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Techno-Economic Comparison of Low Carbon Energy Carriers Based on Electricity for Air Mobility

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Abstract: Decarbonization of air mobility requires the decarbonization of its energy. While biofuels will play an important role, other low carbon energy carriers based on electricity are considered: battery electrification, liquid hydrogen (LH_2) or eFuel, a hydrogen-based energy carrier. Each energy carrier has its own conversion steps and losses and its own integration effects with the aircraft. These combinations lead to different energy requirements and must be understood to compare their cost and CO_2 emissions. Since they are all electricity-based, this study compares these energy carriers using the well to rotor methodology when applied to a standard Vertical Take-Off and Landing (VTOL) air mobility mission. This novel approach allows one to understand that the choice of the energy carrier dictates the propulsive system architecture, leading to integration effects with the aircraft which can significantly change the energy required, from 400 to 2665 kWh for the same mission. These deviations lead significant differences in CO_2 emissions and costs. Battery electrification is impacted by the battery manufacturing but has the lowest electricity consumption. It is an optimum solution but only until the battery weight can be lifted. In all scenarios eFuel is more efficient than LH_2. We conclude that carrying the most efficient molecule in an aircraft pays the extra energy cost spent on the ground. Finally, we found that for each of these energy carriers, it is the electricity carbon intensity and price which will dictate the cost and CO_2 emissions of an air mobility mission.

Keywords: air mobility; eFuel; hydrogen; battery; electricity; CO_2

1. Introduction

Despite significant technological progress, the aviation industry's carbon footprint continues to grow as the result of current air traffic growth [1]. Meanwhile, the Air Transport Action Group forecast for 2050 concludes that the flight demand could increase on average by 3.1% per year and that the CO_2 emissions would consequently climb to 2 Gt [2] if no specific measures are put in place.

As for the entirety of air transportation, Vertical and Take Off aircrafts, which currently account for 1% of the total jet fuel consumption and CO_2 emissions [3], it will rely on Sustainable Aviation Fuels (SAF) to lower their carbon footprint [2]. SAF are sustainable if they are produced from renewable sources such as biomass (biofuels), and low carbon intensity electricity such as eFuels.

Since each energy carrier has its own conversion steps and losses and since each energy carrier has also a specific impact on the aircraft propulsive system and therefore its energy consumption, defining the cleanest and most affordable energy carrier might require a novel approach.

Air mobility is often recognized as a "hard to abate" sector, and several technologies are currently considered for lowering its CO_2 emissions. While biofuels will play an important role in the near and long-term, low carbon electricity is now considered. Either with direct electrification: rechargeable batteries using the electrical grid (BE) or using energy vectors such as hydrogen or Efuel. Hydrogen. While eFuel, which will use electricity for water electrolysis, CO_2 capture and Fischer-

Tropsch process ($H_2 + CO_2 + H_2O$), require no modification to the carrier, hydrogen can be combined either with a fuel cell + battery hybrid system (FCH_2) or a gas turbine (GTH_2), in both cases requiring significant modification to the carrier. This comes with a significant mass impact. Other pathways such as NH_3 (ammonia) and CH_4 (methane) are also sometimes cited [4], however these pathways are not considered in this study.

The mission profile and the mean of transportation could have an impact on the results, we therefore focus on vertical take-off and landing vehicle (VTOL) which is the most demanding in energy when expressed in payload/distance. VTOL and short-range aircrafts are often considered in studies analyzing the opportunity to switch from fossil jet fuel to more disruptive energy vectors such as battery and / or H_2 fuel cell [4–6]. Since our study focuses on VTOL, the conclusions might not apply for large aircraft [7]. H_2 is considered liquified and not compressed due to its volumetric density [7].

Since the path to low carbon energy for air mobility induces low yield energy vectors and that limited resources already reveal some tensions on biomass supplies for biofuels [8,9], this study reviews a combination of the most cited energy vectors, based on electricity combined with the most studied propulsive energy concept for VTOL.

The energy required to fulfill the mission is first expressed in the unit of energy carrier before being translated into kWh at the well. The electricity grid and its carbon intensity are our central focus of analysis. Electricity is being used either for direct charging, or liquid hydrogen production through water electrolysis, or eFuel conversion using the Fischer-Tropsch process which requires hydrogen and carbon dioxide. Results are then finally converted in CO_2 emissions and direct energy cost.

While results from this research could later be extended to fixed wing aircrafts, at present this study focuses on the VTOL aircraft due to vertical take-off and hovering being the most demanding maneuvers regarding energy requirements, thus magnifying the need for energy efficiency.

1.1. Previous work

A significant number of articles cover alternative aviation fuels and propulsion systems. Grahn et al in 2022 reviewed the eFuel cost and their environmental impact [10] with no clear conclusions regarding the CO_2 impact. The Académie des Technologies report on the role SAF for air transport [11] highlighted the needs and limits to the deployment of low carbon electricity to reach a viable production volume of eFuel. In Europe, the ReFuel EU regulation will impose 70% of sustainable aviation fuel by 2050, of which half should be eFuel [12]. Rojas-Michaga et al [13] reviewed the SAF production through power to liquid (eFuel) and concluded that the dominant factor for the eFuel CO_2 emissions is the electricity.

Dahal et al [4] established a techno-economic review of alternative fuels and propulsion systems for the aviation sector. Using the available literature, the model is based on aircraft top level requirements applied to Airbus A321 and A350 models using the Pacelab APD design tool. The conclusions are expressed in US cent per passenger kilometers to allow a fair comparison between the different fuels evaluated and the biofuel appears to be the most competitive while H_2 and eFuel share very close figures. Compared to fossil jet fuel, the cost range is 15 to 500% higher.

2. Materials and Methods

2.1. Methodology

In this study, we follow the same approach as [4] but applied to a VTOL with design principles based on the Froude-Rankin theory and the statistical design method for VTOL. We also introduce the electricity input from the well to the tank to allow a direct comparison in cost and CO_2 emissions.

Electricity, expressed here in kWh, is the common and main feedstock for all energy carriers considered: battery electrification (BE), H_2 with fuel cells (FCH_2), H_2 with gas turbine (GTH_2) and eFuels. Fossil jet fuel and SAF issued from biomass will only be considered in the conclusion and discussion section to compare the results.

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The electricity requirements to produce H_2 and eFuels are important [11,13–17] and therefore the impacts associated with the production of these energy carriers shall be considered, cost and CO_2 in this study.

To compare the different energy vectors, we therefore combine the efficiency of the energy vector from the electricity grid to the tank "well to tank" for each pathway. We then introduce the adaptation required by the choice of the energy carrier and its associated propulsive system, considering the integration effects on the aircraft weight to determine the energy requirements, the "tank to rotor" efficiency.

This is described in Figure 1 below:

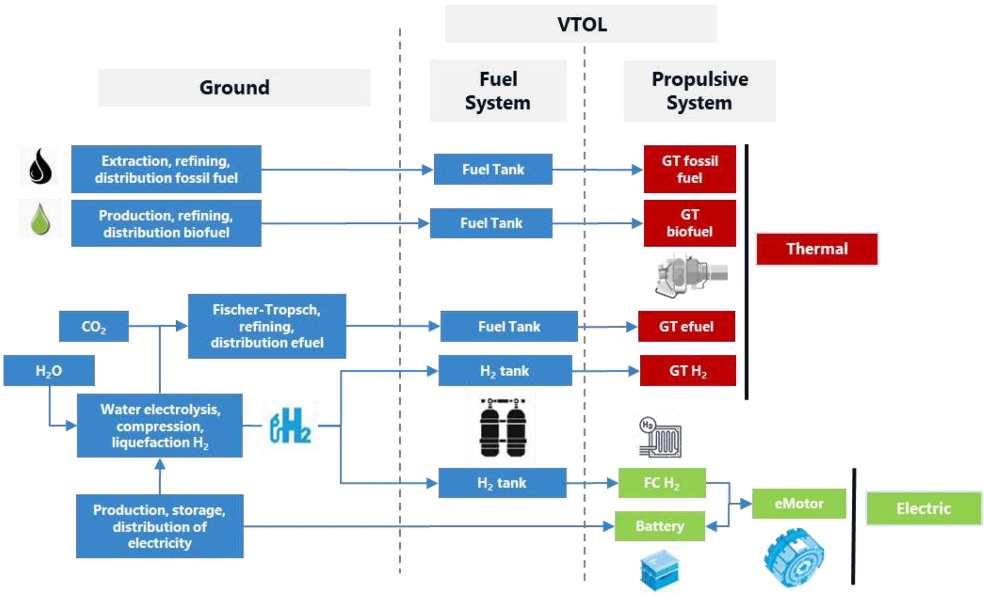

Figure 1. Energy vector applied to the VTOL and associated pathways and propulsive architecture.

We apply these calculations to a standard VTOL mission, which is to carry 4 passenger or an equivalent of 400 kg of payload, over 80 nautical miles (nm) with a reserve of 20 nm to ensure the safety. The mission profile is described below in Figure 2.

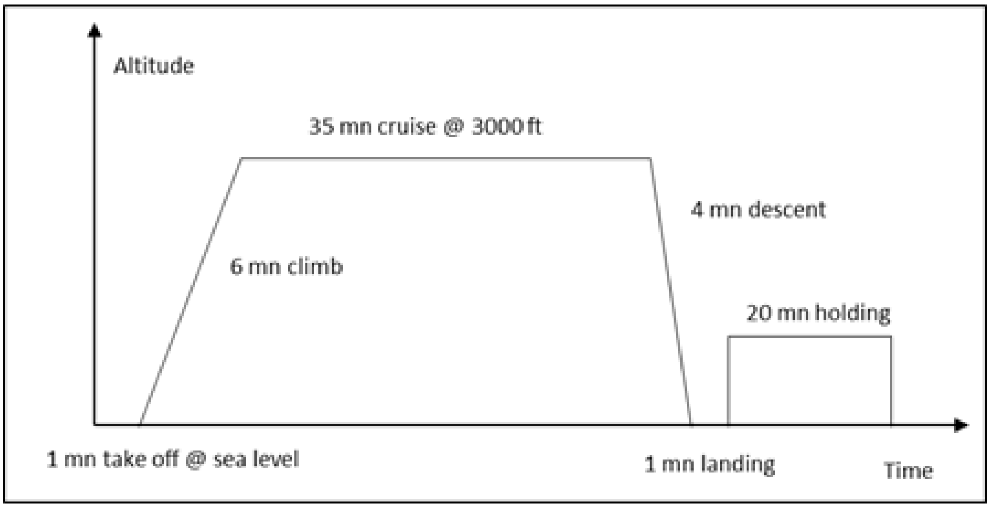

Figure 2. Mission profile.

As efficient as it can be, a VTOL aircraft need to continuously fight against gravity and will always consume more energy than a fixed wing aircraft with similar payload / range. The typical mission before refueling is approximately 45 minutes of flight as described in Figure 2. While VTOL

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range are often above 300 nm and that typical missions often go beyond this range in between two refueling, the limit of 80 nm is here to reflect the opportunity to introduce battery electrification, as some potential air taxi missions are considered in the future with BE [18]. The crew is limited to 1 pilot and the altitude to 4000 feet.

2.2. Design of VTOL

The properties of the energy carrier are extremely important when designing an aircraft. An excellent gravimetric energy density can be penalized by a too low volumetric energetic density which will lead to larger tanks, penalizing drag and aircraft empty weight, thus leading to structural reinforcement, thus more weight, thus higher power requirements and finally an increased energy consumption. The payload and the range also have major contributive effects [18]. In our model the limited distance and payload limit these effects, allowing the comparison with battery electrification.

In our approach we have to determine the required power at the main gearbox input to calculate the aircraft performance and ability to perform the mission. No modification is assumed on the aircraft and a standard configuration including a large main rotor and tail rotor to counter the main rotor torque is used. The modelling is based on the two main known principles: the Froude-Rankin theory and the statistical design method for VTOL in the range of 1500 to 3000 kg as proposed by Arnaud Tremolet in "Modèles et méthodes numériques pour les études conceptuelles d'aéronefs à voilure tournante", 2014 [19].

Table 1. Power required calculations formula.

Power required
$PW_{req} = {(PW_{ind} + PW_{bld} + PW_{fus}) \cdot (1 + \alpha_{TR})}/{\eta_{PGB}}$
$PW_{ind} = T \cdot (V_z + V_i)$
$T = W_{TO} \cdot g \cdot (1 + \alpha_{dw})$
$\left(\frac{V_{i0}}{V_i}\right)^2 = \left(\frac{V_X}{V_{i0}}\right)^2 + \left(\frac{V_Z + V_i}{V_{i0}}\right)^2$
$V_{i0}^2 = \frac{T}{2 \cdot \rho_{air} \cdot S_{MR}}$
$PW_{bld} = \frac{\rho_{air} \cdot b_{MR} \cdot C_{MR} \cdot D_{MR} \cdot C_{xp} \cdot U_{MR}^2}{16} \cdot (1 + 5\mu^2)$
$D_{MR} = {W_{TO}}^{0,3}$
$PW_{fus} = \frac{\rho_{air} \cdot S \cdot C_x \cdot V_x^3}{2}$

Each propulsion system is designed to meet the power and energy requirements which are issued from the aircraft modelling with the weight breakdown being $W_{TO} = WE_P + W_{PS} + W_{CR} + W_{PL} + W_{FL}$ when $W_{EP} = \alpha_{EW}.W_{TO}$

aDW	Downwash coefficient (-)
aTR	Tail rotor coefficient (-)
hPGB	Gearbox efficiency (%)
m	Advance ratio (-)
rair	Air density (kg/m3)
bMR	Number of blade of the main rotor (-)
CMR	Main rotor chord (m)
DMR	Main rotor diameter (m)
FC	Fuel Cell
GT	Gas Turbine
PWBLD	Blade profile power (kW)
PWFUS	Fuselage power (kW)
PWIND	Induced power (kW)
SMR	Main rotor surface (m2)
SCx	Helicopter drag (m2)
T	Rotor vertical thrust (N)

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UMR End tip blade velocity (m/s)
Vi Induced velocity (m/s)
Vi0 Induced velocity in hover (m/s)
Vx Aircraft horizontal speed (m/s)
Vz Aircraft vertical speed (m/s)
WCR Crew Weight (kg)
WEP Empty Weight (kg)
WFL Fuel Weight (kg)
WPL PayLoad Weight (kg)
WPS Propulsion System Weight (kg)
WTO Take Off Weight (kg)

The aircraft sizing method depending on the propulsion system is detailed hereafter so that the helicopter take-off weight (TOW) for a given mission is different from an energy source to another. This is explained by the properties of the energy, as shown in Table 2, and this is integrated in our model with the design steps for calculation (Figure 3).

Table 2. Jet Fuel and LH_2 main properties.

Property	*Jet Fuel*	*LH_2*
Specific energy (MJ/kg)	*43.2*	*120*
Energy density (MJ/L)	*34.9*	*8.5*
Storage temperature (K)	*Ambient*	*21°K*
Storage pressure (bar)	*Ambient*	*2*
Tank gravimetric efficiency (%)	*100%*	*30%*

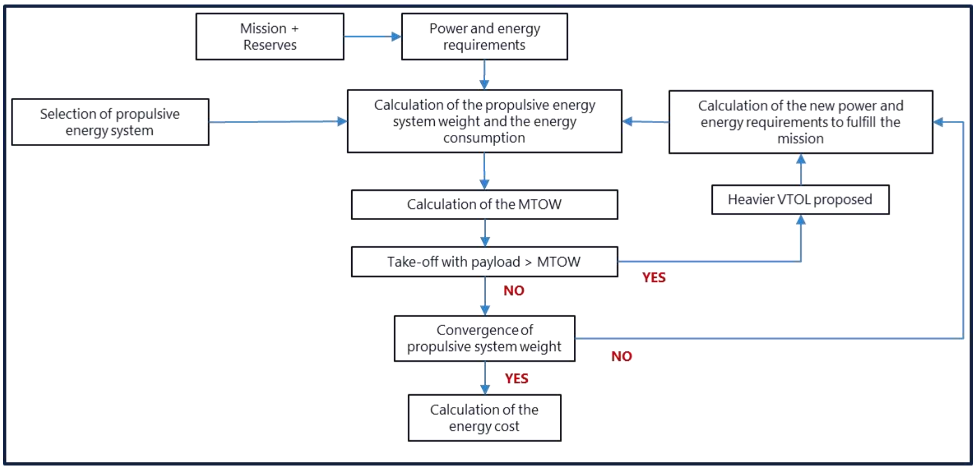

Figure 3. Design step for calculation.

The hypothesis used in this study for the propulsive system design are summarized in Table 3 below:

Table 3. Main hypothesis used for propulsive system design.

H_2 and Fuel Cell	**Batteries**	**Power Distribution**
H_2 LHV: 33 kWh / kg LH_2 density @ 21°K 1 atm: 71 kg / m^3 LH_2 max usable fuel in tank: 80% LH_2 gravimetric index: 30% Fuel Cell efficiency: 50% Fuel Cell power density: 1.5 kW / kg	Max C Rate: 6 Depth of discharge: 90% Cell energy density @ 2C: 600 Whkg^{-1} Integration factor: 1.35	Distribution efficiency: 99% eMotor efficiency: 95% eMotor power density: 8 kW / kg

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In our model, the LH_2 gravimetric index, the full cell efficiency and the battery cell energy density have a significant impact in the VTOL design and hypothesis are detailed below:

- LH_2 gravimetric index: The tanks to store hydrogen as cryogenic liquid result in added weight which will be carried during the entire mission, and which means a more robust airframe such as a more robust, so a heavier, landing system (in an aircraft the max landing weight is below the take-off weight to benefit from the fuel burned during the mission which makes the aircraft lighter). An important performance metric to assess the storage efficiency of a tank is gravimetric efficiency, defined as $\eta_{\text{tank}} = \frac{W_{H_2}}{W_{H_2}+W_{\text{tank}}}$ where W_{H2} is the weight of hydrogen the tank can hold and W_{tank} is the weight of the empty tank. The gravimetric efficiency is the fraction of the storage system weight taken up by fuel when it is full. While this tank metric does not represent the volumetric efficiency, it quantifies the weight penalty incurred by using a given hydrogen storage solution. The gravimetric efficiency of kerosene tanks is limited in a VTOL (approx. 20 kg). Evolutionary improvements are predicted to be 25%–40% [7] and we have used a 30% value in our design model.
- Fuel cell efficiency: This has a direct impact on the quantity of H_2 on board the VTOL, thus the size and weight of the H_2 tanks, thus the power requirements, thus the energy consumption. The proton exchange membrane (PEM) is preferred to the solid-oxide fuel cells (SOFC) as PEM can operate at low temperatures. Lower temperatures allow quick response times and SOFC, which operates at higher temperatures (600 to 1000 °C) require some time to start up and shut down "at least 10 min, and maybe an hour or more" as highlighted by Adler & Martins [7], and therefore are inappropriate with most VTOL operations such as emergency medical services or search and rescue. The same article from Adler and Martins [7] mention of 50% efficiency for the fuel cell, which is the value used in this study.
- Battery Cell energy density: External energy is electrochemically stored. The Li-Ion battery is currently the main technology used in electric vehicles and still progressing. "Li-ions and electrons travel between cathode and anode during charge-discharge cycles repeatedly and the process goes on throughout the life cycle" [20]. While the current cell energy density is close to 300 $Whkg^{-1}$, the target for 2030 is 500 Wh^{-1}/kg by 2030 [21] and we have made the hypothesis of a further improvement to 600 Wh^{-1}/kg when associated with an integration factor of 1.35.

2.3. Energy carriers

In this study we focus on energy carriers based on electricity. However, sustainable aviation fuels issued from biomass (biofuel) will play a significant role in the decarbonization of aviation and therefore be used as a reference for comparing the CO_2 emissions and affordability of the energy for air mobility in the discussion and conclusions section. Since biofuels can have different cost and CO_2 emissions [22,23], we will compare the different energy carriers with the most available SAF in 2023, which is HEFA-UCO (hydro-esterification of fatty acids, using used cooking oil as raw material). This biofuel is certified according to the ASTM standard and already in operation in the air transport industry in blend up to 50% with fossil Jet Fuel.

- Fossil Jet Fuel: used as a reference with CO_2 emissions of 94 gCO_2/MJ [24] with a LHV of 44.1 GJ/t [25]
- Biofuel: HEFA-UCO used as a reference with CO_2 emissions of 20 gCO_2/MJ [24] with a LHV of 44.1 GJ/t [25]
- Electricity: used for battery electrification (BE), the production of liquid H_2 and eFuels. Electricity is considered as the raw material for all the combination of energy carrier / propulsive systems studied here as described in Figure 1 above. We assume that electricity is supplied by the grid with no consideration of load factor: electricity is always available either for charging a battery electrified VTOL or to produce H_2 and / or eFuel. The carbon intensity is expressed in gCO_2/kWh and costs in €/kWh.

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- Electricity for BE: 10% charging losses are added to the energy required to fulfill the mission; a figure slightly above the best mean efficiency of 87% found by Reick et al in 2021 [26] to reflect a 2030 state of the art.
- Electricity for liquid H_2: green LH_2 produced from water electrolysis will be either used in a gas turbine or in a fuel cell. Our hypothesis is that H_2 will be directly manufactured on site to avoid any long-distance transportation of LH_2 as carrying hydrogen significantly impacts the cost and CO_2 emissions [16]. The value for electrolysis is 20 g / kWh or 50 kWh per kg of H_2 as proposed by Younas et al in An Overview of Hydrogen Production: Current Status, Potential, and Challenges [15] while the energy cost for liquefaction adds 15 kWh per kg of H_2 as highlighted by Al Ghafri et al in Hydrogen liquefaction: a review of the fundamental physics, engineering practice and future opportunities [27]. A total of 65 kWh of electricity per kg of LH_2 is considered in this study.
- Electricity for eFuel: as for LH_2, electricity is the dominant factor when producing eFuel [11,17,28]. Low carbon eFuel will require an optimized unit of production as proposed in [11,17] using direct air captured or biogenic CO_2 [28]. The H_2 shall be produced the same water electrolysis as above, but located in an integrated plant which will optimize the Fischer-Tropsch, Water Electrolysis and Direct Air Capture units as proposed by Peters et al in "a techno-economic assessment of Fischer-Trosch fuels based on syngas from co-electrolysis" [17]. The efficiency ranges from 46 to 67% and we have used the value refined by the Académie des Technologies in 2023 of 22.2 kWh per kg of eFuel, an efficiency of 55% [11]. This figure considers a selectivity of 60%, which means 40% of co-products such as diesel or naphtha [11,17].

2.4. Life Cycle Assessment

The energy used in operation represents more than 99% of the emissions of the aircraft and the impacts associated with the manufacturing are negligeable [29,30]. We therefore consider all VTOL architecture to be equal and do not take in consideration the environmental impact, nor the CAPEX, associated to the various aircraft configurations except for the battery pack as battery manufacturing have a significative impact over the lifetime costs and CO_2 emissions of a vehicle [31]. The hypothesis for the battery manufacturing is a GHG of 72.9 kg CO_2 per kWh of battery, cell and battery management system included [32]. With frequent high-speed charge, our hypothesis for battery replacement is 1350 cycles [33] or 200.000 km while the battery cost hypothesis is 75$ / kWh as proposed by Lutsey and Nicholas in Update on electric vehicle costs through 2030 [34].

For the $FCLH_2$ configuration (fuel cell with LH_2), a battery pack of 100 kWh is required to accommodate the transient and voltage stabilization [20,35]. The above numbers, CO_2 emissions per kWh and battery cost per kWh will apply and be adapted to the battery pack size.

The LCA of the water electrolysis units and eFuels units are directly proportional to the carbon intensity (CI) of electricity as highlighted by Liu et al in A life cycle assessment of greenhouse gas emissions from direct air capture and Fischer–Tropsch fuel, Royal Society of Chemistry in 2020 [36] : "the synthetic fuel CI is dictated by the electricity emission factor; the lower the electricity CI, the lower is the GHG impact of the fuel produced". This is in accordance with [11,17] and the CO_2 emissions of LH_2 and eFuel will be calculated with $Q_{kWh} . CI_{kWh}$ whereas Q is the quantity of electricity required (65 kWh / kg of LH_2 and 22.2 kWh / kg of eFuel) and CI being the carbon intensity of the electricity used to produce the above molecules.

3. Results

3.1. VTOL energy requirements per energy carrier

The analysis was conducted for each propulsion system, leading to different helicopter sizing's, to perform the same design mission.

The results are presented in Table 4 below with the weight breakdown of each propulsion system and associated energy consumption to fulfill the mission.

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The choice of the energy carrier has a significant impact on the take-off weight thus the energy required when applying the integration effects.

Propulsive System	Component weight in kg					Propulsive System weight	VTOL Take-Off weight	Energy required to perform the mission
	Turbine / Fuel Cell	Tank	Battery	Electric Motor	Others			
Gas Turbine with efuel	120	20			N/A	190	1400	63 kg of efuel
Gas Turbine with LH2	160	210			670	1040	2500	36 kg of LH2
Fuel Cell with LH2	800	220	160	80	40	1300	2900	41 kg of LH2
Battery Electrification			870	80	100	1050	2700	360 kWh of electricity

Table 4: MTOW and associated energy requirements according to the VTOL energy vector / propulsive energy system

The lowest TOW, which is rounded at 1400 kg, apply for the liquid fuel at ambient temperature: eFuel, but also biofuel and the current Jet-A1 (fossil). This would require 63 kg of eFuel. The TOW and energy required which are calculated using methodology described in 2.2 are consistent with the current VTOL in operation [3], which brings credibility to the model used for this study.

When using LH_2, while the gravimetric density is favorable, the lower volumetric density and the need to accommodate wider and more robust tanks as explained in 2.2 leads to a heavier VTOL. TOW is almost doubled compared to liquid hydrocarbons, reaching 2500 kg (rounded value) for GTH_2 and 2900 kg (rounded value) for FCH_2.

- The propulsive system based on fuel cell is penalized by the fuel cell weight and the associated balance of plant [7], the need to dissipate the heat generated and the integration of a 100-kWh battery pack to cope with the transient and voltage stabilization [35].
- The gas turbine, while lighter, must accommodate a complex fuel system to allow the stored LH_2 @ 21°K to reach the combustion chamber without safety issues, leading to heavier pipes and additional monitoring and safety components [36].

Heavier TOW requires greater amount of energy: respectively 36 and 41 kg of LH_2 for GTH_2 and FCH_2.

To calculate the battery electrification VTOL take-off weight, the battery pack size was calculated. With the baseline requirement to fulfill the mission, to 360 kWh of electricity, the battery pack must grow to 625 kWh. This is explained by the integration of the safety reserve, 90 kWh for 20 nm, the minimum of 10% state of charge before charging [37], and the aging of the battery before replacement, with an hypothesis of 80% before reaching the battery knee-point [38].

3.2. Energy requirements "well to rotor" in kWh

To calculate the total electricity consumption, we apply the methodology explained in 2.3:

- Battery electrification: charging losses are added, so 10% of 360 kWh: 400 kWh of electricity will be used from the grid.
- eFuel: the electricity required for the Fischer-Tropsch process (H_2+CO_2+H_2O) is 22.2 kWh per kg of eFuel. Since 63 kg of eFuel are required to fulfill the mission, this leads to 1399 kWh of electricity used from the grid.
- LH_2: 65 kWh of electricity are required to produce 1 kg of LH_2:
    - GTH_2: 36 kg of LH_2 are required to fulfill the mission, so 2340 kWh of electricity will be used from the grid.
    - FCH_2: 41 kg of LH_2 are required to fulfill the mission, so 2665 kWh of electricity will be used from the grid.

The results are synthetized in Table 5 below:

Mission 4 pax , 80 NM	VTOL Energy Vector requirement	Electricity required to produce the energy vector		Total Electricity Consumption, kWh
eFuel	63 kg		22,2 kWh / kg	**1399**
H2 Gas Turbine	36 kg		65 kWh / kg	**2340**
H2 Fuel Cell	41 kg		65 kWh / kg	**2665**
Battery Electrification	360 kWh	10% charging losses		**400**

Table 5: Total electricity required from the grid for each energy vector, in kWh

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One can notice that when expressed in kWh at the well, the electricity grid in our model, the consumptions are extremely different, which will significantly impact not only the affordability of the mission, but also the associated CO_2 emissions: using clean energy shall come with efficiency.

3.3. CO_2 emissions

The CO_2 emissions are proportional to the carbon intensity of the electricity in gCO_2/kWh multiplied by the quantity of electricity required to perform the mission: $Q_{kWh} * CI_{kWh}$.

Q_{kWh} being the Quantity of kWh required and CI_{kWh} being the carbon intensity of the electricity in gCO_2 equivalent.

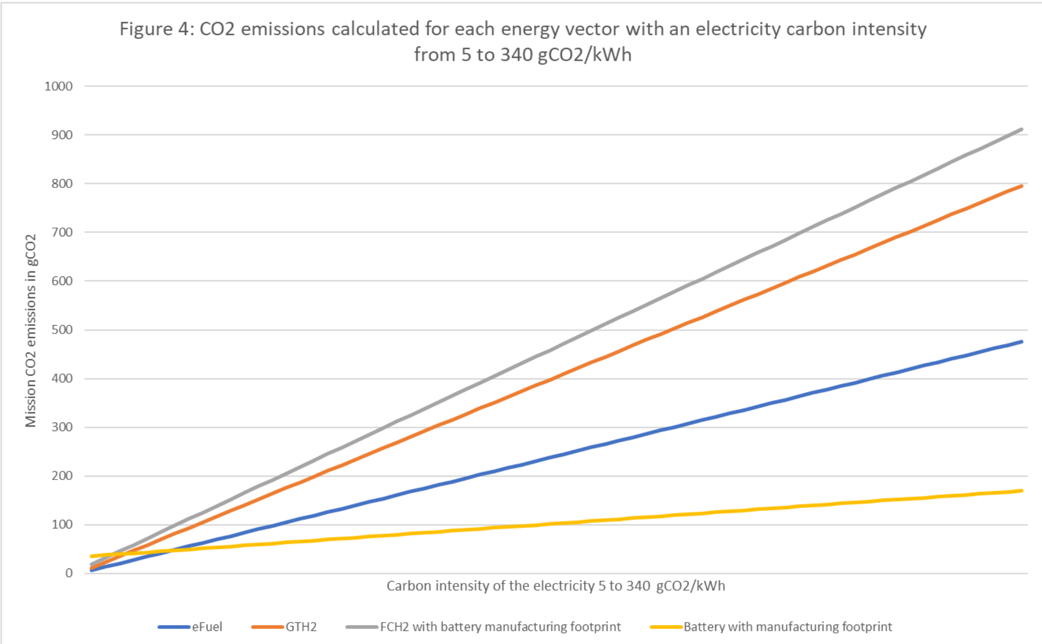
This is true for all energy vectors except for Battery Electrification and FCH_2 as the battery manufacturing comes with significant CO_2 emissions as described in section 2.4. The CI of the battery manufacturing shall therefore be added to the result of $Q_{kWh} * CI_{kWh}$.

For battery electrification, the hypothesis for the battery manufacturing is a GHG of 72.9 kg CO_2 / kWh [32], which means 45562 kg of CO_2 for the 625-kWh battery pack calculated in 3.1. Since the battery pack will be replaced every 200.000 km as detailed in 2.3, we therefore conclude that 0.228 kg of CO_2 should be added per km, or 33.7 kg of CO_2 per mission (80 nm being equivalent to 148 km: 0.228*148=33.7).

For FCH_2, the 100-kWh battery pack, using the same approach, would add 5.4 kg of CO_2 per mission.

For battery electrification and FCH_2, the formula is $BatCO_2 + Q_{kWh} * CI_{kWh}$, $BatCO_2$ being the fixed CO_2 emissions associated to the battery pack manufacturing.

Since the CO_2 emissions are proportional to the CI of the electricity and while this could be infinite, we used the European Union carbon intensity of electricity which decreased from 641 gCO_2/kWh in 1990 to 334 gCO_2/kWh in 2019 [39] to draw the first results as shown in Figure 4 below:



Calculations are based on $Q_{kWh} * CI_{kWh}$ for eFuel and GTH_2, and $BatCO_2 + Q_{kWh} * CI_{kWh}$ for FCH_2 and BE.

CI in Figure 4 goes from 5 to 340 gCO_2/kWh (x-axis) and the result for the mission is expressed in gCO_2 in the y-axis.

One can notice that LH_2 has higher CO_2 emissions than eFuel whatever the carbon intensity of the electricity, the gap widening with the CI of electricity. This can be explained by the overall efficiency of the energy carrier when applied to air mobility as described in 3.2, with 1399 kWh for eFuel, 2340 kWh for GTH_2 and 2665 kWh for FCH_2.

Battery electrification shows the lowest CO_2 emissions except when the carbon intensity is very low, which could be explained by the impact of the battery manufacturing.

While the results are clear when the CI of electricity is above 50 gCO_2/kWh, this is not the case when the CI of electricity is below 50 gCO_2/kWh.

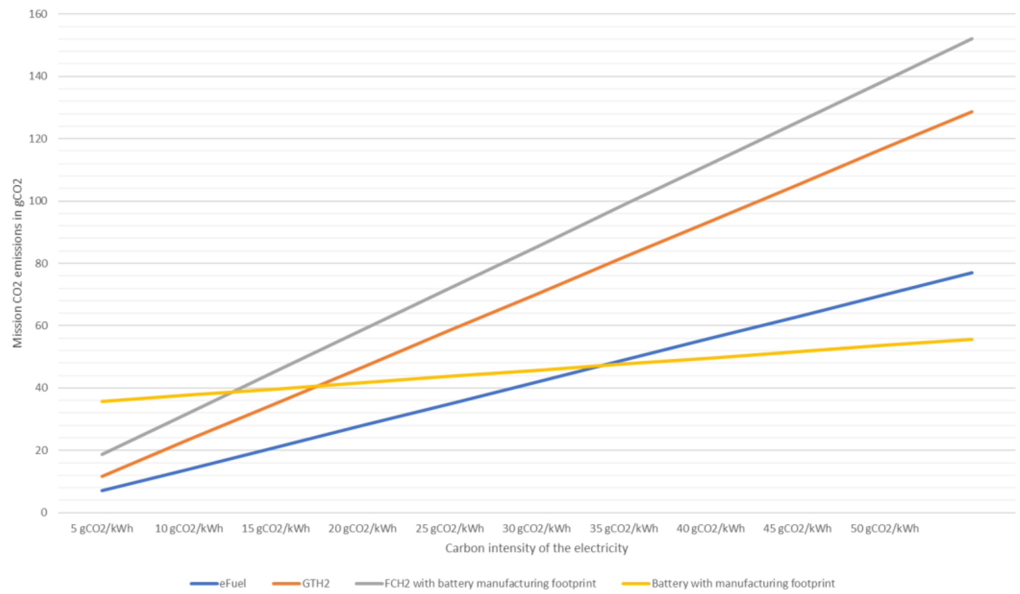
These results should also be put in perspective of the recent pledges for low carbon energies in the transport sector. For instance, the European Union recently implemented dedicated regulations such as the European Regulation for Renewable and Low Carbon Fuels [40]. This regulation defines what can be considered as a low carbon fuel, and the minimum reduction for RFNBOs compared to the fossil fuel reference shall be -70%. A potential definition of clean energy.

With a CI of 94gCO_2/MJ [24] and a LHV of 44.1 GJ/ton [25], so 4.15 kg of CO_2 per kg of fossil fuel, this means that eFuel CI shall remain below 1.25 kg of CO_2 per kg. Since the CI of eFuel is directly proportional to Q_{kWh} * CI_{kWh}, and Q being 22.2 kWh, the maximum CI of electricity is 56 gCO_2/kWh for the eFuel to be considered as a clean energy.

In Figure 5 we therefore focus on carbon intensity of the electricity from 0 to 50 g CO_2/kWh. One can notice that when the carbon intensity of the electricity is very low, the choice of the energy carrier is less obvious.

When electricity CI is below 35 gCO_2/kWh eFuel can show lower emissions than any other pathway, including battery electrification. This can be explained by the impact of the battery pack manufacturing associated CO_2 emissions. However, it is difficult to conclude as battery recycling is expected to grow in the coming years, lowering the carbon footprint of the battery pack.

Figure 5: CO_2 emissions calculated for each energy vector with an electricity carbon intensity from 5 to 50 gCO_2/kWh



For the hydrogen and eFuel energy carriers, Figure 5 confirms that whatever the carbon intensity of the electricity, eFuel has lower CO_2 emissions than any propulsive systems using H_2 (FCH_2 and GTH_2). This is mainly explained by the VTOL design, which is significantly heavier, thus requiring more energy so more electricity from the grid.

3.4. Cost of electricity for the mission

The costs calculated here apply to the cost of the electricity required to perform the mission and the cost of the battery when necessary. CAPEX are not considered.

The cost of the mission is therefore proportional to the electricity required for the mission (M_{kWh}) and the electricity price expressed in \$/kWh: M_{kWh} * $\$_{.kWh}$

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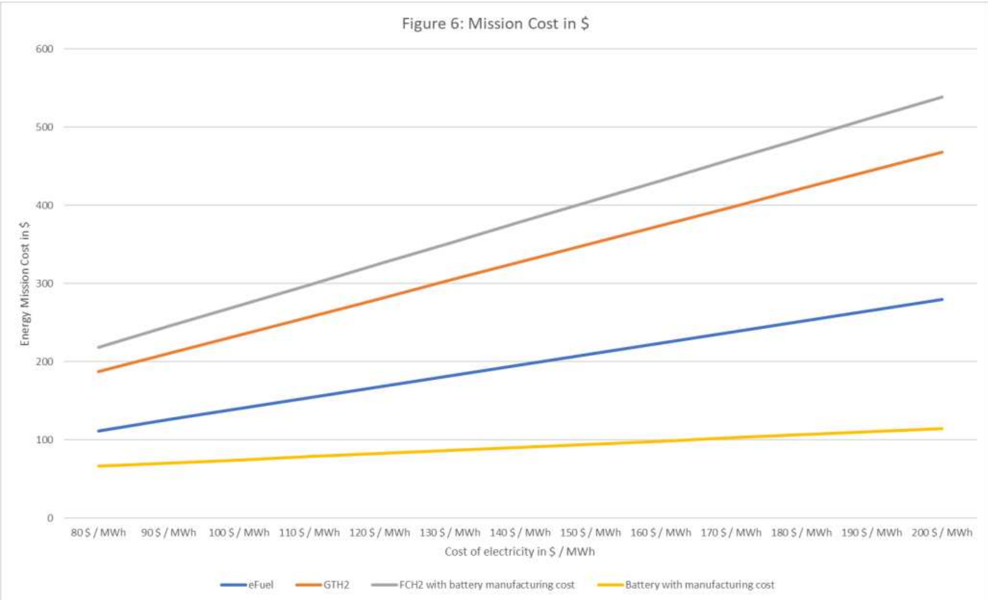
This is true for all energy vectors except for Battery Electrification and FCH_2 as the battery manufacturing implicates significant costs as described in section 2.4.

For battery electrification, the hypothesis for the battery manufacturing is a cost of 75$/kWh [34], which means 46875 $ for the 625 kWh battery pack which will be replaced every 1350 cycles [33] or an equivalent of 200.000 km. This means 0.234 $ to be added per km, or 34.7 $ for the mission, 80 nm being equivalent to 148 km (0.234*148).

For FCH_2, the 100 kWh battery pack, using the same formula, would add 5.5 $.

Since in our model the costs are proportional to the price of electricity, and while this could be infinite, we used the levelized full system costs of electricity applied to low carbon electricity plants with a load factor greater than 95%, so between 90 and 192 $ / MWh as proposed by Idel in "Levelized Full System Costs Of Electricity" (LFSCOE) [41].



Results are shown in Figure 6 above with the cost of the mission expressed in $ in the y-axis while the LFSCOE is in the x-axis.

Whatever the price of electricity, battery electrification is always the cheapest option while a VTOL using LH_2 either with a gas turbine or fuel cell is always the most expensive options.

4. Discussion and conclusions

In this study we compared the energy requirements of different energy vectors requiring electricity as a raw material when applied to a standard VTOL mission (4 passengers over 80 nm) using the well to rotor methodology.

While there are various solutions when considering the implementation of renewable energy [42], flying requires much more energy than floating or rolling and the integration effects when considering new energy carriers such as eFuel, battery electrification or H_2, either coupled with a gas turbine or with fuel cells, shall be considered.

We found that energy carriers using electricity as a raw material can be directly compared, either to evaluate the CO_2 emissions or the cost of energy when applied to a given mission.

Battery electrification should be the preferred option if the take-off weight is compatible with the payload and the range, which is in line with the conclusions of Zhang et al [43]. However, battery electrification means heavier platforms and the opportunity of such a technology could remain limited to short distances and / or limited payload, thus in competition with public transportation and / or electric cars which are far more efficient [18]. The impact on battery material could also be an issue as a medium and long-range aircraft often travel more than 2 million kilometers per year,

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consuming almost 1 battery pack per month as the average lifetime of a battery pack is 1350 cycles or 200.000 kilometers [33].

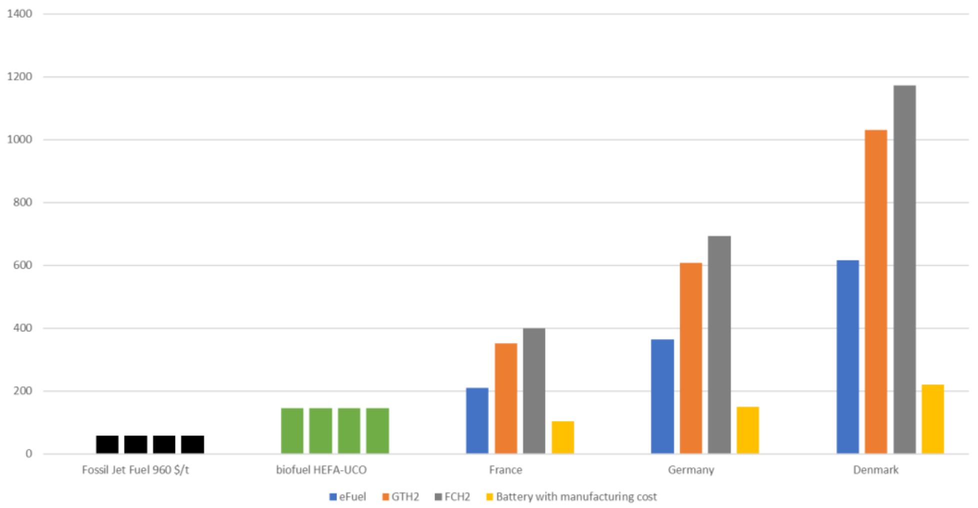
In all scenarios, eFuel shows less CO_2 emissions and lower costs than H_2 based propulsive systems. We conclude that carrying the most efficient molecule in an aircraft pays the extra energy cost spent on the ground required by the Fischer-Tropsch process which combines H_2+CO_2+H_2O. This will be further investigated in future works since the VTOL requirements, such as hovering, are extremely energy demanding thus probably magnifying the results.

A first limit in this study is that the boil-off rate of LH_2 is not considered as the model does not introduce turnaround time and durations between flights. This would further penalize the LH_2 option. Another limit in this study concerns the impacts on NOx, contrails and noise which are not considered here, and future works should be done to refine the FCH_2 potential for small fixed wing aircrafts which could perhaps accommodate more efficiently a fuel cell than a VTOL [6,7]. For larger aircrafts which would require a significant amount of power, thus switching from fuel cell to gas turbine to use the H_2, the eFuel option should be preferred as it is more affordable and comes with lower CO_2 emissions: clean energy should be placed in perspective of its associated consumption to measure its overall CO_2 impact.

As the aviation industry intends to decarbonize its energy, one shall consider that the H_2 option requires not only more electricity from the grid compared to eFuel, but that hydrogen also comes with the need to be produced at the point of use as it does not travel efficiently [16]. H_2 should be produced locally, which could significantly harm the cost for airlines in countries where electricity prices are high as shown in Figure 7 below.

In Figure 7 we apply the price of electricity (€/kWh) of 3 European countries, using data from Statista [44] for the second semester 2022, respectively 150, 260 and 440 € per MWh in France, Germany, and Denmark. We have introduced the cost of the fossil fuel and the cost of the most common biofuel (HEFA-UCO) [4] for comparison.

Figure 7: Direct Energy Costs for each energy vectors in 4 European countries with different electricity prices and introducing fossil fuel and biofuel for comparison, in € for the mission



One can notice that fossil fuel remains the cheapest option, but also that biofuel could almost compete with battery electrification. More interestingly, a country with high electricity prices such as Denmark could almost consider importing eFuel from France where electricity is much cheaper rather than charging a battery electrified VTOL within the country. While probably not an option, this highlight the disparities between future producers of low carbon energy carriers: the electricity shall not only be low carbon, but also affordable.

Finally, we found that the choice of the energy carrier needs to be carefully evaluated as the impacts on the electricity production are significant. Therefore, the impact on the electricity production should be considered at the nation and / or the continent level. In Europe, the European

Union recently set the objective of 35% of RFNBO in its ReFuel EU regulation for 2050 [45] and this will most probably be eFuel. Would Europe require 50 Mt of Jet Fuel by 2050, this would translate in 17.5 Mt of eFuel. With a selectivity of 60%, which means 60% of eFuel and 40% of co-products [11], 37 TWh of electricity would be required per Mt of eFuel.

This means 650 TWh (17.5 Mt * 37 TWh/Mt) in an optimized scenario. In 2022 the European Union produced 2641 TWh of which 23.5% of wind and solar, or 607 TWh [46]. The production of eFuel at scale would therefore require significant amount of low carbon electricity and this could lead to future conflict of use issues. These conclusions are in line with the ones of Becken et al in "Implications of preferential access to land and clean energy for Sustainable Aviation Fuels, Science of the Total Environment" [9] and this aspect of the decarbonization of the energy for air mobility will be further investigated in future works.

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Conflicts of Interest: Jean-Baptiste Jarin has worked for Safran for 25 years and is now a PhD student and researcher at University of Pau UPPA-E2S, working on the conflict of use associated to the decarbonization of energy for air mobility. Stéphane Beddok is a Safran employee, in charge of propulsive system architecture. Safran is a leading aerospace company, involved in gas turbine, battery electrification, fuel cells and other aerospace components.

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