Economic and environmental sustainability of liquid hydrogen fuel for hypersonic transportation systems

Economic and Environmental Sustainability of Liquid Hydrogen Fuel for Hypersonic Transportation Systems

Roberta Fusaro[1], Valeria Vercella[1], Davide Ferretto[1], Nicole Viola[1]

Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 – Turin (Italy), roberta.fusaro@polito.it, nicole.viola@polito.it, davide.ferretto@polito.it, valeria.vercella@polito.it

and Johan Steelant[2]

European Space Agency - ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, (Netherlands), johan.steelant@esa.int

Based on recent research activities, the cost of the propellant may represent up to the 90% of the Direct Operating Cost for a hypersonic vehicle. Therefore, it can be considered the most relevant cost item of the overall Life Cycle Cost. In this context, the paper focuses on the estimation of the cost of Liquid Hydrogen, one of the most promising fuels for high-speed applications, considering its specific energy content. In particular, a methodology is here presented to guide engineers through the evaluation of the impact of the LH_2 price on Direct Operating Cost and then onto the overall Life Cycle Cost for a long-haul point-to-point transportation system. Starting from an overview of the current H_2 productive scenarios, future possible technological improvements allowing an increment of the production rate and a reduction of the related socio-economic impact are described. Then, a detailed Cost Estimation model is presented for the so called "green" hydrogen. Eventually, the developed cost model is applied to the LAPCAT A2 and LAPCAT MR2.4 vehicles and mission concepts, demonstrating that in a future scenario (2050), whether the LH_2 cost can be lowered down up to 2 €/kg. With this fuel price, the share of fuel cost onto Direct Operating cost can be reduced up to 70%.

Keywords: LH_2 fuel, Direct Operating Costs Estimation, LAPCAT A2, LAPCAT MR2.4

Nomenclature

CCUS – Carbon Capture Utilization and Storage
CAPEX– Capital Cost Expenditures
CER – Cost Estimation Relationship
CFRP – Carbon Fibre Reinforced Polymer
CH_4 – Methane
CMC – Ceramic Matrix Composites
CO – Carbon monoxide
CO_2 – Carbon dioxide
CPI– Consumer Price Index
DOC – Direct Operating Cost
ESA – European Space Agency
ESFC – Energy Specific Fuel Consumption
EU – European Union
EEX– Electricity Expenditures
FY – Fiscal Year
GTOW – Gross Take-Off Weight
IEA – International Energy Agency
H_2O – Water
IOC – Indirect Operating Cost
LCC – Life Cycle Cost
LCOH – Levelized Cost of Hydrogen
LH_2 – Liquid Hydrogen
LHV – Lower Heating Value
PEM– Proton Exchange Membrane
NO_x – Nitrogen oxides
OPEX– Operational Expenditures
RDTE – Research, Development, Test and Evaluation
REL – Reaction Engines Limited
ROM – Rough Order of Magnitude
SSTO – Single Stage to Orbit
SOEC – Solid oxide electrolysis cells

1. Introduction

As stated by S. Yigit et al., Hydrogen is a versatile energy carrier which can be produced in various ways from many sources. Its unique attributes such as global availability, safety, high energy content per unit mass and low pollution indexes make it an ideal fuel. [1]

Hydrogen has a long tradition in space travels both as a propellant and an on-board power source for launchers, where propulsion and power supply systems have to satisfy strict requirements in terms of robustness, performance and safety. Despite cryogenic Liquid Hydrogen (LH_2) being used as a rocket propellant since the 1950s, very few cost-estimating models have been developed in order to predict fuel cost during conceptual and preliminary design phases. The few existing and available estimations date back to the 70s, following the energy crisis of 1973. Numerous engineers and scientists developed estimation models to assess the viability of LH_2 as aviation fuel. In particular, for the vehicles and mission concepts under development, the life cycle costs, capital condition, energy resource utilization, fuel production, airport storage, distribution facilities as well as environmental compatibility were assessed [2]. This is further important to economically assess the business opportunity high-speed travel is likely to create, as e.g. done in the study by Airbus and ESA [3]. In ATLLAS I/II [4][5] and LAPCAT I/II [6][7], various civil high-speed transportation concepts were worked out covering a wide range of Mach numbers (3 to 8), various fuels (kerosene, methane, hydrogen) and trajectories (transatlantic e.g. London-New York up to antipodal e.g. Brussel-Sydney). Assessing these various concepts, Steelant [8] derived some interesting trends related to high-speed transport vehicles. With respect to the used fuel, he states: '*aircraft covering a same range have a 2 times lower GTOW if fuelled with hydrogen instead of hydrocarbons. Aircraft with the same GTOW have a range which is about 1.75 times larger with hydrogen in contrast to hydrocarbons'*.

As such LH_2 is almost the main enabling technology for hypersonic travel.

Nowadays, according to the latest results of research activities in the field of high-speed transportation, fuel cost represents the highest contribution to Direct Operating Cost (DOC). In particular, in the case of hypersonic point-to-point transportation systems exploiting LH_2, fuel cost may represent up to the 90% of the DOC as shown in [9]. However, thanks to its specific calorific energy that is higher than for hydrocarbon fuels, the exploitation of hydrogen fuel appears to be mandatory for the future spaceplanes. Moreover, an in-depth literature review revealed that the LH_2 cost is mainly influenced by several factors such as the geographical context in which it is produced, its daily production rate and the production process. Indeed, there is a clear difference between United States (US) and European Union (EU) scenarios, mainly due to the cost of the energy used to transform the hydrogen. According to TransCost [10], the LH_2 produced in Europe can be twice as expensive as in the US due to different electrical energy costs. In addition, the amount of LH_2 produced per day is strongly affecting the LH_2 costs as clearly stated in different literature sources [11][12]. Moreover, it is important to notice that the final product cost is given by the sum of all the costs incurred during the phases of the production process, mainly the gaseous hydrogen production and the subsequent liquefaction.

Thus, in Section 2, after a brief summary of the main advantages and criticalities of the exploitation of LH_2 for long-duration aerospace missions (such as commercial hypersonic long-haul routes), an overview of the current and future viable LH_2 production technologies is presented together with a preliminary assessment of the socio-economic impact of each of them. Following this overview, technologies for electrolysis are investigated in detail in Section 3 proposing a cost model for the production of H_2 via electrolysis and the consequent liquefaction process, to make it available for aviation purposes. Then, in Section 4, the main results of the application of the developed Cost Estimation Model to the hypersonic vehicles LAPCAT A2 and LAPCAT MR2.4 are presented and discussed. Finally, Section 5 summarizes the major results of this work underlining the urgent need of improvements for the LH_2 productive scenarios for the socio-economical sustainability of the upcoming spaceplanes.

2. Overview of eco-environmental aspects of Hydrogen exploitation in the aerospace sector

2.1 Hydrogen as a valuable propellant for aerospace applications

Even if hydrogen is the most abundant element in the universe, on Earth, it is mostly found back in one or another molecular form, e.g. water and hydrocarbons, and therefore it must be extracted for its various uses. Hydrogen's very high energy content per unit mass makes it very appealing and competitive in aerospace. However, the hydrogen high gravimetric energy (about 120 MJ/kg) needs to be traded off with respect to its low volumetric energy density (lower than 10 MJ/l) [13]. In addition, the exploitation of hydrogen as propellant can allow a complete decarbonization of the flight, knowing that a complete environmental sustainability can only be guaranteed looking at the entire lifecycle of hydrogen, including the production phase. When exploiting renewable resources, the environmental compatibility of the overall energy chain makes LH_2 a very attractive fuel with emissions confined to some units of g CO_2/MJ H_2 (see [13]. In addition, it might be noticed that LH_2 allows a very stable combustion over an equally wide range of operating conditions, enabling lower production of nitrogen oxides (NO_x). Indeed, even though carbon monoxide (CO), carbon dioxide (CO_2), unburned hydrocarbons, and particulates are absent, NO_x are still formed. It is also necessary to consider its high flame velocity and low ignition energy. These positive combustion characteristics make hydrogen the ideal fuel for gas turbine engines. As for any kind of fuel, the amount of NO_x changes exponentially with flame temperature and linearly with reaction-zone dwell time. These variables are the design drivers to produce low quantities of NO_x, at least as low as those produced with the best carbon content jet fuel [1][14][15] compares CO_2 emissions using the fuels kerosene, methane and hydrogen for the same heat release [16]. However, even if the main product of H_2 combustion is water vapour, a careful investigation of its residence time at different altitudes shall be performed, to minimize the climate impact of this greenhouse gas.

From the chemical perspective, the exploitation of hydrogen as propellant might cause material embrittlement, posing serious constraint on material selection. In addition, for the aerospace sector, the cryogenic storage is the only viable option, and this poses some challenges to the designers. Tanks shall be properly insulated but the presence of cryogenic fuel on board can be an important benefit for thermal management. Moreover, a proper design of the insulation might allow the exploitation of boil-off in an innovative and integrated thermodynamic cycle [9].

Table 1 summarizes the main advantages and drawbacks of the exploitation of Liquid Hydrogen on-board aircraft, specifically looking at the future civil hypersonic long-range transportation.

Table 1. *Effects of the choice of LH_2 as propellant on aircraft design and performance*

Properties	***Advantages***	***Disadvantages***
High heat of combustion	• Reduced fuel weight • Reduced gross weight • Reduced SFC	• More stringent safety requirements
Low Molecular weight	• High specific heat • Higher cooling capabilities	• Materials more prone to (hydrogen) embrittlement • Innovative material shall be developed
Low density	• Lower wing loading	• Increased tank volume • Larger external wetted area resulting in larger viscous drag
Cryogenic	• Lighter tank and fuel system • Lowering of thermal management system mass • Larger on-board cooling capability • Lighter tank and fuel system • Enables lowering the thermal management system mass. Larger cooling on-board capability.	• Specific light weight cryogenic insulation system required e.g. avoiding cryo pumping • New and expensive materials might be required

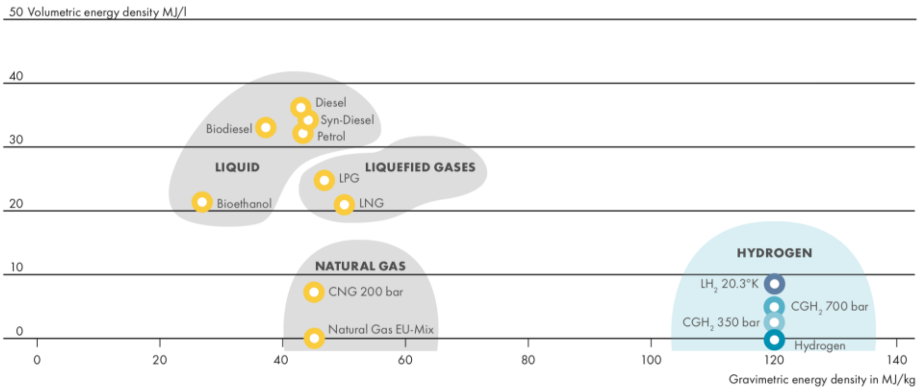

Figure 1. **H_2 energy density overview [13]**

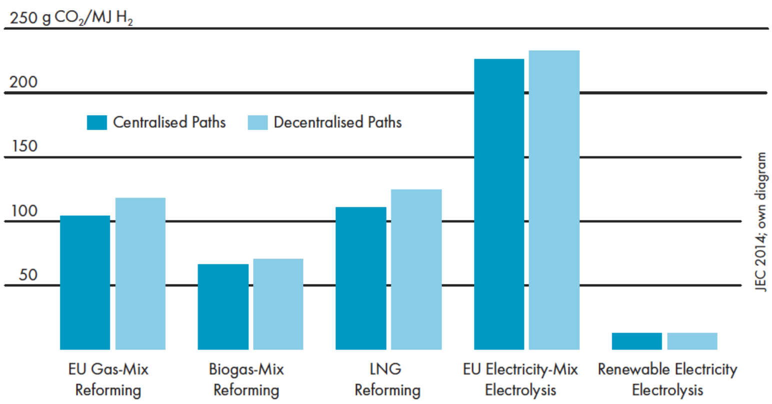

Figure 2. **Environmental impact of LH_2 production [13]**

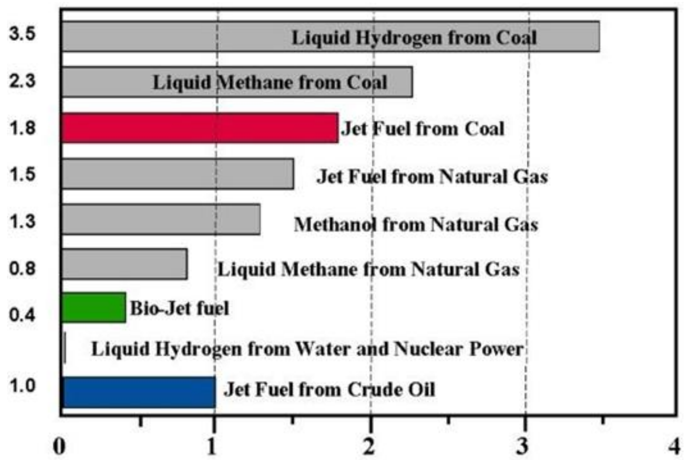

Figure 3. **Relative CO_2 emissions as compared to jet fuels [16]**

2.2 Eco-environmental impact of "Grey", "Blue" and "Green" Hydrogen

According to IEA (International Energy Agency) [17], there is a growing international consensus that clean hydrogen will play a key role in the world's transition to a sustainable energy future. In this context, depending on sources and feedstocks used and on the technologies adopted to produce hydrogen, a roadmap towards an economically and environmentally sustainable hydrogen can be envisaged. Indeed, at present hydrogen is mainly produced using fossil fuels with significant carbon emissions (the so called "grey" hydrogen). Adopting proper Carbon Capture Utilization and Storage (CCUS) technologies, a cleaner version, "blue" hydrogen, might be envisaged, for which the carbon emissions are captured and stored, or reused. The cleanest of all is "green" hydrogen, which is generated by renewable energy sources without producing carbon emissions in the first place.

In this context, this section aims at summarizing the main environmental and economic challenges of hydrogen coming from different feedstocks and productive scenarios.

Looking at the historical data collected by IEA [18], the overall production of H_2 is dramatically increasing since the '70s and the current annual production is greater than 77 million tons with an expected increase of about 20% by 2030 and of the 60% by 2050 (see Figure 4, left). Considering that hydrogen is not only the strongest chemical fuel, but it serves also as an energy carrier, the global production capacity can also be expressed in GW, referring to the heat that would be generated per unit of time if the hydrogen produced was combusted [12] (see Figure 4, right).

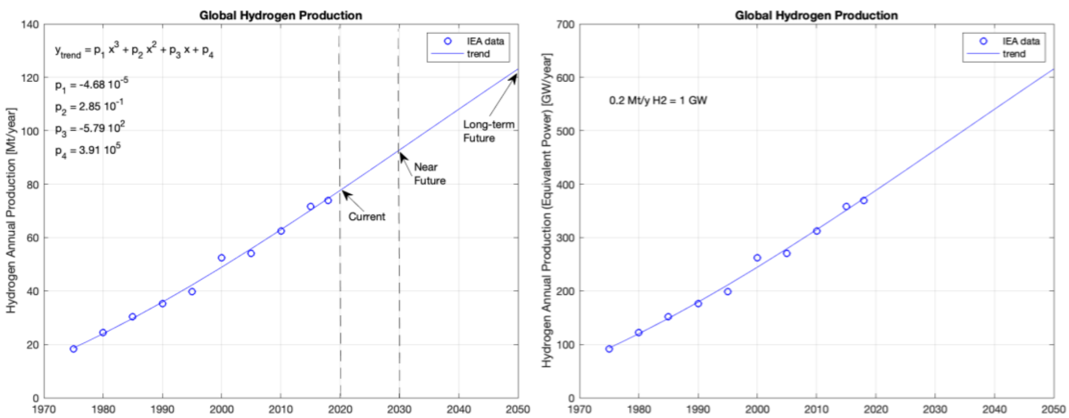

Figure 4. Global Hydrogen Production derived from [12] and [18]

Hydrogen production technologies might be grouped into two different families:

- Hydrogen separation from hydrocarbons
- Hydrogen extraction from water

Looking at the first family, both coal and natural gas are used as primary sources with different technologies involved and therefore with a different environmental impact. Table 2aims at summarizing the main characteristics of the hydrogen production scenarios through the exploitation of hydrocarbons.

Considering the production of hydrogen from water, different energy sources need to be investigated. Though electrical power can be directly used to run electrolysers from a wide range of sources, H_2 can also be produced exploiting the 4th generation of nuclear reactors via thermochemical processes. In addition, in order to assess the environmental and economic impact of the solution, the different available ways to produce the necessary electrical power shall be properly assessed, especially looking to renewals (Table 3).

Table 2. *Eco-environmental impact of hydrogen from natural gas and coal*

Hydrogen from Natural Gas	Hydrogen from Coal
Raw material availability	
Natural gas resources are abundant and expected to increase in the coming two decades. Noticeable regional disparities exist and this may lead to differences in the final hydrogen price depending on the location of the production sites.	Coal resources are enormous. Less regional disparities for resources distribution exist.
H_2 Extraction Capacity	
H_2 can be obtained from natural gas through steam methane reforming, partial oxidation or autothermal reforming. According to [11][18], 35 million tons per year are produced through steam methane reforming, covering about the 48% of the global overall production.	According to [11], single gasifier 2.83 million m^3 H_2/day (250 t/day). A typical installation would include two to three gasifiers (750 ton/day) Current annual production is about 13 million tons per year [11][18], about the 18% of the global overall production. Future hydrogen production scenarios are envisaging an annual production from coal higher than 40 million tons per year (expectations by 2050).
Environmental Impact	
Hydrogen extracted from natural gas contains a mixture of carbon monoxide, carbon dioxide and unconverted methane. Purification is requested to purify the hydrogen.	The main pollutants resulting from conventional extraction of H_2 from coal are sulphur oxides, nitrogen oxides, particulates, mercury and of CO_2. sulphur oxides can be minimized by using coal with

A "blue" H_2 can be obtained avoiding a simple venting of the subtracting CO_2 in the atmosphere, but adopting CO_2 sequestration technologies. - Without sequestration, 10 kg_{CO2}/kg_{H2} are emitted [11][18], - With sequestration techniques, pollutant emissions can be reduced up to less than 1.5 kg_{CO2}/kg_{H2} [11][18],	a low sulphur content and adopting flue gas desulfurization process. Integrated gasification combined cycle systems are currently under development to reduce the environmental impact of H_2 production from coal. - Without CO_2 capture systems, 19 kg_{CO2}/kg_{H2} are emitted [11][18] - With CO_2 capture systems, 2 kg_{CO2}/kg_{H2} are emitted [11][18]
Economic Impact	
In future, the unit capital cost of a typical distributed hydrogen plant producing 480 kilograms of hydrogen per day (kg/d) might be reduced from 3996 to 2073 €2019/kg/d, and the unit cost of hydrogen might be reduced from 4.09 to 2.42 €2019/kg. These hydrogen unit costs are based on a natural gas price of 6.40 €2019/GJ; a change in the natural gas price of plus or minus 1.97 €2019/GJ would change the hydrogen cost by about 12% with current technology [11].	Capital costs incurred per kilogram of produced hydrogen are higher with respect to the natural gas scenario Raw material costs per kilogram of produced hydrogen are lower with respect to the natural gas scenario. If the sustainable technologies will be successfully implemented on large scale, the estimated hydrogen production costs can be reduced to 0.7 €2019/kg [11]. If the coal price would change by 25%, hydrogen costs would change by 0.053 €2019/kg only. If the costs of the plant would change by 25%, however, hydrogen costs would change by 0.17 €2019/kg [11]. This should lead to a very stable cost of hydrogen production that will even be lowered by future technology improvements.

Table 3. *Eco-environmental impact of hydrogen from Electrolysis*

Hydrogen from Electrolysis using Electricity from Fossil Fuels
Environmental Impact
The impact of traditional electrolysis exploiting grid energy can be up to two times higher with respect to the worst cases envisaged for H_2 extraction from Natural gas and coal. If power from the grid is assumed to be based on a grid's average mix a value ranging from 15 to 20 kg_{CO2}/kg_{H2} can be assumed. [11]
Economic Impact
According to [11], electrolyser installation costs range between 34,200 and 456,000 € (respectively for a 0.5 and 30 nm3/h, at 15 bar and a purity of 99.7 or 99.999%). In general, the smaller the quantities of hydrogen required by a customer are, the higher is the all-inclusive cost. The value of hydrogen on distributed chemical markets today is much higher than the value of hydrogen used as fuel. The current average price of 13 €2019/kg have to be lowered targeting 2.00 €2019/kg range to compete with conventional fuels for transportation. [11] The cost of hydrogen from electrolysis is dominated by the cost of electricity and the capital cost recovery for the system. Another factor – operation and maintenance expenses (O&M) may add 3 to 5% to the total annual costs. The electrochemical efficiency of the unit, coupled with the price of electricity, determines the variable cost. The total capital cost of the electrolyser unit, including compression, storage, and dispensing equipment, is the basis of fixed-cost recovery. Regarding capital cost recovery, the cost of the 480 kg/day system, excluding compression and dispensing, is assumed to be around 1000 €2019/kW input.

Hydrogen from Electrolysis using Electricity from Nuclear Plant
Environmental Impact
In the last decade, two main approaches have emerged as leading contenders for high-temperature water splitting using heat from advanced nuclear reactors: Thermochemical cycles and high-temperature (steam) electrolysis (HTE). Thermochemical cycle technology still is in a relatively early stage, and only a few cycles have been demonstrated on the laboratory scale. Unlike power plants using fossil fuels, nuclear reactors do not produce air pollution or carbon dioxide while operating. However, the processes for mining and refining uranium ore and making reactor fuel all require large amounts of energy. Nuclear power plants also have large amounts of metal and concrete, which require large amounts of energy to manufacture. If fossil fuels are used for mining and refining uranium ore, or if fossil fuels are used when constructing the nuclear power plant, then the emissions from burning those fuels could be associated with the electricity that nuclear power plants generate. However, the main environmental impact of the exploitation of nuclear reactors is related to the radioactive waste.
Economic Impact
The cost of hydrogen from thermochemical cycles depends primarily on the capital cost of the nuclear reactor, the capital cost of the hydrogen plant, and the overall efficiency of converting nuclear heat into hydrogen. Estimates for mature, large centralized plants using gas-cooled nuclear reactors and the Hybrid Sulphur process thermochemical cycle reveal hydrogen production costs of 2.10 €2019/kg or less [11].
Hydrogen from Electrolysis using Electricity from Wind Energy
Environmental Impact
Hydrogen extraction from electrolysis using electricity from wind energy is a particularly interesting zero-emission activity. In case of hybrid scenarios, exploiting mix electricity from grid as backup, more than 3 kg_{CO2}/kg_{H2} can be emitted. In addition, wind turbines are not compatible with urban environment and shall be placed far away for inhabited areas due to the high noise emissions.
Economic Impact
Water electrolysis using electricity coming from wind turbines could become a major player towards environmental sustainability. However, to make the state-of-the-art technologies in the field economically competitive, further cost reduction shall be pursued, mainly in terms of cost of wind turbine technology and electricity generated by wind, of electrolysers, and the optimization of the wind turbine-electrolyser with the hydrogen storage system. Since the establishment of the first production sites dating back to the early 1980s, the cost of generating electricity from wind has been dramatically reduced by the 80%, reaching a current value of 0.04 €2019/kWh [11][19]. Further reductions are expected in short- and long-term future scenarios thanks to major improvements in turbine design and optimization of rotor blades and related control devices.

Hydrogen from wind can be produced everywhere with theoretically no geo-political restrictions. This will also allow the possibility of reducing costs relating to energy distribution and storage. Currently, a distributed wind-electrolysis hydrogen generation system in the US provides H_2 at approximately 7 €2019/kg. Hybrid scenarios, exploiting mix electricity from grid as backup provides H_2 at more than 10 €2019/kg.
Hydrogen from Electrolysis using Electricity from Solar Energy
Environmental Impact
- Complete green scenario
Economic Impact
- The current cost of electricity coming from state-of-the-art photovoltaic solar energy technologies is at least 6 times more expensive than the electricity produce from fossil fuels, and the same applies to the H_2 production cost. - The exploitation of new technologies on both solar cells and electrolysers may allow to reach a H_2 cost of about 6 €2019/kg.
Hydrogen from Electrolysis using Electricity from Biomass
Environmental Impact
- In the overall process of biomass production and gasification to obtain H_2, CO_2 is only released from fossil fuels used for harvesting and transportation of biomass, operating of the gasification systems, and for electricity. - Profitable hydrogen production from biomass requires increased need for fertilizers, energy for production of fertilizers, and potentially water. As is the case with the production of food crops, erosion, nutrient depletion of the soil, and altered water use practices could result in potentially significant environmental impacts as a consequence of farming activities. [11]
Economic Impact
- In a long-term sustainable scenario, it would require biomass production at the same rate as its consumption. It is unlikely that such localized operations would contribute significantly to the needed H_2 supply. - According to [11], assuming some technological improvements to crop plantation as well as to the gasifier efficiencies, the future costs per kilogram of hydrogen produced from biomass and delivered to the vehicle can amount to about \$3.60.

Looking specifically at Electrolysis technologies, two main technologies are currently used for hydrogen mass production: Alkaline and Proton Exchange Membrane (PEM) technologies. M. Rashid [20] has recently compared the two technologies highlighting main advantages and disadvantages (see Table 4). Although the PEM technology is very promising, mainly because of the higher current and voltage density capability, it is characterised by a much higher investment costs mainly due to the type of materials to be used.

Table 4. *Comparison of Alkaline and PEM electrolysis [20]*

Technology	Advantages	Disadvantages
Alkaline Electrolysis	Technology: oldest and well established Cost: cheapest and effective Catalyst type: noble Durability: long-term Stacks: MW range Efficiency: 70% Commercialized	Current Density: low Degree of purity: low (crossover of gases) Electrolyte: liquid and corrosive Dynamics: low dynamic operation Load range: low for partial load Pressure: low operational pressure
PEM Electrolysis	Current density: high Voltage efficiency: high Load range: good partial load range System Design: compact Degree of purity: high gas purity Dynamic: high dynamic operation Response: rapid system response	Technology: new and partially established Cost: high cost of components Catalyst type: Noble Corrosion: acidic environment Durability: comparatively low Stack: below MW range Membrane: limited and costly Commercialization in near term

3. LH_2 Cost Estimation Model

3.1 Towards economical sustainable hydrogen production

In a nutshell, producing hydrogen currently turns out to be a challenge principally with respect to the environmental impact and costs. The best option appears the electrolysis of water coupled with a renewable energy source such as photovoltaic cells and wind turbines. Even in this case, however, we will need to consider all possible problems. It will be necessary to build technological industrial facilities with new technologies that are environmentally compatible with LH_2 production, since world production currently does not cover the daily needs of even 20 airports.

At present, there are initiatives ongoing using off-shore wind-turbines to store excess energy into hydrogen in Belgium (Hyoffwind 25-100 MW, Hyport 50MW) and the Netherlands (NorthH2).

3.2 H_2 Production Cost Modelling

Figure 5 summarises the logical breakdown of the costs associated to liquid hydrogen to be exploited in future high-speed aerospace vehicles. At first, Gaseous hydrogen production cost shall be assessed, which includes the Capital Expenditures (CAPEX), directly linked to the Investment cost, the Electricity Expenditures (EEX) requested to run the electrolysers and the Operational Expenditures (OPEX) associated to the costs of operating and maintaining the infrastructures. Indeed, the main goal of the cost estimation is to evaluate the Levelized Cost Of Hydrogen (LCOH). In analogy with what reported in [21] generically for energy, the LCOH can be defined as the present value of the price of the produced hydrogen, considering the economic life of the plant and the costs incurred in the construction, operation and maintenance, and the fuel costs. Thus, the LCOH can be easily estimated once CAPEX, EEX and OPEX are known. In addition to that, following a similar approach, the cost of liquefying the hydrogen can be estimated. Then, depending on the specific scenario, storage and distribution costs can be predicted as well allowing the estimation of the expected price of LH_2 per kg.

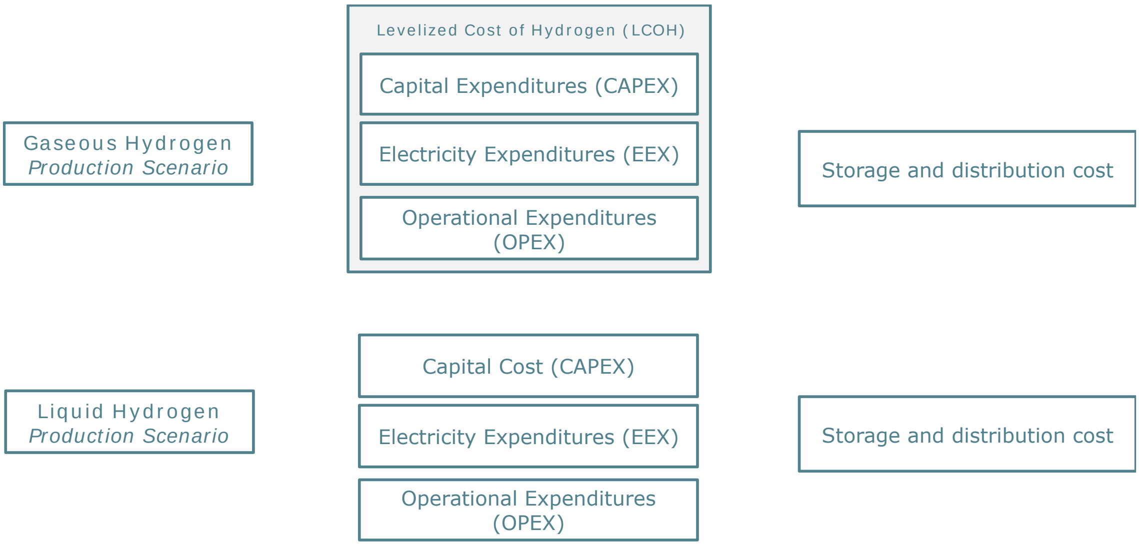

Figure 5. Hydrogen Cost Estimation procedure

3.2.1 Scenario Definition

According to [18], Electrolysis production currently represents only 4% of the global H_2 production (i.e. about 3 Mton/year in 2020). However, the current push towards renewables is reflected in a higher number of plants and in an increase in size.

In order to properly assess the current H_2 productive scenario for Electrolysis and to envisage the trends for short-and long-term future scenarios, the database provided by the International Energy Agency (IEA) has been considered as main reference [22] (Figure 6).

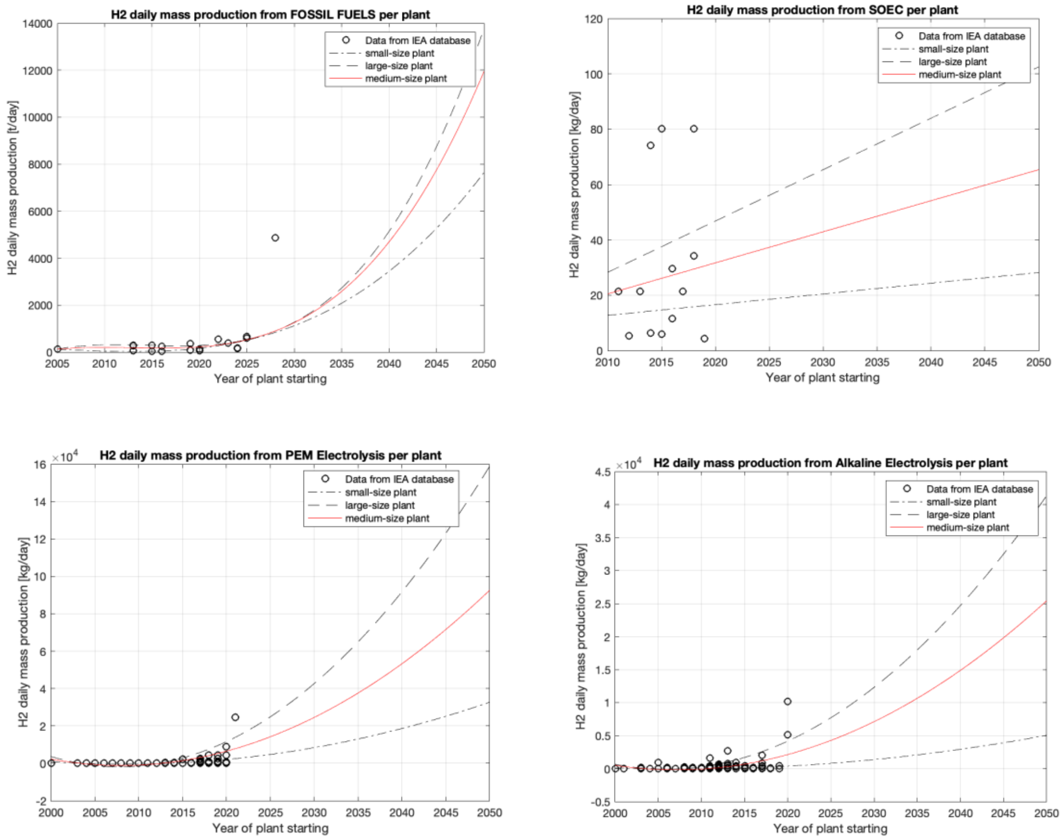

Figure 6. Hydrogen global production per day derived from [22]

Data from [22] have been properly analysed and the productive scenarios ranges have been derived (Table 5). Values obtained for the future scenarios are in line with the expectations reported in [23].

Table 5. *Hydrogen Production Scenarios Definition (Data from [22])*

	Current Scenario (2020)	**Near Future Scenario (2030)**	**Long-term Future Scenario (2050)**

	[ton/day] per plant *Min – Max (average)*	**[ton/day] per plant** *Min – Max (average)*	**[ton/day] per plant** *Min – Max (average)*
H_2 from Fossil fuels	166.2 - 281.2 (221)	1,124 – 1,270 (1,254)	7,587 – 13,650 (11,940)
H_2 from SOEC Electrolysis	0.017 – 0.047 (0.031)	0.021 – 0.066 (0.43)	0.028 – 0.10 (0.064)
H_2 from PEM Electrolysis	2.06 – 11.4 (6.38)	8.3 – 43.1 (24.6)	32.36 – 158.2 (92.13)
H_2 from Alkaline Electrolysis	0.36 – 4.11 (2.13)	1.35 – 12.21 (7.05)	8 – 42 (25)

3.2.2. Investment and Capital Cost modelling (CAPEX)

Depending on the type of technology considered, the cost of the investment might dramatically impact the final cost of hydrogen as fuel.

Looking at the available literature, the expenses requested to build a new infrastructure for H_2 extraction can be expressed as function of the technology adopted, the size of the plant and the year of development.

Following the approach reported in [23], the size of the plant can be directly related to the daily production capacity and thus to the average installed power, i.e. the maximum peak power available in the plant.

In this section, cost models for the Alkaline and PEM electrolysis technologies are reported. In particular on the basis of the results of the work performed in [23], a correlation suggesting the expected investment per kW (power request from the grid) in all the scenarios has been formulated for both Alkaline and PEM technologies (see Figure 7). Current Investment cost per each electrolyser stack and the predicted values for long-term future are perfectly in line with data reported in [18], where the average investment cost in 2020 is about 840 US$/kW (770 €/kg) and a reduction up to 200 US$/kg (184 €/kg) is envisaged by 2050.

Table 6 reports installed power for each scenario, for both alkaline and PEM electrolysis, on the basis of data available in the IEA Database [22]. Then, exploiting the validated trend reported in

Figure. 7, for each scenario, a reference value for the investment cost has been evaluated (Table 7).

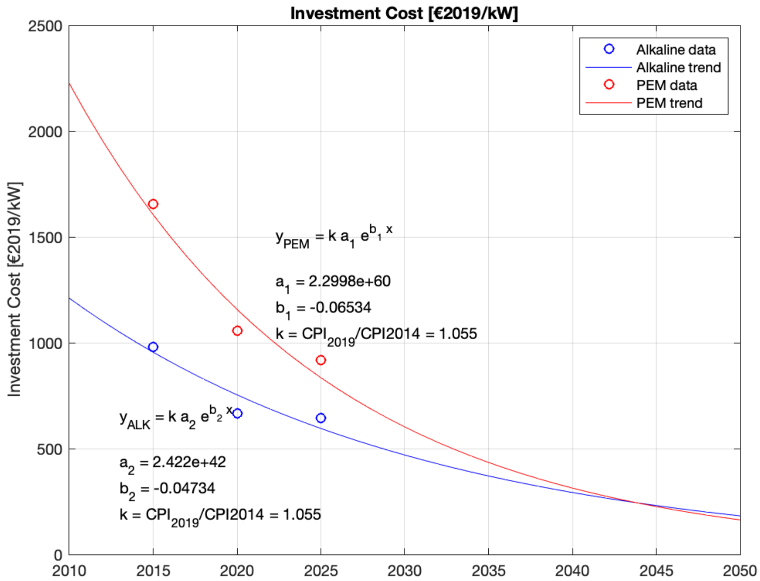

Figure 7. **Investment Cost for Alkaline and PEM Electrolysers [23]**

Table 6. *Hydrogen Production: Installed Power [22]*

	Current Scenario (2020)	**Near Future Scenario (2030)**	**Long-term Future Scenario (2050)**
Installed Power	**[kW]**	**[kW]**	**[kW]**
H_2 from PEM Electrolysis	6038	22200	82700
H_2 from Alkaline Electrolysis	1461	3048	7831

Table 7. *Hydrogen Production: Investment Cost*

	Current Scenario (2020)	**Near Future Scenario (2030)**	**Long-term Future Scenario (2050)**
Investment Cost	**[M€ 2019]**	**[M€ 2019]**	**[M€ 2019]**
H_2 from PEM Electrolysis	6.99	13.36	13.48
H_2 from Alkaline Electrolysis	1.10	1.43	1.43

Then, assuming a 91% load factor (i.e. a plant working for 91% of the days in a year), and 20 years of activities, it is possible to evaluate the so-called Capital Expenditure (CAPEX) (see Table 8). A validation of the Investment Cost model with the results reported in different literature sources such as [12] are currently on-going. The model correctly predicts higher investment costs for the PEM technology in line with the results of the study in [20].

Table 8. *Hydrogen Production: CAPEX*

	Current Scenario (2020)	**Near Future Scenario (2030)**	**Long-term Future Scenario (2050)**
CAPEX	**[€2019/kg]**	**[€2019/kg]**	**[€2019/kg]**
H_2 from PEM Electrolysis	0.16	0.08	0.02
H_2 from Alkaline Electrolysis	0.08	0.03	0.01

3.2.3 Production Process Cost modelling

Focusing on electrolysis processes, the main expenditure to obtain H_2 is for sure related to the electrical power demand to extract the molecules from water. For this purpose, based on the electricity cost forecast reported in [24] an average electricity price of 0.196 €2019/kWh for current and near future scenarios and of 0.193 €2019/kWh for long-term future scenario were assumed. Therefore, production cost for PEM and Alkaline Electrolysis were evaluated (Table 9). This cost is also referred to as Electricity Expenditure (EEX).

However, according to [18] and [19] the cost of renewable power generation has fallen dramatically in recent years, reaching values of 0.04 €2019/kWh.

Table 9. *Hydrogen Production: EEX*

	Current Scenario (2020)	**Near Future Scenario (2030)**	**Long-term Future Scenario (2050)**
EEX (EU Scenario)	**[€2019/kg]**	**[€2019/kg]**	**[€2019/kg]**
H_2 from PEM Electrolysis (from Grid)	4.46	4.24	4.16
H_2 from Alkaline Electrolysis (from Grid)	3.23	2.03	1.45

H_2 from PEM Electrolysis (renewables)	0.91	0.87	0.86
H_2 from Alkaline Electrolysis (renewables)	0.66	0.42	0.30

Moreover, EEX strongly depends on the geographical location of the plant. For example, grid electricity in Europe is almost twice as expensive as in US [10][22], and four times as expensive in Arabic Countries [22].

3.2.4 Operations and Maintenance Cost modelling

Differently from the Electricity Expenditure, Operational Expenditures (OPEX) are less affected by the geographical location of the plant. Indeed, analysing both a European [25] and a US scenario [26], OPEX is about 5% of the initial CAPEX. However, for a more precise evaluation of OPEX, the dependency from the plant size has been introduced, following the results reported in [23] and shown in Figure 8. OPEX derived for both PEM and Alkaline electrolysis for the considered scenario are gathered in Table 10.

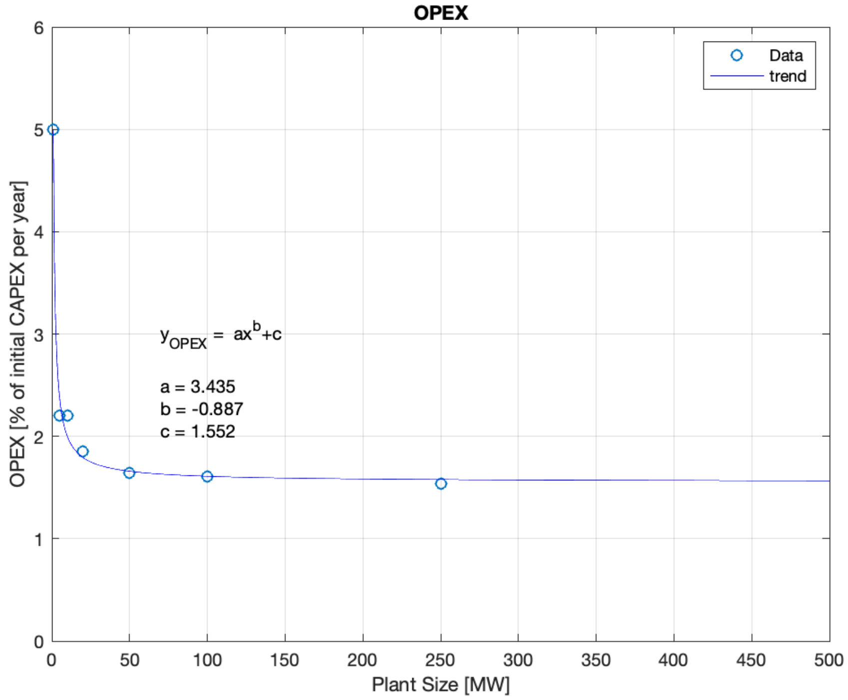

Figure 8. **OPEX for different plant size [23]**

Table 10. *Hydrogen Production: OPEX*

	Current Scenario (2020)	**Near Future Scenario (2030)**	**Long-term Future Scenario (2050)**
OPEX	**[€2019/kg]**	**[€2019/kg]**	**[€2019/kg]**
H_2 from PEM Electrolysis	0.11	0.09	0.03
H_2 from Alkaline Electrolysis	0.05	0.02	0.005

3.2.5 Levelized Cost Of Gaseous Hydrogen

It is now possible to estimate the overall cost per kg of gaseous hydrogen production using the expression shown in Eq. 1.

$$LCOH = (CAPEX)_{GH2} + (EEX)_{GH2} + (OPEX)_{GH2} \quad (1)$$

Eventually, Table 11 reports Levelized Cost Of Gaseous Hydrogen for the electrolysis technologies analysed (considering separately electricity from grid and from renewable sources) for current and future scenarios. Final results are also depicted in Figure 9 and Figure 10 for PEM and Alkaline electrolysis respectively.

Table 11. *Levelized Cost of Gaseous Hydrogen*

	Current Scenario (2020)	**Near Future Scenario (2030)**	**Long-term Future Scenario (2050)**
LCOH	**[€2019/kg]**	**[€2019/kg]**	**[€2019/kg]**
H_2 from PEM Electrolysis (electricity from Grid)	4.73	4.41	4.21
H_2 from Alkaline Electrolysis (electricity from Grid)	3.34	2.08	1.47
H_2 from PEM Electrolysis (electricity from renewables)	1.18	1.04	0.91
H_2 from Alkaline Electrolysis (electricity from renewables)	0.79	0.47	0.31

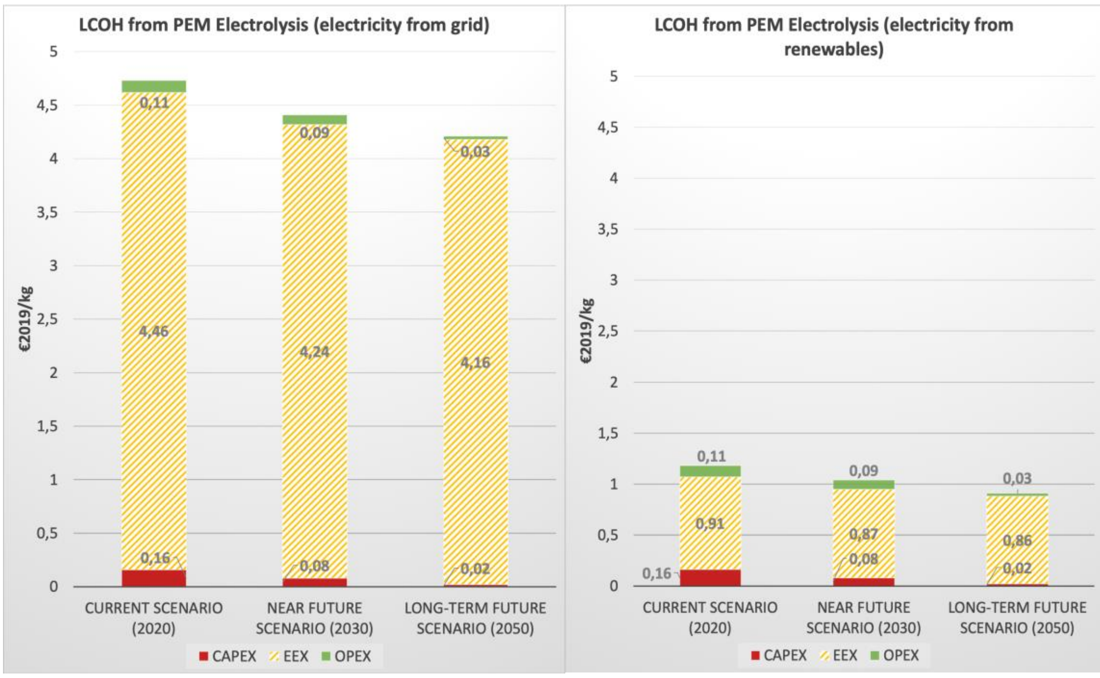

Figure 9. LCOH from PEM electrolysis

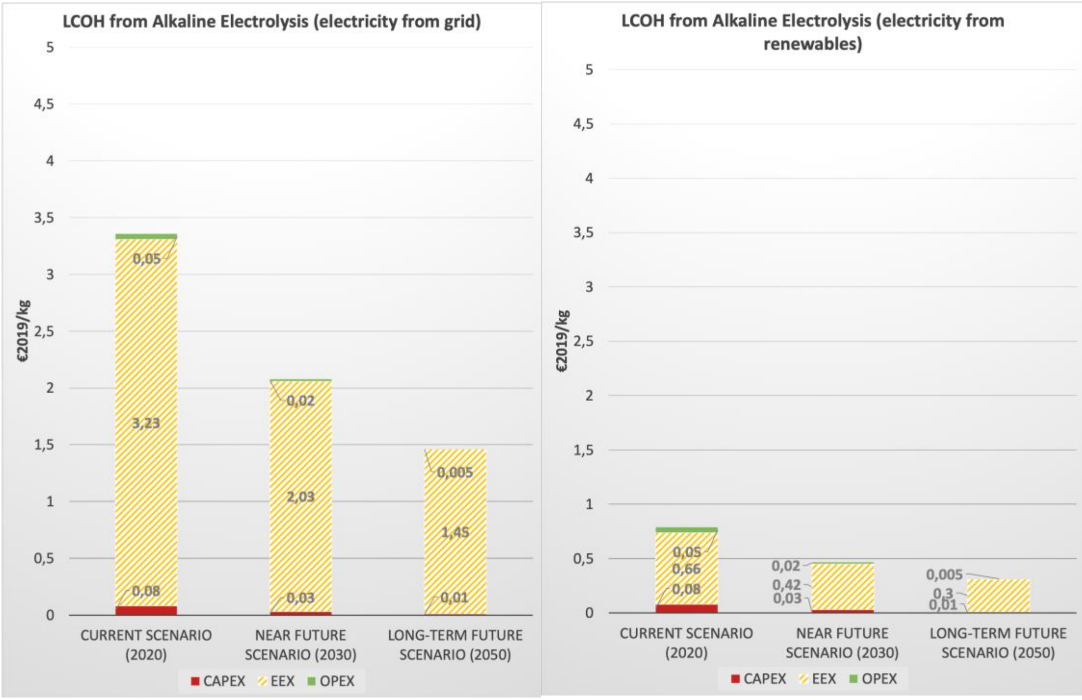

Figure 10. LCOH from Alkaline electrolysis

3.3 H_2 Liquefaction Cost Modelling

Current liquefiers systems are based either on the Reversed Helium Brayton cycle or on the hydrogen Claude cycle to convert gaseous hydrogen into liquid. The Brayton cycle type is nowadays used to handle small liquefaction capacities (up to 3 ton/day) and is characterized by lower capital costs, whilst the operating costs are higher. The hydrogen Claude cycle is adopted for larger liquefiers (up to 15 ton/day) and it is usually associated to higher capital costs and lower operating costs. Both solutions make use of liquid nitrogen (LN_2) evaporation at 80 K for precooling [27].

More specifically, Table 12 provides information on the three liquefaction plants currently available in Europe, where it can be noticed that the overall European scenario is able to sustain a daily production of about 20 ton/day, a very small amount compared to a global liquefaction capacity of about 350 ton/day [28]. In this context, it is worth mentioning that most of the current production occurs in the US (215 ton/day) and in Canada (81 ton/day) [28].

Table 12. *Current Capacity of Liquid Hydrogen in Europe [28]*

Producer	City	Country	Process	Capacity (Nm^3/day)	Capacity (ton/day)	Year Opened
Air Liquide	Waziers	France	SMR	4,864	10	1987
Air Products	Rotterdam/ Rosenberg	Netherlands	SMR	2,502	5	1990
Linde	Leuna	Germany	SMR	2,038	5	2007

3.3.1 Scenario Definition

In line with the cost estimation model for H_2 production, as well as of hydrogen liquefaction, three different scenarios were defined (Table 13). According to data reported in [29] only Claude cycles will be adopted in the future considering the increased size of the plants, whilst for the current scenario both Brayton and Claude Cycles technologies can be envisaged. However, considering the high amount of LH_2 request by the aerospace sector, only Claude cycle technology can be of interest.

Table 13. *Hydrogen Liquefaction: Scenarios definition [29]*

Current Scenario (2020)	Near Future Scenario (2030)	Long-term Future Scenario (2050)
[ton/day] per plant *Min – Max (average)*	**[ton/day] per plant** *Min – Max (average)*	**[ton/day] per plant** *Min – Max (average)*
2 - 15 (8.5)	15 - 30 (22.5)	150 - 200 (175)

3.3.2 Investment and Capital Cost modelling

Different methodologies reported in literature for the cost estimation of liquefaction plant have been analysed. In particular, [30] (indicated as CAPEX (1)) and [31] (indicated as CAPEX (2)) have been used to estimate a plausible range of values for the investment cost of a liquefaction plant. CAPEX (1) [30] suggests the evaluation of CAPEX on the basis of the production rate using power law derived on few data points (mainly European plants running in the 80s-90s). Complementary, CAPEX (2) [31] exploits recent public information about new liquefaction plants built in the US by 2015.

Figure 11 reports both the regression curves built upon the information provided from the two sources, allowing the estimation of minimum and maximum investment cost per daily capacity.

Then, assuming 20 years of operations and 95% of load factor of the plant, the CAPEX for the different scenarios have been defined. Results are reported in Table 14.

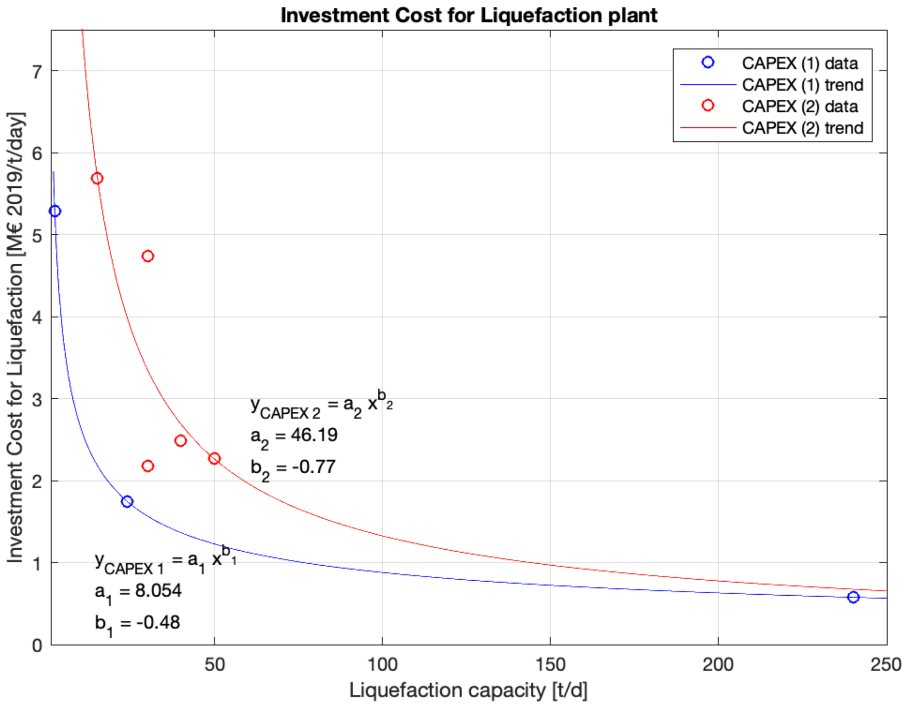

Figure 11. Investment Cost per Liquefaction plant from [30] and [31]

Table 14. *Hydrogen Liquefaction: CAPEX*

	Current Scenario (2020)	Near Future Scenario (2030)	Long-term Future Scenario (2050)
Investments Cost [M€ 2019]	24.44 – 75.31	40.5 – 94.16	117.25 – 150.85
CAPEX [€2019/kg]	0.22 – 0.69	0.19 – 0.43	0.08 – 0.10

3.3.3 Liquefaction Process Cost modelling

Similar to the case of electrolysis, the liquefaction process cost is mainly due to the expenses for the electricity. Thus, considering the electricity cost forecast reported in [24], the EEX for H_2 liquefaction can be estimated, once the energy demand is known for each scenario. Results are reported in Table 15. However, also in this case, the EEX here reported are valid for a European average scenario but the developed methodology has, of course, a general validity.

Table 15. *Hydrogen Liquefaction: EEX*

	Current Scenario (2020)	Near Future Scenario (2030)	Long-term Future Scenario (2050)
Energy Demand [kWh/kg] [29]	10.8	7.7	7.5
EEX [€2019/kg] with electricity from grid	2.12	1.51	1.44
EEX [€2019/kg] with electricity from renewables	0.43	0.31	0.3

3.4.4 Operations and Maintenance Cost modelling

The cost model for the estimation of OPEX for H_2 liquefaction was obtained from the study presented in [29]. In particular, from Figure 12, the regression in Figure 13 has been derived allowing a direct estimation of OPEX for the different scenarios. Numerical results are reported in Table 16.

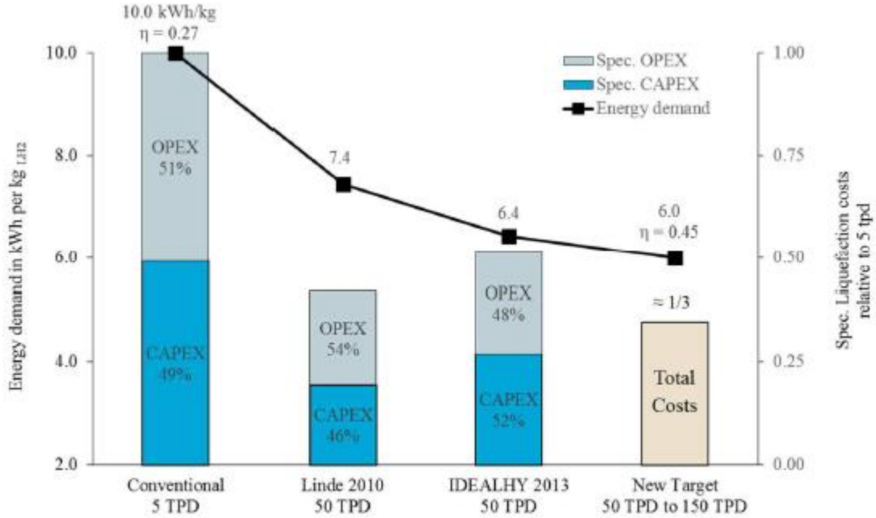

Figure 12. **Cost Breakdown for hydrogen liquefaction [29]**

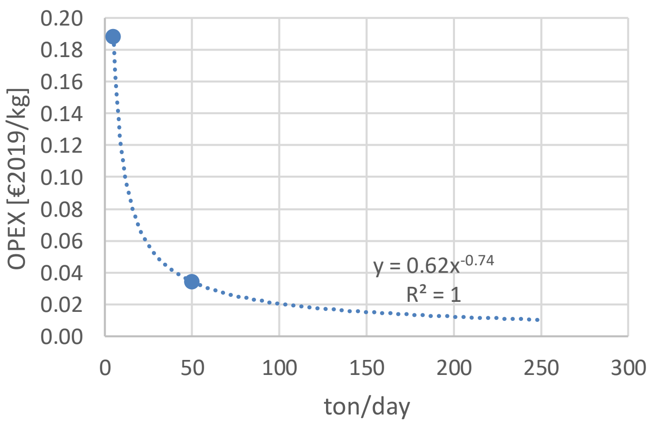

Figure 13. **OPEX for hydrogen liquefaction derived from [29]**

Table 16. *Hydrogen Liquefaction: OPEX derived from [29]*

	Current Scenario (2020)	Near Future Scenario (2030)	Long-term Future Scenario (2050)
OPEX [€2019/kg]	0.19	0.03	0.02

3.4.5 Total Liquefaction Cost

The Total Liquefaction Cost (TLC) for the three different scenarios can be estimated using Eq.2. Results are reported in Table 17. The latter are also graphically depicted in Figure 14 and Figure 15.

$$TLC = (CAPEX)_{LH2} + (EEX)_{LH2} + (OPEX)_{LH2} \quad (2)$$

Table 17. *Total Liquefaction Hydrogen Cost*

	Current Scenario (2020)	Near Future Scenario (2030)	Long-term Future Scenario (2050)
	[€2019/kg]	**[€2019/kg]**	**[€2019/kg]**
Total Liquefaction Cost (electricity from grid)	2.53 – 3	1.73 – 1.97	1.52 – 1.79
Total Liquefaction Cost (electricity from renewables)	0.84 – 1.31	0.84– 1.31	0.4 0– 0.42

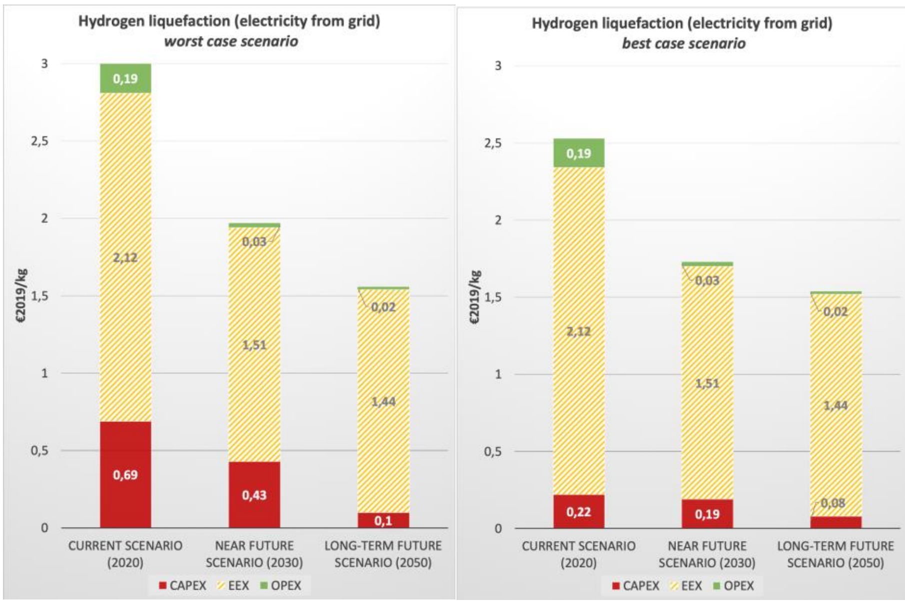

Figure 14. **Hydrogen liquefaction cost (electricity from grid), worst and best case scenarios**

Figure 15. **Hydrogen liquefaction cost (electricity from renewables), worst and best case scenarios**

From these results it can be noticed that an environmentally and economically sustainable production of LH_2 can be envisaged in the long-term scenario, with the exploitation of Alkaline electrolysers, big liquefaction plants and a high percentage of electricity coming from renewables. In that case, the fuel price can be lower than 2 €2019/kg.

3.5 Liquid Hydrogen total cost

Table 18 and Figure 16 report the final outcomes of the analysis on average fuel cost of liquid hydrogen, hypothesizing a balanced mix of PEM and Alkaline technologies and different percentages of electricity coming from grid or from renewable sources. Assuming a long-term future scenario with at least the 70% of electricity coming from renewables, a cost of 2 €2019/kg can be reached. This value is used in the following sections of this paper.

Table 18. *Liquid hydrogen Cost variation depending on electricity source*

		Liquid hydrogen total cost [€2019/kg]		
Electricity from grid [%]	**Electricity from renewables [%]**	**Current Scenario (2020)**	**Near Future Scenario (2030)**	**Long-term Future Scenario (2050)**
100	0	6.8	5.1	4.4
90	10	6.3	4.7	4.1
80	20	5.9	4.4	3.7
70	30	5.4	4.0	3.4
60	40	4.9	3.6	3.0

50	50	4.4	3.3	2.7
40	60	4.0	2.9	2.4
30	**70**	**3.5**	**2.5**	**2.0**
20	80	3.0	2.1	1.7
10	90	2.5	1.8	1.4
0	100	2.1	1.4	1.0

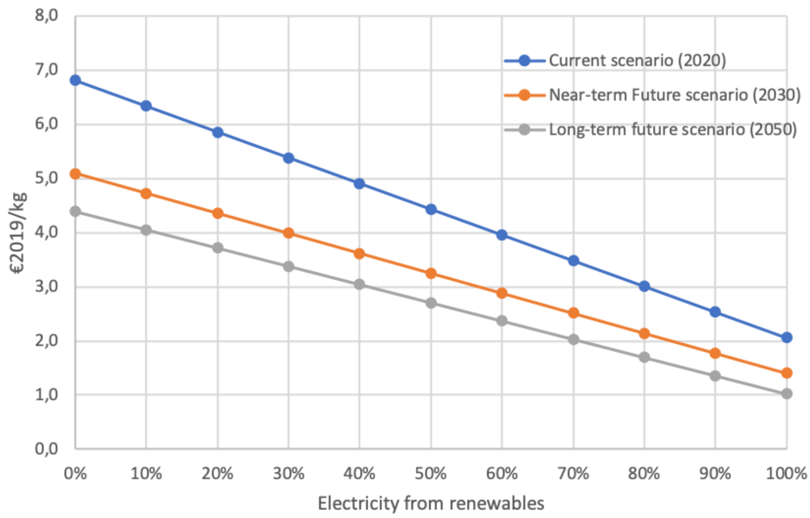

Figure 16. Summary of Liquid Hydrogen Cost

3.6 Distribution and airport service

Apart from being associated to a relevant level of risk, the transport and storage of hydrogen as cryogenic liquid imposes some technical and operational challenges in order to maximize the cost effectiveness of the overall set of activities.

Referring to Brewer studies carried out in the 70s [32], the identification of a proper location for the production plant is a prerequisite to properly assess the impact of distribution costs of the final fuel price is. Considering property availability, costs and safety requirements, it might be cost-effective to locate it in the vicinity of the airport and to plan for an appropriate distribution. According to [32], three viable options to transport liquid hydrogen can be considered, i.e. Vacuum-Jacketed (VJ) pipeline, Truck-trailer and Railroad tank car. The results of the study carried out by Brewer [32] for a specific fictional case study assuming the San Francisco International Airport as an example are summarized in Figure 17 where costs, originally expressed in million US Dollars and referred to Fiscal Year (FY) 1975, have been updated to million Euro 2019. Not surprisingly, the case in which the liquefaction plant is located on the airport premises proved to be the most economical choice. In case this solution cannot be considered, transport of LH_2 via the VJ pipeline seems to be the most economical method for distances under 75 km. For distances greater than 75 km railcar transport shall be considered. Hydrogen production facilities would have to be constructed along with liquefaction and LH_2 storage facilities. An option could be the construction of a large-scale centre with trailer trucks and a railway near the airport. An entire fuel distribution system would have to be created, which would increase in complexity with the distance. Several extensive hydrogen pipelines networks exist throughout the world, for example the Air Liquide Network in North Europe, which covers a distance of 1500 km and connects various ports and chemical industries. Transport pipelines of liquid hydrogen are only viable in case of large volumes and shorter distances, but will not be advantageous due to the high evaporation losses caused by heat entry. In this case, liquefaction facilities are required at the airfield. The airport must then have a large space dedicated to the production of liquid hydrogen. At the same time, real supply stations or systems suitable to supply liquid hydrogen aircraft will be required. It is envisaged that the delivery of LH_2 to the aircraft would be done by tanker trucks and pipelines. This implies a need for high investments for infrastructure (such as filling and exchange system) and would be technologically more challenging. Actual refuelling systems would have to be converted to deliver the cryogenic hydrogen. The selection of materials, means and devices must be managed with care.

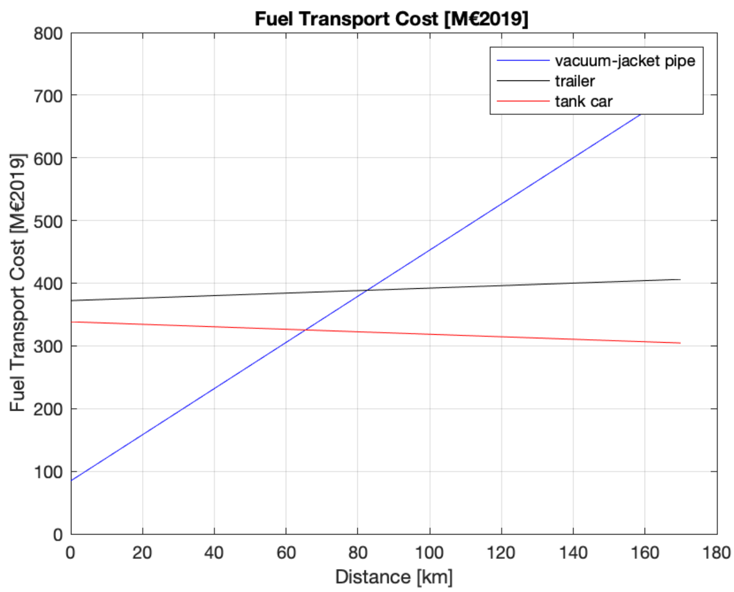

Figure 17. **Cryogenic fuel transport costs as a function of the distance between production site and airport premises [32]**

Experiences gained and technologies developed for refuelling cars with a LH_2 tank or launchers can be useful for an aircraft LH_2 refuelling system as well [33]. Ground Servicing system must be reviewed and verified capable of offload safely before propellant is loaded. The special equipment and personnel training for safety during and after servicing must be available and functional. The service equipment, procedures and personnel must be also checked out and certified ready for propellant service, especially for spills and leaks.

The already available hydrogen at the airport could be exploited by all ground vehicles and machines, such as buses and baggage trucks (Figure 18). The design features of a liquid hydrogen delivery system are determined by the demand. The design and implementation of LH_2 facilities involves financial risks. The investment risk is mainly due to operating costs, in addition to the operation of the plants during the first phase of development. Synergies between LH_2 aircraft and other hydrogen applications inside or outside airports should therefore be considered. Hydrogen fuelled ground support equipment and vehicles, small applications and airport bound landside traffic (e.g. buses, taxis, etc.) will increase the overall hydrogen demand at the airport, and hence cause economy of scale effects [33]. The use of equipment in common or at the same time the exploitation of the boil off hydrogen mass, which could be preferred by these applications, could therefore lead to a reduction in costs.

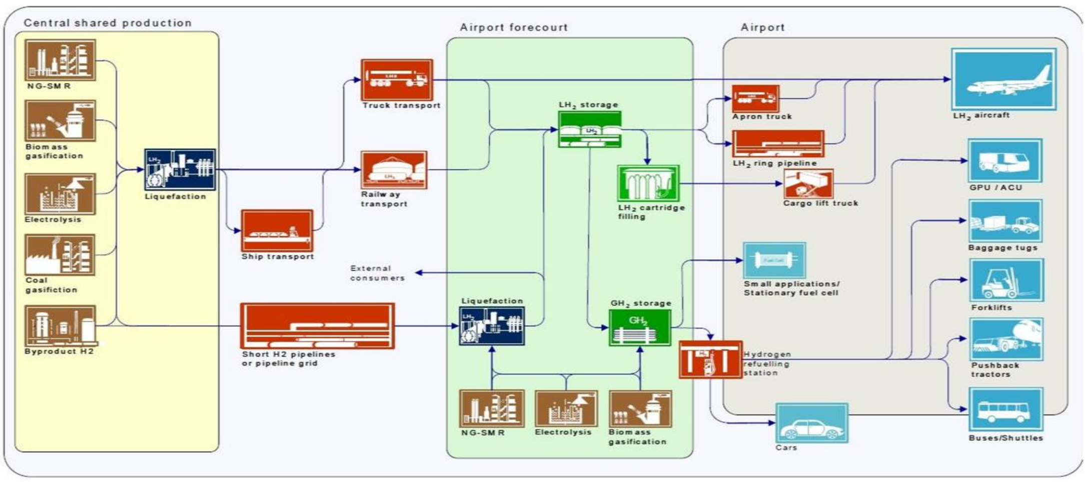

Figure 18. Exploitation of Liquid Hydrogen [33]

A first service station is operational in the Berlin airport area. Implementing and expanding a network like this for the distribution and use of hydrogen is the fundamental requirement, especially in trying to make the most of its benefits, as the environmental compatibility. The future use of hydrogen in the road transportation sector is expected to have a significant hydrogen demand, especially with the introduction to the market of vehicles powered by fuel cells. This will lead to a greater availability of hydrogen and maybe shorter delivery distances. The successful introduction of hydrogen as a fuel will also depend on its public acceptance.

However according to [34], the extent of pipeline systems is limited, and they do not provide an extensive basis for rapid upscaling of hydrogen deployment. Conversely, in certain parts of the world, significant infrastructure is in place for natural gas transmission and distribution. Such infrastructure can be leveraged to facilitate the delivery of hydrogen, as well as acting as a large and low-cost source of storage capacity [35]. A recent study confirms that its transmission pipelines can be converted to hydrogen gas with a limited impact onto infrastructures, replacing compressors and gaskets [36]. Of course, hydrogen will lead to more fatigue of the pipelines, but with the current level of technologies, the process can be performed safely and reliably. Finally, hydrogen can be used to produce synthetic methane, a gas that is fully compatible with existing natural gas infrastructure. In conclusion, joint use of the natural gas infrastructure for hydrogen and natural gas might be a win-win transition strategy. For hydrogen, this would allow for a scale-up of production from renewables and from the electrolyzes industry by tapping into large, existing demand and its supply chain, in particular gas pipeline infrastructure. This, in turn, can help leverage the role of natural gas as a low-carbon transition fuel.

4. LH_2 cost impact on Direct Operating Costs of a hypersonic transportation

The overall Life Cycle Cost (LCC) methodology described in [9] is here applied to two different case studies: the LAPCAT A2 (Figure 19, right) and the LAPCAT MR2.4 (Figure 19, left) vehicle configuration [6][7][37] using the cost model presented in this paper to better evaluate the fuel price.

Following the cost model suggested by NASA for hypersonic transportation systems [38], the impact of fuel cost on DOC (i.e. $\mathrm{DOC_{Fuel}}$) can be estimated through the following equation (Eq. (3)) where the fuel cost is determined by multiplying the quantity of fuel used per flight by the fuel price per unit weight taking into account the impact of fuel reserves (allowance for reserve).

$$\mathrm{DOC_{Fuel}} = \mathrm{C_f} m_f (1 - K_R) \quad (3)$$

Where:

- C_f is the cost of fuel (i.e. fuel price) per unit mass;
- m_{fT} is the total fuel weight per trip (including reserve allowances);
- K_R is the reserve fuel fraction, including boil-off (if applicable);

Figure 19. Exploitation of Liquid Hydrogen [37][39]

4.1 LAPCAT A2

LAPCAT A2 is a Mach 5 vehicle, designed to perform antipodal flights (>16000 km). The A2 presents a conventional wing-body configuration. Its fuselage consists of external aeroshell (probably reinforced with glass ceramic), insulation, actively cooled screen, structure in carbon fibre reinforced polymer (CFRP) with Ti-joints, and hydrogen tankage in welded aluminium. Furthermore, it is equipped with the SCIMITAR precooled engine, that can be seen as a derivative of the SABRE engine, which is intended for Single Stage to Orbit (SSTO) launcher application, but designed to a longer life. It is based on existing gas turbine, rocket, and subsonic ramjet technology.

Concerning cost estimation, Reaction Engines Limited (REL) experts provided a preliminary evaluation of the Research, Development, Test and Evaluation (RDTE), production, and operating costs associated to the LAPCAT A2 vehicle during a program with ESA [40]. These estimations represent a benchmark for great part of the costs' considerations performed by Politecnico di Torino [9]. In addition, all the Direct Operating Cost (DOC) and Indirect Operating Cost (IOC) estimations have been compared to the REL ones. It is important to point out that REL estimations are referred to FY2006, therefore they have been scaled to FY2019.

Table 19 and Figure 20 report the detailed evaluation of DOC for the present case study, assuming a sustainable fuel price of 2 €/kg (long-term scenario with high share of electricity coming from renewables). In this case, the impact of fuel cost on the overall direct operating costs per flight is less than 75%, with a 15%-point reduction with respect to the current scenario (10€/kg). Figure 21 provides a variation of the DOC per flight per different fuel prices.

Table 19. *LAPCAT A2 – Direct Operating Cost*

Cost Item	**Definition**	**Cost Breakdown assuming C_f = 2 €2019/kg**	
DOC_{Fuel}	Fuel Cost	360,000	73.8%
DOC_{Crew}	Crew Cost	8016	1.6%
$DOC_{Insurance}$	Insurance Cost	10,006	2.0%
$DOC_{Depreciation}$	Depreciation Cost	62,004	12.5%
$DOC_{M/AF/L}$	Maintenance Cost (Airframe Labour)	3605	0.7%
$DOC_{M/AF/M}$	Maintenance Cost (Airframe Material)	6521	1.3%
$DOC_{M/E/L}$	Maintenance Cost (Engine Labour)	22,041	4.5%
$DOC_{M/E/M}$	Maintenance Cost (Engine Material)	22,586	4.6%
$DOC_{MAINT\ TOT}$	Total Maintenance Cost	54,753	11.1%
Total DOC	Total Direct Operating Cost	494,779	

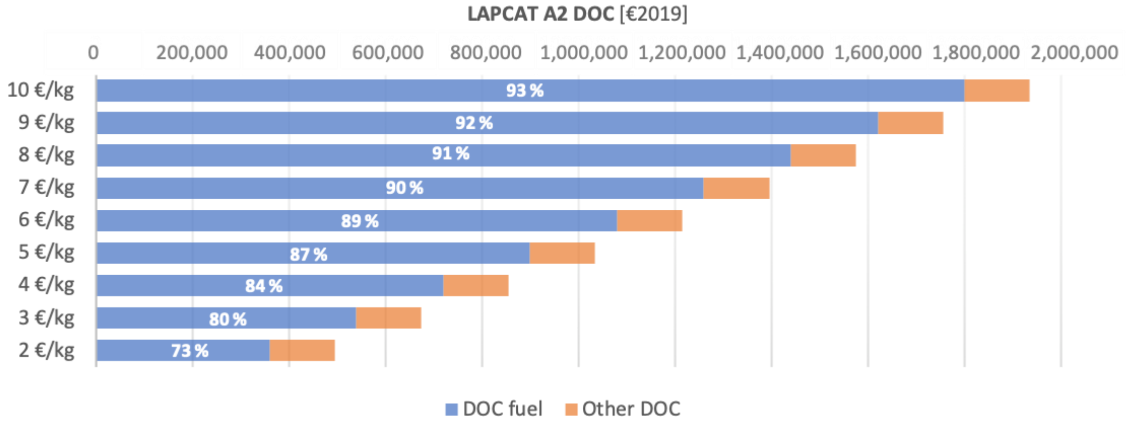

Figure 20. Impact of fuel price on DOC – LAPCAT A2

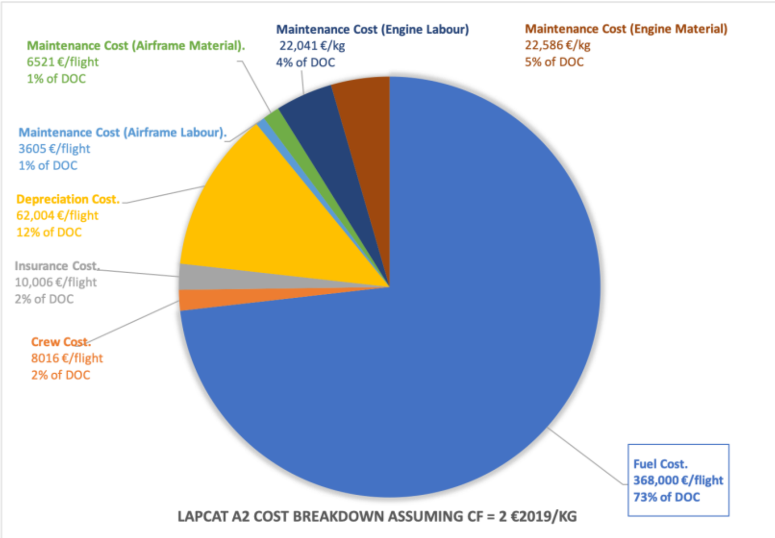

Figure 21. **DOC Breakdown for LAPCAT A2 (Fuel Cost: 2 €/kg 2019)**

4.2 LAPCAT MR2.4

A similar exercise has been carried out for the LAPCAT MR2.4 vehicle, for which a preliminary Cost Assessment has been reported in [9]. Results of the evaluation are reported in Table 20 and in Figure 22, while Figure 23 reports the sensitivity analysis performed to evaluate the impact of the variation of the fuel price onto the final DOC per flight. A reduction from 10 to 2 €/kg allows to reduce the impact of fuel on the LAPCAT MR2.4 operating costs with 20% point.

Table 20. *LAPCAT MR2.4 – Direct Operating Cost*

Cost Item	**Definition**	**Cost Breakdown assuming C_f = 2 €2019/kg**	
DOC_{Fuel}	Fuel Cost	360,000.00 €	77.7%
DOC_{Crew}	Crew Cost	4,946.46 €	1.1%
$DOC_{Insurance}$	Insurance Cost	10,642.70 €	2.3%
$DOC_{Depreciation}$	Depreciation Cost	65,376.17 €	14.1%
$DOC_{M/AF/L}$	Maintenance Cost (Airframe Labour)	2,913.41 €	0.6%
$DOC_{M/AF/M}$	Maintenance Cost (Airframe Material)	4,578.21 €	1.0%
$DOC_{M/ATR/L}$	Maintenance Cost (ATR Engine Labour)	1,251.66 €	0.3%
$DOC_{M/ATR/M}$	Maintenance Cost (ATR Engine Material)	10,395.84 €	2,2%
$DOC_{M/DMR/L}$	Maintenance Cost (DMR Engine Labour)	1,112.93 €	0,2%
$DOC_{M/DMR/M}$	Maintenance Cost (DMR Engine Material)	2,085.08 €	0,5%
$DOC_{MAINT\ TOT}$	Total Maintenance Cost	22,337.13 €	4,8%
Total DOC	Total Direct Operating Cost	463,302.47 €	

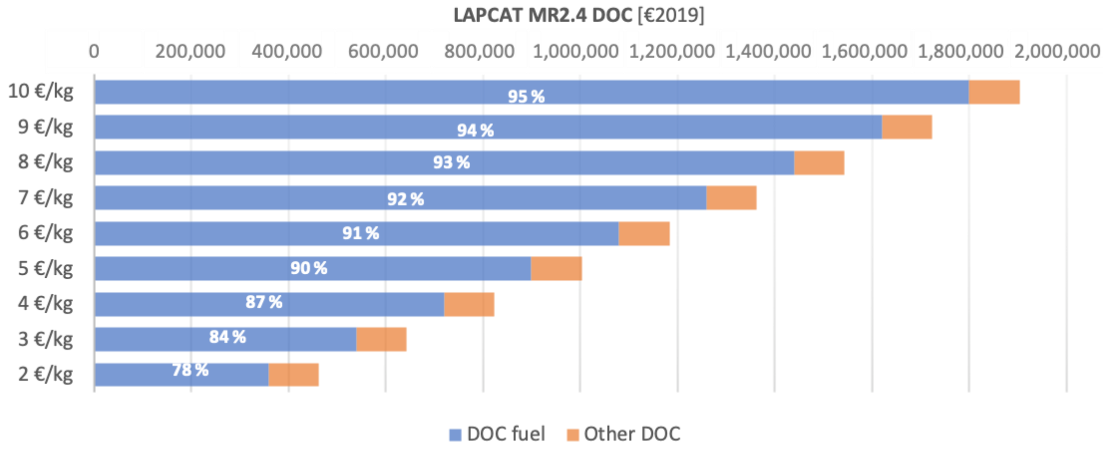

Figure 22. Impact of fuel price on DOC – LAPCAT MR2.4

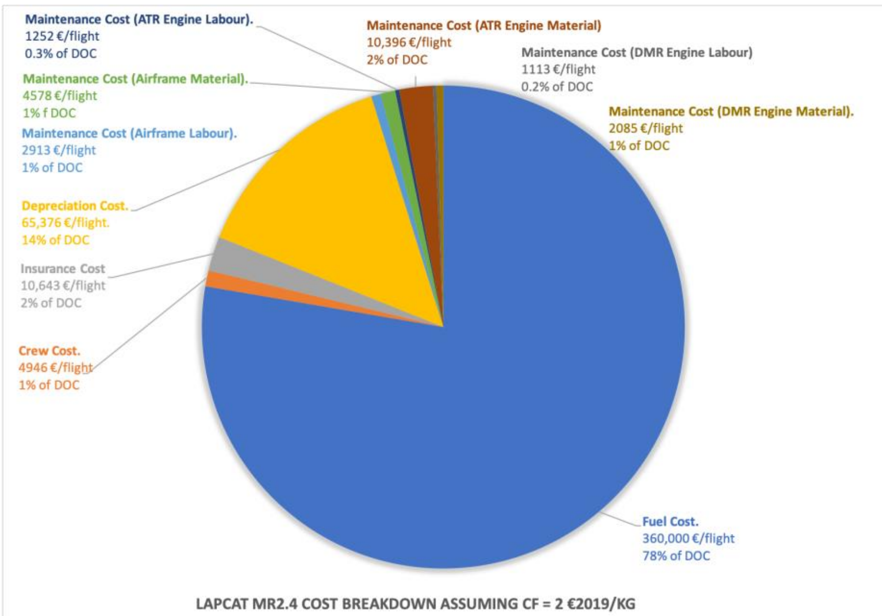

Figure 23. DOC Breakdown for LAPCAT MR2.4 (Fuel Cost: 2 €/kg 2019)

According to a very recent study [41], the impact of fuel cost for a long-range (about 11000 km) subsonic aircraft carrying 300 passengers can represent more than the 20% of the DOC, about 0.012 €2019/km/pax. Looking at the results reported in Table 21, even if the fuel cost for the LAPCAT MR2.4 hypersonic vehicle is about the 78%, the higher operative range (about 16,000 km) brings the cost per km per passenger down to 0.075 €2019/km/pax. Table 21 also reports a detailed comparison with subsonic aircraft. It is worth noticing that Table 21 contains also the comparison with the fuel cost of hypothetical A380 and A350 using LH_2. In these cases, the amount of fuel requested has been evaluated purely based on the ratio between the HHV of kerosene and LH_2 (about 1:3). This gives a Rough Order of Magnitude (ROM) indication of the DOC_{fuel} for a hydrogen-fuelled aircraft prior to go into a conceptual redesign.

Table 21. *Fuel cost comparison with subsonic aircraft*

Aircraft	Cruise Mach	Range [km]	Passengers	Fuel Mass [t]	$DOC_{fuel}\left[\frac{€_{2019}}{km\ pax}\right]$
A380	0.85	11,100	450	254	0.016
A350	0.85	11,100	300	110	0.012
LAPCAT A2	5	16,000	300	180	0.075
LAPCAT MR2.4	8	16,000	300	180	0.075
A380 with LH_2*	0.85	11,100	450	85	0.034
A350 with LH_2*	0.85	11,100	300	37	0.022

*without any conceptual redesign

5. Conclusions and Future Perspectives

This paper has clearly highlighted the importance to properly select environmentally and economically sustainable technologies to produce liquid hydrogen to make high-speed aviation feasible. After an overview of the available sources of hydrogen and related production technologies, a cost estimation model was here presented. This model allows the evaluation of the final cost of liquid hydrogen looking at the different cost components and reflecting different productive scenarios. At first, gaseous hydrogen production cost has been assessed, including the Capital Expenditures (CAPEX), directly linked to the Investment cost, the Electricity Expenditures (EEX) requested to run the electrolysers and the Operational Expenditures (OPEX) associated to the costs of operating and maintaining the infrastructures. Thanks to this model, the Levelized Cost of Hydrogen (LCOH) can be estimated as the present value of the price of the produced hydrogen, considering the economic life of the plant and the costs incurred in the construction, operation and maintenance, and the fuel costs. In addition, a similar approach has been suggested to estimate the cost of liquefying the hydrogen. It is important to notice that the cost model supports not only the hydrogen cost estimation for the current scenario, but it enables the prediction of in a near-future scenario (2030) and a long-term future scenario (2050).

This paper has also presented the application of the developed cost model to different hypersonic vehicle concept: the LAPCAT A2 and the LAPCAT MR2.4. In both cases, the authors have already demonstrated in previous publication that within the current LH_2 productive scenario, i.e. approximately 10 €/kg of LH_2, the expenses related to the fuel can be greater than 90% of the Direct Operating Costs. However, thanks to the technological progresses expected in the coming years together with a deep exploitation of renewable sources for electricity production, values of 2€/kg of LH_2 can be expected. In this case, the impact of fuel expenses onto DOC can be lowered down to the 70%. Therefore, in the long-term future scenario, the contribution of fuel to the Direct Operating Cost is expected to be in the same order of magnitude as for subsonic civil aviation.

Eventually, the paper has demonstrated the socio-economic viability of a “green” hydrogen solution, and encourages the development of even bigger plants to increase the share of electricity coming from renewables into the grid.

In future, this LH_2 cost model will be implemented within the HyCost Tool [9], an ad-hoc software currently under development at Politecnico di Torino under the ESA coordination and funding.

References

[1]. Contreras, A., et al. "Hydrogen as aviation fuel: a comparison with hydrocarbon fuels." International Journal of Hydrogen Energy 22.10-11 (1997): 1053-1060.

[2]. Witcofski, R.: Comparison of alternative fuel for aircraft. NASA-TM-80155 (1979) https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19790024466.pdf

[3]. Margaretic P. and Steelant J., 'Economical Assessment of Commerical High-Speed Transport', CEAS Aeronautical Journal, July 2018, doi.org/10.1007/s13272-018-0319-y

[4]. Steelant J., 'Achievements obtained on Aero-Thermal Loaded Materials for High-Speed Atmospheric Vehicles within ATLLAS', 16th AIAA/DLR/DGLR International Space Planes and Hypersonic Systems and Technologies Conference, October 19-22, 2009, Bremen, Germany, AIAA-2009-7225.

[5]. Steelant J., Dalenbring M., Kuhn M., Bouchez M. and von Wolfersdorf J., 'Achievements obtained within the ATLLAS-II Project on Aero-Thermal Loaded Material Investigations for High-Speed Vehicles', 21st Int. Space Planes and Hypersonic Systems and Technology Conference, AIAA-2017-2393, 6-9 March 2017, Xiamen, China.

[6]. Steelant J., Achievements Obtained for Sustained Hypersonic Flight within the LAPCAT project, in: 15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, 28 April - 1 May 2008, Dayton, Ohio, AIAA-2008-2578.

[7]. Steelant J., R. Varvill, C. Walton, S. Defoort, K. Hannemann, M. Marini, Achievements Obtained for Sustained Hypersonic Flight within the LAPCAT-II project, in: 20th AIAA International Space Planes and Hypersonic Systems and Technologies Conference AIAA, 6-9 July 2015, Glasgow, Scotland, AIAA-2015-3677.

[8]. Steelant, J.: Evolutionary Technology Developments towards an International Flight Platform for High-Speed Transportation, Aviation in Europe Innovating for Growth, Proceedings of the 7th European Aeronautics Days, ed. D. Knörzer et al., 20-22/10/2015, London, UK, doi:10.2777/62810 and doi:10.2777/49217.

[9]. Fusaro, R., Viola, N., Ferretto, D. et al. Life cycle cost estimation for high-speed transportation systems. CEAS Space J (2019). https://doi.org/10.1007/s12567-019-00291-7

[10]. Koelle, D. E.: Handbook of Cost Engineering and Design of Space Transportation Systems. Revision 4b. (2013)

[11]. Léon, Aline, ed. Hydrogen technology: mobile and portable applications. Springer Science & Business Media, 2008.

[12]. Schoots, K., et al. "Learning curves for hydrogen production technology: an assessment of observed cost reductions." International Journal of Hydrogen Energy 33.11 (2008): 2630-2645.

[13]. Adolf, J., Balzer, C. H., Louis, J., Schabla, U., Fischedick, M., Arnold, K., Schüwer, D.: Energy of the future?: Sustainable mobility through fuel cells and H2; Shell hydrogen study. (2017)

[14]. Verstraete, D.: The potential of Liquid Hydrogen for long range aircraft propulsion. (2009)

[15]. Pohl, Hans-Wilhelm, ed. Hydrogen and other alternative fuels for air and ground transportation. Chichester: Wiley, 1995.

[16]. Hadaller, O., Daggett, D., Hendricks, R., Walther, R.: Alternative Fuels and Their Potential Impact on Aviation. NASA/TM—2006-214365 (2006) https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20060051881.pdf

[17]. Noé van Hulst, Hydrogen Envoy at the Ministry of Economic Affairs & Climate Policy of the Netherlands Commentary "The clean hydrogen future has already begun" April 2019

[18]. IRENA. "Hydrogen from renewable power: technology outlook for the energy transition." (2018). http://www.eugcc-cleanergy.net/sites/default/files/1._session_1_dr._asami_miketa_irena.pdf

[19]. IRENA, Renewable power generation costs in 2018. International Renewable Energy Agency, Abu Dhabi, 2019. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/May/IRENA_Renewable-Power-Generations-Costs-in-2018.pdf

[20]. Rashid, Md Mamoon, et al. "Hydrogen production by water electrolysis: a review of alkaline water electrolysis, PEM water electrolysis and high temperature water electrolysis." Int. J. Eng. Adv. Technol 4.3 (2015): 2249-8958.

[21]. Ragheb, Magdi. "Economics of wind power generation." Wind Energy Engineering. Academic Press, 2017. 537-555.

[22]. IEA Database, https://www.iea.org/data-and-statistics/charts/hydrogen-production-costs-using-natural-gas-in-selected-regions-2018-2

[23]. Bertuccioli, L., et al. "Study on development of water electrolysis in the EU. Final report." Fuel cells and hydrogen joint undertaking, 160p (2014).

[24]. Capros, P, et al. "EU Reference Scenario 2016-Energy, transport and GHG emissions Trends to 2050." (2016).

[25]. Riis, Trygve, et al. "Hydrogen production and storage—R&D priorities and gaps." International Energy Agency-Hydrogen Co-Ordination Group-Hydrogen Implementing Agreement (2006).

[26]. Schmidt, Oliver, et al. "Future cost and performance of water electrolysis: An expert elicitation study." International Journal of Hydrogen Energy 42.52 (2017): 30470-30492.

[27]. Cardella, U., L. Decker, and H. Klein. "Economically viable large-scale hydrogen liquefaction." IOP conference series: materials science and engineering. Vol. 171. No. 1. IOP Publishing, 2017.

[28]. Norwegian Centres of Expertise (NCE), Norwegian Future Value Chains for Liquid Hydrogen, NCE Maritime CleanTech, 2019. https://maritimecleantech.no/wp-content/uploads/2016/11/Report-liquid-hydrogen.pdf [27]

[29]. Ohlig, K., and L. Decker. "The latest developments and outlook for hydrogen liquefaction technology." AIP conference proceedings. Vol. 1573. No. 1. American Institute of Physics, 2014.

[30]. Krewitt, W., and S. Schmid. "Fuel cell technologies and hydrogen production/distribution options." EU-Project CASCADE Mints. Deutsches Zentrum fur Luft-und Raumfahrt, Stuttgart (2005).

[31]. Department of Energy (DOE), Hydrogen and fuel program record: Current status off Hydrogen liquefaction cost, 2019 https://www.hydrogen.energy.gov/pdfs/19001_hydrogen_liquefaction_costs.pdf

[32]. Brewer, G. Daniel. Hydrogen aircraft technology. CRC press, 1991.

[33]. Schmidt, P., Stiller, C.: Airport Liquid Hydrogen Infrastructure for Aircraft Auxiliary Power Units'. 18th World Hydrogen Energy Conference (WHEC 2010), Essen, Germany. (2010)

[34]. IRENA, Hydrogen: A Renewable Energy Perspective. 2019 https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf

[35]. Panfilov, M., 2016. Underground and pipeline hydrogen storage, in: Compendium of Hydrogen Energy. Elsevier, pp. 91–115. https://doi.org/10.1016/B978-1-78242-362-1.00004-3

[36]. DNV, GL. "Verkenning waterstofinfrastructuur." DNV-GL, November (2017).

[37]. Steelant J., Sustained Hypersonic Flight in Europe: Technology Drivers for LAPCAT II', 16th AIAA/DLR/DGLR International Space Planes and Hypersonic System Technologies Conference. Bremen, Germany: AIAA 2009-7240. (2009)

[38]. Repic, E. M., Olson, G. A., Milliken, R. J.: A Methodology for Hypersonic Transport Technology Planning. NASA CR-2286. (1973)

[39]. Langener, T., et al. "Layout and design verification of a small scale scramjet combustion chamber." 21st International Symposium on Air breathing Engine. ISABE-2013-1655. 2013.

[40]. REL: Cost analysis of Configuration A2 vehicle and Scimitar engine. Deliverable. D2.1.4. (2006)

[41]. Minwoo, L. E. E., K. B. Larry, and S. O. N. G. Wenbin. "Analysis of direct operating cost of wide-body passenger aircraft: A parametric study based on Hong Kong." Chinese Journal of Aeronautics 32.5 (2019): 1222-1243.