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

Jean-Baptiste Jarin [1,*], Stéphane Beddok [2] and Carole Haritchabalet [1]

[1] Universite de Pau et des Pays de l'Adour, E2S UPPA, CNRS, TREE, 64000 Pau, France; carole.haritchabalet@univ-pau.fr
[2] Safran Helicopter Engines, 64510 Bordes, France; stephane.beddok@safrangroup.com
* Correspondence: jean-baptiste.jarin@univ-pau.fr

Abstract: The 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, such as battery electrification and 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 aircraft. These combinations lead to different energy requirements and must be understood in order 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 energy carrier dictates the propulsive system architecture, leading to integration effects with aircraft, which can significantly change the energy required for the same mission, increasing it from 400 to 2665 kWh. These deviations led to significant differences in CO_2 emissions and costs. Battery electrification is impacted by battery manufacturing but has the lowest electricity consumption. This 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 using the most efficient molecule in an aircraft can compensate for 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

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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's forecast for 2050 concludes that the flight demand could increase, on average, by 3.1% per year and that the CO_2 emissions could consequently climb to 2 Gt [2] if no specific measures are put in place.

As for the entirety of air transportation, vertical take-off and landing (VTOL) aircraft, which currently account for 1% of the total jet fuel consumption and CO_2 emissions [3], will rely on sustainable aviation fuels (SAFs) to lower their carbon footprint [2]. SAFs 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 an aircraft's propulsive system and, therefore, its energy consumption, defining the cleanest and most affordable energy carrier might require a novel approach.

As air mobility is often recognized as a "hard to abate" sector, several technologies are currently being considered in attempts to lower its CO_2 emissions. While biofuels will play an important role in the short- and long-term, low-carbon electricity is now considered, using either direct electrification with rechargeable batteries (BE) or energy vectors such as hydrogen (H_2) or eFuel. eFuel requires electricity for water electrolysis, CO_2 capture and the Fischer–Tropsch process (H_2 + CO_2 + H_2O) but requires no modification to the carrier. H_2 can be combined either with a fuel cell + battery hybrid system (FCH_2) or a gas turbine (GTH_2), in both cases requiring significant modifications to the carrier. Similarly, direct battery electrification (BE) requires major modifications to the aircraft. For BE, FCH_2 and GTH_2, this means a significant weight gain for the aircraft. 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 means of transportation could have an impact on the results and this study focuses on vertical take-off and landing (VTOL) aircraft as they are the most demanding in terms of energy when expressed in terms of payload–distance. VTOL aircraft are also often considered in studies analyzing the opportunity to switch from fossil jet fuel to more disruptive energy vectors, such as BE and/or H_2 [4–6]. Since our study focuses on VTOL, the conclusions might not apply to large aircraft [7]. In this study, H_2 is considered liquified and not compressed due to its too low volumetric density [7].

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

The energy required to fulfill the considered mission is first expressed in the units of the energy carrier before being translated into kWh at the well, the electricity grid, and its carbon intensity (CI), being the central focus of our analysis. Electricity is used either for direct charging, for liquified hydrogen (LH_2) production through water electrolysis or for eFuel conversion using the Fischer–Tropsch process, which requires hydrogen and carbon dioxide. The results are then finally converted to CO_2 emissions and direct energy cost to fulfill the mission.

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

Previous Work

A significant number of articles cover alternative aviation fuels and propulsion systems. Grahn et al., in 2022, reviewed the cost of eFuel and its environmental impact [10] with no clear conclusions regarding the CO_2 impact. The Académie des Technologies report on the role of SAFs in air transport in 2023 [11] highlighted the needs and limits of the deployment of low-carbon electricity to reach a viable production volume of eFuel. In Europe, the recent ReFuel EU regulation will require 70% of aviation fuel to be sustainable by 2050, of which half would be eFuel [12]. Rojas-Michaga et al. [13] reviewed the SAF production through power to liquid (eFuel) and concluded that the dominant factor in eFuel's CO_2 emissions is 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 top-level aircraft requirements, applied to Airbus A321 and A350 models using the Pacelab APD design tool. Their conclusions are then expressed in USD per passenger/kilometers to allow for a fair comparison between the different fuels evaluated. 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 aircraft with design principles based on the Froude–Rankine theory and the statistical design method for VTOL. We also introduce the electricity input from the well to the tank to allow for 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), liquified H_2 with fuel cells (FCH_2), liquified H_2 with gas turbine (GTH_2) and eFuels. Fossil jet fuel and sustainable aviation fuels (SAF) issued from the biomass will only be considered in the Section 4 to compare the results.

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

To compare the different energy vectors, we, therefore, review the efficiency of each energy carrier from the electricity grid to the tank ("well to tank") before introducing its associated propulsive system. We then consider the integration effects on the aircraft's weight to determine the final energy requirements, the "tank to rotor" efficiency.

This is described in Figure 1 below:

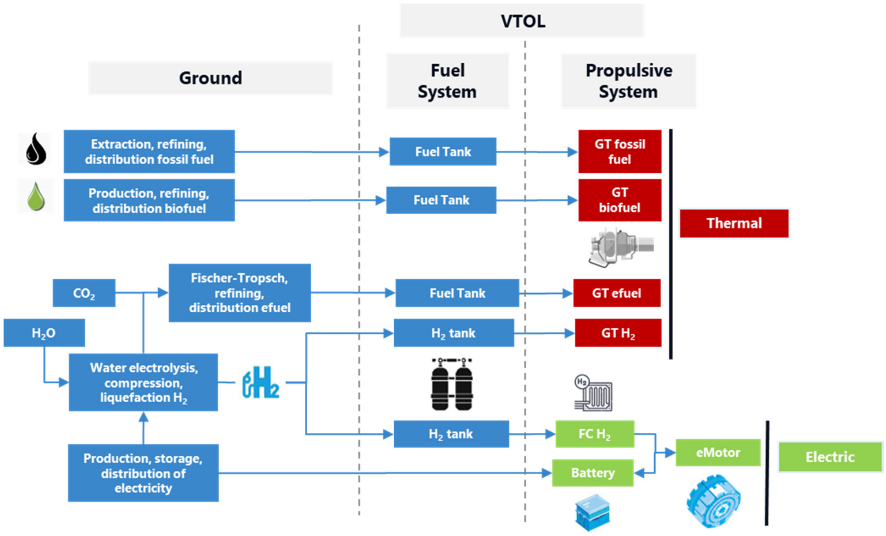

Figure 1. Energy carriers applied to VTOL with the associated propulsive architecture.

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

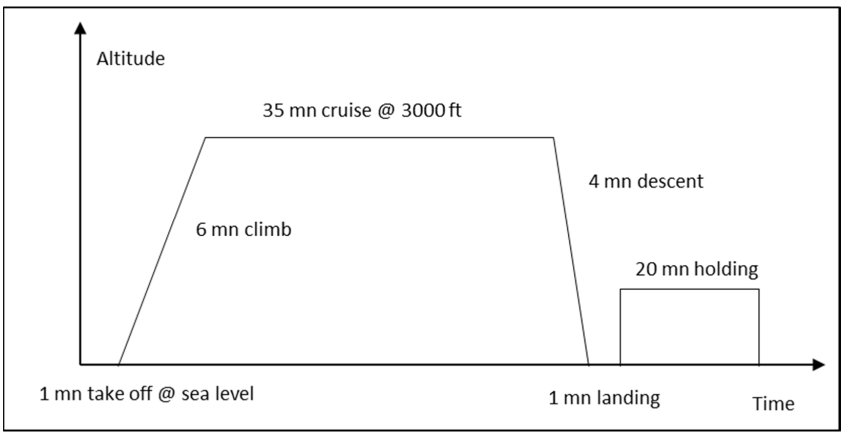

Figure 2. Mission profile.

Although the range of VTOL aircraft is often in excess of 300 nm, and typical missions often exceed this range between refueling, the 80 nm limit was set to take into account the possibility of introducing BE, as some potential air taxi missions are envisaged in the future with BE [18]. The crew is limited to one pilot, and the altitude is up to 4000 feet. A typical mission before refueling is around 45 min of flight time, as shown in Figure 2 above. However efficient it may be, a VTOL aircraft must continually fight gravity and will always consume more energy than a fixed-wing aircraft with a similar payload and range.

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 volumetric energy density that is too low. This will lead to larger tanks, penalizing the drag and empty weight of the aircraft, leading to structural reinforcement and thus more weight. A heavier aircraft will require higher power requirements and ultimately increased energy consumption. Payload and range also have significant contributory effects [18]. In this study the limited range and payload limit these effects, enabling a comparison with battery electrification (BE).

In our approach, we need to determine the power required at the main gearbox input to calculate the aircraft performance and ability to perform the mission. No modifications are assumed on the aircraft and a standard configuration comprising a large main rotor and a tail rotor to counteract the main rotor torque is used. The modelling is based on two well-known principles: the Froude–Rankine theory and the statistical design method for VTOL, here in the range of 1500 to 3000 kg, as proposed by A.Tremolet in "Numerical models and methods for conceptual studies of rotary-wing aircraft" [19]. The performance equations are described in Figure 3 below.

Power required

$$PW_{req} = \left(PW_{ind} + PW_{bld} + PW_{fus}\right) \cdot (1 + \alpha_{TR}) \Big/ \eta_{PGB}$$

$$PW_{ind} = T \cdot (V_z + V_i)$$

$$T = W_{TO} \cdot g \cdot (1 + \alpha_{dw})$$

$$\left(\frac{V_{i0}}{V_i}\right)^2 = \left(\frac{V_X}{V_{i0}}\right)^2 + \left(\frac{V_Z + V_i}{V_{i0}}\right)^2$$

$$V_{i0}^2 = \frac{T}{2 \cdot \rho_{air} \cdot S_{MR}}$$

$$PW_{bld} = \frac{\rho_{air} \cdot b_{MR} \cdot C_{MR} \cdot D_{MR} \cdot C_{xp} \cdot U_{MR}^2}{16} \cdot (1 + 5\mu^2)$$

$$D_{MR} = {W_{TO}}^{0.3}$$

$$PW_{fus} = \frac{\rho_{air} \cdot S \cdot C_x \cdot V_x^3}{2}$$

Figure 3. Performance equations.

Each propulsion system is designed to meet the power and energy requirements which are issued from the aircraft modeling. Weight breakdown is described in Equation (1):

$$W_{TO} = W_{EP} + W_{PS} + W_{CR} + W_{PL} + W_{FL} \text{ when } W_{EP} = \alpha_{EW} \cdot W_{TO} \quad (1)$$

The take-off weight of a VTOL aircraft for a given mission is then calculated for each energy carrier/propulsive system combination. The assumptions made in this study are detailed in Tables 1 and 2 while the design stages are described in Figure 4.

Table 1. Main properties of jet fuel and LH_2.

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%

Table 2. Main hypotheses 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%	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
LH_2 gravimetric index: 30% Fuel Cell efficiency: 50% Fuel Cell power density: 1.5 kW/kg		

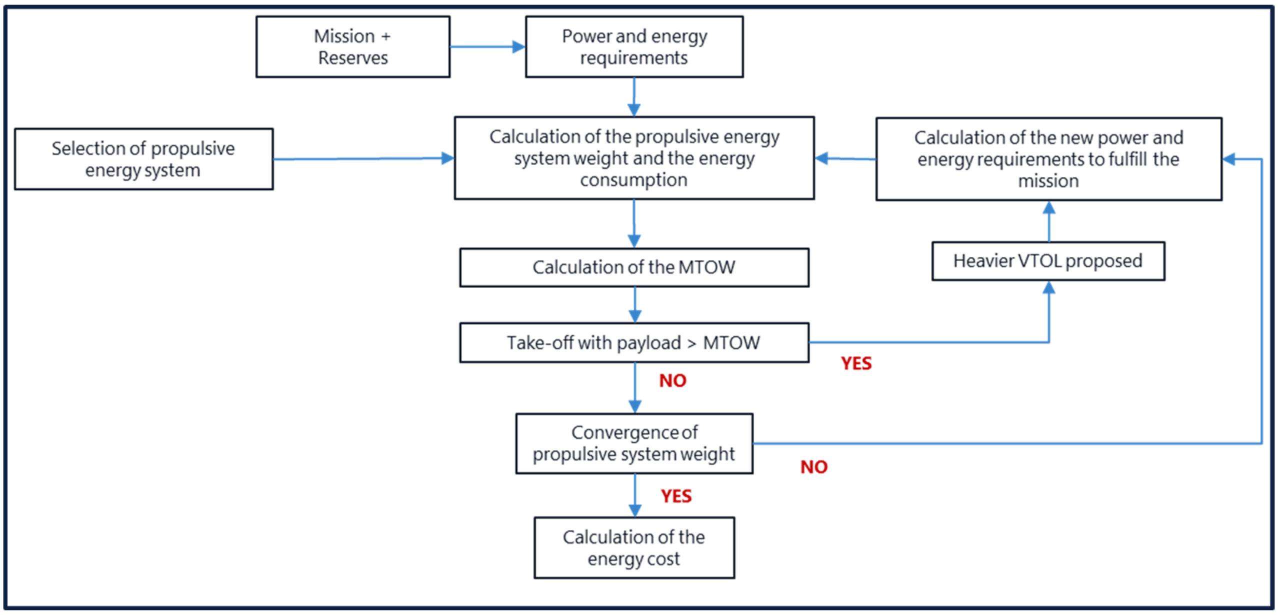

Figure 4. Design step for calculation.

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. Hypotheses are detailed below.

LH_2 gravimetric index: The tanks required to store H_2 as cryogenic liquid result in added weight which will be carried during the entire mission. This means a more robust airframe such as a more robust, i.e., thus heavier, landing system (in an aircraft, the max landing weight is below the TOW to benefit from the fuel burned during the mission which makes the aircraft lighter). An important performance measure for assessing tank storage efficiency is gravimetric efficiency, presented in Equation (2), where W_{H2} is the weight of hydrogen the tank can hold and W_{tank} represents the weight of the empty tank. Gravimetric efficiency is the fraction of the storage system's weight absorbed by the 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. Evolutionary improvements are predicted to be 25–40% [7] and we have used a 30% value in our design model. For comparison, the gravimetric efficiency of kerosene tanks is limited in a VTOL aircraft to ~20 kg.

$$n_{tank} = \frac{w_{H_2}}{w_{H_2} + w_{tank}} \tag{2}$$

- Fuel cell efficiency: This has a direct impact on the quantity of LH_2 onboard the VTOL aircraft and, thus, the size and weight of the LH_2 tanks and, thus, the power requirements and, thus, the energy consumption. In our model, a proton exchange membrane (PEM) is preferred to solid-oxide fuel cells (SOFC) as a PEM can operate at low temperatures. Lower temperatures allow quick response times while SOFC, which operate 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 and 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] mentions 50% efficiency for the fuel cell, which is the value used in this study.
- Battery cell energy density: Electricity is electrochemically stored. Li-ion batteries are currently the main technology used in electric vehicles and are 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 assumed a further improvement to 600 Wh^{-1}/kg when associated with an integration factor of 1.35.

2.3. Energy Carriers

This study focuses 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, are used as a reference for comparing the CO_2 emissions and affordability of the energy for air mobility in the Section 4. Since biofuels can have different costs and CO_2 emissions [22,23], we compare the different energy carriers with the most readily available SAF in 2023, which is HEFA-UCO (hydro-esterification of fatty acids, made from used cooking oil). This biofuel is certified according to the ASTM standard and already in operation in the air transport industry in blend proportions 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 energy carrier/propulsive system combinations studied here as described in Figure 1. We assume that electricity is supplied by the grid with no consideration of load factor: electricity is always available either for charging a BE VTOL or to produce LH_2 or eFuel. The carbon intensity is expressed in gCO_2/kWh and costs in €/kWh.
    - 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: LH_2 produced from water electrolysis will be either used in a gas turbine or in a fuel cell. Our assumptions is that LH_2 will be directly manufactured on site to avoid any long-distance transportation 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, therefore, considered in this study.
    - Electricity for eFuel: as for LH_2, electricity is the dominant factor when producing eFuel [11,17,28]. eFuel will require an optimized unit of production as proposed in [11,17] using either direct air capture or biogenic CO_2 [28]. As for LH_2, H_2 is produced using water electrolysis but collocated with Fischer–Tropsch and direct air capture (DAC) units to optimize the efficiency of eFuel production. This significantly improves the efficiency as described by Peters et al. in "a techno-economic assessment of Fischer-Tropsch fuels based on syngas from co-electrolysis" [17]. The efficiency ranges from 46 to 67% and we 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 (LCA)

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 architectures to be equal and do not take into consideration the environmental impact, nor the CAPEX, associated with the various aircraft configurations with the exception of the battery pack as battery manufacturing has a significative impact on the lifetime costs and CO_2 emissions of a vehicle [31]. The hypothesis for 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 charging, our assumption for battery replacement is 1350 cycles [33], equivalent to 200.000 km, while the battery cost hypothesis is 75 USD/kWh as proposed by Lutsey and Nicholas in "update on electric vehicle costs through 2030" [34].

For FCH_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 being proportional to the battery pack size.

The LCA of 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" [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 are calculated with $Q_{kWh} \cdot CI_{kWh}$ whereas Q is the quantity of electricity required (65 kWh/kg of LH_2 and 22.2 kWh/kg of eFuel) and CI is 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 carried out for each propulsion system, leading to different VTOL sizes for carrying out the same mission. The results are presented in Table 3 below, with the weight distribution of each propulsion system and the associated energy consumption to complete the mission.

Table 3. Max TOW and associated energy requirements according to each VTOL energy carrier/propulsive system combination.

Propulsive System	Component Weight in kg					Propulsive System Weight	VTOL TOW	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 LH_2	160	210			670	1040	2500	36 kg of LH_2
Fuel Cell with LH_2	800	220	160	80	40	1300	2900	41 kg of LH_2
Battery Electrification			870	80	100	1050	2700	360 kWh of electricity

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

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

When using LH_2, the need to accommodate wider and more robust tanks (Section 2.2) leads to a heavier VTOL. TOW is almost doubled compared to GT with eFuel, reaching 2500 kg (rounded value) for GTH_2 and 2900 kg (rounded value) for FCH_2. This added weight can be explained as follows:

- The propulsive system based on fuel cells is penalized by the fuel cell weight and the associated balance of the 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].

A heavier TOW requires a greater amount of energy: 36 and 41 kg of LH_2 for GTH_2 and FCH_2, respectively.

To calculate the BE VTOL TOW, the battery pack size is calculated with the above hypotheses. Since the energy required to fulfill the mission reaches 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 10% state of charge before charging [37], and the aging of the battery before replacement with the assumption of 80% before reaching the battery's knee-point [38].

3.2. Energy Requirements "Well to Rotor" in kWh

To calculate the total electricity consumption, we apply the methodology detailed in Section 2.3 (energy carriers):

- 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 is required to fulfill the mission, this leads to 1399 kWh of electricity used from the grid.
- LH_2: 65 kWh of electricity is required to produce 1 kg of LH_2:
    - GTH_2: 36 kg of LH_2 is required to fulfill the mission, so 2340 kWh of electricity will be used from the grid.
    - FCH_2: 41 kg of LH_2 is required to fulfill the mission, so 2665 kWh of electricity will be used from the grid.

The results are synthetized in Table 4 below:

Table 4. Total electricity required from the grid for each energy carrier, well to rotor, in kWh.

Mission: 4 Pax, 80 NM	VTOL Energy Carrier Requirement	Electricity Required to Produce the Energy Vector	Total Electricity Consumption, kWh
Gas Turbine with eFuel	63 kg	22.2 kWh/kg	1399
Gas Turbine with LH_2	36 kg	65 kWh/kg	2340
Fuel Cell with LH_2	41 kg	65 kWh/kg	2665
Battery Electrification	360 kWh	10% charging losses	400

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: $Q_{kWh} \cdot CI_{kWh}$.

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 carriers except for BE and FCH_2 as battery manufacturing comes with significant CO_2 emissions as described in Section 2.4 (LCA). The CI of the battery manufacturing shall, therefore, be added to the result of $Q_{kWh} \cdot CI_{kWh}$.

For battery electrification, the hypothesis for battery manufacturing is a GHG of 72.9 kg CO_2/kWh [32], which means 45.56 kg of CO_2 for the 625-kWh battery pack calculated in Section 3.1. The battery pack will be replaced every 200.000 km as detailed in Section 2.4 (LCA); therefore, 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 BE and FCH_2, the equation is $Bat_{CO2} + Q_{kWh} \cdot CI_{kWh}$, Bat_{CO2} being the fixed CO_2 emissions associated to 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 5 below:

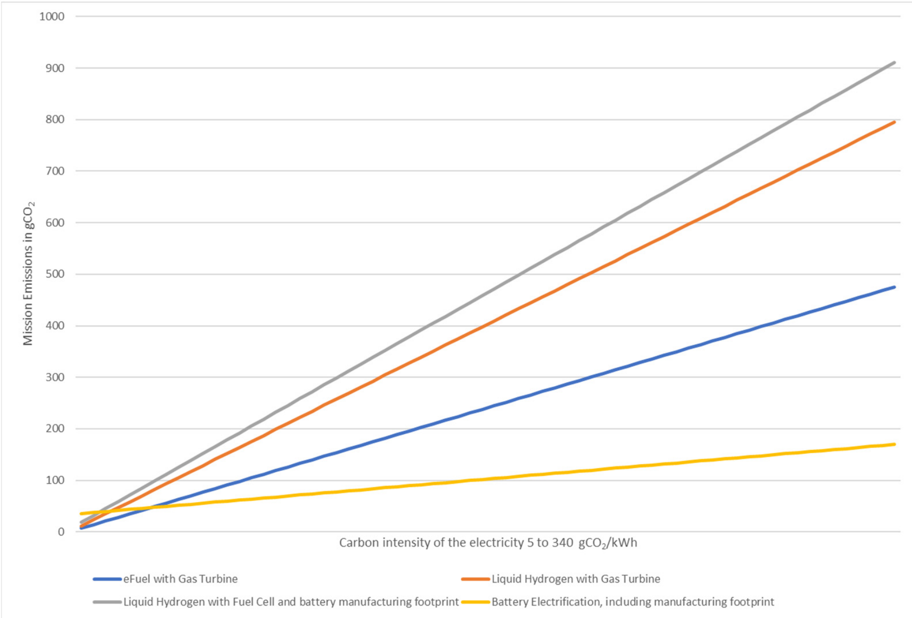

Figure 5. CO_2 emissions calculated for each energy carrier with an electricity CI from 5 to 340 gCO_2/kWh.

Calculations are based on $Q_{kWh} \cdot CI_{kWh}$ for eFuel with Gas Turbine and Liquid Hydrogen with Gas Trbine (GTH_2) and $Bat_{CO2} + Q_{kWh} \cdot CI_{kWh}$ for Liquid Hydrogen with Fuel Cell ($FCH_{2)}$ and Battery Electrification (BE).

CI in Figure 5 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, either combined with a Fuel Cell or a Gas Turbine, 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 Table 4, with 1399 kWh for eFuel, 2340 kWh for GTH_2 and 2665 kWh for FCH_2.

Battery electrification has the lowest CO_2 emissions except when the carbon intensity is very low, which could be explained by the impact of 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 94 gCO_2/MJ [24] and a LHV of 44.1 GJ/t [25], i.e., 4.15 kg of CO_2 per kg of fossil fuel, eFuel CI shall remain below 1.25 kg of CO_2 per kg. Since the CI of eFuel is directly proportional to $Q_{kWh} \cdot CI_{kWh}$, and with Q being 22.2 kWh, the maximum CI of electricity is 56 gCO_2/kWh for eFuel to be considered as a clean energy.

In Figure 6, we, therefore, focus on carbon intensity of the electricity from 5 to 50 g CO_2/kWh. One can notice that when the carbon intensity of the electricity is very low, the choice of energy carrier is less obvious.

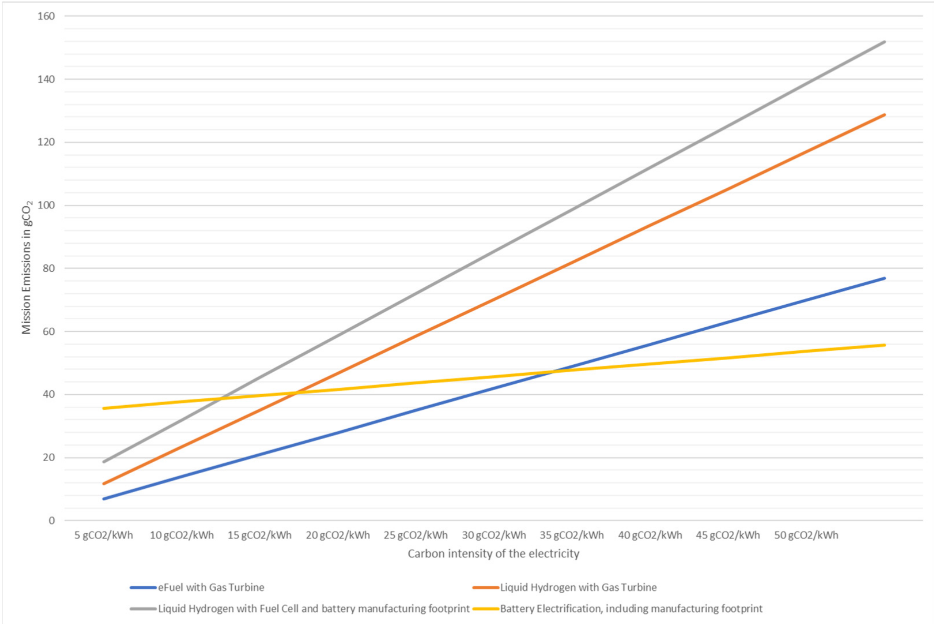

Figure 6. CO_2 emissions calculated for each energy vector with an electricity CI from 5 to 50 gCO_2/kWh.

When electricity CI is below 35 gCO_2/kWh, eFuel shows lower emissions than any other pathway, including battery electrification. This can be explained by the impact of battery pack manufacturing 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 battery packs.

For LH_2 and eFuel energy carriers, Figure 6 confirms that whatever the carbon intensity of the electricity, eFuel has lower CO_2 emissions than any propulsive systems using LH_2 (FCH_2 and GTH_2). This is mainly explained by the VTOL TOW, which is significantly heavier for FCH_2 and GTH_2, thus requiring more energy and, thus, 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 plus the cost of the battery pack when applicable. CAPEX is 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 USD/kWh: $M_{kWh} \cdot \$_{kWh}$

This is true for all energy carriers except for BE and FCH_2 as battery manufacturing implicates significant costs as described in Section 2.4 (LCA).

For battery electrification, the hypothesis for the battery manufacturing is a cost of 75 USD/kWh [34], which means USD 46875 for the 625-kWh battery pack which will be replaced every 1350 cycles [33] or an equivalent of 200.000 km. This means USD 0.23 is to be added per km, or USD 34.7 for the mission, 80 nm being equivalent to 148 km ($0.234 \cdot 148$).

For FCH_2, the 100-kWh battery pack, using the same formula, would add USD 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 USD/MWh as proposed by Idel in "Levelized Full System Costs Of Electricity" (LFSCOE) [41].

Results are shown in Figure 7; the cost of the mission is expressed in USD in the y axis while the LFSCOE is in the x axis.

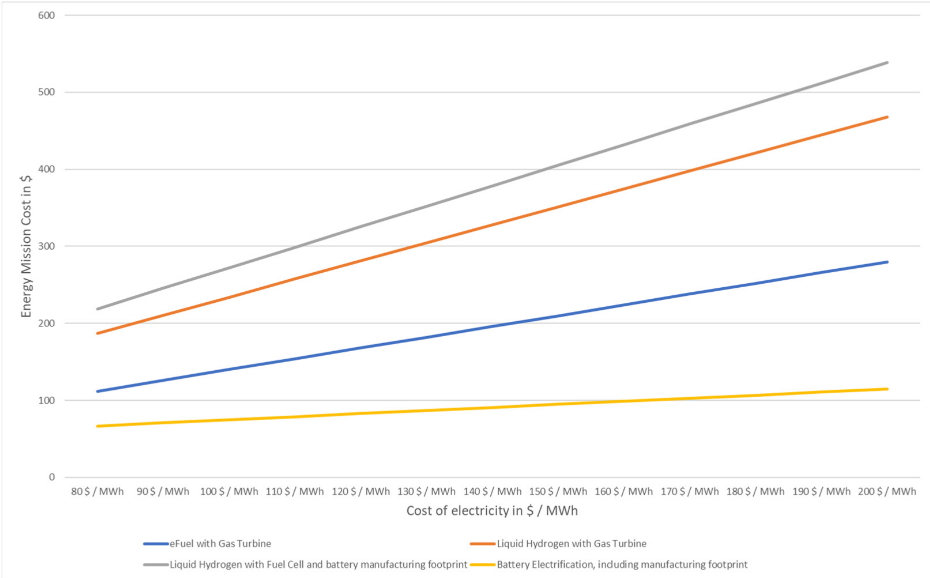

Figure 7. Energy Mission cost in USD.

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

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, four passengers over 80 nm, using the well-to-rotor methodology.

While there are various solutions when considering the transition to low-carbon energy [42], flying requires much more energy than floating or rolling. Therefore, 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 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 payloads and, 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 aircraft can travel more than 2 million kilometers per year, therefore consuming almost one battery pack per month since the average lifetime of a battery pack is 1350 cycles or 200.000 km [33].

In all scenarios, eFuel shows less CO_2 emissions and lower costs than LH_2-based propulsive systems. We can conclude that carrying the most efficient molecule in an aircraft pays the extra energy cost spent on the ground for its production, namely the Fischer–Tropsch process which combines H_2 + CO_2 + H_2O. This will be further investigated in future works since VTOL requirements, such as hovering, are extremely energy demanding, thus probably magnifying the results.

A limitation of this study is that the boil-off rate of LH_2 is not considered as the model does not consider turnaround time nor the time between two flights. This would further penalize the LH_2 option. Another limitation of this study concerns the impacts of NOx, contrails and noise which are not considered here. Future works should be conducted to refine the FCH_2 potential for small, fixed-wing aircrafts which could perhaps accommodate a fuel cell more efficiently than a VTOL aircraft [6,7].

As the aviation industry intends to decarbonize its energy, one shall consider that the LH_2 option requires not only more electricity from the grid compared to eFuel but also that it comes with the need to be produced at the point of use as it does not travel efficiently [16]. LH_2 should be produced locally, which could significantly harm the cost for airlines in countries where electricity prices are high as shown in Figure 8 below.

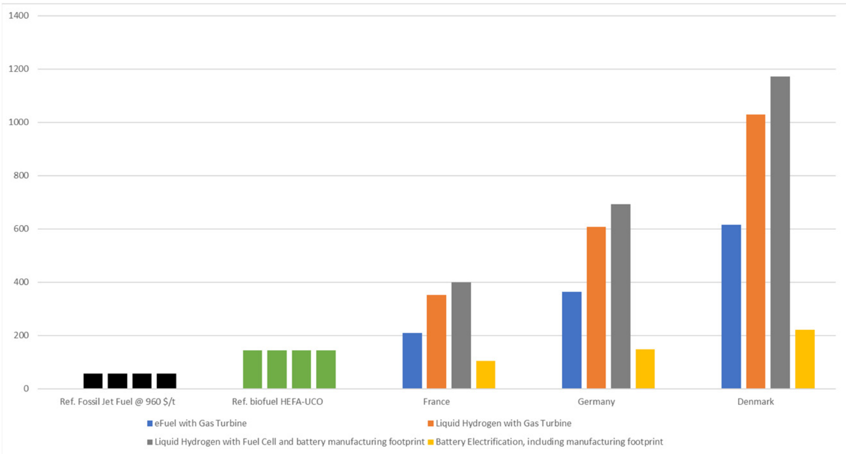

Figure 8. Direct energy cost for each energy carrier in 3 European countries, in EUR/mission. Fossil jet fuel and biofuel (HEFA-UCO) are introduced for comparison only.

In Figure 8 we apply the price of electricity (EUR/kWh) of three European countries, using data from Statista [44] for the second semester of 2022: EUR 150, 260 and 440 per MWh in France, Germany and Denmark, respectively. We introduced the cost of fossil fuel and the cost of the most common biofuel (HEFA-UCO) [4] for comparison.

One can notice that fossil fuel remains the cheapest option but also that biofuel (HEFA-UCO) could almost compete with battery electrification. More interestingly, a country with high electricity prices, such as Denmark, might consider importing eFuel from France, where electricity is much cheaper, rather than charging a BE VTOL aircraft domestically. While this is probably not an option, it does highlight the disparities between future producers of low-carbon energy carriers: electricity not only needs to be low-carbon but also affordable.

Finally, we note that the impacts on electricity production could be significant. Consequently, the impact on electricity production must be considered at a national and/or continental level. In Europe, the European Union (EU) recently set a target of 35% RFNBO in its ReFuel EU regulation for 2050 [12], and this study concludes that it would most likely be eFuel. If the EU needs 50 Mt of jet fuel by 2050, this would mean 17.5 Mt of eFuel. With 60% selectivity, meaning 60% eFuel and 40% co-products [11], 37 TWh of electricity would be needed per Mt of eFuel. This equals 650 TWh (17.5 Mt $\cdot$ 37 TWh/Mt) in an optimized scenario. In 2022, the European Union produced 2641 TWh, of which 23.5% was of wind and solar, or 607 TWh [45]. Large-scale eFuel production would, therefore, require a significant amount of low-carbon electricity, which could lead to conflicts of use in the future. These findings are in line with those 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 energy decarbonization for air mobility will be explored in more detail in future work.

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Conflicts of Interest: Jean-Baptiste Jarin has been working for Safran for 25 years and is now a PhD student at the University of Pau UPPA-E2S. Stéphane Beddok is employed by Safran as engineer in charge of propulsive system architecture. Safran is a leading aerospace company, involved in gas turbines, battery electrification, fuel cells and other aerospace components. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

a_{DW}	Downwash coefficient (-)
a_{TR}	Tail rotor coefficient (-)
BAT	Battery
h_{PGB}	Gearbox efficiency (%)
m	Advance ratio (-)
r_{air}	Air density (kg/m^3)
b_{MR}	Number of blade of the main rotor (-)
C_{MR}	Main rotor chord (m)
CAF	Conventional Aviation Fuel
D_{MR}	Main rotor diameter (m)
FC	Fuel Cell
GT	Gas Turbine
PW_{BLD}	Blade profile power (kW)
PW_{FUS}	Fuselage power (kW)
PW_{IND}	Induced power (kW)
SAF	Sustainable Aviation Fuel
S_{MR}	Main rotor surface (m^2)
SC_x	Helicopter drag (m^2)
T	Rotor vertical thrust (N)
U_{MR}	End tip blade velocity (m/s)
V_i	Induced velocity (m/s)
V_{i0}	Induced velocity in hover (m/s)
V_x	Aircraft horizontal speed (m/s)
V_z	Aircraft vertical speed (m/s)
W_{CR}	Crew Weight (kg)
W_{EP}	Empty Weight (kg)

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