ALTERNATIVE PROPULSION SYSTEM FOR HELICOPTER AND CO2 EMISSIONS

Stéphane Beddok, Safran Helicopter Engines, Bordes, France
Jean-Baptiste Jarin, Université de Pau et Pays de l'Adour, Pau, France

Abstract

The aviation sector is now facing one of its biggest challenges as it aims to reduce its carbon emissions close to zero and decarbonization of air mobility requires to lower the carbon intensity of its energy. Several technologies are potential candidates both at aircraft level, including configurations and at propulsion system level, including architectures and energy sources. Biofuels will, of course, play an important role, but other low carbon energy carriers based on electricity will be also considered.

This study focuses on small helicopter aircraft and on propulsion system by looking at the six main propulsion systems known as conventional turboshaft engine with either standard jet fuel, sustainable aviation fuel or electro fuel issued from hydrogen or direct hydrogen combustion, full electric supplied by batteries and full electric supplied by fuel cell and hydrogen. Each energy has its own conversion steps and losses and its own integration effects. Hence, the aircraft will be sized for a given mission, depending on the propulsion system weight and efficiency and each solution will be compared with respects to energy consumption.

Then the different energy will expressed in CO2 emissions using the Well To Wake methodology that will lead to significant differences in greenhouse gas emissions and electricity needs. We will focused how the electricity carbon intensity will affects the CO2 emissions of an air mobility mission.

1. NOTATION

Symbols and acronyms

α_{DW}	Downwash coefficient (-)
α_{TR}	Tail rotor coefficient (-)
BAT	Battery
CAF	Conventionnal Aviation Fuel
η_{PGB}	Gearbox efficiency (%)
μ	Advance ratio (-)
ρ_{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)
DOD	Depth Of Discharge
EOL	End Of Life
EU	Europe
FC	Fuel Cell
FR	France
GT	Gas Turbine
H2	Dihydrogen
H2B	Hydrogen To Burn
HEFA	Hydroprocessed Esters and Fatty Acids
LH2	Liquid Hydrogen
PCI	Pouvoir Calorifique Inférieur
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)
TtW	Tank to Wake
TS	TurboShaft engine
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)
W_{FL}	Fuel Weight (kg)
W_{PL}	PayLoad Weight (kg)

W_{PS}	Propulsion System Weight (kg)
W_{TO}	Take Off Weight (kg)
WtT	Well to Tank
WtW	Well to Wake

2. INTRODUCTION

The aviation sector is now facing one of its biggest challenges as it aims to reduce its carbon emissions close to zero. Several technologies are potential candidates both at aircraft level, including configuration and at propulsion system level, including architectures and energy sources.

This study focuses on helicopter aircraft and on propulsion system by looking at the six main propulsion systems known as conventional turboshaft engine with either standard jet fuel, sustainable aviation fuel or electro fuel issued from hydrogen or direct hydrogen combustion, full electric supplied by batteries and full electric supplied by fuel cell and hydrogen. The aircraft will be sized for a given mission, depending on the propulsion system weight and efficiency and each solution will be compared with respects to energy consumption.

3. AIRCRAFT MISSION

The selected mission is a transport path for four passengers and a pilot over 80 nm and including a 20 mn loitering reserve. All the calculation are performed in standard atmosphere. The mission is illustrated in Figure 1.

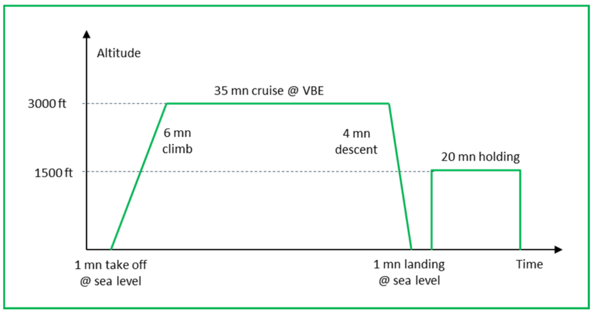

Figure 1: Mission profile

4. HELICOPTER PERFORMANCES MODELING

The modelling of the aircraft performance is based on the state of the art knowledge to determine the required power at the main gearbox input. No modification are 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 helicopter in the range of 1 500 to 3 000 kg.

The theoretical formulation used for the calculations are detailed with the equations in Figure 2 and Figure 3 (Reference 1 and Reference 2).

Weight breakdown

$$W_{TO} = W_{EP} + W_{PS} + W_{CR} + W_{PL} + W_{FL}$$

$$W_{EP} = \alpha_{EW} \cdot W_{TO}$$

Figure 2: Weight breakdown equations

Power required

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

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

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

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

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

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

$$D_{MR} = W_{TO}{}^{0,3}$$

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

Figure 3: Performance equations

5. PROPULSION SYSTEM ASSUMPTIONS

Each propulsion system is design to meet the power profile and the energy requirement issued from the aircraft modelling in order to complete the mission including the reserve path.

The symbol are presented in Figure 4 and then the architecture in Figure 5.

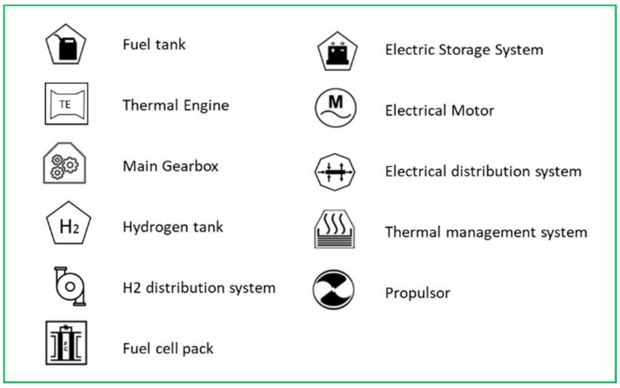

Figure 4: component symbols

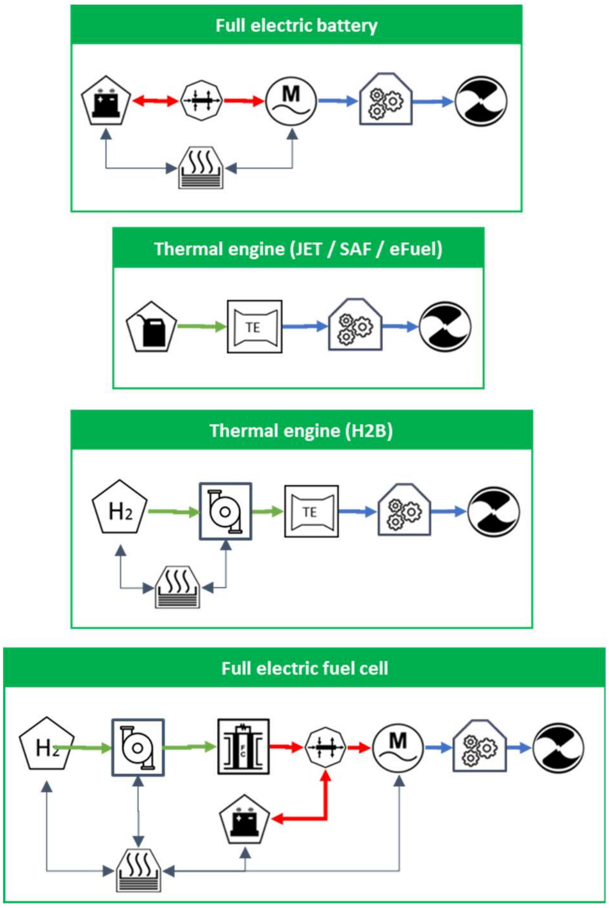

Figure 5: Propulsion system architectures

The components performance projection is based on different Safran's and supplier roadmap and literature for a 2040 EIS (Reference 3).

Table 1: Components assumptions

Gas turbine and fuels	
PCI CAF	12 kWh/kg
PCI H2	33 kWh/kg
Power density	7 kW/kg
Efficiency	33%
Installation losses	5%
Battery	
Energy density	600 Wh/kg
System integration factor	1,35
DOD	90%
EOL Energy	85%
Fuel cells	
System power density	1,5 kW/kg
Efficiency	50%
Electric motor	
Power density	8 kW/kg
Efficiency	95%
H2 storage	
PCI H2	33 kWh/kg
H2 density	70 kg/m3
LH2 gravimetric index	30%

The aircraft sizing method depending on the propulsion system is detailed hereafter so that the helicopter take-off weight, for a given mission, is different from an energy source to another:

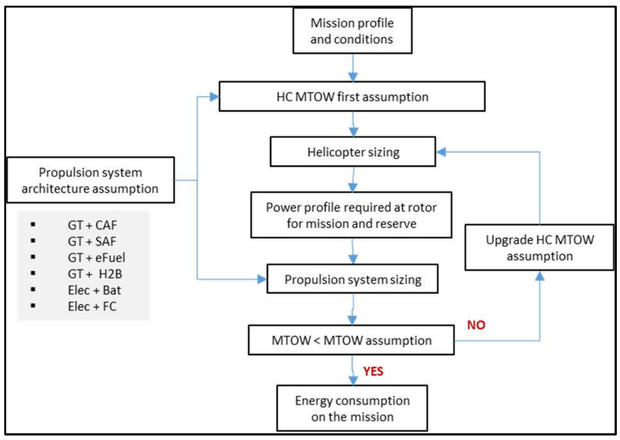

Figure 6: Design step for calculation

6. CO2 ENERGY INTENSITY

The different energies are then converted in CO2 emissions through their carbon intensity and depending on the way the electricity is produced for several countries. The carbon intensity is defined by the references [5], [6] and [7].

For the CO2 emissions, we need to both take into account the production of these energy, wich is known as the Well to Tank perimeter, and the on-board emissions as known as the Tank to Wake emissions. The whole emissions are then well to wake global emissions are are taking intaking the full lyfe cycle into account from profuction to usage including transport, transformation and storage.

It is important to notice that the global CO2 emissions are not only linked to the aircraft and propulsion system performances but also to the energy production technology and since most of these energy are linked to electricity the production area has to be taken into account.

Table *2*: CO2 intensity of energies

	WtT	TtW
	gCO2eq/kWh	gCO2eq/kWh
CAF	79	259
SAF oil HEFA	-209	259
Electricity FR	58	0
Electricity EU	270	0
Electricity WD	425	0
H2 gas	333	0
H2 electrolyze FR	83	0
H2 electrolyze EU	594	0
eFuel FR	-152	259
eFuel EU	787	259

7. RESULTS

The analysis was conducted for each propulsion system, leading to different helicopter sizings, in order to perform the same design mission.

The results hereafter are presented first with the weight breakdown of each propulsion system (Figure 7) and then in energy consumption (figure 8).

Propulsion system	Main components weight						
							Miscellaneous*
GT CAF	120 kg	20 kg					50 kg
GT SAF	120 kg	20 kg					50 kg
BAT + e motor				80 kg	870 kg		100 kg
GT H2B	160 kg		210 kg				670 kg
FC + e motor			220 kg	80 kg	160 kg	800 kg	40 kg
GT + eFuel	120 kg	20 kg					50 kg

* Miscellaneous = harnesses, electric distribution, thermal management, H2 distribution, control system, ...

Figure 7: Weight breakdown results

Propulsion system	EHPS Weight	HC TOW	Energy for mission
GT CAF	190 kg	1 400 kg	CAF 63 kg
GT SAF	190 kg	1 400 kg	SAF 63 kg
BAT + e motor	1 050 kg	2 700 kg	Elec 360 kWhe
GT H2B	1 040 kg	2 500 kg	H2: 36 kg
FC + e motor	1 300 kg	2 900 kg	H2 41 kg
GT + eFuel	190 kg	1 400 kg	eFuel 63 kg

Figure 8: Total weight and energy results

Finally, each energy consumption is converted into global CO2 emissions using carbon intensity and depending on the production process and region (Table 3).

Table *3*: CO2 emissions results

	WtT	TtW
	Kg CO2	Kg CO2
CAF	60	196
SAF oil HEFA	-158	196
Electricity FR	21	0
Electricity EU	94	0
Electricity WD	153	0
H2 gas	444	0
H2 electrolyze FR	110	0

H2 electrolyze EU	550	0
eFuel FR	-115	196
eFuel EU	278	196

8. CONCLUSIONS AND WAY FORWARD

The main conclusions from this study are:

1- The SAF id one of the best opportunity to reduce greenhouse emissions but the volume might be limited and use can face the concurrence of other transportation means.
2- The electric battery propulsion is promising and the energy to produce and recycle the storage device should be further considered.
3- For both the hydrogen and the electrofuel, the need of production of huge amount of green electricity is one of the major point.

Based on this study it seems relevant to extend the perimeter to other aircraft such as any kind of VTOL or CTOL both conventional and associated to distributed propulsion. For the propulsion system, the target is to model hybrid propulsion like association of battery and fuel cell or thermal engine and electric propulsion.

Authors contact:

Stéphane Beddok

stephane.beddok@safrangroup.com

Jean-Baptiste

jean-baptiste.jarin@univ-pau.fr

9. REFERENCES

1. Arnaud Tremolet, Modèles et méthodes numériques pour les études conceptuelles d'aéronefs à voilure tournante, Thèse de doctorat, Octobre 2013.

2. Omri Rand & Vladimir Khromov, Helicopter Sizing by Statistics, American Helicopter Society 58th Annual Forum, June 2002.

3. Vincenzo Palladino, Méthode de conception pluridisciplinaire appliquée à un avion régional à faibles émissions, Thèse de doctorat de l'université de Toulouse, Mars 2023.

4. Jean-Baptiste Jarin, Stéphane Beddok and Carole Haritchabalet, Techno-economic comparison of low carbon energy carriers based on electricity for air mobility. Energies March 2023.

5. ADEME, Electrocarburants en 2050, Octobre 2023, L. Bonideau, P. Sacher, L. Antoine, O. Toma, A. El Khamlichi, A. Bichot, M. Cottignies, N. Dore, P. Cauneau, S. Barbusse.

6. Référentiel ISAE-SUPAERO Aviation et climat, Septembre 2021, S. Delbecq, J. Fontane, N. Gourdain, H. Mugnier, T. Planès & F. Simatos.

7. Nature communication 2022, Understanding variability in petroleum jet fuel life cycle greenhouse gas emissions to inform aviation decarbonization. L. Jing, H. El-Houjeiri, JC. Monfort, J. Littlefield, A. Al-Qahtani, Y. Dixit, R. Speth, A. Brandt, M. Masnadi, H. MacLean, W. Peltier, D. Gordon & J. Bergerson.

10. CLASSIFICATION & COPYRIGHT