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SUSTAINABILITY ANALYSIS OF A SUBSONIC AIRLINER POWERED BY LIQUID HYDROGEN

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Losing is a part of winning, because if you don't fail
you're not even trying.

Summary

Introduction

Nowadays buying a plane ticket to travel around the world is not so uncommon. As a matter of fact, each year billions of people fly around the world, and millions of airplanes take off. Despite being relatively young, the aviation sector is already embedded in the very fabric of today's society. The possibility to bind almost all countries with one another, overcoming land and sea borders challenges via air with a fast mean of transport, shrank continental distances and expanded commercial, social and economic routes.

From its birth in the early 20th century, aircraft technology is under constant development, starting from wing form factor, materials, fuselage dimensions, aerodynamic appendages, flight speed and other mechanical systems or components. However, today's airplanes look mostly like the ones that started flying in the 1980s. Modern configurations only slightly changed from few decades ago because in the last 30 to 40 years engineers' emphasis shifted from electro-mechanical equipment to the digitalization of avionics and manufacturing methods, implementing new automated controls.

Even from the engine point of view, there hasn't been a technological leap, but only smaller improvements in the architecture, allowing it to burn less fuel and produce less carbon dioxide. This lack of advancement is an issue since the fundamental thermodynamic cycle that powers turbojets and turboprops requires a specific kerosene called Jet A1, which burns and produces massive quantities of CO_2.

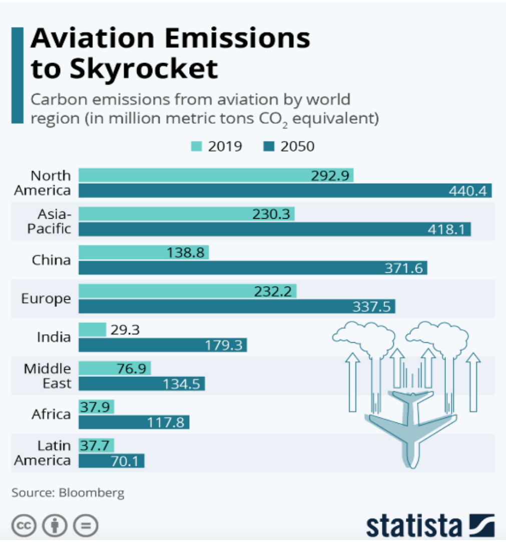


Figure 1: Aviation emission trends with actual engine options [1]

The awareness of greenhouse gas emissions has been spread globally over the last decades, making people self-conscious about the planet's biodiversity and eco-system damages, in relation to climate change, caused by these exhaust gases. Aviation emissions are part of the problem, and newest political agreements push every sector towards decarbonization in the most efficient and fast way possible before it is too late.

Figure 1 shows how much the carbon emission would be from the aviation sector in 2050 if still operating with today's engine options. These data are critical also in today's scenario, in which emissions from both commercial and cargo flights, from all aircraft categories, have been taken into consideration.

Narrow-body planes are widely favored for operating flights due to their exceptional efficiency over short to medium range distances, which are typically the most popular routes for passengers. On the other hand, wide-body aircraft are commonly utilized for cargo transportation, almost as frequently as narrow-body planes. This is due to the fact that import and export demands are distributed across a broader geographic area.

It is worth noting that a significant majority of global air travel is made up of two distinct types of aircraft. These planes are primarily manufactured by Airbus and Boeing, which collectively produce the vast majority of the civil aircraft currently in use. Each company boasts a narrow-body aircraft as their flagship model, which has been expanded into a range of planes to meet diverse market needs. For the purposes of this study, our focus will be primarily on this category of aircraft.

Boeing was the first to produce a highly valuable airliner in this category, creating the popular Boeing 737 in the late 1960s. Its success remains unparalleled to this day, as it is still in operation and has the highest number of flights per year. Original variants were the B737-100 and -200 which were conceived for less passengers for national trips, later also the -300/-400 and -500 versions were built, in order to expand the possible range. The familial unit continued to expand, even in light of the advent of the "next generation" variants, namely the -700 and -900 models, as well as the highly popular and widely distributed B737-800.

Figure 2: B737 stock design [3]

In 1984, Airbus launched its well-known A320, a double engine airliner intended to rival the B737 in the growing aviation marketplace that was concurrently becoming accessible to the middle class. In the next decades, the company decided to produce a family base of this type of certificate, starting with the A321, a longer aircraft with a wider range. After that, Airbus produced also the A319 and A318, shorter versions of the original A320 for a low number of passengers.

Figure 3: Original A320 type certificate aircraft [4]

Being the two most in-use civil aircraft, their performance impacts directly on aviation's averages, and most importantly they are responsible for a major part of the total emissions of this category. In recent years, significant improvements have been made to the propulsion system and operative modes. In the case of the A320 neo engine's architecture has been hugely modified with the aim of reducing fuel consumption and environmental pollution.

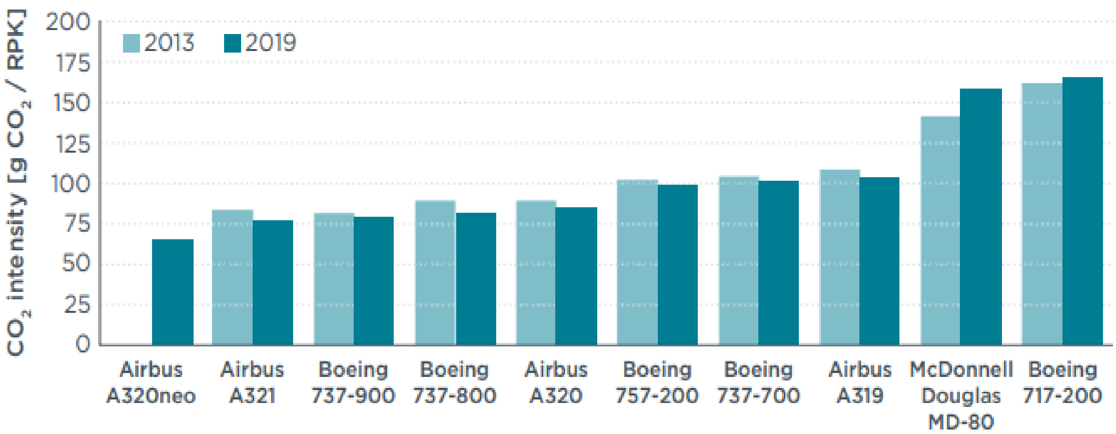


Figure 4: Emissions per RPK between 2013 and 2019 from narrow-body aircraft [5]

As displayed in Figure 4, which is reported from [5], there is a slight improvement, but all aircraft have similar output, except for the MD-80 and B717-200 which are almost unused today.

These numbers show that emissions are still high, and in order to meet the decarbonization requirements set by global agreements, researchers have started exploring new solutions and conceptual designs that would eliminate greenhouse gas production or reduce it drastically. The most advanced option is the possibility to reduce the kerosene-based fuel with a Sustainable Aviation Fuel (SAF), which can be blended with Jet-A1 and limit CO_2 emissions from propulsion. Another possibility is the implementation of a hybrid electric engine or a full electric aircraft, which is still a conceptual study. Especially Airbus is investing a lot in explore those options, and some of prototypes are being tested in the last couple of years. Their most famous project is the Airbus E-Fan X, which is a hybrid demonstrator that is powered by two electric motors from Rolls-Royce and two turboshafts.

Figure 5: Airbus E-Fan x concept [6]

As of today, there are no full-electric aircraft demonstrators, but there are some conceptual prototypes for unmanned mobility.

A promising project is the "Airbus A^3 Vahana" which is an eVTOL propelled by eight full electric engines and is part of a study over urban air mobility.

Figure 6: Airbus A^3 Vahana prototype [7]

The aviation industry's commitment to eliminating carbon dioxide emissions has opened up a new avenue for exploration in the aerospace sector: the use of liquid hydrogen. LH_2 can be used as fuel, as it is already for rocket boosters, but it requires some specific storage and refueling technology. Airbus is also developing a conceptual design for this specific type of possible airplane, the Airbus Zero-e model, which takes a standard configuration but with cryogenic hydrogen tanks placed in the tail cone, reducing the payload's volume.

Figure 7: Airbus Zero-e model concept [8]

This opportunity might be revolutionary since it could allow for a re-design of actual aircraft, changing tanks and propulsion systems to be powered by liquid hydrogen. This study report will focus on this possibility, in which the conceptual aircraft's performance will be investigated and if it can be a real solution today to reduce overall global emissions related to aviation both direct and indirect ones.

A feasibility study over a fixed configuration aircraft will be made, calculating operative performances, possible range and payload, criticalities about center of gravity and requirements around wing area and thrust. It is important to understand if such a plane could complete a mission of short-medium distance in similar ways to current narrow-body aircraft.

Other than that, a cost model for hydrogen as a fuel will be studied, evaluating if the final price can be comparable with kerosene since economic reasons are almost always a primary focus when pushing global agenda towards new means of production or expanding actual. The different types of hydrogen have a different cost, but also have a different environmental impact, depending on source and energy used, that can affect air quality in a bigger way than kerosene itself.

CHAPTER 1: AIRCRAFT FEASIBILITY ANALYSIS

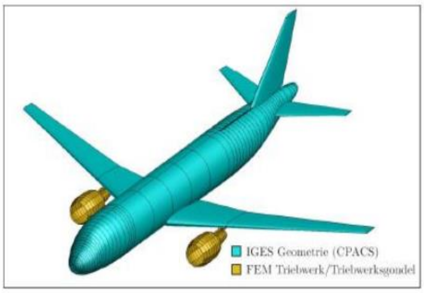
1.1 Mission Profile Estimation

The following report proposes itself as a mission analysis for a plane re-design, in which a standard model is modified in order to limit emissions. The designed reference aircraft has the same form factor as an A320, both in terms of market presence and product and system structures. As said in the introduction, the main difference for this study will be the propulsion feed system and fuel storage, which must be re-arranged according to liquid hydrogen propulsion. The first change that should be evaluated is the mission profile, in which some of the nominal parameters need to be rewritten, mainly because they are estimated considering Jet A1's (classic Kerosene) chemical performances.

The biggest difference between a LH_2 propulsion system, and the ones that use kerosene or sustainable aviation fuels is the complexity of the storage. In order to maintain hydrogen in a liquid state, it is required to use specific tanks that can preserve a cryogenic temperature (around 20 K degrees). This kind of technological solution is well-known, but it is used mostly in the space industry due to its huge complexity.

Wing	
Surface area	$122.3m^2$
Span	$33.91m$
Reference chord	$4.19m$
Aspect ratio	9.4
Taper ratio	0.246
Sweep angle at 25% chord line	24.94^o
HTP	
Area	$30.98m^2$
Span	$12.45m$
Aspect ratio	5.0
Taper ratio	0.33
Sweep angle at 25% chord line	28.0^o
VTP	
Area	$21.51m^2$
Span	$5.87m$
Aspect ratio	1.6
Taper ratio	0.35
Sweep angle at 25% chord line	35.0^o
Operational empty weight (OEM)	$40638kg$
Maximum zero-fuel weight (MZFM)	$60500kg$
Maximum take-off weight (MTOM)	$72500kg$
Cruise Mach number	0.78
Cruise speed / Mach number	$180m/s$ EAS, Mach 0.82
Dive speed / Mach number	$209m/s$ EAS, Mach 0.89
Maximum flight level	$12500m$

Kier, T., Meddaikar, Y., Wuestenhagen, M., Yu, F., Vanek, B., Poussot-Vassal, C. D5.1 Reference Model Definition, Deliverable of the Flight Phase Adaptive Aeroservo-elastic Aircraft Design Methods (FliPASED), 2021.



- The aircraft matches the A320-200 (CEO) WV00, being still in line with the majority of A320 platforms (both CEO and NEO)

Figure 8: Reference aircraft's data sheet

State-of-the-art solutions do not allow this type of preservation to be implemented inside the wing box, where kerosene is usually stored.
The model considered to evaluate the propellant system mass is the *Airbus ZEROe*, in which the hypothetical fuel tanks are located in the fuselage tail cone. The hydrogen would be stored in two communicating parts, approximated as a cylinder and a truncated cone.

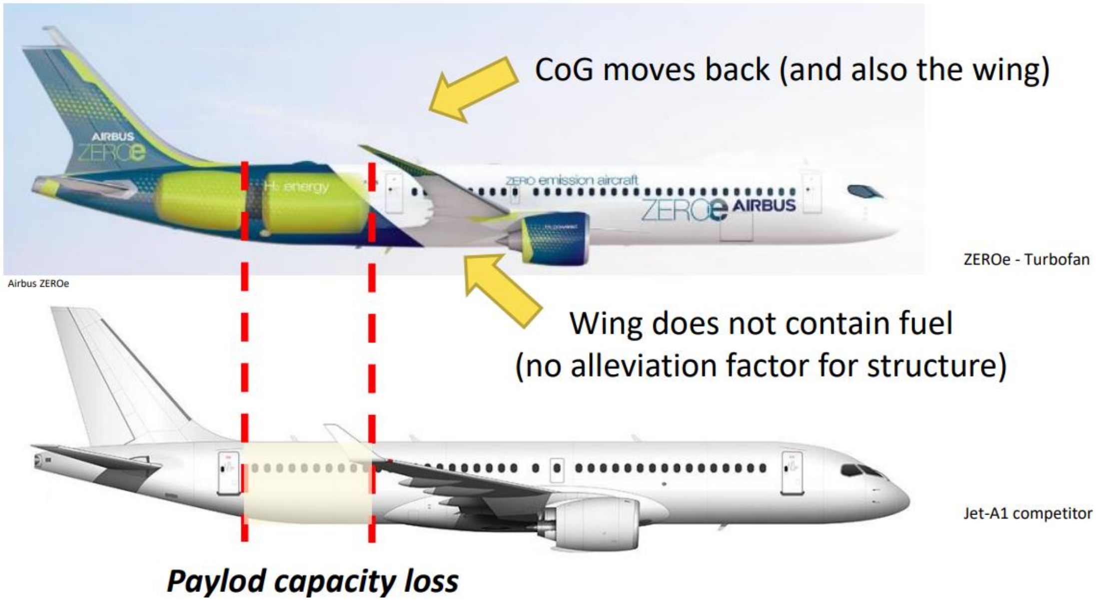


Figure 9: Airbus ZEROe Model

Performance and operational requirements are fixed, as well as aircraft parameters and internal configuration. Thus, the analysis will have to factor in the tradeoff between payload mass and fuel stored in order to verify that the airplane is able to complete the mission within the market competitiveness requirements, both in possible range and passengers on board.

The first step is defining the mission profile that generally the aircraft is expected to carry out. Raymer's[1] method proposes a sequential order for attaining this objective: take-off, climb, cruise, descent, loiter, re-climb, deviation, land. It is also deemed important to consider a destination diversion stretch as a sufficiently predictable safety margin in terms of mission accomplishment.

Afterwards, the actual total mass at take-off needs to be calculated, knowing that the Operative Empty Mass (Structures and Board crew) is set. Then it is required to

[1] Raymer, Daniel (2012). *Aircraft design: a conceptual approach.* American Institute of Aeronautics and Astronautics, Inc.

account for the payload mass, calculated as 120 Kg for each passenger, which will amount to 180 at most. So, it is possible to redefine the maximum 0-fuel mass[2] as follows:

$$MZFM = \mathrm{W_p} - \mathrm{OEM} = 65300\ Kg\ (\mathrm{OEM\ approx.\ to\ 43700\ Kg})$$

The fuel mass cannot be estimated as a subtraction between the maximum take-off mass and the other components, since liquid hydrogen density is so low (70.99 $\frac{Kg}{m^3}$) that would result in a big overestimation. So, the evaluation for the propellant has been made considering the tanks' geometry and volume, which are obtained from the aircraft's known dimensions, and considering a thickness parameter.

With 180 passengers on board in economy class, it is possible to embark up to 3804.1 Kg of liquid hydrogen (plus 798.9 Kg for the tanks), making it clear that the aircraft won't reach MTOM, taking off underweight.

Now that the overall mass components are known, it is possible to calculate the possible operational range covered by the aircraft. The operative mission profile is identified considering a loitering stage[3] and a deviation from arrival point so that there is a safety margin in the evaluation. To evaluate this distance, it is required to know the weight fractions of each mission phase, which can be found in Raymer (2012). The ratios must be adjusted, since the consumption will be much lower, due to hydrogen internal energy (3.29 times higher than kerosene's).

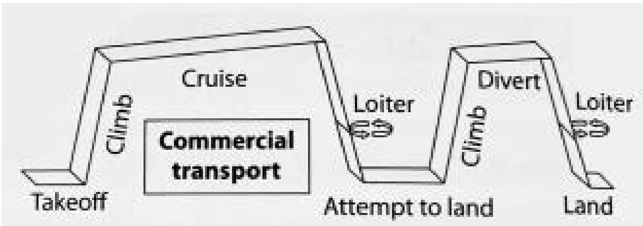


Figure 10: Mission Profile [9]

The table indicating the new fraction is reported below:

PHASE	WEIGHT FRACTION
Take-Off	0.9909
Climb	0.9954
Loiter	0.9975
Landing	0.9985

Table 1: Weight fractions for different mission phases

[2] The parameter written in Figure 8 can be modified knowing it has been roughly estimated for a classic design aircraft.

[3] Mission profile: Take-Off, Climb, Cruise, Loiter, Climb, Landing.

The only unknown quantity is the cruise fraction, which is the most important and can be determined by reversing the fuel mass fraction expression. This data will be important for range calculation, using Breguét's equation for leveled flight, as shown later.

These parameters allow the evaluation of the cruise phase ratio, considering a safety coefficient k_{allow}, and knowing the fuel fraction with respect to take-off mass.

$$\frac{W_F}{MZFM + W_F} = k_{allow}\left(1 - \frac{W_{f_n}}{MZFM + W_F}\right)$$

The last term is the total product between all phases' weight fraction; thus, it is possible to extract $\frac{W_{f_3}}{W_{f_2}}$, which is the cruise ratio, necessary to calculate the range.

Now that all the information is known, the range can be estimated through Breguét's relation:

$$\frac{W_{f_3}}{W_{f_2}} = e^{-\frac{R*TSFC}{V*E}}$$

The other parameters that occur in the formula are either a project fixed value or easily obtainable term, using a path suggested in literature, which accounts for the wetted aspect ratio and surface coefficients to calculate aerodynamic efficiency. Velocity can be traced back to operative Mach number and flight level, meanwhile the specific consumption is deemed known from reference architecture, adjusted for hydrogen's different internal energy [TSFC=0.180 $\frac{\frac{Kg}{h}}{daN}$].

$$V = Mach_{cruise} * \sqrt{\gamma RT_{10Km}} = 245.54\frac{m}{s}$$

$$E = k_{LD} * \sqrt{\frac{AR * S_{ref}}{S_{wet}}} = 19.4$$

The resulting distance has been increased by 400 Km, obtaining a total of 3292.3 Km, so that all the phases are included in the calculation. This outcome is not very close to the requirements edge, which is set at 2000 nautical miles (around 3700 Km), but there is the possibility to study how this aircraft can perform in the continental market, as shown later in this paper. To improve the operative range, a trade-off study needs to be conducted, lowering payload mass, and generating more room for the fuel tanks.

The fuselage internal configuration provides for passengers to be arranged in several rows of 6 people each, up to 150 to 180 seats in total (as a requirement): these numbers have been estimated through a statistical analysis of airplanes like the A320. Starting from the previous case, the calculations were repeated for multiple cases, in which rows were eliminated one by one, adding more fuel as the seat pitch becomes the same value as the tank's depth (72 cm for every row as expected from regulations).

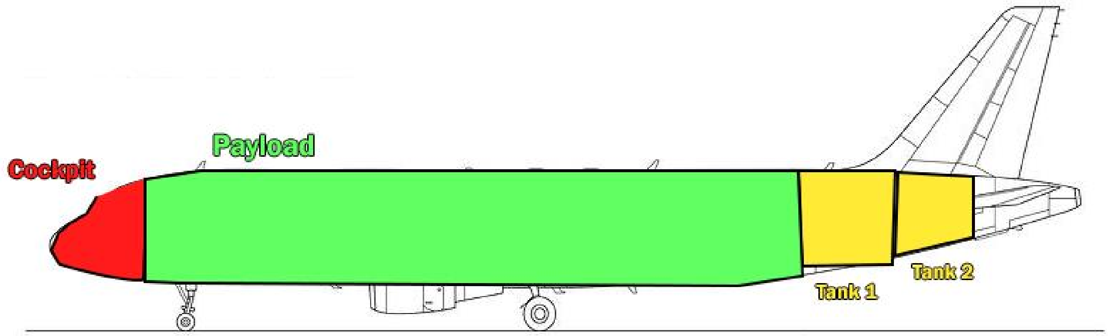


Figure 11: Volume distribution

After ensuring that the new total mass is lower than MTOM, each iteration gives a new result, as shown in the table and graph below. The dashed line indicates the minimum range accepted for the requested mission.

PAYLOAD [KG]	***RANGE [KM]***
19800	3292.3
19140	4023
18480	4761
17820	5506.4
17160	6259.4
16500	7019.9

Table 2: Payload-Range results

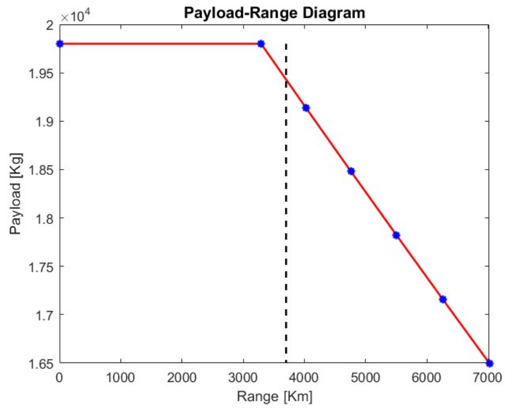


Figure 12: Payload-range diagram

Unlike regular payload-range diagrams, where the tradeoff is studied between payload and fuel weight, for this model each configuration represents a single operative mode, since the aircraft configuration is fixed, and the tanks allocated volume cannot be changed afterward. This means that the obtained curve helps evaluate which can be the best operative configuration to choose, rather than analyze a single internal design that might work for different distances. Spacing from almost 3300 Km to more than 7000 Km gives the opportunity to consider assessing different setups, so that the same concept can generate a family which can cover a wider part of the market, as shown in a later chapter.

The payload-range diagram indicates that both payload and operative distance requirements can be fulfilled, and the results show how the reference aircraft has the possibility to operate like classic state of the art's airliners. To complete the mission profile analysis, it is important to verify take-off condition in terms of total mass on board, therefore the graphical expression is reported hereunder. The image points out immediately how it is impossible to reach MTOM for any given case, forcing the airplane to fly underweight.

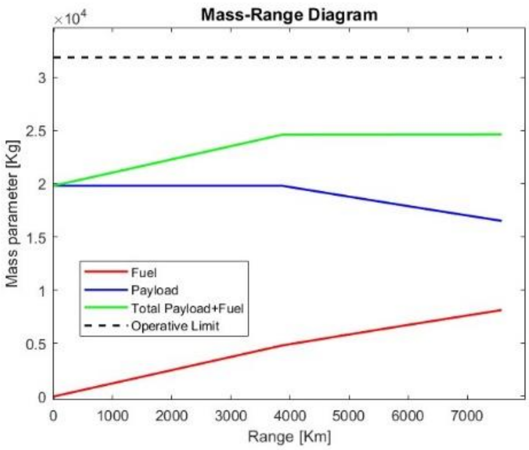


Figure 13: Mass-range diagram

1.2 Matching Chart

Once preliminary operative performances have been evaluated, it is necessary to study design's mechanics feasibility. For each mission phase or condition the aircraft must adhere to flight mechanic requirements in terms of thrust load, which will be expressed as a function of wing loading. In the matching chart all the 6 functions curves considered are expressed, identifying the feasibility zone and the optimized design point.

Physical demands derive from the equation for: stall speed, maximum speed, maximum rate of climb, Take-Off Run required, Maximum range configuration in cruise and ceiling altitude.

Stall speed represents the condition in which the lift coefficient is maximum. This velocity can be derived directly from A320's reference parameter, that is set at 120 kts ($V_s \approx 61.73 \frac{m}{s}$). According to flight dynamics, it is possible to calculate wing loading, using a physical equation.

$$\frac{W}{S} = \frac{1}{2} V_s \rho c_{L_{max}} = 689.92 \frac{Kg}{m^2}$$

Lift coefficient value can be estimated from reference wing geometry, also utilizing literature data[4], knowing that the configuration is "double slotted flap and slat", thus obtaining $c_{L_{max}} = 2.9$. Air density is considered at sea level in standard conditions. In the equation, thrust load is not a factor, therefore the curve will be a vertical line that borders the feasibility zone.

While cruising, the aircraft reaches the highest operative speed - as already expressed previously - which is a fundamental condition of levelled flight. In this case, the physic of the problem is slightly different than the previous case, but it is possible to express the thrust load as shown:

$$\frac{T}{W} = \frac{\rho_0 V_{max}^2 c_{D_0}}{2\frac{W}{S}} + \frac{2K}{\rho_0 V_{max}^2} \frac{W}{S}$$

The maximum velocity is set by the model and already stated above ($V_{max} = 245.54 \frac{m}{s}$), while the unknown parameters can be estimated from baseline books data sheets. For this aircraft class, the 0-Drag coefficient is set at 0.02 and Ostwald's corrective

[4] Sadraey, Mohammad (2012). *Aicraft Design: a system engineering approach.* Wiley Publisher.

coefficient e=0.9. The constant K is expressed as $K = \frac{1}{\pi e AR}$, in which all the data are known. In this curve, as well as the next ones, the feasibility zone is above the line drawn.

During the cruise part of the mission, it is crucial to account for aerodynamic setup of the aircraft, which will be set to maximize kilometrical autonomy. As per flight dynamics equations, in order to achieve such goal, it is required to calculate the ratio $\left(\frac{E}{\sqrt{c_L}}\right)_{max}$. This condition states that the drag coefficient is equal to $\frac{4}{3}c_{D_0}$ and the resulting equation is:

$$\frac{T}{W} = \frac{\frac{1}{2}\rho V_{cruise}^2 c_D}{\Pi \frac{W}{S}}$$

The thrust load is expressed as a hyperbole, a function of the wing loading, in which the cruise speed parameter is the same as the maximum velocity, and the coefficient Π indicates the engine's throttle, which is set at 0.8, since should not be necessary to require full power while cruising.

The fourth equation expresses flight dynamics for the maximum rate of climb, which requires the aircraft to operate at the maximum aerodynamic efficiency. Looking at the A320 and other similar planes the highest operative ROC stands around 2500 ft/min (during the initial part of the ascent).

$$\frac{T}{W} = \frac{ROC_{max}}{\sigma\sqrt{\frac{2W}{S\rho\sqrt{\frac{c_{D_0}}{K}}}}} + \frac{1}{\left(\frac{L}{D}\right)_{max}}\frac{1}{\sigma}$$

All the required parameters of this relation are known, remarking that σ is the ratio between air density at nominal flight level and sea level. The maximum rate of climb is designed for the initial take-off phase, where $\sigma = 1$. Also, for this function, the resulting curve is an expression of thrust load. This expression can be calculated multiple times, considering different segments of the climb phase, for example: Take-off with initial climb (2500 ft/min), from initial climb to FL150 (2000 ft/min), from FL150 to FL240 (1700 ft/min) and FL240 to cruise flight level (1500 ft/min).

Next, it is required to verify that this aircraft can take-off within runway length. Through equations that calculate take-off run, a linear relationship between thrust load and wing loading can be derived.

$$\frac{T}{W} = \frac{\frac{W}{S}}{\sigma\rho_0 l_{TO} c_{L_{TO}}}$$

The lift coefficient for the take-off aerodynamic configuration can be obtained from the peak value, divided by 1.21, as suggested by reference books [Raymer]. The parameter l_{TO} is set at 1800 m and it represents an average runway length available also in medium-sized airports, which are fundamental to serve to maintain aircraft's competitiveness.

The last case we need to account for is when the airplane reaches its ceiling altitude, meaning that it cannot climb any more. Therefore, we can use the same equation found for the rate of climb but setting ROC to 0.

$$\frac{T}{W} = \frac{1}{\sigma\left(\frac{L}{D}\right)_{max}}$$

For this scenario, we need to know σ at ceiling altitude fixed in the model (12500m) which is 0.2456. The thrust load is expressed as a constant parameter so that it will be drawn as a horizontal line above which the design is feasible.

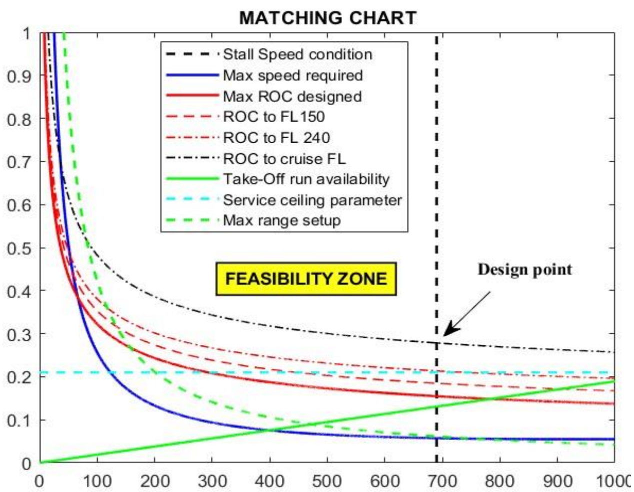


Figure 14: Matching chart

Plotting all equations shown before, it is possible to highlight the feasibility zone and find the design point from which the wing surface and thrust required can be calculated knowing MTOM. Results obtained are aligned with model estimates: Wing Surface=105.09 m^2; minimum required Thrust=99 kN for both engines.

1.3 Center of gravity estimation

Once operative and performance design parameters have been carried out, it is necessary to make sure that the model's preliminary concept is practicable. At first, it is of great importance to understand where the center of gravity is approximately and how it shifts when the configuration changes.

To analyze CoG position, the concentrated mass model has been used, dividing the aircraft into different portions: airframe/fuselage (engines included), fuel (tanks included), payload and cargo bay (rear and front).

The focus is to verify that the barycenter is in front of the main landing gear floor contact point so that the airplane is statically stable while on ground. To simplify the evaluation, CoG Y and Z-body coordinates are considered constants, and the X-body is measured starting from the nose.

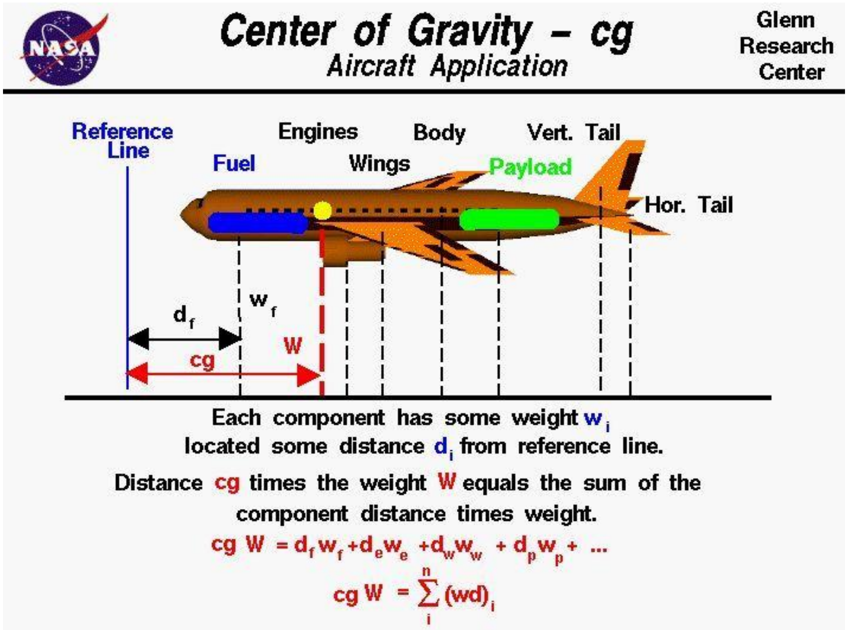


Figure 15: Mass concentrated model illustration [10]

The image shown above is just a general exemplification and does not represent the study case. The aircraft's structure is the only mass that does not vary either in position or weight while changing the configuration with different payloads. The model sets the airframe position at 16 meters from the nose, while its mass is set as the OEM already seen before (43700 Kg).

All the data required (coordinate and weight) are reported below for each iteration. The calculation has been performed likewise for range's evaluations.

PAX	Payload [m-Kg]	Fuel and tanks	Front Cargo Bay	Rear Cargo Bay
180	15.85-16200	30.68-4603	9.94-2250	22.145-3150
174	15.49-15660	30.3-5247.2	9.94-2370	21.715-2850
168	15.13-15120	29.93-3891.4	9.94-2460	21.285-2580
162	14.77-14580	29.54-6535.6	9.94-2580	20.855-2280
156	14.41-14040	29.18-7179.8	9.94-2700	20.425-1980
150	14.05-13500	28.81-7824	9.94-2820	10.995-1680

Table 3: Center of gravity data for aircraft's components

Payload's weight is considered to be distributed between passengers inside the fuselage and luggage weight is placed in both cargo bays. While it does not change position, the front part of the cargo bay must carry more weight when lowering the number of people embarked, since the rear bay gets smaller every iteration due to the increasing fuel tanks' volume.

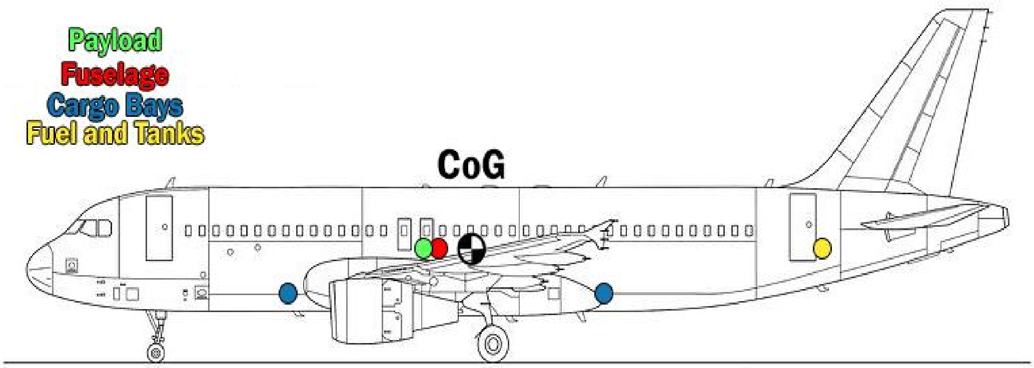


Figure 16: Concentrated mass model used

The formula used to calculate the aircraft's Center of Gravity is repeated for each configuration giving a set of results:

$$X_{CoG} = \frac{\sum_{parts}^{N} X_i * W_i}{\sum_{parts}^{N} W_i}$$

PAX	180	174	168	162	156	150
CoG [M]	17.0137	16.9906	16.9749	16.9540	16.9376	16.9221

Table 4: CoG coordinates in different configurations

The barycenter coordinate does not shift much, which is a good outcome since it validates the aircraft's steadiness. The reference model shows that landing gear touchpoint is designed at 17.71 m from the nose, thus the CoG position is placed in front of it, as requested, also giving enough room to assess a safety margin.

Furthermore, the fuselage's general weight can be higher, since the wing box must be reinforced structurally, due to the lack of counterweight derived from missing fuel in the wing. This could shift the barycenter a little bit more in front.

Granting dynamic stability is a challenging issue since the aircraft's center of mass is behind the focal point of the wing. This configuration can be problematic during flight maneuvers because it strives to magnify perturbations rather than containing them. The focal point is located around the first quarter of the wing, approximately 3 meters in front of CoG, which is hard to compensate.

During the landing phase, having emptied the tanks, the plane might be close to stability or even within the dynamic's requirement, but take-off and climb are a major issue to assess. Like many big aircraft, it is possible to design specific aerodynamic appendages on the wing, such as slotted flaps and slats, that can compensate for instability.

For this study case the external configuration is fixed, using the A320 form factor, but if this was not the case, then also wing's pitch and dihedral angle could be modified to ensure more stability.

1.4 Aircraft operativity competitiveness

One of the most important performance parameters is the market competitiveness since it would be quite useless creating an innovative model which could not fit in today's cost/benefit value or in the foreseeable future. Therefore, the studied aircraft must be analyzed in terms of possible operative routes and compared to existing reference airplanes.

The main benchmark for this study case is the A320 (mainly CEO configuration but also NEO), which has already an extensive operative data sheet. The seating configuration for these planes varies from 140 to 180 passengers maximum (as per Airbus' website [23]), which is the desired target. The nominal operative range is between 5700 and 6200 Km, depending on the configuration.

As already shown in a previous paragraph, the model powered by LH_2 fuel might have a wider spectrum of range possibility, going from 3293 to 7020 Km, due to a big difference in tanks and feed system placing and integration. This feature can be considered both as an advantage and a disadvantage, depending on the operational routes we want to cover, and the geographical areas of interest.

A plane with such seating capability is usually conceived to fly within continental borders, trying to connect major airports and destinations of a geographical area. It is no coincidence that airlines' most numerous flock's model is the A320 or the B737 (both intended as a family), depending on manufacturer.

The two main regions that will be considered are Europe[5] and the US, in which almost every flight is carried out by Airbus or Boeing aircraft. At first a table indicating the distance (in Kilometers) between the main European airports[6] is shown, giving a first glimpse of the model possibilities.

[5] Russia and Ukraine's routes will not be part of the study due to actual geopolitical concerns.
[6] Airports in the table are expressed in IATA code.

	IST	LHR	CDG	AMS	MAD	FRA	FCO	LIS	DUB	VIE
IST	X	2489	2241	2214	2720	1867	1386	3230	2956	1252
LHR		X	348	372	1243	655	1446	1564	450	1279
CDG			X	399	1063	448	1102	1471	787	1038
AMS				X	1459	366	1297	1847	753	962
MAD					X	1420	1334	514	1452	1808
FRA						X	958	1874	1089	624
FCO							X	1844	1889	779
LIS								X	1642	2310
DUB									X	1707
VIE										X

Table 5: European airports distances

When considering the configuration with maximum payload, it is possible to cover almost every European route without a refueling operation, since the available range allows up to approximately 3300 Km. The only critical trip would be between Lisbon and Istanbul airports, which is close to the operational limit.

The United States' geographical area is a bit more critical, since it is bigger than Europe, hence some long-distance routes may be unfeasible for some configuration of the aircraft in the study case. The following table with American airports and their operative distance shows how traditional planes perform better than the one powered by liquid hydrogen.

	ATL	DFW	DEN	ORD	LAX	JFK	LAS	MCO	CLT	SEA
ATL	X	1177	1930	975	3133	1223	2811	650	365	3511
DFW		X	1032	1290	1987	2239	1698	1585	1506	2671
DEN			X	1430	1387	2616	1011	2489	2153	1648
ORD				X	2808	1191	2437	1617	965	2769
LAX					X	3983	380	3569	3420	1535
JFK						X	3618	1519	871	3897
LAS							X	3282	3084	1394
MCO								X	753	4110
CLT									X	3668
SEA										X

Table 6: US airports distances

The classic A320 can perform each trip without any problem, even at its maximum capacity, while the airplane that has been presented in this paper cannot complete the critical trips highlighted above without refueling when at its most payload configuration. The necessity of lowering passenger number, thus modifying the aircraft's configuration, is a significant disadvantage against competitors in the market.

On the other hand, when considering lower payload layouts, the proposed model outgrows its benchmark in terms of operational range. This perk is very useful when some of the shortest international routes are considered, especially the ones connecting Western Europe with United States' Eastern coast.

A clear example is the possibility to reach Atlanta's international airport[7], one of the busiest in the world, even from inland European major airports like Madrid or Frankfurt, which would be impracticable or even impossible for a classic A320 (or similar) without any stopover. Moreover, if Lisbon airport is the departure/arrival point, the LH_2 airplane might reach as far as Memphis International Airport, almost in the middle of the US.

[7] Hartsfield-Jackson Atlanta International Airport.

As already mentioned in the first paragraph, the hydrogen-powered aircraft does not reach its maximum takeoff mass, meaning it will not require a tradeoff between payload and fuel. But this also means that once the configuration is fixed, it cannot be modified to adapt to a different mission.

Although this form factor can highlight the possibility of creating a proper aircraft family, using the points highlighted on the curve in figure 12 to find the best operative conditions and configurations. Even if the aircraft does not perform as well as traditional jets, it can either complete the same routes with similar payload or reach a bit further with just a few less passengers. In addition to that, the LH_2 airplane does a better job in reducing emissions, and it might be suitable for the foreseeable future rather than old traditional planes. For example, both configurations set at 180 or 150 passengers can be two planes of the family described. The first would operate almost only continental, medium-low range flights, while the latter could be used for intercontinental purposes too. Over and above, even a configuration in between would be feasible, and it could be useful to cover all internal routes in the US and other medium-high distances.

CHAPTER 2: LIQUID HYDROGEN AGAINST KEROSENE

2.1 Comparative overview between Jet A1 and LH_2 fuel

As of today, main aviation fuel is a petrol-based kerosene called JET A1, that is extremely refined to prevent uncontrolled ignition, deposition in the pipeline and free electrical charges. This technology is well-known and represents the main performance benchmark to overtake both for emissions and cost.

On a global scale, aviation sector is responsible for 2% of the CO_2 emissions [11], which is around 800 Mt of carbon dioxide produced only in 2022. After the pandemic there was a reduction, but the growing flight number sets the trend for increasing emissions in the next couple years, surpassing 2019 level of CO_2 in 2025. This record shows how this sector is not on track with decarbonization mid- and long-term goals, which require to keep the overall release under 1000 MT of carbon dioxide by 2030.

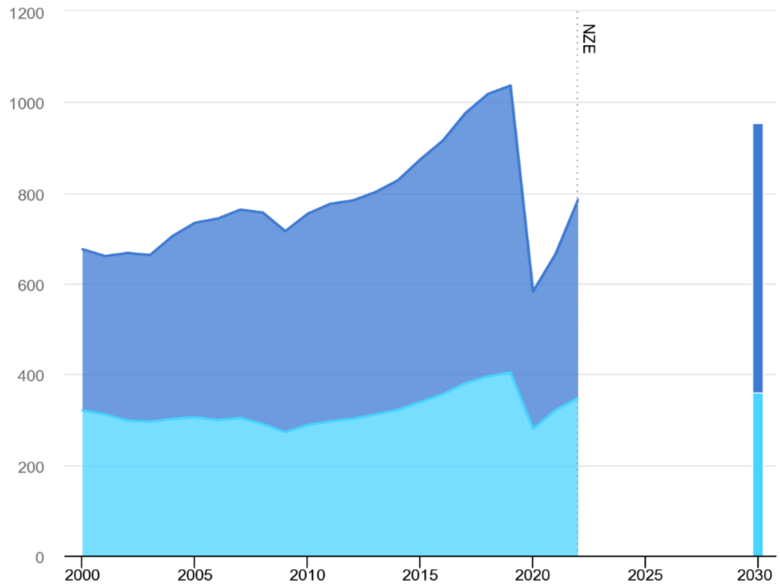


Figure 17: Mt of CO2 from domestic (below) and international (above) aviation [11]

Over the course of the last decade, with new engine options and progressions, fuel efficiency parameters have gotten better each year, apart from 2020 and 2021 for obvious reasons. The IEA report claims that actual efficiency is about 12 MJ/RPK[8] (already at the pre-pandemic level), but the goal for the foreseeable future should be to reduce it to 9.6 MJ/RPK.

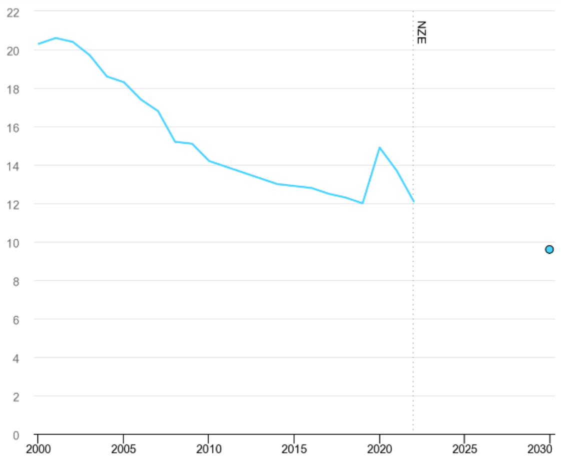


Figure 18: CO2 MJ/RPK trend [11]

This study case focuses on narrowbody airplanes, in particular the A320, which is the main model, similar to the B737-800 too. These two aircraft were responsible for 59% of all the emissions from this type of plane in 2019 [5].

This class accounts also for 53% of the total RPKs, making it the most used one in aviation. The increase of total and relative CO_2 emitted from 2013, due to a bigger flight demand, is a critical factor but carbon dioxide weight in relation to RPKs decreased.

(a) 2013

Aircraft Class	Departures		RPKs		Avg distance [km]	CO_2		CO_2 intensity [g CO_2/RPK]
	Million	% of total	Billion	% of global total		Mt	% of global total	
Regional	10.8	34	305	5	563	50	9	164
Narrowbody	18.2	58	2,903	50	1,262	275	48	95
Widebody	2.51	8	2,597	45	4,431	241	43	93
Total	31.6	100	5,805	100	1,274	566	100	98

(c) 2019

Aircraft Class	Departures		RPKs		Avg distance [km]	CO_2		CO_2 intensity [g CO_2/RPK]
	Million	% of total	Billion	% of global total		Mt	% of global total	
Regional	11.2	29	345	4	551	56	7	162
Narrowbody	24.4	63	4,588	53	1,322	393	51	86
Widebody	3.21	8	3,777	43	4,675	336	42	89
Total	38.8	100	8,710	100	1,378	785	100	90

Figure 19: CO2 emissions by aircraft class in 2013 and 2019 [5]

[8] RPK: Revenue Passenger per Kilometer, a measure of passenger volume per Kilometer flown.

Fuel evaluations are not based upon CO_2 production only. Still, there are cost assessments that must be made, since it constitutes 15-20% of direct operating cost for airlines [24], depending on current prices, actual regulations, competition and technological advances. As per recent estimation, Jet A1's average price around the world is set at $743{,}50\ {}^{€}/_{t}$, lower than the last years but still higher than pre-Covid costs.

The airplane this model is based on, the A320ceo, consumes averagely 2.5 tons of fuel per flight hour [25], meaning that every 60 minutes the airline shall bear 1859 € in burnt fuel. Before the pandemic outbreak, narrowbody planes would fly nearly 169 passengers per trip [Figure 19, [5]], each one carrying $11\ {}^{€}/_{hr}$ in fuel operating cost that the airline needs to address.

The price tag for a plane ticket, which is a fundamental marker for product viability, is calculated on the total direct operating cost of the aircraft, evaluated as $55\ {}^{€}/_{hr}$ for each person on average in 2023.

The leading cause for recent studies, this included, over new fuel sources for aviation is to limit emissions and decarbonize aviation, as proposed in ICAO's long-term goal net-zero CO_2 by 2050. Liquid hydrogen is one of the possible solutions for near and long-term future, as well as full-electric aircraft and the latest Sustainable Aviation Fuels, but these models are very different from one another, each one carrying its own pros and cons. Figure 20 gives a reference for hydrogen's advantages and disadvantages.

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 20: H2 advantages and disadvantages [2]

Even though hydrogen is the most abundant element in the universe, its use is still very little since its molecular form cannot be found in nature, but it is extracted from other sources like water or hydrocarbons. Its versatility, high-energy content, low pollution and availability would make hydrogen look as an ideal aviation fuel, but its main use in transportation is only related to space travels, given that LH_2 has been used as rocket fuel since the 1950s. The possibilities for this power source have been studied for civil aviation too, identifying it as one of the most promising alternative fuel solutions for aviation[9].

To assess viability of a hydrogen-powered airplane, it is required to also evaluate a preliminary life cycle costs model, accounting for capital condition, energy resource utilization, fuel production, airport storage, distribution facilities as well as environmental compatibility. The most recent and complete piece of literature that provides an in-depth analysis over LH_2 LCC for aviation purposes is *Economic and environmental sustainability of liquid hydrogen fuel for hypersonic transportation*[10], which will also be the basis for this study on subsonic aircraft.

Having a major role in the decarbonization process, hydrogen production keeps growing considerably since the 1970s, even though H2 manufacture started in the early part of the 20th century. According to the latest IEA data and other estimations [26], in 2022 the mole of hydrogen yielded was around 95 Mt [Figure 21] (or 500 GW if referring to the energy carried out per time unit if combusted).

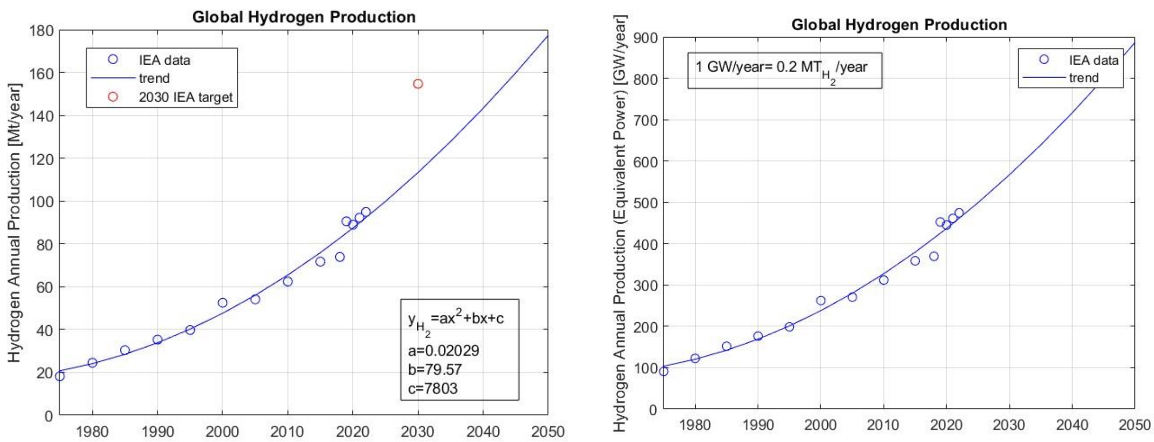


Figure 21: Global hydrogen production

9 Witcofski, R. (1979). *Comparison of alternative fuel for aircraft*, NASA-TM-80155.

10 Fusaro, R. et al. (2020). *Economic and environmental sustainability of liquid hydrogen for hypersonic transportation systems*. CEAS Space Journal 12: 441-462.

Despite its importance, hydrogen is still produced mainly with fossil fuel technology and partially as a by-product of the petrochemical industry [Figure 22 [12]]. These methods are still considered high-emission cycles, while low-emission ones take up less than 1% of the entire production.

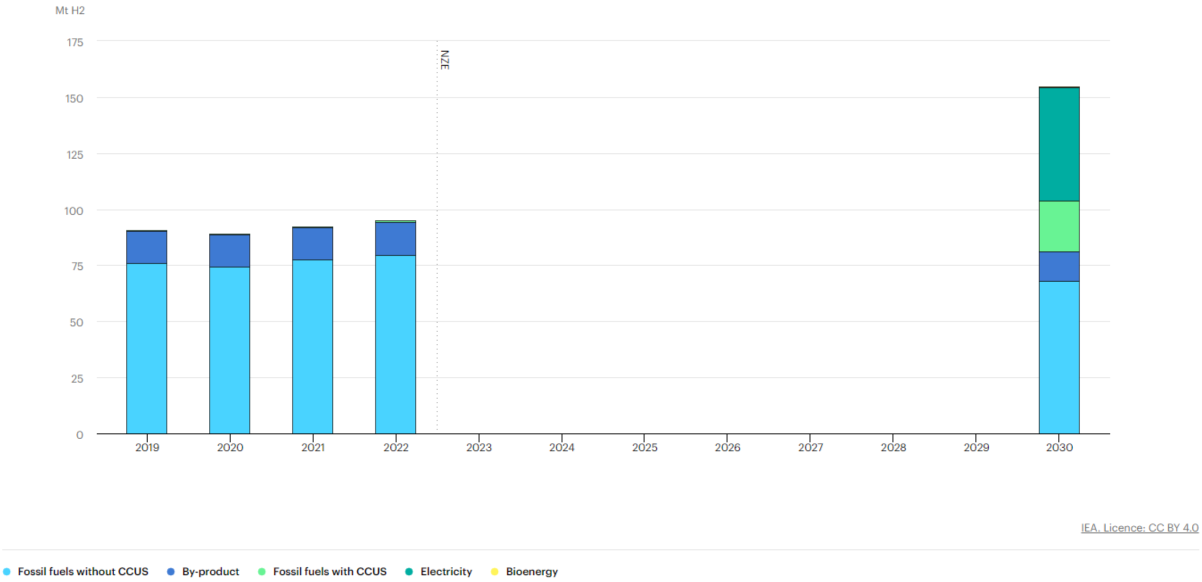


Figure 22: IEA's analysis over current and targeted H2 manufacturing strategies [12]

H_2 manufacture can be categorized into three different colors according to carbon dioxide output in the making: grey, blue and green. In addition to that, hydrogen extraction can be divided into two separate families: from hydrocarbons or from water. The former uses coal and natural gas as a primary source, which have a substantial environmental impact, therefore it is considered “grey hydrogen” due to high CO_2 emissions ($10 - 20\ {}^{kg\ CO_2}/_{kg\ H_2}$). There can be CCUS (Carbon Capture Utilization and Storage) techniques that allow the process to be cleaner, identifying the so-called “blue hydrogen”.

Extraction from water needs to investigate different power sources, considering where the electrical power used for electrolysis comes from or the thermochemical processes in latest nuclear reactors. Depending on energy resources, electrolysers can produce "green hydrogen" which is the one that does not emit carbon in the first place. Figure 23 [13] shows the difference between fuels (kerosene, methane and hydrogen) in terms of CO_2 output for the same heat release.

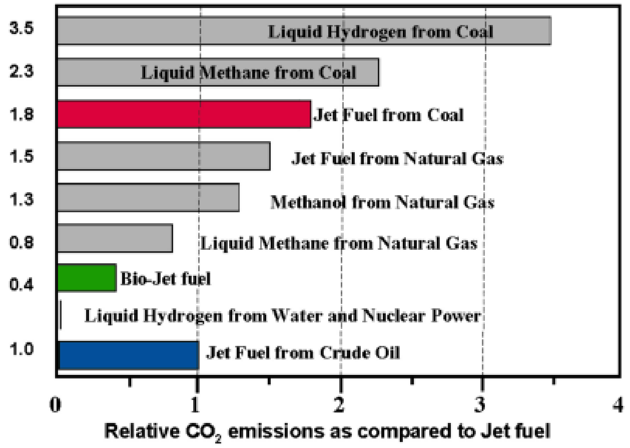


Figure 23: Relative CO2 emission compared [13]

Electrolysis using electricity from fossil fuels produces emissions comparable to hydrocarbon extraction, generating grey hydrogen which is even economically worse than the one derived from coal or natural gas. The other electrical sources, like renewable energies or nuclear plants, allow to contain or avoid CO_2 emissions: in addition to that, they can be favorable in terms of tax regulation and energy density cost.

Nuclear plants use two main approaches, that have emerged as leading contenders for high-temperature water splitting using heat from advanced nuclear reactors: thermochemical cycles and high-temperature (steam) electrolysis (HTE). These processes do not pollute and have virtually zero-carbon emission, but the manufacturing operations require a lot of energy for uranium refining and building infrastructure, which themselves can be the cause of CO_2 production. Thus, it will not be investigated in this study, as well as the radioactive waste produced, which is a different problem to address. From a cost perspective, this production path might show the best compromise between price tag, manufacture and emissions.

Renewable energy power sources have the ability to produce clean "green" hydrogen, using mainly wind energy or solar panel electricity. Turbines for wind farms must be placed far from an urban environment and can be implemented in a hybrid scenario, in which electricity from the grid is in the mix but generates a low emission of carbon dioxide. Solar energy theoretically presents a completely green scenario, keeping net-zero carbon. The cost of sustaining production through renewable energy is still far from market viability, but the trends and new regulations might help funding these new technologies.

The cost model and estimating relationships will be presented in the next section, highlighting the feasibility of liquid hydrogen manufacture as a fuel for aviation, analyzing market competitiveness with current Jet A1 and environmental trends, looking at the near and long-term future.

CHAPTER 3: HYDROGEN COST BREAKDOWN ESTIMATION

3.1 LH2 production and cost model

The technological challenge of producing liquid hydrogen can be divided into two sub-problems: extracting the gaseous H_2 and then liquefying it. The same cost breakdown logic can be used for both applications.

As seen in the previous chapter, the most suitable way of producing hydrogen is to exploit electrolysis methods, possibly using renewable energy as the main electric power generator. Thanks to IEA's database, it is possible to display the current scenario of hydrogen production through electrolysis and develop possible trends for the near and long-term future for plants' output. Not only the electrical demand can be provided by different sources, but there are a few different electrolysis techniques too.

The most used and well-established method is Alkaline water electrolysis, characterized by two electrodes operating in a liquid alkaline electrolyte solution of potassium hydroxide (KOH) or sodium hydroxide (NaOH). The other two approaches that will be taken into account are the Proton Exchange Membrane (fuel cells that use a solid polymer membrane, a thin plastic film that is permeable to hydrogen ions when it is saturated with water but does not conduct electrons), and the Solid oxide electrolyzer cell (a solid oxide fuel cell that runs in regenerative mode to achieve the electrolysis of water or carbon dioxide by using a solid oxide, or ceramic, electrolyte to produce hydrogen gas or carbon monoxide and oxygen).

The IEA G20 report [29] indicates that electrolysis makes up less than 0.1% of all dedicated hydrogen production, as shown in Figure 22 too. The graphs reported below show today's data retrieved from IEA's database and possible trends mathematically fitted.

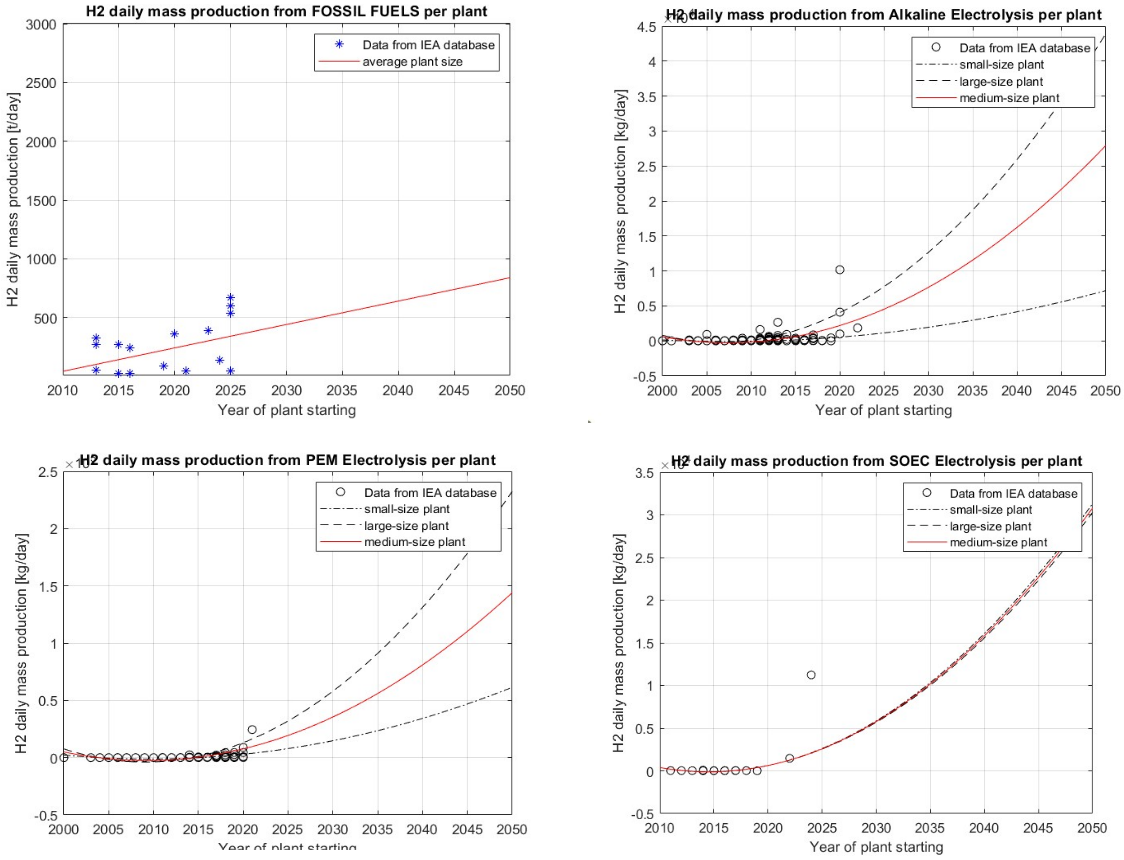


Figure 24: Daily hydrogen production with different technologies

Every different technology comes with advantages and disadvantages, mainly regarding its maturity and cost factors. SOEC is not quite mature as the other mentioned, so it will not be part of the cost estimation, also because uncertain data could give wrong results.

Both H_2 production and liquefaction cost logic breakdown can be described as the sum of three components: CAPEX, EEX, and OPEX, in addition to stock and distribution expenses. CAPEX stands for Capital Expenditures, which are investments made to build and install the dedicated infrastructure, the Electricity Expenditures (EEX) is the price of the required power to run the electrolyser that produce hydrogen and the Operational Expenditures (OPEX) are associated with the operational life of a plant and maintenance required to keep it functional.

The goal is to generate the Levelized Cost of Hydrogen (LCOH), which is the present value of hydrogen accounting for plant's economic life cycle and support, this breakdown procedure is furtherly expressed in Figure 25.

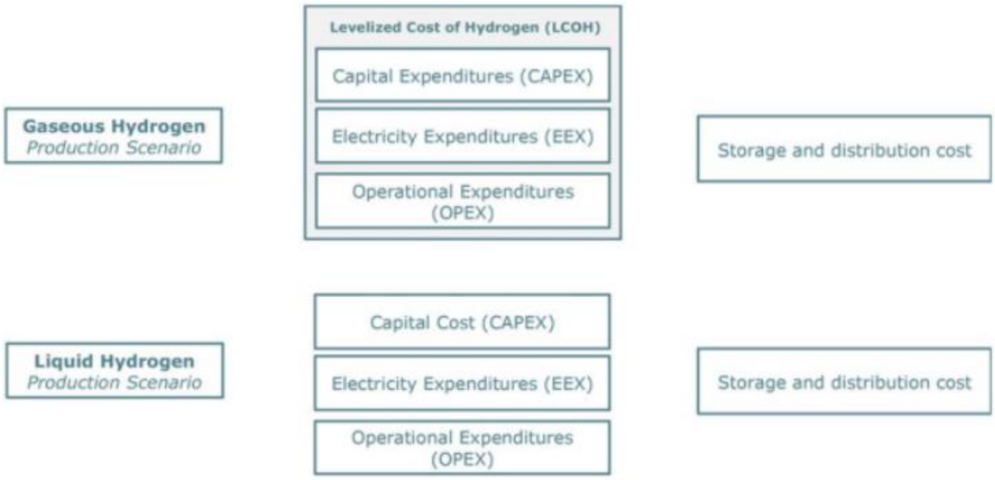


Figure 25: H_2 production cost breakdown structure [2]

The investment required to build dedicated infrastructure is directly linked to the plant's size, the construction year and the type of technology for the electrolysis. The facility's dimension can be expressed as the production capacity and thus as the power installed. Thanks to all information available in [30] and in previous reports [2, 22, 30, 33, 34], it is possible to evaluate the cost investment trend for Alkaline and PEM electrolysers, given in terms of €2022/kW[11]. In the graph below the curves start to converge, showing that even for different studies with different inputs and years there is a common behavior. The results presented are coherent with current official data [12] and latest geo-political development.

[11] Currency value taken on 31st December 2022 as it is the last fiscal full year to obtain precise evaluation.

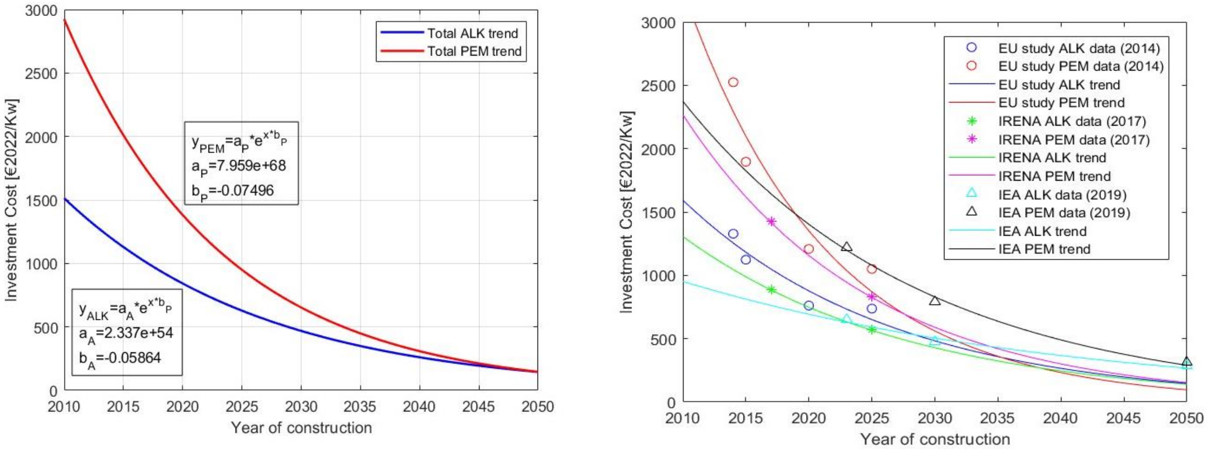


Figure 26: Investment cost per kW for ALK and PEM hydrogen production

The following table presents some notable results, derived from Figure 26, which sums up relative information for hydrogen production. This helps understand the overall situation related to costs and available infrastructure, which are a fundamental input to evaluate capital expenditures. These results, combined with evaluated expectations, validate the model derived from different sources [2, 34].

H_2 production per plant Min-Max (average)[ton/day]	Current scenario (2022)	Near-future scenario (2030)	Long-term scenario (2050)
H_2 from alkaline electrolysis	0.76-5.4 (3.04)	1.95-12.67 (7.67)	7.19-43.93 (27.94)
H_2 from PEM electrolysis	4.71-19.79 (11.9)	14.79-58.04 (35.53)	61.42-232.6 (144.1)

Table 7: Hydrogen production from electrolysis

The current literature and records from IEA show past, present and future projects within hydrogen production, both dedicated and as a by-product. Exploiting the public database, it is possible to collect information about the installed power globally, of which the main results are reported in the next table.

Global installed power [kW]	Current scenario (2022)	Near-future scenario (2030)	Long-term scenario (2050)
H_2 from alkaline electrolysis	17498	34072	120030
H_2 from PEM electrolysis	20999	68030	200645

Table 8: Electrolysis installed power

Having already calculated the trends for the specific investment cost per kW according to different studies and reports, and the correlated power required to operate, a reference value for the investment cost has been made, which is presented in this paragraph for all three scenarios already mentioned.

Investments cost [M€2022]	Current scenario (2022)	Near-future scenario (2030)	Long-term scenario (2050)
H_2 from alkaline electrolysis	11.64	16.06	22.14
H_2 from PEM electrolysis	22.25	44.86	55.33

Table 9: Investments required in electrolysers plants.

To obtain the specific CAPEX, evaluated per hydrogen's kilogram produced, years of activity and operational time of the electrolyser need to be considered. According to the mentioned reports and sources, the investment can be divided into 20 years of activity and, for each year, only 90% of the days is considered as operative. Table 10 presents the specific CAPEX results, highlighting a cost decrease that is expected in the next decades, as hydrogen will become more of a protagonist in the energy scene.

Hydrogen production CAPEX [€2022/Kg_{H_2}]	Current scenario (2022)	Near-future scenario (2030)	Long-term scenario (2050)
H_2 from alkaline electrolysis	0.151	0.107	0.042
H_2 from PEM electrolysis	0.241	0.15	0.063

Table 10: gH_2 CAPEX evaluations

All the outputs obtained and displayed can be considered aligned with other research and papers, even though the numbers are not the same. All the references were written before 2020, in which the Covid outbreak started, also marking an energetic crisis which exploded with the Ukrainian conflict, for these reasons latest policies, incentives and investments around the energy field were very different in the last couple of years. Hydrogen and renewable energy sources underwent a setback which has been followed by numerous growth opportunity due to the urge of finding new energy paths.

Furthermore, the most affected cost item in this cost breakdown is the EEX. The electricity demand to make electrolysis happen is an expenditure linked directly to the energy price, which varies from country to country, and by source (grid or renewable).

Electricity wholesale price course over the last decade has been observed and analyzed, giving out a reliable forecast for future scenarios. Based on accurate reports [35, 36] and latest, post-crisis energy policies, it was possible to obtain results for the electric expenses per kilowatt hour, which has been combined with derived energy demand for production to obtain the energetic monetary cost of a hydrogen kilogram. The following table displays the values calculated for the European Union state of the art electricity production expenditures, which are expected to slightly grow for grid power (0.181 €/kWh to 0.192 €/kWh) while renewable energy price will decrease to favor a green transition (from 0.064 €/kWh to 0.033 €/kWh).

Hydrogen production EEX [€2022/Kg_{H_2}] (EU reference)	Current scenario (2022)	Near-future scenario (2030)	Long-term scenario (2050)
H_2 from alkaline electrolysis (grid source)	2.98	1.98	1.44
H_2 from PEM electrolysis (grid source)	4.12	4.13	4.14
H_2 from alkaline electrolysis (renewable source)	1.06	0.42	0.25
H_2 from PEM electrolysis (renewable source)	1.46	0.87	0.71

Table 11: gH_2 EEX evaluations

Less affected by geographical location, the operational expenditures are roughly estimated as a CAPEX percentage, typically 5%. More accurate research show how OPEX cost is a variable depending on both capital expenditures and plant size as

Megawatt installed. Using the data described in sources [34], a trend can be estimated and so the right percentage can be considered. Having already presented CAPEX evaluation it becomes easy to calculate the specific OPEX per Kg_{H_2} as reported below.

Hydrogen production OPEX [€2022/Kg_{H_2}]	Current scenario (2022)	Near-future scenario (2030)	Long-term scenario (2050)
H_2 from alkaline electrolysis	0.06	0.04	0.013
H_2 from PEM electrolysis	0.09	0.05	0.020

Table 12: gH_2OPEX evaluations

Knowing the cost items for hydrogen production it is now possible to calculate the levelized cost of hydrogen (LCOH), which sets expenses required to produce a single Kilogram of gaseous hydrogen by summing CAPEX, EEX and OPEX:

$$(LCOH)_{gH_2} = (CAPEX)_{gH_2} + (EEX)_{gH_2} + (OPEX)_{gH_2}$$

Results are shown in Table 13 according to power source difference and electrolysis' technology used, for current scenario and future possibilities.

LCOH [€2022/Kg_{H_2}]	Current scenario (2022)	Near-future scenario (2030)	Long-term scenario (2050)
H_2 from alkaline electrolysis (grid source)	3.191	2.127	1.495
H_2 from PEM electrolysis (grid source)	4.451	4.330	4.223
H_2 from alkaline electrolysis (renewable source)	1.271	0.567	0.305
H_2 from PEM electrolysis (renewable source)	1.791	1.070	0.793

Table 13: LCOH total results

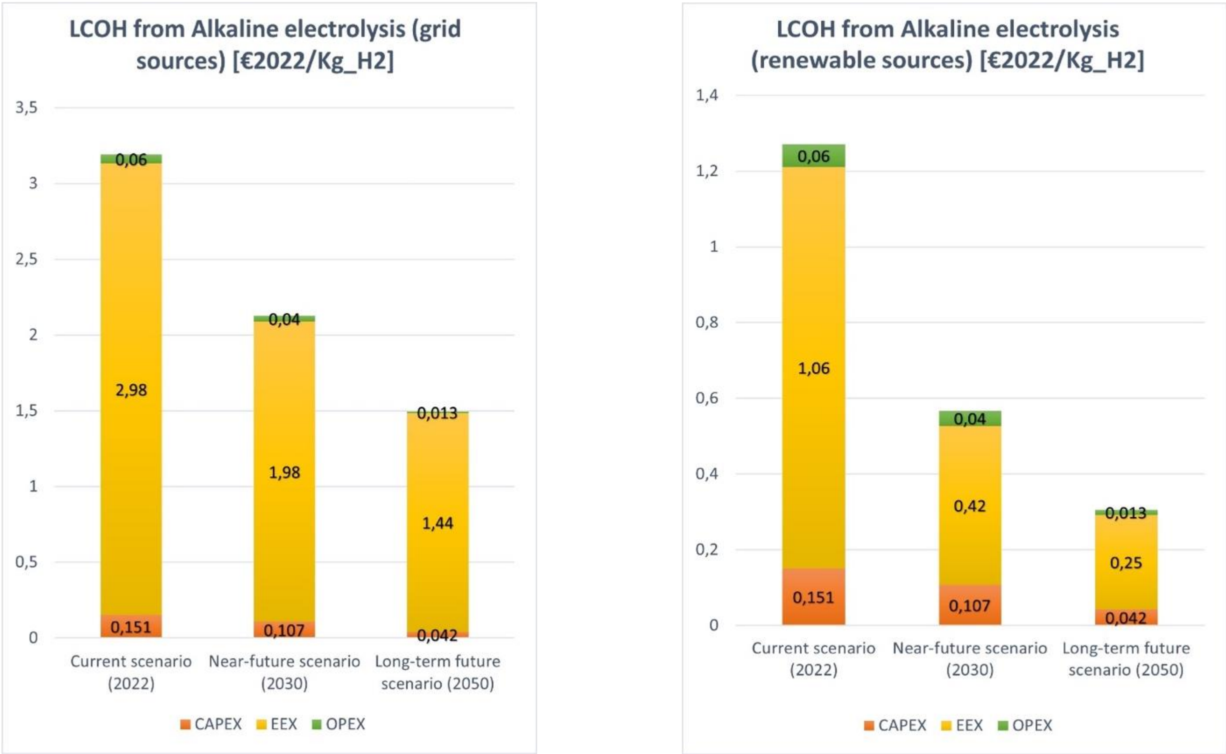


Figure 27: LCOH for PEM electrolysis by source of electricity in multiple scenarios

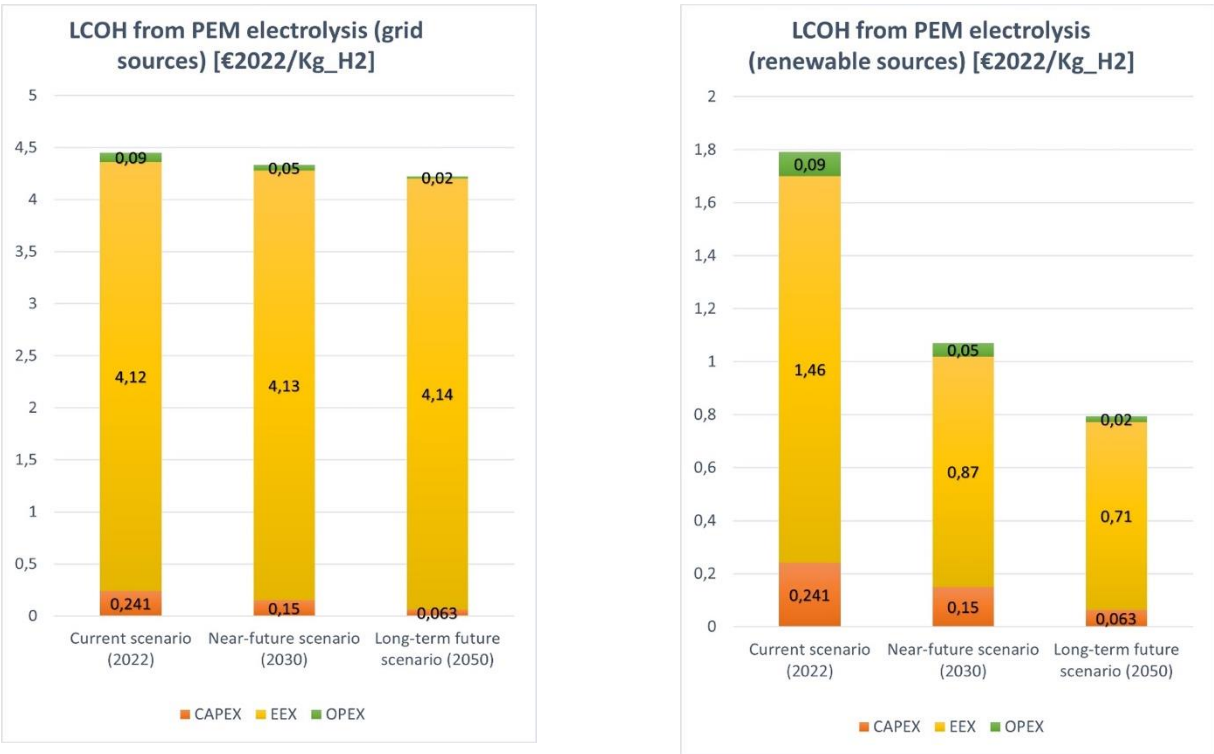


Figure 28: LCOH for Alkaline electrolysis by source of electricity in multiple scenarios

Now that gaseous hydrogen has been assessed, liquefaction process must be considered, which will ultimately give the final product that can be used as fuel, especially for aviation purposes as considered in this study case. Also, for LH_2 cost assessment it will be used the same approach, investigating main expenditures in the manufacturing process.

At first, looking at the current scenario, it is possible to analyze state-of-the-art global capacities, intended as tons produced per day and liquefaction processes available. As of today, there are two main liquefaction methods: the first is Brayton cycle refrigeration, which is well known and mature and requires fewer capital investments, but its smaller production rate (up to 3 ton/day) and limited effectiveness requires more operative expenses, the second is the hydrogen Claude cycle which is more complex and costly, but its high efficiency and bigger production (15 ton/day) help reduce considerably operational costs.

According to different sources [38, 14] today's[12] global production capacity is around 381 ton/day, with a steady growth in the last decades mainly driven by the US and Canada. From 2010 to 2020 there was no capacity development in the European region, with only three facilities operating for a total of 20 tons/day, which data are reported in Table 14. In the meantime, reports show [38] how the United States went from 208 to 241 ton/day, and Canada from 51 to 81, also Japan invested in this field increasing its own production from 21 to 31 ton/day.

Manifacturer	*Country*	gH_2 *Capacity* (Nm^3/day)	LH_2 *Capacity* (ton/day)	*Opening Year*
Air Liquide	France	4864	10	1987
Air Products	Netherlands	2502	5	1990
Linde	Germany	2038	5	2007

Table 14: Hydrogen liquefaction sites in Europe

[12] Latest references are dated in 2020.

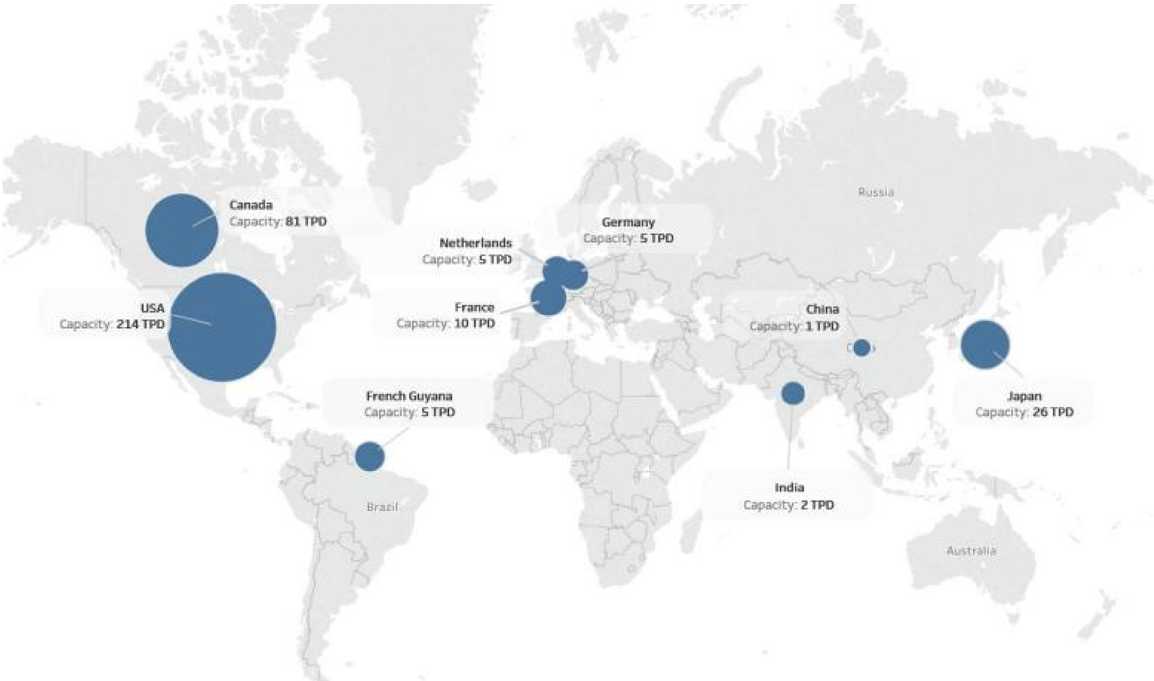


Figure 29: Global liquid hydrogen production capacity in 2016 [14]

The cost estimation for LH_2 will consider different time scenarios too, similarly to the previous part, so that a possible trend can be envisaged. In this case, only one processing method will be treated, the Claude cycle, as it has more efficiency and production, and it is forecasted to be the mainly used one, particularly for the aviation sector. Provided sources give enough data to roughly estimate global production in 2030 and 2050, set as 451.2 and 585.2 ton per day of liquid hydrogen.

Techno-economical information can be gathered from different reports. A DLR study [16] and a DOE analysis [39] give a numerical formulation for investments cost of a liquefaction plant, given its production capacity. Due to their differences in geographical focus, maturity of the field and release year, results will not match precisely, but the estimations will follow the same behavior, making possible to identify a window of acceptable outcomes. Both formulas are reported below, adjusted for today's currency value, and the graph derived from these is displayed in Figure 30.

$$\text{[DLR] Specific Investment} = 1.63 * 828313 * c^{-0.48}\ [\frac{€2022}{Kg/h}]\ ;\ c = [\frac{€2022}{Kg/h}]$$

$$\text{[DOE] Investment Cost} = \frac{1000000 * 5.6 * 1.16}{1.07 * 1.08} * C^{0.8}\ [€2022]\ ;\ C = [\frac{€2022}{ton/day}]$$

In the DLR formula the coefficient 1.63 is the ratio between 2000 and 2022 CPI, used to adjust results to today's value, while other factors are the fitting data gathered. On the other hand, DOE estimation uses 5.6 as the fitting coefficient, 1.16 as plant cost index and the denominator is needed to account for discount rate and dollar to euro conversion. The results obtained are measured in millions of euros, so that is why it is necessary to explicit the factor of a million.

Table 15 summarize results for all scenarios, which are aligned with forecasts and have the same tendency as in older study papers.

As estimated by technological reports from studies and from manufacturers, the average plant life expectancy has been set at 20 years, while keeping a constant 95% load factor for production, giving the numerical data.

Liquid Hydrogen plants CAPEX data	Current scenario (2022)	Near-future scenario (2030)	Long-term scenario (2050)
Capital Investments [M€2022]	206.42-652.5	225.4-747.02	258-919.8
Specific CAPEX [$€2022/Kg_{LH_2}$]	0.08-0.25	0.07-0.24	0.06-0.23

Table 15: Liquefaction CAPEX

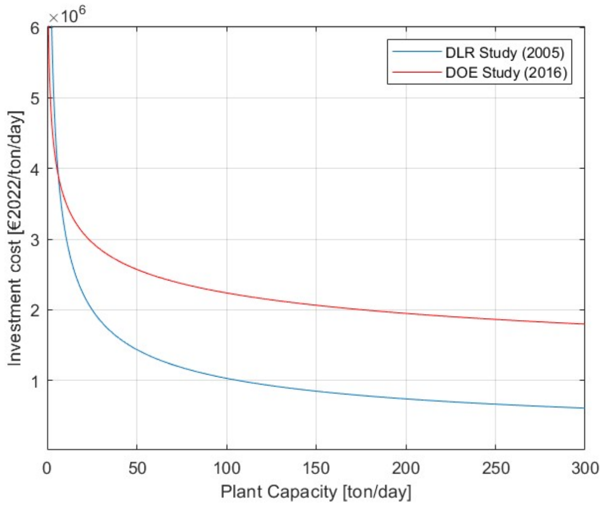


Figure 30: CAPEX trend for liquid hydrogen production scenarios

Energy expenditures depend on the demand required to operate the liquefaction process, which can be taken out from sources that also predict this input for future scenario, according to technology development [2, 40].

Similarly to gaseous hydrogen, EEX is the bigger part of the production cost for LH_2 too, for which the expenses results are shown in Table 16. Electric energy prices were already investigated in the previous section, and same value will be used for this calculation, meaning that expenditures are referred to European standards.

Liquid Hydrogen EEX [€2022/Kg_{LH_2}] (EU reference)	Current scenario (2022)	Near-future scenario (2030)	Long-term scenario (2050)
LH_2 from grid sources	1.95	1.48	1.45
LH_2 from renewable sources	0.69	0.31	0.25

Table 16: Liquefaction EEX

OPEX cost model for liquid hydrogen can be easily derived from study reports [41], which clarify how lower energy demand and better technology efficiency will sensibly decrease operating costs. Current and forecasted data can be interpolated to obtain a trend for OPEX, allowing to calculate the value also for long-term future scenario. Numerical results are reported in the following table.

	Current scenario (2022)	Near-future scenario (2030)	Long-term scenario (2050)
Hydrogen OPEX [€2022/Kg_{LH_2}]	0.22	0.035	0.02

Table 17: Liquefaction OPEX

Just like for hydrogen extraction, adding all cost items for the liquefaction process can give out the Total Liquefaction Cost (TLC):

$$(TLC)_{LH_2} = (CAPEX)_{LH_2} + (EEX)_{LH_2} + (OPEX)_{LH_2}$$

Table 18 shows all the numerical results, from which it is possible to notice that having large production sites, working mostly with electricity from renewable sources, is the most suitable way to keep hydrogen cost as low as possible, as well as the gas extraction.

TLC [€2022/Kg_{LH_2}]	Current scenario (2022)	Near-future scenario (2030)	Long-term scenario (2050)
LH_2 from grid sources	2.25-2.42	1.59-1.76	1.53-1.70
LH_2 from renewable sources	0.99-1.16	0.42-0.59	0.33-0.50

Table 18: TLC results

Trends displayed in Figure 32 and further analysis take into account just the median value of the specific capex of a liquefaction plant, since in Figure 30 it is clear that the equations do not converge.

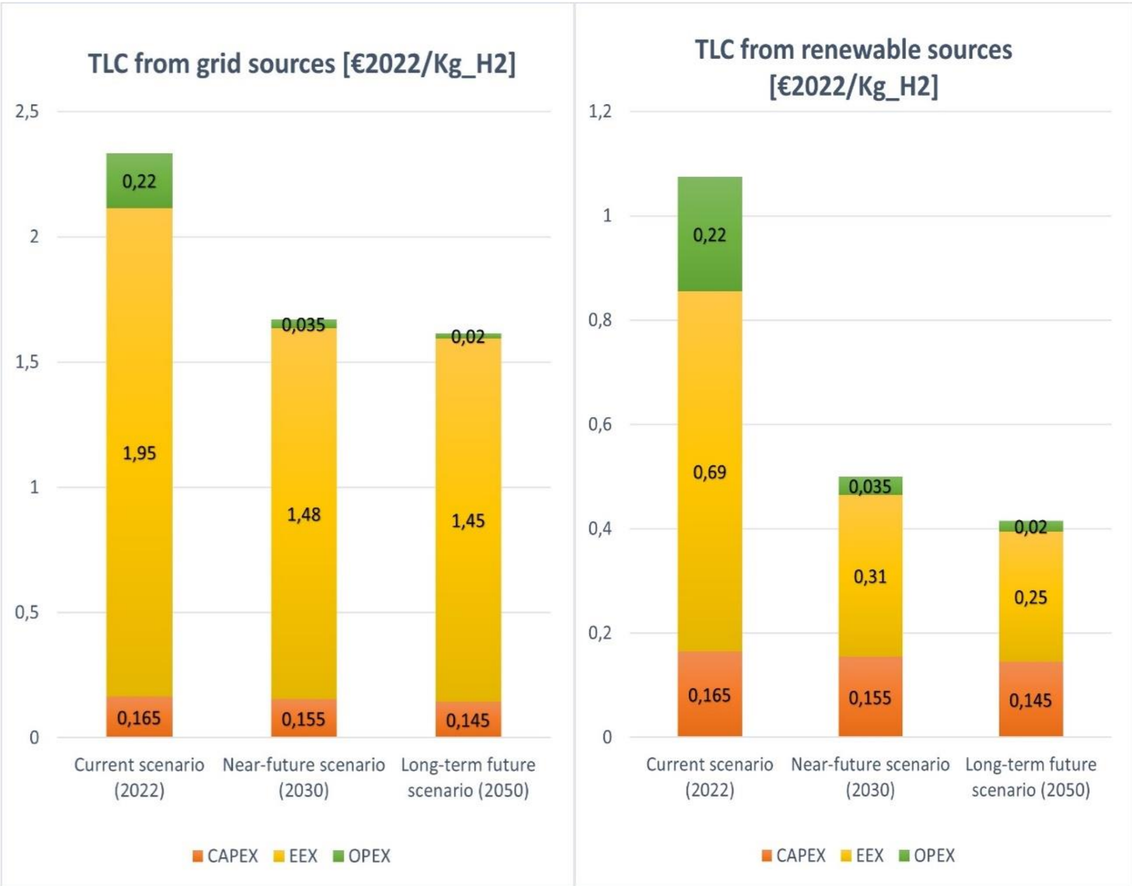


Figure 31: Total liquefaction cost breakdown by source of power

Combining LCOH and TCL the Levelized Cost of Hydrogen (LCOH) is achieved, which allows to comprehend expenditures to generate one kilogram of hydrogen. The overall results are reported in the subsequent chart, in form of little ranges due to liquefaction uncertainties.

TCOH [€2022/Kg_{H_2}]	Current scenario (2022)	Near-future scenario (2030)	Long-term scenario (2050)
H_2 by alkaline electrolysis and liquefaction from grid sources	5.44-5.61	3.81-3.98	3.03-3.20
H_2 by PEM electrolysis and liquefaction from grid source	6.70-6.87	5.92-6.09	5.75-5.92
H_2 by alkaline electrolysis from renewable source and liquefaction from grid	3.52-3.69	2.16-2.33	1.84-2.01
H_2 by PEM electrolysis from renewable source and liquefaction from grid	4.04-4.21	2.66-2.83	2.32-2.49
H_2 by alkaline electrolysis from grid source and liquefaction from renewable sources	4.18-4.35	2.64-2.81	1.83-2.00
H_2 by PEM electrolysis from grid source and liquefaction from renewable sources	5.44-5.61	4.75-4.92	4.45-4.72
H_2 by alkaline electrolysis and liquefaction from renewable sources	2.26-2.43	0.99-1.16	0.64-0.81
H_2 by PEM electrolysis and liquefaction from renewable source	2.78-2.96	1.49-1.66	1.12-1.29

Table 19: TCOH from different cases and scenarios

The electric power source can be mixed when differentiating H_2 extraction and liquefaction, but it is possible to assume that both facilities can have mixed source themselves. Especially in most western countries, due to latest environmental policies and public opinion pressure, many different plants draw electricity from both grid and renewable sources with varying percentages. Figure 32 show the cost trend when sustainable energy ranges from 0 to 100%, also considering a mix in Alkaline and PEM electrolysis technology calculated upon available data listed in Table 9[13], since there is not a fixed ratio or an analogous trend within those methods.

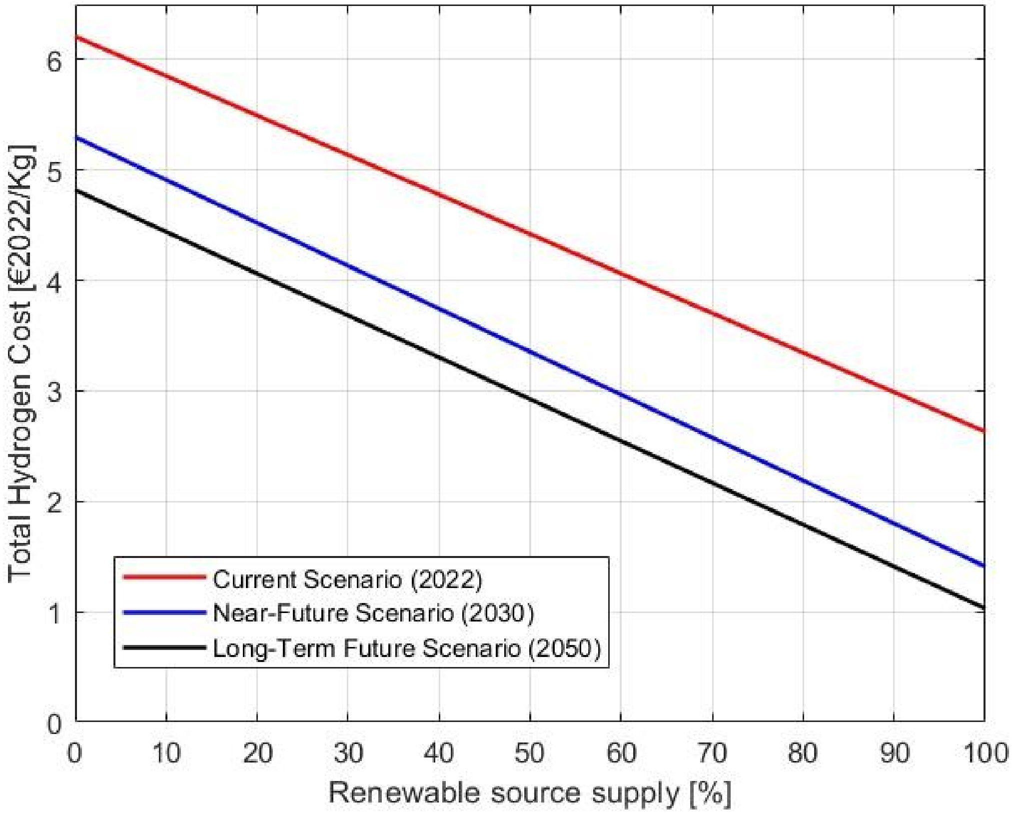


Figure 32: TCOH trend for different renewable energy supply percentage

According to IEA's prediction [15] portrayed in figure 33 for total hydrogen cost in 2050, the goal set for LCOH is between 1.3 and 3.3 $€/Kg_{H_2}$, which is comparable to the obtained results. To furtherly validate the cost model used in this paper, it is possible to observe that the actual hydrogen production cost is within range estimated by IEA.

In order to assess the competitiveness of hydrogen as a fuel source it is necessary to establish a benchmark price, which will secure LH_2 better or similar cost efficiency to actual jet fuels. Based on BEE[14] methodology this value can be set at 2.3 $€/Kg_{H_2}$, which is going to impact A320 redesigned model Direct Operating Cost of fuel, that would have to be comparable to current value with Jet A1.

[13] Alkaline-PEM mix [in %]: 45.5-54.4 (2022); 33.4-66.6 (2030); 37.4-62.6 (2050)
[14] Best Engineer Estimate.

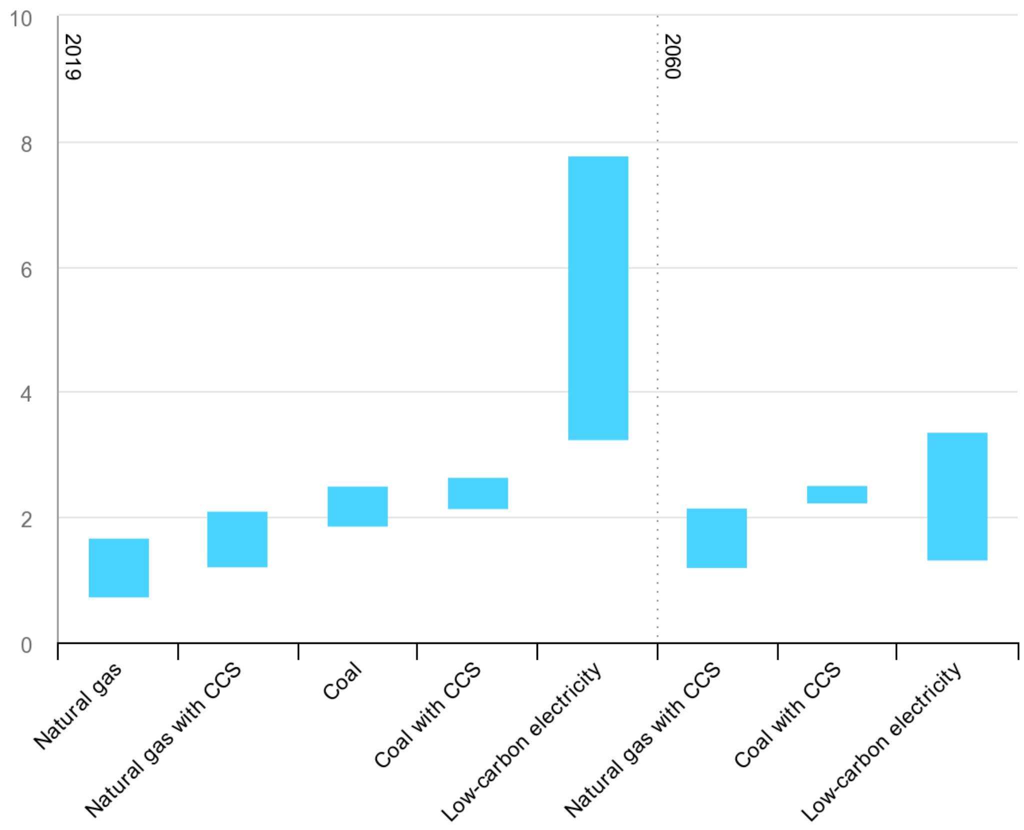


Figure 33: Total hydrogen cost forecasts [15]

As of today, the price goal cannot be achieved without using any grid source for electric demand. Future scenarios trends displayed in Figure 32 show how hydrogen can become a viable option when using a certain amount of renewable energy, such that the total cost per kilogram can be the same or lower than the fixed goal. Table 20 contains numerical data displayed in Figure 32, highlighting in which cases TCOH is acceptable.

Electricity from renewable sources [%]	TCOH (2022) [€2022/Kg_{H_2}]	TCOH (2030) [€2022/Kg_{H_2}]	TCOH (2050) [€2022/Kg_{H_2}]
0	6.21	5.30	4.82
10	5.85	4.91	4.44
20	5.49	4.52	4.06
30	5.14	4.13	3.68
40	4.78	3.74	3.30
50	4.42	3.36	2.93
60	4.06	2.97	2.55
70	3.70	2.58	**2.17**
80	3.35	**2.19**	**1.79**
90	2.99	**1.80**	**1.41**
100	2.63	**1.41**	**1.03**

Table 20: TCOH per different percentage of renewable energy

The chart helps understand that renewable energy sources are a key factor in lowering hydrogen cost, already in the next future it is possible to consider LH_2 as a market-cost-competitive fuel when around 80% of production energy demand comes from green electricity. For the long-term scenario even just 70% could be enough to meet the price goal.

Starting from raw materials to actually refuel an aircraft with liquid hydrogen it is not enough to consider production and liquefaction as the only cost items. As already cited in Figure 25, part of the final dispenser price is made by transportation, stock and refuel services that an airline needs to have. Reference study report [2] focuses also on risks associated with shipping facilities, claiming rightfully that likely the best option is to minimize the distance between the airport and the liquefaction sites.

In this paper carriers', technology will not be explored but the main target will be to understand the impact on hydrogen's price of delivery and storing services, when coming from on-site facilities or off-site facilities. Schematic differences between possibilities are explained in sources [18] and reported in Figure 34, in which the green energy sources were investigated.

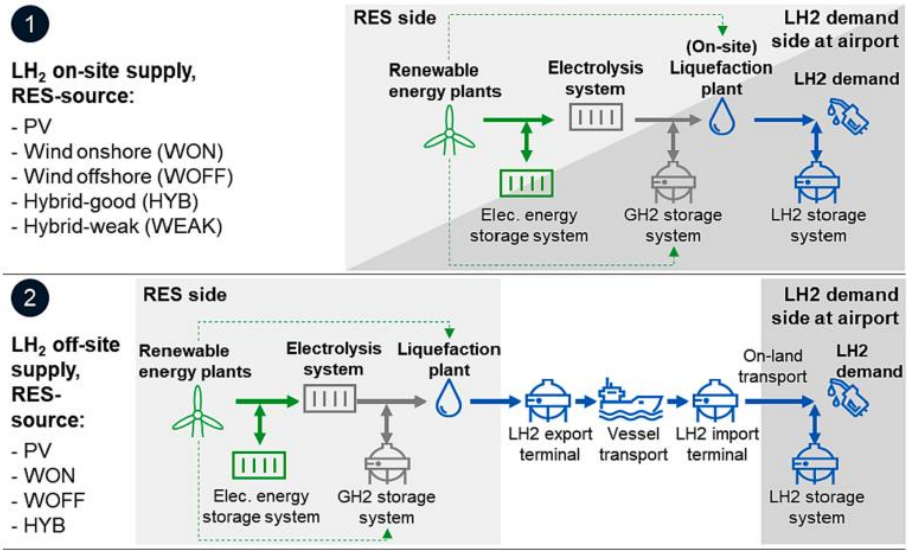


Figure 34: On-site and off-site supply chain [18]

In today's scenario, there are not many ways or facilities to transport liquid hydrogen, due to actual low demand in the aviation sector. Thanks to experiences made from refueling rocket launchers, different technologies and ground services can be acknowledged. The most viable options are Vacuum-Jacketed Pipelines, Railroad-tank car and Truck trailers, which have different costs depending on the distance that needs to be covered in terms of total investment. To assess the specific cost of ground services per hydrogen kilogram delivered it is possible to observe, from different reports [2, 17], that the expenditure is around 7% of the total cost at delivery, depending on proximity, plus the specific cost for transport for off-site production. Due to long distances that need to be covered on average (more than 3000 Km via vessel plus 300 Km with trucks), this expenditure is approximately estimated at 0.62 €2022/Kg_{LH_2} [18].

Considering all the factors already mentioned it is possible to roughly estimate the actual hydrogen cost at delivery for the current scenario, keeping the same technology mix and taking 70% of the required electricity from renewable sources.

Hydrogen cost delivered [€2022/Kg_{LH_2}]	Current Scenario (2022)
On-site production plant	3.98
Off-site production plant	4.65

Table 21: LH_2 price at nozzle today

Results obtained in Table 21 are aligned with the sources' possible range of value [17], in which cost criticalities are explained with respect to classic kerosene, clarifying how today's LH_2 price impacts operating cost too much with respect to Jet A1.

These data gathered help understand the current situation but aiming at making the hydrogen market valuable by 2050, which is the horizon for the Net Zero Emission goal, future trends must be analyzed. These are directly derived from sources [18], which estimate the final price of delivered LH_2 based on the annual production, on-site or off-site production, and which green energy source is used[15]. Storage and refueling cost items are foreseen to be 4-5% of the total cost in the near- and long-term future, while planned enlargements of the transportation infrastructure could lower its specific expenditure to 0.42 €2022/Kg_{LH_2} by 2035 (average distance estimated under 3000 Km via vessel plus truck transport).

Figure 35 shows the graphical trend of liquid hydrogen price at nozzle for on-site production, from which numerical data can be grossed up. Results are comparable to this paper's cost model so further analysis in the next chapter can be considered reliable.

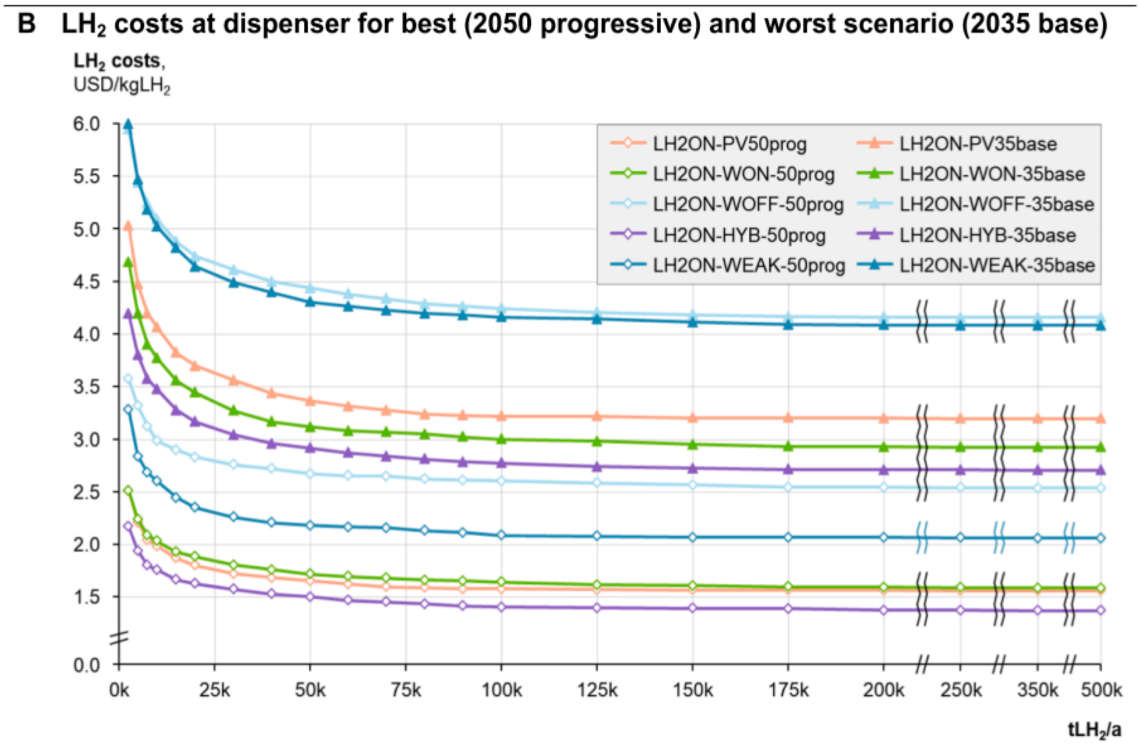


Figure 35: LH_2 delivered cost for future scenarios from green sources [18]

[15] For this study case only Solar panels, Onshore wind and offshore wind are considered.

Latest reliable predictions and reports suggest that transportation costs could decrease further, becoming a stable expenditure set around 10% of the total hydrogen cost at delivery, thanks to growing demand and new means of carry. This scenario, coupled with the realistic possibility to supply energy from renewable sources alone could make hydrogen a viable fuel from an economic and operational point of view.

For the sake of completeness, Table 22 shows the numerical data for TCOH considering both on-site and off-site production in future forecasts.

Hydrogen cost delivered [€2022/$\boldsymbol{Kg_{LH_2}}$]	Near Future Scenario (2030)	Long-Term Future Scenario (2050)
On-site production plant	2.72	2.26
Off-site production plant	3.16	2.52

Table 22: LH2 price at nozzle trend

These projections are aligned with IEA's [Figure 33 [15]], but they are over the benchmark price set in the previous analysis, except for on-site production in 2050 which is just below it. To further lower LH_2 cost at nozzle, there should be a bigger exploitation of green energy, which is cheaper.

Until now, the cost model has considered only the green hydrogen production, which is supposedly the most sustainable way of producing H_2. As seen in Chapter 5 and Figure 36, in today's world the manufacture of hydrogen comes mainly from other sources like coal or natural gas.

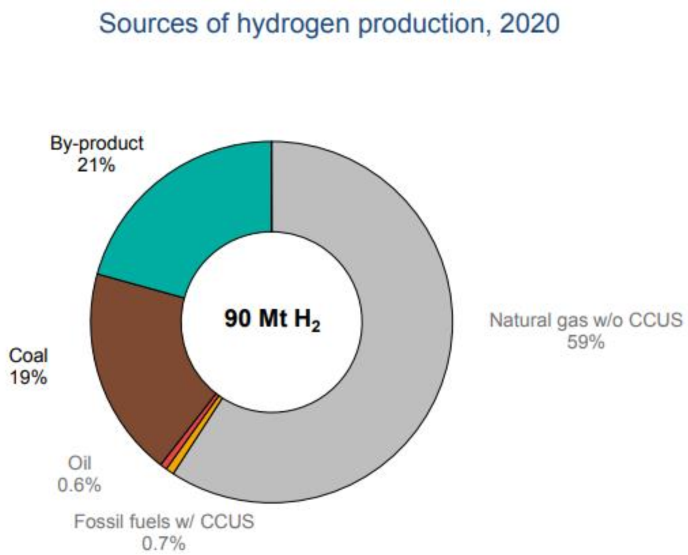


Figure 36: Hydrogen production by source in 2020 [22]

Insights about the cost breakdown structure for grey and blue hydrogen production will not be investigated in this study, but for the sake of completeness the final price per Kilogram is reported below here in Table 23. Value shown are derived from Figure 35 and all the fees related to transport services and ground support are not included.

Manufacturing method	**Hydrogen color**	TCOH $[\frac{€2022}{KgH_2}]$
Coal Gasification w/o CCUS	Grey	1,77-2,33
Steam Methane reforming w/o CCUS	Grey	0,65-1,49
Coal Gasification with 98% CCUS	Blue	1,96-2,42
Steam Methane reforming with 93% CCUS	Blue	1,12-1,96

Table 23: TCOH for grey and blue hydrogen

For all of the cases displayed, the total cost of hydrogen is lower than the electrolysis process, which makes blue and grey hydrogen more appealing from an economic point of view. The downsides of these methods are obviously emission, which will be investigated later, and the fact that overall price, considering transportation services, is still not super competitive with respect to Jet A1 fuel, as it will be portrayed in the next chapter.

3.2 Operating cost analysis

After identifying possible forecasts on liquid hydrogen's price at distribution, it is required to evaluate its economic competitiveness in the aviation field, which is powered almost only by kerosene-based fuels as the Jet A1.

Literature and sources [17, 42] about aircraft operating costs suggest calculating expenditures over Available Seats per Kilometer (ASK) to address the potential of the airplane. The comparison investigated in this chapter will be between the reference A320 and the hydrogen-powered equivalent. Using its own payload-range diagram [43] and data from Airbus, two possible scenarios can be derived: the first one considering 180 passengers with lower fuel and the second with lower payload (150 passengers) but fully loaded in fuel.

This distinction allows an equal comparison with maximum and minimum payload fixed configurations for the hydrogen-powered version, mentioned in the first part of this study. The evaluation is simply made using given information and considering fuel price as mentioned in a previous section[16], while for LH_2 benchmark price will be considered. All the values reported in Table 24 are the outcome of the analysis suggested [42], using a simple equation:

$$Specific\ Fuel\ Operating\ Cost\ [\frac{€}{ASK}] = \frac{Fuel\ [Kg]\ \times\ Fuel\ Price\ [€/Kg]}{Pax \times Range[Km]}$$

	A320 (Max Payload)	A320 (Max Fuel)	LH_2 aircraft equivalent (Max Payload)	LH_2 aircraft equivalent (Max Range)
Number of passengers	180	150	180	150
Range [Km]	5700	6200	3292	7020
Fuel on board [Kg]	19360	21760	3804	6466
Specific operating cost [$\frac{€}{ASK}$]	0.0141	0.0174	0.0148	0.141

Table 24: Aircraft operational reference data

[16] Jet A1: 0.7435 €/Kg

This method is used also by NASA [44] to calculate the fuel Direct Operating Cost (DOC_{fuel}), which is furthermore validated by results obtained for subsonic aircraft in other papers [2]. Applying NASA's equation, outcomes would be analogous, with little differences due to fuel reserve evaluations.

From the results displayed, it is possible to observe that hydrogen-powered aircraft, considering a standard fixed setup, are more cost efficient when are intended for higher ranges, unlike traditional planes that are conceived to maximize payload capacity while optimizing all the other parameters. This difference in behavior might be a consequence of the fact that today's airplanes cannot have both maximum payload and fuel, but they have to trade off in order to not exceed MTOW. As seen in a prior section, LH_2 aircraft will not reach the designed Maximum Take-Off Weight due to hydrogen's very low density. The other factor that plays a big role is the major internal energy of hydrogen, which helps to contain the fuel mass needed, allowing for comparable distances as kerosene planes.

Assessing what percentage of total operating costs is made by the fuel part is not as straightforward as it might seems, because it depends also on which country and airports the plane would operate in, airline policies and variable fuel price. Looking at cost breakdowns proposed in literature [17, 42], this value can vary between 22 and 27%, since the A320ceo is not as efficient as other aircraft of the same family, latter percentage will be considered. To simplify the tricky estimation of operating costs all the other components of DOC will be considered constant between both configurations and both fuels. Figure 37 shows how fuel operating cost occupies a different percentage of total operating expenses when switching to liquid hydrogen power generation.

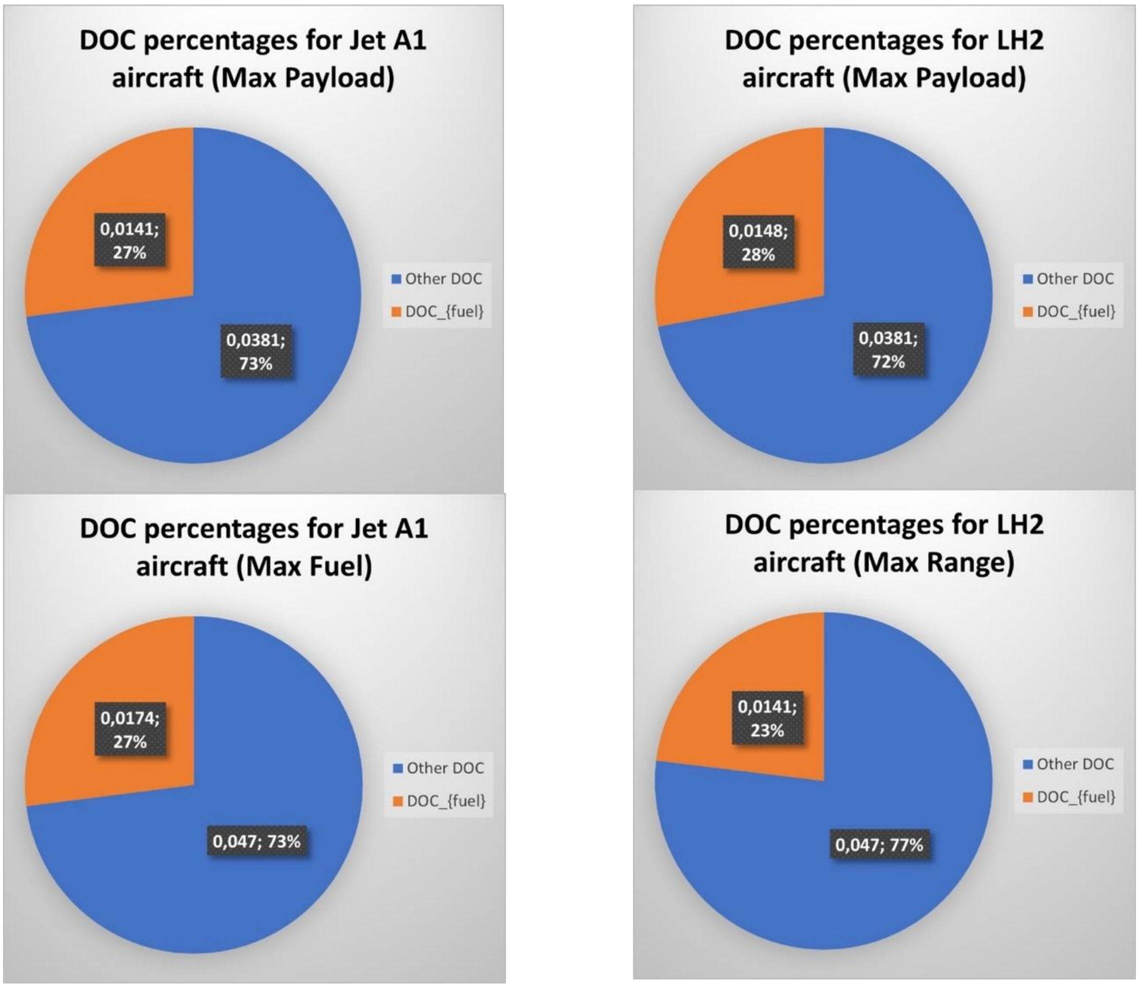


Figure 37: Fuel DOC value and percentage for different configurations [€/ASK]

As said before, in order to get an improvement in cost efficiency, a plane with further range and fewer passengers has to be considered, so that from a market perspective it is preferable to a standard one. In addition to that airlines might consider an adaptation of standard models if overall savings will cover investments for the changing propulsion system.

On the other hand, the fixed configuration with a lower range and more passengers is a little more expensive, meaning that a potential adaptation wouldn't be considered an option from an economic perspective. A liquid hydrogen propulsion system, in this case, might be considered for new aircraft, that won't need adaptation, even if they are more expensive than traditional ones. This possibility could be realistic if new, strict laws and standards towards decarbonization take place, especially in the Western world, in which governments tend to look after this huge problem proactively.

Containing emissions is a fundamental step toward the NZE target mentioned in previous parts of this report. All the evaluations made before, both from a feasibility and economic perspective, have a counterpart when looking at the CO_2 emitted. Trying to eliminate carbon dioxide from aviation is the main driver that leads studies on new forms of energy such as liquid hydrogen. In the next chapter, a comparison between today's emissions and hydrogen's impact on the environment will be analyzed.

CHAPTER 4: ENVIRONMENTAL SUSTAINABILITY OF LH2

4.1 CO_2 emission analysis and comparison

From an environmental perspective, aviation sector is surely part of greenhouse gas emission problem. As already cited in a prior chapter, 2% of the entire carbon dioxide emissions is made by this field, mainly due to the combustion of kerosene fuel that powers aircraft engines.

According to multiple sources and as laid down by the FAA [45], the estimation of CO_2 produced by Jet A1 fuel when burnt is well known, giving out a ratio of $3.16\,\frac{KgCO_2}{KgA1}$.

Using A320 configurations shown in table 24 it is possible to estimate the emission per ASK, in order to identify a benchmark of the current state of the art that needs to be improved.

	A320 (Max Payload)	A320 (Max Fuel)
Specific CO_2 emissions [gCO_2/ASK]	59.6	73.9

Table 25: Current operative emission

These results are lower than expected, considering data from Figure 19, but they are coherent with information gathered about the aircraft. Another explanation might be that this outcome is an evaluation of the best operating scenario, while airplanes do not operate under optimum conditions actually.

Theoretically, hydrogen-powered aircraft will not produce any carbon dioxide when combusted, but it is necessary to analyze the upstream and midstream emissions made by the manufacturing process. In this study report H_2 production from electrolysis has been the main focus, but as mentioned in previous parts of the paper, today's hydrogen production is led mainly by Coal gasification and Steam Methane reforming, which might use CCUS technology.

Grey and blue hydrogen are the products of these manufacturing methods, which means that there are emissions of CO_2, with different magnitudes, as cited in Chapter 2. Overall emissions of greenhouse gases, differentiated by source, in reported in figure 38 [19], which account also for grid electricity carbon dioxide production. Numerical results of interest are furthermore reported in Table 26, which considers only the main manufacturing methods.

Manufacturing method	**Hydrogen color**	Production emission $[\frac{KgCO_2}{KgH_2}]$
Coal Gasification w/o CCUS	Grey	21.5
Coal Gasification with 98% CCUS	Blue	1
Steam Methane reforming with 93% CCUS	Blue	2.9
Electrolysis (grid powered)	Green	23.5
Electrolysis (renewable sources)	Green	0

Table 26: Total emission from different types of hydrogen

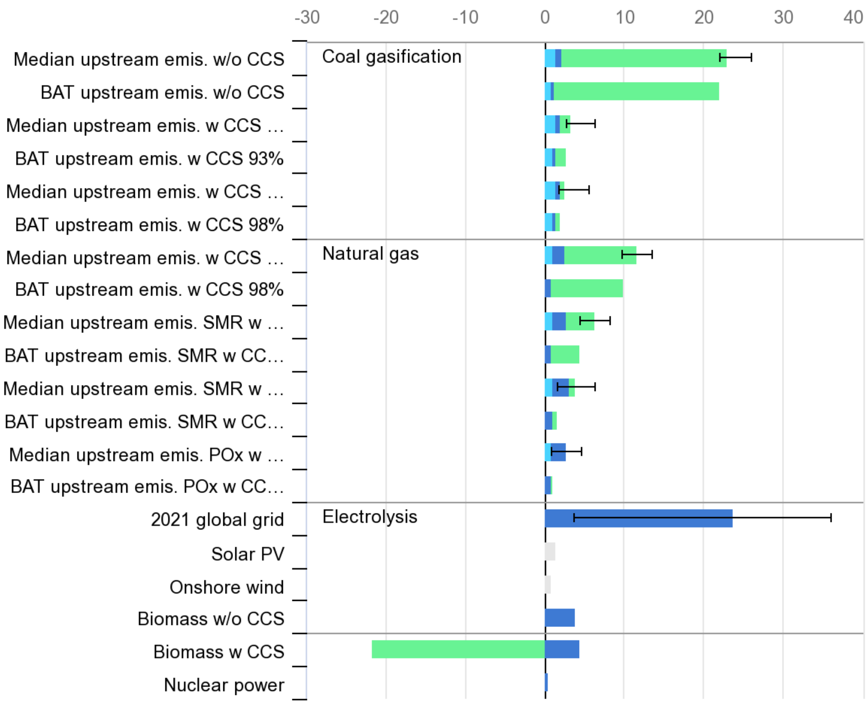


Figure 38: CO_2 production by hydrogen production source [19]

Even though the hydrogen produced by electrolysis is always considered "green", if electricity is derived only from grid sources the upstream carbon emissions are higher than CO_2 produced by the coal gasification overall, even without CCUS.

Knowing these results, it is now possible to evaluate specific emissions also for hydrogen powered aircraft, using the fixed configurations already cited in this paper and displayed in Table 27.

Specific CO_2 emissions [gCO_2/ASK]	LH_2 aircraft equivalent (Max Payload)	LH_2 aircraft equivalent (Max Range)
Coal Gasification w/o CCUS	138	132
Coal Gasification with 98% CCUS	6.4	6.1
Steam Methane reforming with 93% CCUS	18.6	17.8
Electrolysis (grid powered)	151	144

Table 27: Operative emissions of hydrogen divided by manufacturing methods.

With respect to state-of-the-art emissions, liquid hydrogen can have far better performances, as well as way worse, depending on the manufacturing methods. Using coal and natural gas can be a viable option only if CCUS technology is used, while electrolysis made by grid power supply is possibly the worst option in terms of carbon dioxide produced in the process.

The issue with fossil fuels and gases like methane is that they are non-renewable, and it is forecasted that eventually the world will run out of these resources. The proposed electricity mix[17] cited before might help contain electrolysis upstream greenhouse gases emissions, while finite power sources reserves would endure much longer.

In this paper, the energy deployed from renewable energy is considered zero-emission, even if Figure 38 shows that wind farms and solar panels have a CO_2 emission factor due to infrastructure and system construction, which is not and will not be considered in this study report.

[17] 70% from renewable sources and 30% from grid.

Using data to interpolate possible electrolysis' upstream emissions when considering mixed electricity supply, gives out the results presented below in table 28. These numbers show how this scenario improves CO_2 emissions with respect to kerosene, but it is still higher than other manufacturing methods that work using carbon capture strategies.

Specific CO_2 emissions [gCO_2/ASK]	LH_2 aircraft equivalent (Max Payload)	LH_2 aircraft equivalent (Max Range)
Electrolysis (Electricity mix)	45.3	39.6

Table 28: Hydrogen's operative emission with electricity mix

CHAPTER 5: EXPLORING THE NUCLEAR POSSIBILITY

5.1 A particular chance: the nuclear energy

Producing hydrogen through an electrolysis process is a focal point in studying this new fuel source since it might be suitable for aviation from an economic and emissions point of view. For these purposes, trying to supply electricity demand from renewable sources rather than the grid is fundamental, but there can be another option that could help the transition and be a protagonist as an energy source: nuclear energy.

The technology behind a nuclear reactor and exploitation of nuclear fission are well-known and, most importantly, the entire process produces very little carbon dioxide. In addition to that the price of electricity coming from such plants is much cheaper than grid sources and comparable to renewable sources, depending on geographical location.

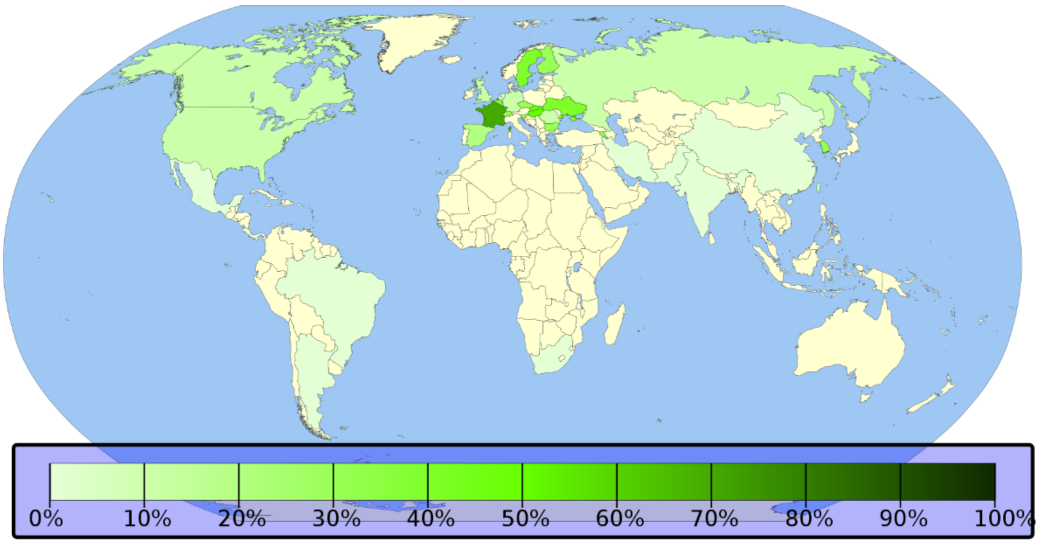


Figure 39: Nations based on nuclear output as a percentage of national power output [20]

Even though plants are widely diffused, only a few countries use them as a primary source of electricity. The United States and China are by far the biggest energy producers from nuclear plants even without relying mainly on it (772 TWh and 395 TWh respectively), while in Europe only France (the only country in the world where 80% of the energy output comes from nuclear output), Slovakia and Belgium are primarily supplied by nuclear energy [20].

The reasons behind a common reluctance to expand or establish nuclear plants are political and ethical. Chernobyl and Fukushima's disasters are globally infamous, to such an extent that there is a common fear of nuclear energy, which is also leveraged by political propaganda in some cases, without acknowledging the scientific reality that nuclear plants safety standards are first level.

The real main issue with nuclear energy is related to radioactive waste, which need specific management, which is not particularly complicated, but the potential risk is higher than normal industrial waste. Fortunately, this problem is hugely limited by the fact that a nuclear plant produces very little waste with respect to its power capacity.

The newest and most advanced nuclear reactor technology can also exploit specific thermochemical or electrochemical cycles to produce hydrogen but in this produced H_2 is labeled "blue" because there are some little emissions.

According to IEA reports on energy cost, electricity coming from nuclear plants has a different price depending on region and plant's life expectancy. In order to equalize this analysis with the other ones, a Long-Term Operation plant is considered, with 20 years of life expectancy operating in the European Union.

	Current scenario (2022)	Near-future scenario (2030)	Long-term scenario (2050)
LCOE from nuclear plants [€$2022/Kg_{LH_2}$]	0.40	0.032	0.028

Table 29: LCOE of nuclear plants trend

Table 29 shows the numerical trend for the levelized cost of energy that will be considered. This forecast is similar to renewable sources, but the prediction has nuclear energy still being cheaper than green energy.

It is possible to use this information, combined with the energy demand required from Alkaline and PEM electrolysis that are already known to calculate the new energy expenditure, which will change LCOH. Furthermore, the same calculations can be applied to liquefaction electricity needs, so that EEX for LH_2 can be found.

Hydrogen production EEX [€2022/Kg_{H_2}] (EU reference)	Current scenario (2022)	Near-future scenario (2030)	Long-term scenario (2050)
H_2 from alkaline electrolysis (nuclear source)	0.66	0.336	0.21
H_2 from PEM electrolysis (nuclear source)	0.91	0.69	0.60

Table 30: gH_2 EEX from nuclear energy

Liquid Hydrogen EEX [€2022/Kg_{LH_2}] (EU reference)	Current scenario (2022)	Near-future scenario (2030)	Long-term scenario (2050)
LH_2 from nuclear sources	0.432	0.250	0.210

Table 31: Liquefaction EEX from nuclear energy

The results obtained in Tables 30 and 31 show that EEX is lower than the previous case analyzed, as predicted by the fact that the energy-specific cost is cheaper. The levelized cost of hydrogen and the total liquefaction cost are reported in Tables 32 and 33. These cost items will also impact the total cost of hydrogen, which will be lower.

LCOH [€2022/Kg_{H_2}]	Current scenario (2022)	Near-future scenario (2030)	Long-term scenario (2050)
H_2 from alkaline electrolysis (nuclear source)	0.871	0.483	0.265
H_2 from PEM electrolysis (nuclear source)	1.241	0.890	0.683

Table 32: LCOH from nuclear energy

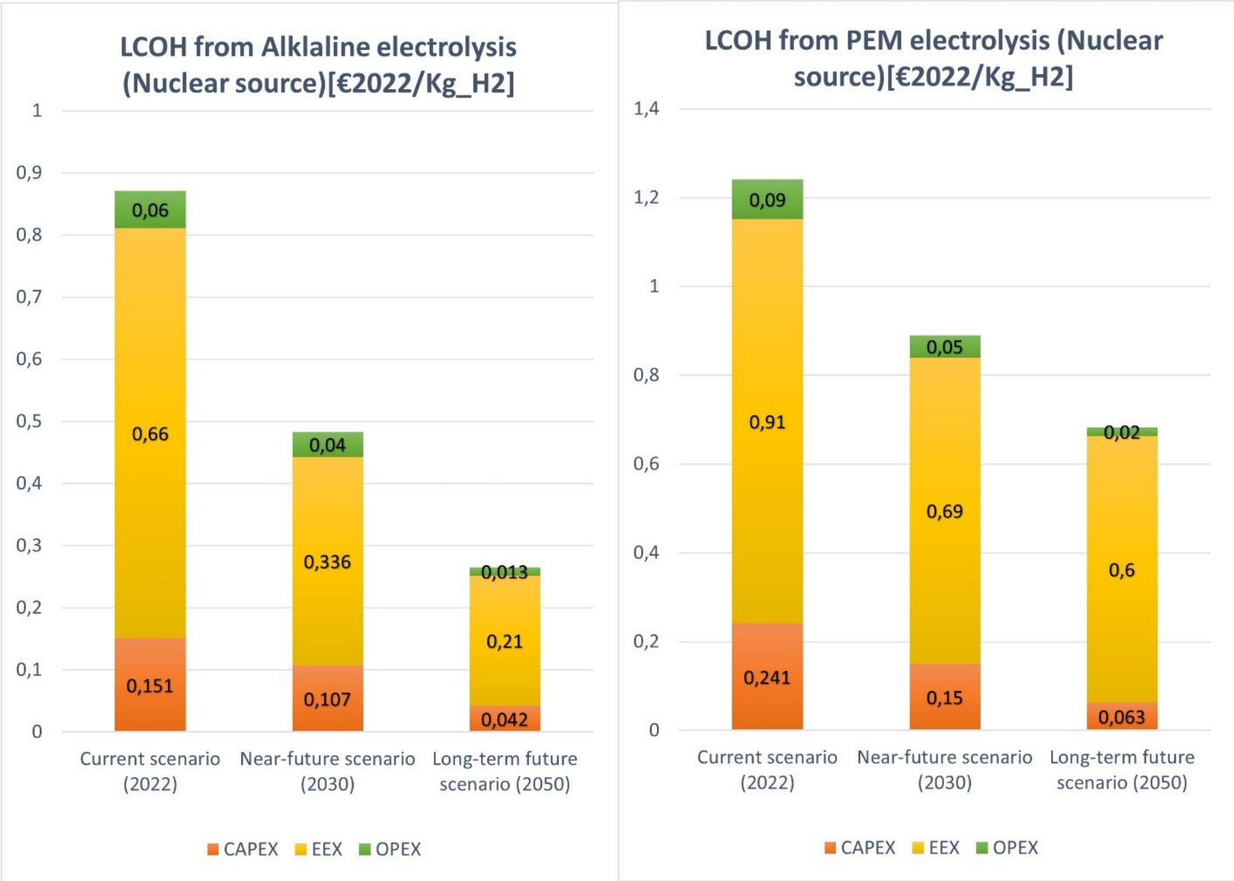


Figure 40: LCOH cost breakdown from nuclear source for ALK and PEM

TLC [€2022/Kg_{LH_2}]	Current scenario (2022)	Near-future scenario (2030)	Long-term scenario (2050)
LH_2 from nuclear sources	0.732-0.902	0.355-0.515	0.290-0.460

Table 33: TLC from nuclear energy

Using the same algorithm and the data calculated in this section, it is possible to evaluate the total cost of hydrogen when exploiting electricity from nuclear plants. TCOH results are reported in the following table.

TCOH [€2022/Kg_{H_2}]	Current scenario (2022)	Near-future scenario (2030)	Long-term scenario (2050)
H_2 by alkaline electrolysis and liquefaction from nuclear sources	1.603-1.773	0.838-0.998	0.555-0.725
H_2 by PEM electrolysis and liquefaction from nuclear source	1.973-2.143	1.245-1.403	0.973-1.143

Table 34: TCOH from nuclear energy

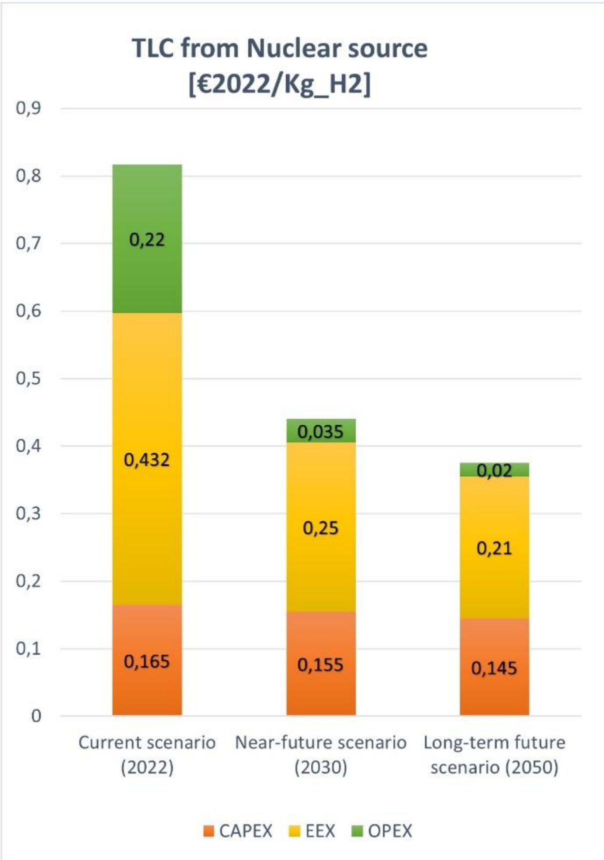


Figure 41: TLC cost breakdown with nuclear energy source

The next step in this analysis is to evaluate how hydrogen cost varies when the energy supply is mixed. A combination of nuclear sources and renewable energy will be considered since this study aims at combining market effectiveness with lowering or eliminating emissions.

The percentage of Alkaline and PEM electrolysis that will be considered is calculated in the same way it has been done in prior evaluations, according to data in Table 9. The trends are estimated in all three scenarios already accounted for in this paper, and the benchmark price remains the same.

Electricity from renewable sources [%]	TCOH (2022) [€2022/Kg_{H_2}]	TCOH (2030) [€2022/Kg_{H_2}]	TCOH (2050) [€2022/Kg_{H_2}]
0	1.89	1.19	0.90
30	2.11	1.26	0.94
70	2.41	1.34	0.99
100	2.63	1.41	1.03

Table 35: Nuclear and renewable energy mix TCOH

To meet the price goal set in today's scenario, more than 70% of the energy demand should be fulfilled by nuclear energy, but soon already green sources could be exploited more. Figure 42 helps to further display the TCOH behavior with mixed energy supply and in different scenarios.

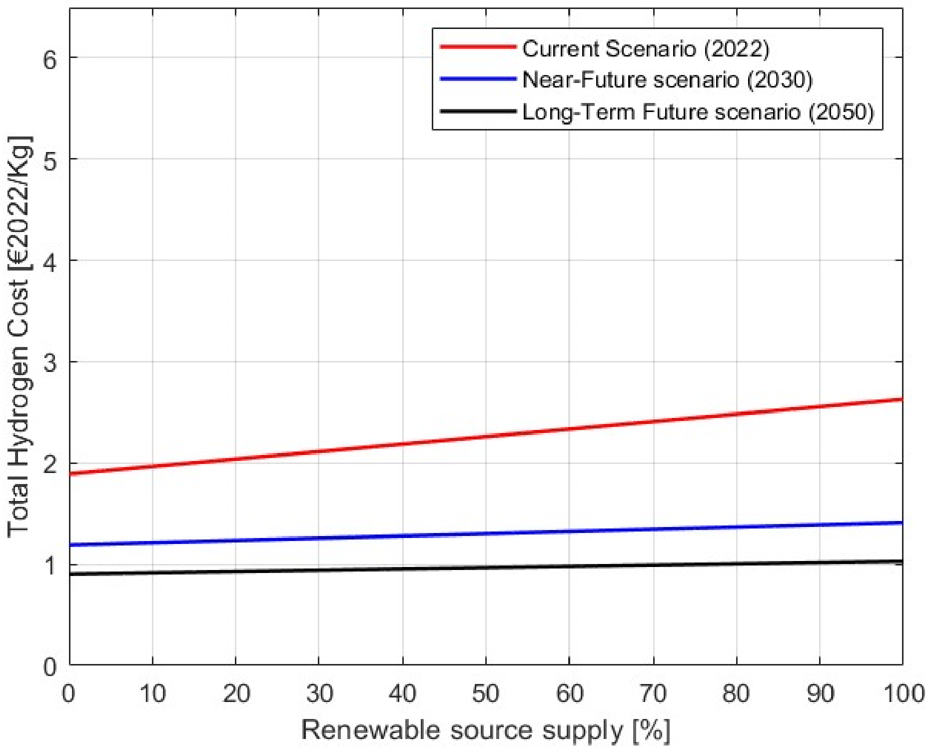


Figure 42: TCOH trend in different scenarios with mixed electricity

The graphs obtained show clearly how nuclear energy and renewable sources could work on similar paths in terms of techno-economic performance in the future, but the gap today is still visible. Trying to push hydrogen as a fuel for subsonic aircraft might be a way of starting to exploit more nuclear energy and new renewable sources rather than coal and gas.

However, to evaluate the market competitiveness in the aviation field it is required to add estimations for ground services and transport to the airport. All the data regarding costs when operating from an on-site plant or an off-site one has been already proposed in a previous chapter, so all the calculations to obtain the H_2 cost at the nozzle can be straightforward. The numerical results of this assessment are reported below in Table 36 while considering 70% of renewable energy, the same amount indicated in this paper before.

Hydrogen cost delivered [€2022/$\boldsymbol{Kg_{LH_2}}$]	Current scenario (2022)	Near Future Scenario (2030)	Long-Term Future Scenario (2050)
On-site production plant	2.59	1.41	1.03
Off-site production plant	3.26	1.85	1.15

Table 36: Hydrogen price at nozzle with nuclear-renewable mix

Also, for this case, the price range attributable to hydrogen is within the International Energy Agency forecast, which is a valid reference to verify the results obtained.

The other important aspect of nuclear energy is its low-emission process, which is a performance parameter on the same level if not more relevant than economic impact. Looking at the data mentioned in Figure 38, exploiting a nuclear reactor to generate electricity for the green hydrogen electrolysis would only emit 0.2 KgCO_2/KgH_2 considering upstream emissions[18]. This value is close enough to zero to see this source almost as helpful as green energy sources.

Now it is possible to use the fixed configurations of the LH_2 powered aircraft proposed in this study case, which parameters are reported in Table 24, so that it is

[18] Radioactive wastes are considered as carbon equivalent.

possible to establish emissions in the same way that has been done for the other hydrogen's production methods. Table 37 displays the results for both 100% nuclear supply and 70% renewable energy sources.

Specific CO_2 emissions [gCO_2/ASK]	LH_2 aircraft equivalent (Max Payload)	LH_2 aircraft equivalent (Max Range)
Electrolysis (Nuclear source)	1.3	1.2
Electrolysis (Electricity mix)	0.39	0.36

Table 37: Hydrogen specific emissions with nuclear energy

These results show once more how the combination of nuclear sources and renewable energy can be efficient and effective since it requires a much lower energy cost and would help sensibly contain emissions. Side problems regarding waste and building new bigger infrastructures should be envisaged, but it is fair to say that a long-lasting cost reduction would pay off the initial investments.

Other than radioactive waste management, nuclear plants differ from global grid or renewable sources because they require a particular source of energy to run, which is uranium. A major part of uranium extraction is done in Kazakhstan and Namibia, where more than 56% of all production is made. Other major countries that have uranium mines are Canada and Australia, which are the main suppliers for European plants. This resource has a fluctuating cost, more than gas and coal, and it could be very sensible to geo-political issues like inland wars, which are not so unpredictable for African countries or other nations that are in the Middle East or that were under soviet influence.

20 years ago, uranium price was very low, since it was not so valuable for the energy market, but starting from this millennium the field has expanded and so the unit cost, which spiked in 2007, reaching 287.53 $\frac{€}{Kg}$. After that, there has been a decade of decreasing trend, with little oscillations, making uranium way cheaper up to 36.97 $\frac{€}{Kg}$ in 2016, before slightly increasing in the last years due to external factors too. From latest reports and as Figure 43 shows, today's uranium price roams around 127.33 $\frac{€}{Kg}$.

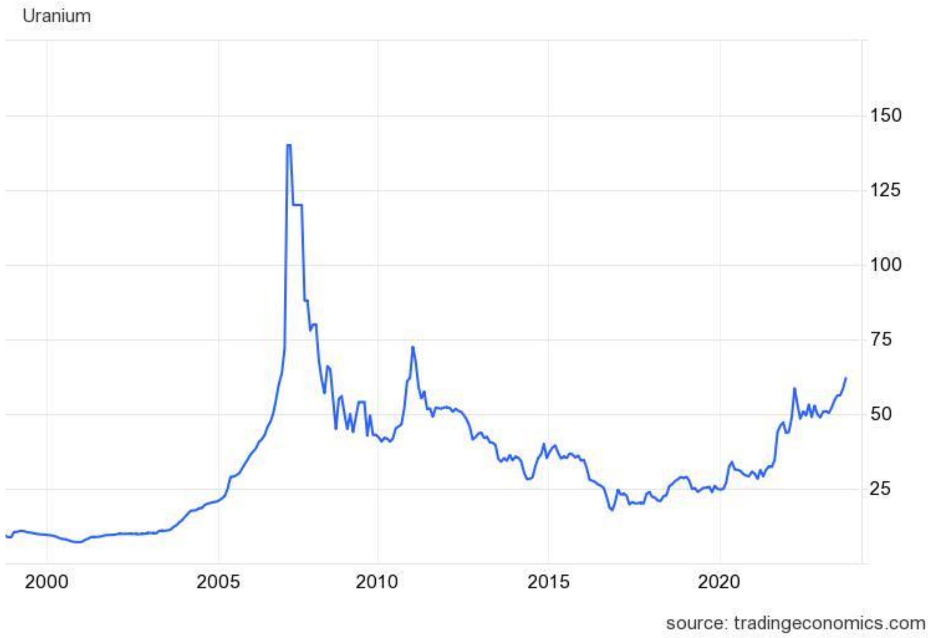


Figure 43: Uranium price trend in last 25 years [USD/lb] [21]

Being the primary source of energy for nuclear plants, uranium cost impacts the final energy price sensibly. Actual price range and future trend might differ a lot from reality if unforeseeable problems will present.

The nuclear possibility could still be a viable option for today and the future, but it requires an in-depth analysis over energy's Life Cycle Assessment, that has to ensure feasibility from economic perspective but also from safety and risk managements point of view.

Conclusions

All the obtained results and evaluations made in this study reports might be a preliminary assessment of a “hydrogen revolution”. With respect to other innovations in air mobility, using liquid hydrogen as a fuel is something that carries more background knowledge, but it also has a different set of complexities, when studying its feasibility from a technological point of view.

LH_2-powered aircraft are doable, and their engine would technically eliminate any type of unwanted emissions, but not all that glitters is gold. Producing hydrogen as a purpose is still something not widely spread, and in addition to that the vast majority of H_2 production comes from coal and gas manufacturers that do not use any Carbon Capture, Usage and Storage system. If airplanes would switch to hydrogen fuel overnight, they would cost the same or more than standard aircraft and the saved carbon dioxide would not be reduced, but only emitted indirectly and likely even more than burning kerosene.

The aviation field could still be a primary boost to expand interest and investments toward a greener transition for fuels. Especially for liquid hydrogen production is fundamental to reduce grey H_2 and push more CCUS system. It is not enough even just focusing on electrolysis, because the energy demand would be supplied by the global grid, which is even worse than coal gasification, but electrolysis should be an opportunity to encourage further transitions to renewable energy and/or nuclear energy.

Figure 44 displays other results presented by IEA’s studies, which are slightly different from the others presented before, meaning that more analysis and more data are required in the future to precisely assess this expanding possibility.

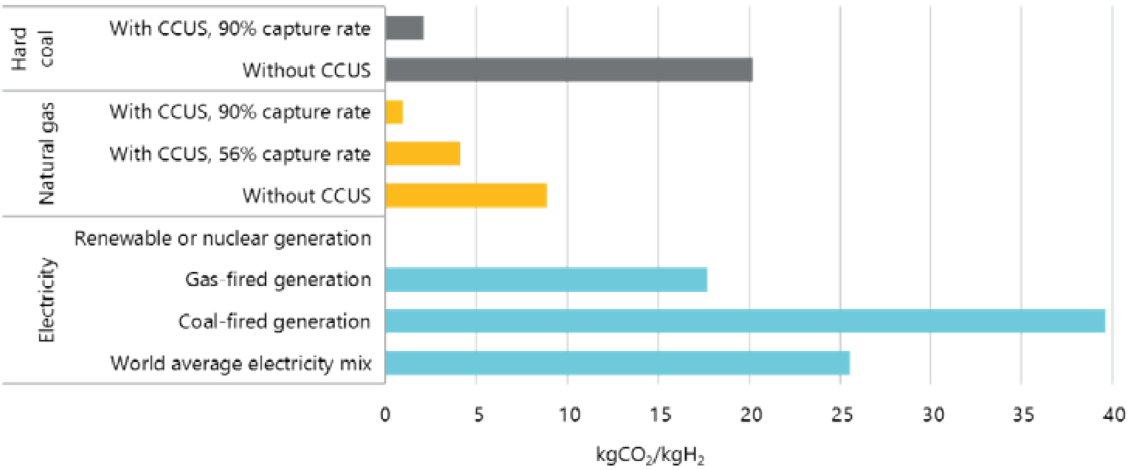


Figure 44: CO_2 emissions from H_2 production by source [22]

The environmental issue is not the only point of view that requires more technological improvements to make hydrogen sustainable, there is also an economic perspective that ultimately is what drives investments and industry targets. As of today, only grey hydrogen is cheap enough to be considered a Jet A1's competitor, but even in this case its price could rise due to transportation fees. H_2 production plants are very few in the world, so if lots of airports require LH_2 supply then it would travel very long distances on average, with high expenses. Furthermore, it has been already said that grey hydrogen is not useful for reducing emissions, which is an essential target in the NZE scenario.

Current Blue and Green hydrogen costs cannot be compared to kerosene, whose price does fluctuate but is way cheaper than LH_2. The upside of this is that data show how in the next decades there could be a sensible reduction in the production cost, thanks to more efficient processes and cheaper energy. Green hydrogen could benefit from an energy mix coming mostly from renewable sources but could even be boosted by nuclear energy which is the cheapest and could allow for a cost-competitive fuel even today.

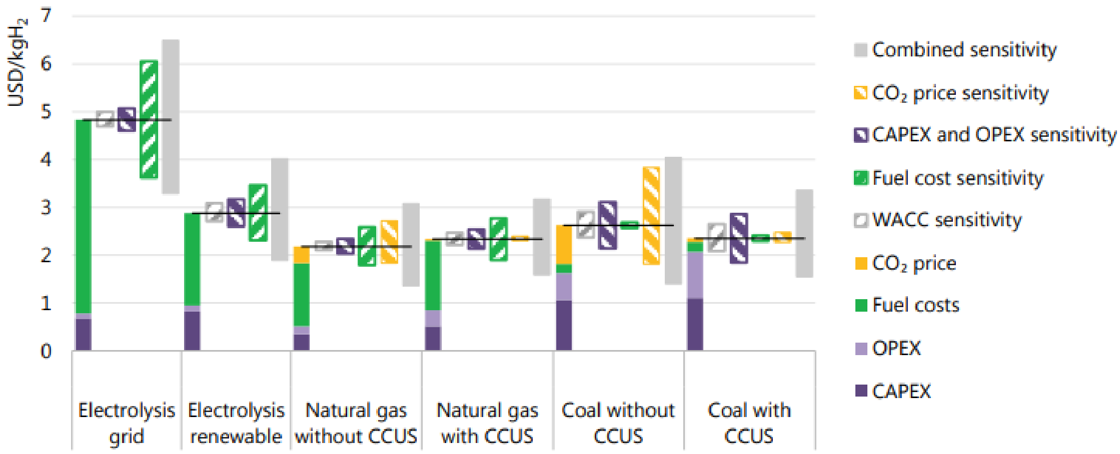


Figure 45: Hydrogen production cost by production process [22]

Also, for this case, the evaluation presented in different reports presents different results from the ones calculated in this paper and reported by IEA. Figure 45 is an example of how hydrogen cost can have a wide sensitivity over its production cost items, in fact, the range displayed is not equal to the one estimated by the agency itself in Figure 33.

Hydrogen as an aviation fuel could be a real possibility in the future only if the right investments are going to be made, combining ethical technology and economic interest. Political agenda could be a factor in this scenario that can push airlines and manufacturers to emit less and forage new facilities in this sector, while expanding renewable source farms and maybe even considering implementing nuclear energy or expanding existing plants.

Even though liquid hydrogen is already considered a fuel in the aerospace field, since it is used for rocket boosters, it is not certain if it will ever be a fuel for aircraft. Using the Airbus Zero-e model it is possible to imagine a mission profile completed by such an airplane. Even mass distribution, center of gravity estimation, and operative competitiveness analysis all have given acceptable results. Nevertheless, to assess the proper feasibility of such a project a more detailed concept would be required, with fully detailed propulsion system integration. This would allow for a first iteration of risk assessment and safety requirements since hydrogen is highly inflammable and volatile.

Personally, I would explore more the concept of a hydrogen-powered aircraft, but bearing in mind that its purpose could be very different at the beginning than commercial flights. Probably it would take more than two decades in order to see a commercial airplane operate as it today with LH_2 in its tank, but this should not stop pushing hydrogen as a proper asset for the transportation field, not only in the aviation.

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