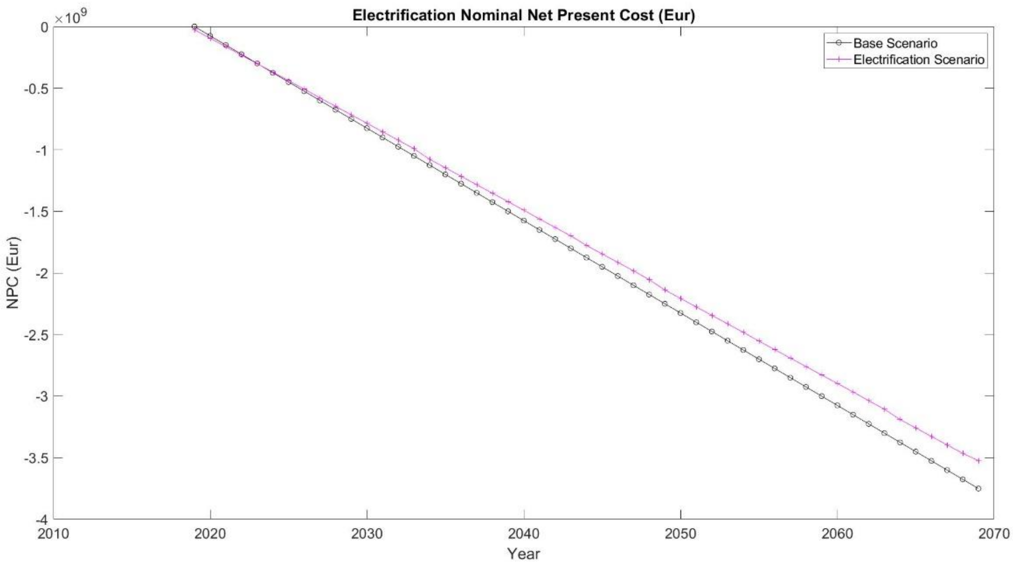


Figure 4-38 - Nominal NPC, Electrification scenario, Fuel costs increase case

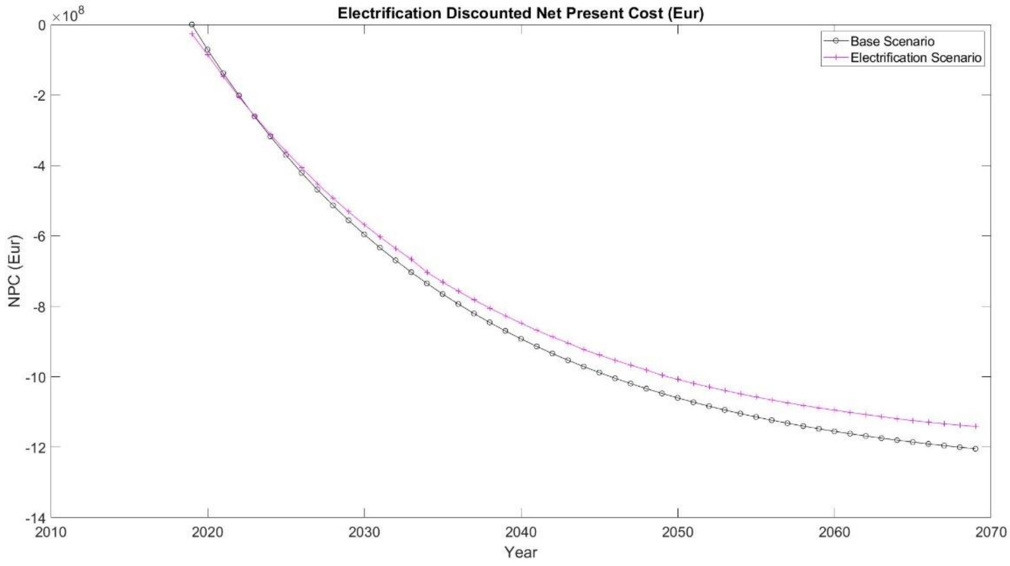


Figure 4-39 - Discounted NPC, Electrification scenario, Fuel costs increase case

Table 4-40 - Economic results, Electrification scenario, Fuel costs increase case

IRR	ROI	SPBT [YEARS]	DPBT [YEARS]	NPV [M€]	PI	NPV25 [M€]	PI25
22%	17%	4.4	5.6	77.82	3.45	71.17	3.16

4.5.3 Regional flights development

In the next table, the main energy result is illustrated, that do not differ much from the Grid cost sensitivity case. As for the other sensitivity cases, the surplus electricity is completely used in the electrolyzer to produce hydrogen, instead of selling it to the grid. As it is possible to notice in the next table, the energy results are similar to the previous sensitivity case (Carbon tax case).

Table 4-41 - Consumption, Regional scenario, Fuel costs increase case

	AC PRIMARY LOAD (MWH)	GRID PURCHASES (MWH)	GRID SELL (MWH)	RENEWABLE OUTPUT (MWH)	H2FC OUTPUT (MWH)	JET FUEL (LT)	CO2 EMISSIONS (TON)
Renewable	17,326.00	5,745.58	5,740.09	13,873.38	3,814.80	56,686,173.00	132,248.15
Variation	+8%	-24%	+6%	0%	+78%	0%	-2%
Electrification	18,782.00	6,781.57	5,166.87	13,873.38	3,987.60	56,686,173.00	130,977.97
Variation (%)	0%	+0%	-100%	0%	0%	-43%	-43%
Regional	18,782.00	6,781.57	0	13,873.00	3,987.60	32,124,736.00	74,224.84
		ELECTROLYZER INPUT (MWH)	5,437.19				
		ELECTROLYZER OPERATION (H)	3,053				

Concerning economic results, the avoided use of jet fuel represents a positive cash flow, as those are costs avoided. In conclusion, as said before, the natural increase in fuel costs will naturally lead to a shift towards green technology, as they will become cheaper with technology improvement and more economically accessible than fossils.

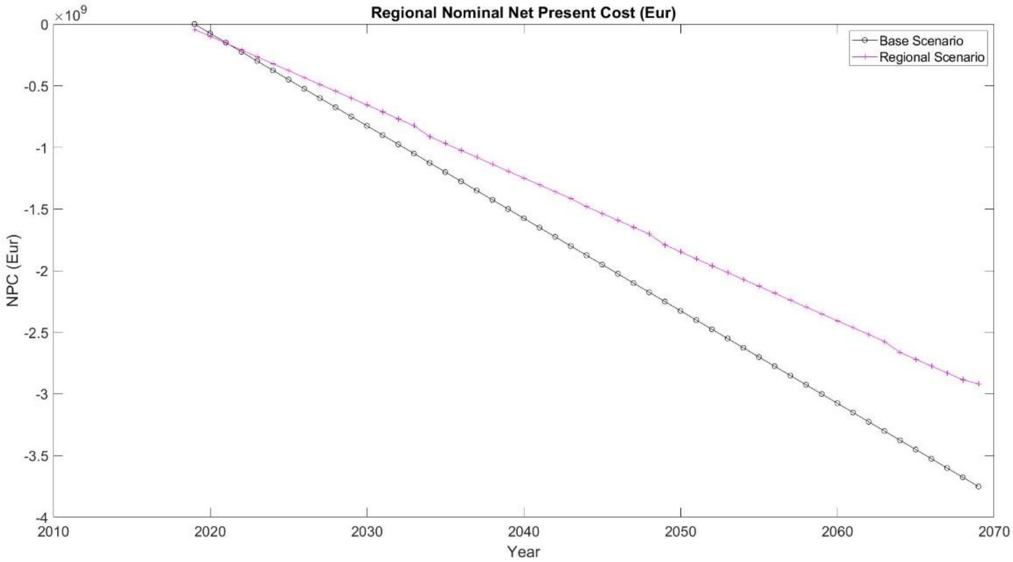


Figure 4-40 - Nominal NPC, Regional scenario, Fuel costs increase case

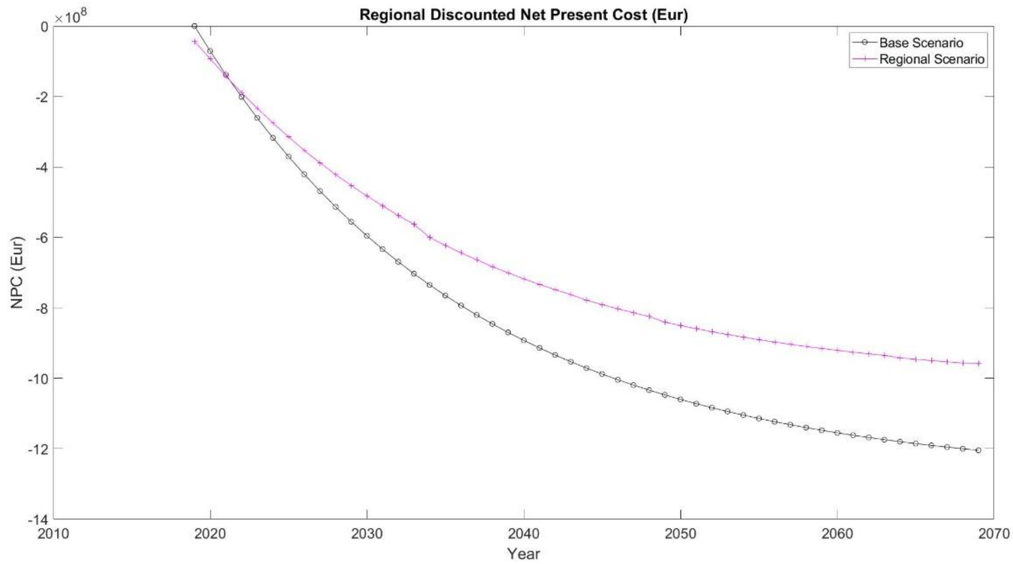


Figure 4-41 - Discounted NPC, Regional scenario, Fuel costs increase case

Table 4-42 - Economic results, Regional scenario, Fuel costs increase case

IRR	ROI	SPBT [YEARS]	DPBT [YEARS]	NPV [M€]	PI	NPV25 [M€]	PI25
131%	125%	0.8	0.8	833.03	16.93	732.26	14.88

4.6 RESULTS COMPARISONS

After having discussed the main results, and having illustrated the main energy loads, in the present section, they are deeply discussed and resumed, highlighting the main pattern of the analysis and similarities.

Moreover, economic results are compared to each other and finally discussed to analyze the best scenarios and the sensitivity cases

The main considerations regard mostly the hydrogen overall consumption, and CO2 emissions, as the aim of such work is to assess the use of hydrogen in the aviation sector and the pathway towards decarbonization. Other energy-related parameters have been analyzed but are the main constraints in the analysis, as they are inputs and can not be changed. However, even if the hydrogen consumption in airplanes is input too, it strongly affects also other industries, that will have to provide the fuel in good quantity. For this reason, the assessment of hydrogen consumption of a typical airport is a key factor to also evaluating its off-site production, the need for resources, and delivery infrastructure.

For what concerns economic results, the NPC and the NPV are the main key performance measures considered, highlighting how the overall operating, investment, and maintenance cost of the airport would change, and how much is money saved due to such changes. Other economic indices are reported such as IRR, ROI, SPBT, and DPBT, that give more information about the investment, assessing not only the overall money saving but also the correlation with the initial capital cost.

4.6.1 Energy and environmental results

Concerning the energy results, it has been assessed how the airport is highly energy consuming, however, due to its nature, the scheduled flights may be an advantage in terms of energy consumption forecast, as the electricity consumption is highly dependent on it. In the previous paragraph, different charts have been proposed, regarding the main loads (electricity, diesel, and jet fuel), in conclusion, there is a low margin of operation regarding diesel and jet fuel, as they depend on flight and bus shuttle schedules and can not be changed. Thinking about electricity, instead, there are different solutions available, one of these is the installation of renewable energies that could cover, fully or in part, the electricity needs, as exploited in the Renewable scenario. This solution allows for drastically reducing the energy purchased from the grid, and the use of a storage system is advantageous to fully exploit surplus energy, trying to reduce as much as possible dependency on the grid. In the present study, however, battery storage has not resulted economically feasible, due to higher costs than the easier solution of selling electricity to the grid. In this specific case, being the Turin airport is already committed to decarbonization, and purchasing electricity from 100% renewable energies, the development of on-site renewable production does not bring further advantages. The next step is the implementation of electric ground vehicles, able to reduce CO2 emissions by 1%. The use of such vehicles, however, needs an increase in overall electricity consumption by 12%. It means that the grid must ensure 8% more renewable energy supply, or, couple the grid with local on-site energy production, as it happens in the Renewable scenario.

In both scenarios the use of H2FC is advantageous, being an added value and contributing to reducing grid dependency, moreover, it allows the exploitation of other renewable sources that may locate elsewhere and can not be installed in the nearby of the airport, such as wind, sea, and hydro sources. Beyond that, the electrification of the airport presents huge advantages, that are more pronounced if the increase in the price of fossils is assessed, as well as if the introduction of a carbon tax is implemented, to promote green energy sources and electrification.

With the implementation of hydrogen systems in airports, its consumption may skyrocket in the following years, however, to be feasible, hydrogen prices must reduce, to be more convenient than jet fuel. Beyond economics, the use of hydrogen needs huge infrastructure development, as it could become very consuming with a huge amount of hydrogen to be delivered and produced daily.

In the next figure, it is highlighted how the development of hydrogen-based airplanes necessitate of a large quantity of hydrogen, moreover, the continuous growth of H2FC also for stationary application may result in an even more increase in hydrogen consumption, directly affecting what will be the hydrogen production industry and the renewable installation.

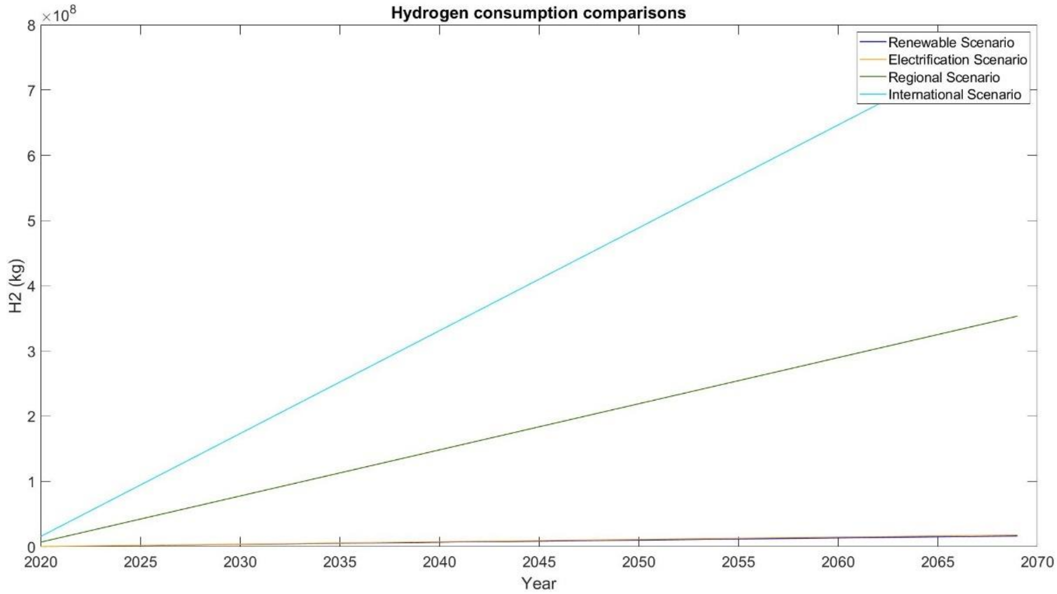


Figure 4-42 - Overall hydrogen consumption

Hydrogen consumption is common to all scenarios and sensitivities, it slightly differs due to different sizes in H2FC, however, it is a small percentage with respect to the consumption in airplanes. Finally, it is possible to assess the overall hydrogen need in Turin airport, about 800,000,000 kg in the International scenario in the whole timeline analysis, being around 15,000,000 kg/year. Said so, it is important to develop first of all a hydrogen infrastructure that is able to supply such a load, then it is necessary to expand renewable generation in order to be able to produce such amount of hydrogen, considering also that the continuous development of other hydrogen-based technology may concur with this field.

Concerning environmental results, it is clear that the use of greener resources helps to reduce CO2 emissions, being the aviation sector is highly polluting, it is necessary to adopt as soon as possible new solutions. The use of green hydrogen could be an opportunity to reduce not only GHGs, as the impact is limited due to the emission of water vapor, but also other harmful pollutants, which are not studied in the present work. In the next figure, it is illustrated the cumulative CO2 emissions in the airport. The investments analyzed in the present study are able to reduce the emission by a huge amount, in particular, the use of electric ground vehicles avoids the release of about 1,270 tons of CO2 yearly. Even greater is the development of hydrogen-base airplanes at the National level, helping in reducing about 66,500 tons of CO2 every year. The implementation of short-range hydrogen aircraft would certainly be a milestone toward decarbonization. The use of hydrogen-based airplanes at the international level would completely erase any carbon emissions. As a final statement, it is important to cite that water vapor emitted by hydrogen turbines is a greenhouse gas, with a lower impact and lower life than CO2, so the complete replacement of jet fuel with hydrogen would only help the reduction of greenhouse gases, but not remove it.

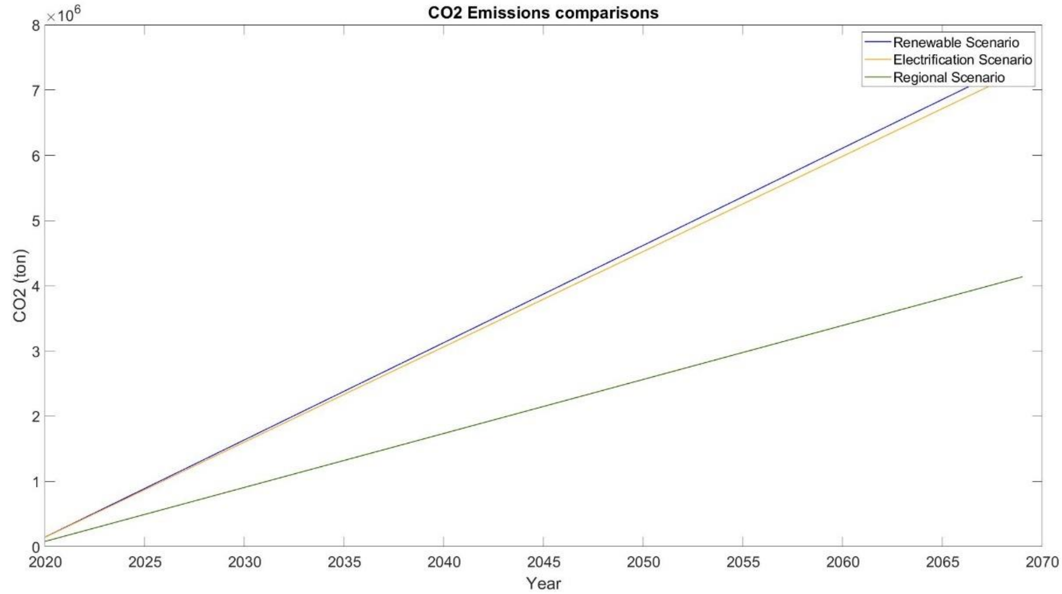


Figure 4-43 - Overall CO2 emissions

4.6.2 Economic results

The main economic results are the key of the present work, aimed not only to confirm the environmental and energy feasibility of green sources implementation in aviation but also to assess the economic practicability of such developments. As previously illustrated, the economic viability of the scenarios is briefly discussed, in the present paragraph they reported and discussed, highlighting the main outcomes.

In general, the use of green resources and the implementation of innovative technologies is a fruitful opportunity, as the costs of such technologies are rapidly decreasing, despite the boost in fossil costs. Lately, the continuous change in the shape of airports allows the use of solar panels to reduce electricity purchase from the grid, allowing a higher independence and lower emission, more than a 100% renewable on-site production. Other technologies may be available in the airport framework but are not discussed in this study due to their high design difficulties and lack of data, given that the airport location must be suitable to address them.

Results have shown a discrete Net Present Value in all cases, in the order of 15 million euros, with a payback time in the order of 1-8 years, depending on the sensitivity case and the index considered (standard or discounted). With further implementation towards green technologies, the use of electric ground vehicles allows increasing the NPV by 3-4 times in the best cases, while in case fuel costs may increase the high share of jet fuel hide the application of electric vehicles, resulting in a lower NPV than other cases, but still convenient. Regarding, instead the use of hydrogen, its actual high price makes it a prohibitive technology to apply in airplanes, in all cases. To start being accessible, the price of hydrogen should fall at least in the order of 4-5 €/kg and have a simultaneous increase in fossil prices. On the other hand, the target of 1.51 €/kg is more than sufficient to allow wide use of it in aviation, resulting in more convenience than fossil, in any case.

Table 4-43 - Scenarios economic results, Base case

			RENEWABLE	ELECTRIFICATION	REGIONAL	INTERNATIONAL	BAU
BASE	1	IRR	18%	15%	<0	<0	
		ROI	15%	11%	<0	<0	
		SPbT (y)	5.37	6.20	<0	<0	
		DPbT (y)	7.29	8.90	<0	<0	
		NPV (€)	27,574,355.03	56,949,311.30	<0	<0	
		IP	3.17	2.69	<0	<0	
		NPC (€)	814,702,993.45	810,336,097.18	1,119,051,872.07	1,486,116,482.98	824,876,060.48

Table 4-44 - Scenarios economic results, Grid costs increase case

			RENEWABLE	ELECTRIFICATION	REGIONAL	INTERNATIONAL	BAU
GRID COSTS INCREASE	2	IRR	20%	15%	<0	<0	
		ROI	16%	11%	<0	<0	
		SPbT (y)	4.95	6.00	<0	<0	
		DPbT (y)	6.54	8.49	<0	<0	
		NPV (€)	29,301,945.74	58,390,562.73	<0	<0	
		IP	3.37	2.75	<0	<0	
		NPC (€)	816,872,158.32	812,791,601.33	1,121,507,364.26	1,488,571,987.14	828,772,816.07
	3	IRR	20%	15%	<0	<0	
		ROI	16%	11%	<0	<0	
		SPbT (y)	4.95	6.00	<0	<0	
		DPbT (y)	6.54	8.49	<0	<0	
		NPV (€)	29,301,945.74	58,390,562.73	<0	<0	
		IP	3.37	2.75	<0	<0	
		NPC (€)	816,872,158.32	812,791,601.33	928,858,046.29	1,040,279,283.38	828,772,816.07
	4	IRR	19%	15%	44%	77%	
		ROI	15%	11%	37%	70%	
		SPbT (y)	4.73	5.69	2.28	1.30	
		DPbT (y)	6.17	7.89	2.61	1.43	
		NPV (€)	34,730,586.21	64,061,522.31	245,132,021.31	499,808,309.59	
		IP	3.24	2.76	6.05	10.16	
		NPC (€)	815,460,145.86	811,137,269.75	664,737,496.76	427,357,176.48	828,772,816.07

Table 4-45 - Scenarios economic results, Carbon tax case

			RENEWABLE	ELECTRIFICATION	REGIONAL	INTERNATIONAL	BAU
CARBON TAX	5	IRR	18%	15%	<0	<0	
		ROI	15%	11%	<0	<0	
		SPbT (y)	5.37	6.10	<0	<0	
		DPbT (y)	7.29	8.69	<0	<0	
		NPV (€)	27,574,355.03	57,654,112.80	<0	<0	
		IP	3.17	2.72	<0	<0	
		NPC (€)	885,082,880.63	880,011,182.86	1,158,537,579.32	1,486,116,482.98	895,255,947.66
	6	IRR	18%	15%	<0	<0	
		ROI	15%	11%	<0	<0	
		SPbT (y)	5.37	6.10	<0	<0	
		DPbT (y)	7.29	8.69	<0	<0	
		NPV (€)	27,574,355.03	57,654,112.80	<0	<0	
		IP	3.17	2.72	<0	<0	
		NPC (€)	885,082,880.63	880,011,182.86	965,888,249.38	1,037,823,779.23	895,255,947.66
	7	IRR	18%	15%	49%	88%	
		ROI	14%	11%	43%	82%	
		SPbT (y)	5.22	5.94	2.02	1.14	
		DPbT (y)	7.03	8.38	2.29	1.24	
		NPV (€)	30,630,571.76	60,873,914.22	273,812,491.31	567,971,661.25	
		IP	3.05	2.70	6.75	11.54	
		NPC (€)	884,704,415.90	879,469,133.44	702,540,158.35	425,676,956.41	895,255,947.66

Table 4-46 - Scenarios economic results, Fuel costs increase case

			RENEWABLE	ELECTRIFICATION	REGIONAL	INTERNATIONAL	BAU
FUEL COSTS INCREASE	8	IRR	18%	22%	0%	<0	
		ROI	15%	17%	0%	<0	
		SPbT (y)	5.37	4.38	0.00	<0	
		DPbT (y)	7.29	5.61	0.00	<0	
		NPV (€)	27,574,367.49	74,603,943.69	0.00	<0	
		IP	3.17	3.52	0.00	<0	
		NPC (€)	1,150,137,258.99	1,128,115,742.79	1,299,141,416.09	1,910,824,038.00	1,548,516,430.00
	9	IRR	18%	22%	21%	31%	
		ROI	15%	17%	16%	26%	
		SPbT (y)	5.37	4.38	4.53	3.15	
		DPbT (y)	7.29	5.61	5.84	3.78	
		NPV (€)	27,574,367.49	74,603,943.69	132,237,202.33	218,201,477.25	
		IP	3.17	3.52	3.37	4.56	
		NPC (€)	1,150,137,258.99	1,128,115,742.79	1,106,492,086.15	1,037,823,779.23	1,160,310,338.48
	10	IRR	18%	22%	74%	131%	
		ROI	14%	17%	68%	125%	
		SPbT (y)	5.22	4.37	1.35	0.76	
		DPbT (y)	7.03	5.59	1.48	0.82	
		NPV (€)	30,630,571.76	77,820,583.31	398,260,207.95	833,026,052.07	
		IP	3.05	3.45	9.82	16.93	
		NPC (€)	1,149,758,806.72	1,127,576,855.17	843,146,832.53	425,676,956.41	1,160,310,338.48

In the next figure, the sensitivity variables are illustrated, with a focus on the Net Present Cost of the whole scenario. The aim is to assess which parameter is the one that has the most effect on the system. The figure represents all scenarios, each one evaluated in a specific case, Base case, Grid costs increase, Carbon tax, and Fuel costs increase, where the latter three it is evaluated the progressive reduction in hydrogen price and PEMFC costs, described by a different shade.

How it is possible to notice, the Base case, which represents a picture of the actual situation, in terms of variables and the not architecture of the system, does not change much from BAU to Renewable and Electrification, on the other hand, it skyrockets on Regional and International scenario, due to the high costs of hydrogen.

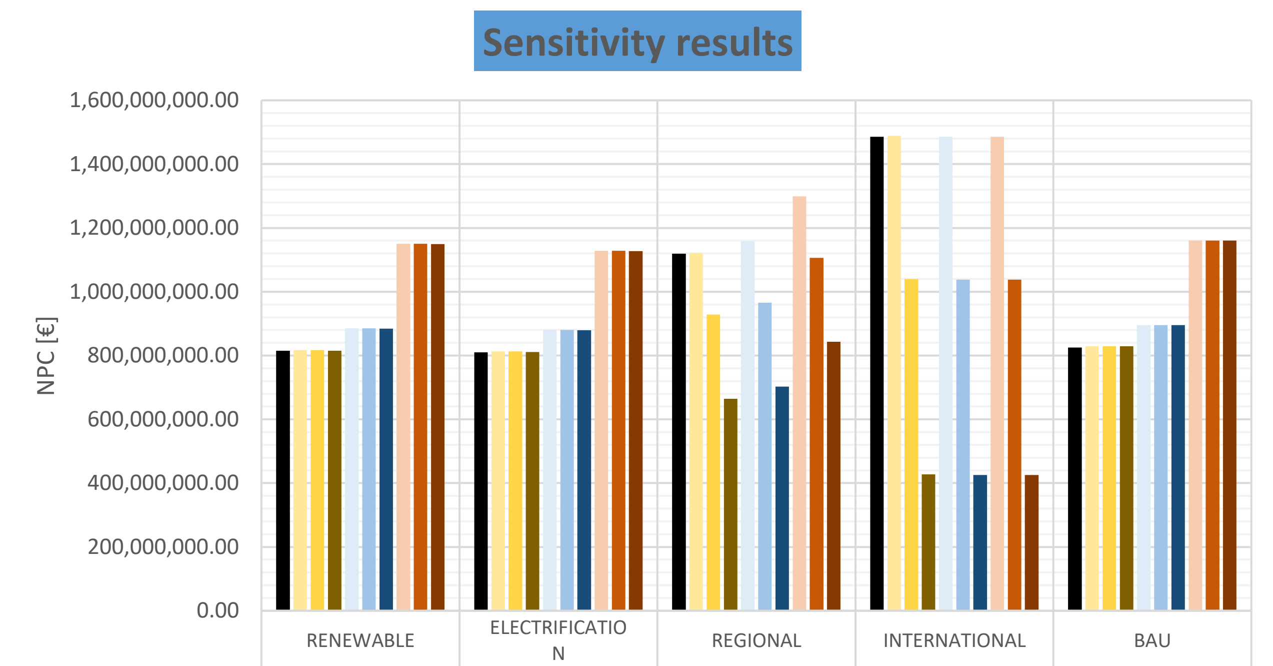
Concerning Grid costs increase, the trend is similar, with a slight increase in NPC in BAU, Renewable, and Electrification scenarios, while in Regional and International, the difference is due to the decrease in hydrogen price.

On the other end, the Carbon tax case affects the BAU, Renewable, and Electrification, while the NPC in Regional increases a bit. In the International scenario, the Carbon tax case has little meaning, since there are no carbon emissions.

Among all parameters, the increase in fossil fuel prices has a high impact on all scenarios, except International. Indeed, it results in the highest NPC in BAU, Renewable, and Electrification, while in Regional the decrease in hydrogen price balances out the Fuel costs increase case. However, at the parity of hydrogen price, it remains the highest. As for the Carbon tax case, the International scenario has little meaning, as no CO_2 is emitted in such a setting.

In the end, it is possible to assess the behavior of hydrogen price and PEMFC costs, following little impact in BAU, Regional, and Electrification scenarios, but it is highly influencing in Regional and International, determining whether the investment is economically convenient or not. Indeed the NPC shift from the highest three to the lowest among all cases.

In conclusion, it is possible to assess the development of hydrogen technology in aviation is strictly correlated by economic parameters, mostly coming from a lack of system infrastructure, and not well-assessed expertise in such field and a not winner technology as it has happened for other structures, as PV, On-shore wind turbines, hydroelectric systems. However, the implementation of other solutions that may occur as foundations for future development plays a key role. Indeed, the installation of solar panels (Renewable scenario), or the use of electric ground vehicles (Electrification scenario) are not strongly affected by sensitivity variables, resulting in any case a profitable investment.



	RENEWABLE	ELECTRIFICATION	REGIONAL	INTERNATIONAL	BAU
Base 1	814,702,993.45	810,336,097.18	1,119,051,872.07	1,486,116,482.98	824,876,060.48
Grid costs increase 2	816,872,158.32	812,791,601.33	1,121,507,364.26	1,488,571,987.14	828,772,816.07
Grid costs increase 3	816,872,158.32	812,791,601.33	928,858,046.29	1,040,279,283.38	828,772,816.07
Grid costs increase 4	815,460,145.86	811,137,269.75	664,737,496.76	427,357,176.48	828,772,816.07
Carbon tax 5	885,082,880.63	880,011,182.86	1,158,537,579.32	1,486,116,482.98	895,255,947.66
Carbon tax 6	885,082,880.63	880,011,182.86	965,888,249.38	1,037,823,779.23	895,255,947.66
Carbon tax 7	884,704,415.90	879,469,133.44	702,540,158.35	425,676,956.41	895,255,947.66
Fuel costs increase 8	1,150,137,258.99	1,128,115,742.79	1,299,141,416.09	1,486,116,482.98	1,160,310,338.48
Fuel costs increase 9	1,150,137,258.99	1,128,115,742.79	1,106,492,086.15	1,037,823,779.23	1,160,310,338.48
Fuel costs increase 10	1,149,758,806.72	1,127,576,855.17	843,146,832.53	425,676,956.41	1,160,310,338.48

Figure 4-44 - Sensitivity results

The same concept is stressed in the next two tables, where it is resumed the variation in NPC between sensitivity variables with respect to the Base case sensitivity (Table 4-47) to compare the different possible future progress with the actual situation, and it has been analyzed scenarios with respect to BAU (Table 4-48), to evaluate how the different scenario act in all cases with respect to the current situation.

The green cells represent the lowest NPC, while the red one symbolizes the highest NPC. In the middle, there is a trade-off situation, that could be convenient (<0%) or not (>0%).

Table 4-47- Sensitivity cases NPC variation

		RENEWABLE	ELECTRIFICATION	REGIONAL	INTERNATIONAL	BAU
Base	**1**	0.00%	0.00%	0.00%	0.00%	0.00%
Grid costs increase	**2**	0.27%	0.30%	0.22%	0.17%	0.47%
	3	0.27%	0.30%	-17.00%	-30.00%	0.47%
	4	0.09%	0.10%	-40.60%	-71.24%	0.47%
Carbon tax	**5**	8.64%	8.60%	3.53%	0.00%	8.53%
	6	8.64%	8.60%	-13.69%	-30.17%	8.53%
	7	8.59%	8.53%	-37.22%	-71.36%	8.53%
Fuel costs increase	**8**	41.17%	39.22%	16.09%	0.00%	40.66%
	9	41.17%	39.22%	-1.12%	-30.17%	40.66%
	10	41.13%	39.15%	-24.66%	-71.36%	40.66%

Table 4-48 - Scenarios NPC variation

		RENEWABLE	ELECTRIFICATION	REGIONAL	INTERNATIONAL	BAU
Base	**1**	-1.23%	-1.76%	35.66%	80.16%	0.00%
Grid costs increase	**2**	-1.44%	-1.93%	35.32%	79.61%	0.00%
	3	-1.44%	-1.93%	12.08%	25.52%	0.00%
	4	-1.61%	-2.13%	-19.79%	-48.43%	0.00%
Carbon tax	**5**	-1.14%	-1.70%	29.41%	66.00%	0.00%
	6	-1.14%	-1.70%	7.89%	15.92%	0.00%
	7	-1.18%	-1.76%	-21.53%	-52.45%	0.00%
Fuel costs increase	**8**	-0.88%	-2.77%	11.96%	28.08%	0.00%
	9	-0.88%	-2.77%	-4.64%	-10.56%	0.00%
	10	-0.91%	-2.82%	-27.33%	-63.31%	0.00%

As it is possible to notice in the first table, the continuous increase in prices (Grid, and fuel), and the introduction of a Carbon tax will generate a growth in operating costs for modern airports. The use of Renewable and Electric vehicles has a minor impact on such increase, while the more we go towards the use of hydrogen, the more the increase in such parameters is less affecting the operation of the airport, on the contrary, the Regional and International scenarios are a very interesting solution to counter the continuous increase in costs, resulting in a reduction in NPC in most cases.

Even more important, are the results illustrated in the second table, where the NPC of each scenario is compared with the BAU one. The main outcome that could be noticed is the economic convenience of Renewable and Electrification scenarios, in all cases, confirming what was discussed in the previous chapters, so that the introduction of green technologies in airports would be beneficial in all cases. Regarding the use of hydrogen in airplanes, instead, it strongly depends on its price, being, so far, too much high. However, the continuous decrease in prices, accompanied by continued technology developments, makes it more than a valid alternative to fossil fuels, resulting in high money savings in all cases where hydrogen has accessible prices (Cases 2, 5, and 10).

5 CONCLUSIONS AND FURTHER DEVELOPMENTS

5.1 CONCLUSIONS

The present project aimed to evaluate future hydrogen consumption in airports and which could be the possible solution to address such radical change in aviation, evaluating not only the technological layout but also economic feasibility.

In general, it is assessed how the use of hydrogen could be a potential solution, once overcome all the issues correlated to it are. Different layouts have been proposed, mainly taking advantage of renewables and hydrogen conversion technologies such as fuel cells and electrolyzers, in the end, the use of them could not be an immediate solution as costs are still not competitive with other systems, rather, starting to develop already well assessed green technologies to beginning reduce emissions and promoting grid and fossils dependency, such as the implementation of renewables of all kinds, depending on the location, and electrification of ground vehicles. Due to the well-established technologies acting in this sense, the profitability is confirmed, with further research to bring on in specific cases, to exploit all opportunities.

In conclusion, the use of hydrogen in aviation will happen in the next future, with a small investment to happen step by step, to reach complete hydrogenation in the aviation sector. There are, however, plenty of barriers to overcome in this field, and while green-hydrogen prices are still prohibitive, the option of using blue hydrogen at the beginning may be a solution to promote hydrogen use in aviation, waiting for the green-hydrogen prices to become accessible and competitive with fossil fuels. Meanwhile, the beginning of a new generation of airplanes may take place in the next years, with the need for initial investments in airports, to start to smooth the way towards the use of green hydrogen. Said so, the foundation may be represented by the Renewable and Electrification scenario analyzed in the present work, with further developments to happen to build on a Regional scenario, maybe starting using blue hydrogen to increase economic convenience, as for this scenario it is needed a hydrogen price to be below 4 €/kg, and later on with a profound expansion, also in other fields, and more expertise of hydrogen use, a shift towards whole hydrogen-based aviation (International scenario)

5.2 FURTHER DEVELOPMENTS

The current project is part of a wide and discussed ongoing research regarding hydrogen use in the energy sector. Plenty are the topics argued in literature and so much are the solutions proposed. Due to an infinite number of variables, it is necessary to highlight the main flaw encountered during the development of such work, to help future researchers and colleagues to improve it:

- The use of a battery to reduce dependency on the grid is strongly recommended, as it could help, in some cases, to reach full independence. In this study this option has not been fully exploited due to the high costs of batteries, preferring to evaluate grid selling opportunities. A better market investigation may help improve such aspects
- Connecting with the previous point, an Intelligent Energy Management System could be employed to improve efficiency and obtain better results.
- Data concerning loads are an estimation of the airport under study, approximated to calculate approximately which could be a good architecture of the airport, facing hydrogen development. Better data could be collected, with deeper research and more time at disposition.

- Emissions considered in this study regard only direct emissions. A Life Cycle Analysis could be assessed to better evaluate carbon emissions, also in the International scenario.
- Following the previous point, the emissions considered are related only to CO2. A deeper analysis of other pollutants may provide better environmental benefits results.
- As well, in this study, the environmental impact coming from water vapor produced by hydrogen airplanes has not been studied. In this regard, could be necessary a richer evaluation of curtails produced by turbines.
- Talking about electrification, in this work the thermal load has not been evaluated. In this sense, the airport could not be considered fully decarbonized and integration of the present work concerning also the heating and cooling aspect could be an interesting study.
- Simplification regarding hydrogen conversion from jet fuel has been done considering a simple mass conversion and use in similar turbines. However, it is possible that more efficient turbines are developed or that short-range routes are covered by fuel-cell-based airplanes, with a consequent lower hydrogen consumption.

APPENDIX A – TABLE CONVERSION

Table 0-1 - TABLE CONVERSION

Value	Unit of measure	Reference	Description
4.32	KWh/passenger	[76]	Specific electricity consumption of the airport, multiplied by 2 to consider both departing and arriving passengers
0.24	L/km	[82]	Average diesel consumption of buses
0.85	Kg/L	[112]	Diesel density
1.5	Gallon/hour	[84]	Specific consumption of GSE
3.85	L/gallon	[113]	Unit of conversion between liter and gallon
0.945	$/€	[114]	Market conversion between dollar and euro 27/06 2022
68.86 98.29	$/barrel	[90]	Projection cost of crude oil in 2022 and 2030
178.2	$/bbl	[91]	Cost of Jet fuel
0.0063	L/bbl	[115]	Conversion between liter and oil barrel
0.762	Kg/L	[37]	Jet fuel density
43.54	MJ/kg	[116]	Jet fuel energy content
3.6	MJ/kWh		Conversion from MJ to kWh
0.35	-	[106]	Gravimetric conversion between Jet fuel and Hydrogen
10.19	Kg/gallon	[120]	Diesel CO2 emission factor

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