PROPOSAL FOR A METHOD OF COMPARING CO2 EMISSIONS FOR HELICOPTERS.

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Abstract:
Major aviation organizations aim for net-zero carbon dioxide emissions by 2050. Even though helicopters represent under 1% of global aviation's 2-3% contribution to worldwide CO2, reducing their emissions is essential to fulfill aviation's commitments and prepare for future regulations. Due to the specific missions of helicopters, standard metrics from automotive and fixed-wing aircraft industries are unsuitable. This article presents the methodology for defining a CO2 metric for helicopters. Several metrics have been challenged before final recommendation. The first one consists of computing the net CO2 emitted on a given mission, directly from the fuel burn. The other approaches introduce dimensionless factors in order to relate the CO2 emission to a “given service”, which naturally increases with the helicopter's carrying capacity. This capacity is analyzed in two ways: by payload for cargo missions, the difficulties being the alignment of configuration; and by seating capacity for passenger transport missions, the advantage being the use of verifiable public data.

1. NOTATIONS

APU:	Auxiliary Power Unit
ATAG:	Air Transport Action Group
AH:	Airbus Helicopters
CO2:	Carbon Dioxide
ECS:	Environmental Cooling System
EEW:	Equipped Empty Weight
ERF:	European Rotorcraft Forum
H/C:	Helicopter
HOGE:	Hover Out of Ground Effect
ISA:	International Standard Atmosphere
MTOW:	Maximum Take-Off Weight
ICAO:	International Civil Aviation Organisation
ISA:	International Standard Atmosphere
OEM:	Original Equipment Manufacturer
RPK:	Revenue Passenger Kilometer
SAF:	Sustainable Aviation Fuel
SL:	Sea Level
SPS:	Standard Passenger per Surface
VBE:	Velocity of Best Endurance
VBR:	Velocity of Best Range
VTOL:	Vertical Take-Off and Landing

2. INTRODUCTION

General context

The Paris Agreement set long-term goals by “holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change” Ref. 1 & Ref . 2.

To keep global warming to no more than 1.5°C, carbon emissions need to be reduced by 45% by 2030 and reach net zero by 2050.

It is imperative that all sections of society and business must support the achievement of this goal.

Aviation commitments

In October 2021, the Air Transport Action Group (ATAG*), announced a goal to achieve net-zero carbon dioxide emissions by 2050 Ref. 3:

“Global civil aviation operations will achieve net-zero carbon emissions by 2050, supported by accelerated efficiency measures, energy transition and innovation across the aviation sector and in partnership with governments around the world.”

Figure 1 presents one of the scenarios envisaged by ATAG for the CO2 reduction by 2050 Ref.3, CO2 being the primary contributor to global warming.
The elements considered for CO2 emission reduction are:

- Technological improvements: could be unconventional airframe, hybrid electric propulsion
- Operation optimization: including load factor for commercial flights
- Sustainable Aviation Fuel (SAF): a powerful potential CO2 reduction
- Offsets to fill any remaining gaps

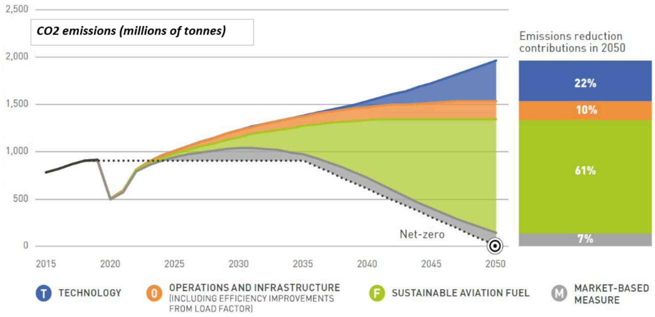

Fig 1. ATAG Net-zero scenario - Ref. 4

(*) ATAG is the world's principal airframe and engine manufacturer. ATAG comprises 45 organisations; representing airlines, airports, air navigation service providers, manufacturers, business aviation and the tourism sector, industry suppliers, sustainable aviation fuel companies, leasing companies and chambers of commerce.
In October 2022, the International Civil Aviation Organization (ICAO), a United Nation agency composed of aviation representatives from 193 nations, adopted a long-term global aspirational goal of net-zero carbon dioxide emissions from international flights by 2050 Ref. 5.
Depending on the perimeter considered, the part of aviation contribution to the CO2 is variable. The International Energy Agency reports Ref. 6 that aviation accounted for 2.5% of the world's carbon dioxide emissions in 2023. According to Ref. 7 "In 2018, emissions from the combustion of kerosene used by the entire aviation sector accounted for 2.4 % of the anthropogenic total, and full life-cycle emissions from commercial aviation accounted for 2.6 % of the total."

Studies conducted on this topic show that, throughout the entire product lifecycle, from the extraction of raw materials to the recycling phase at the end of life, the operational phase is by far the most impactful. According to Ref. 17, "*the impact on the environment due to the production of the helicopter fuselage is extremely low compared to the impact on the environment provoked by the generation and consumption of the aviation jet fuel, which is burned in the use phase of the helicopter*". From this statement, this article will be focused on the operational phase.

At the rotorcrafts level

Although helicopter CO2 emissions represent a low fraction of global carbon emissions (the order of magnitude is less than 1% of the global aviation emission), the rotorcraft manufacturers and operators have also to minimize their CO2 emissions in order to contribute to the aviation commitments and to anticipate potential future regulations.
This article focuses on the impacts of the helicopter usage phase on air pollution, particularly regarding CO2 emissions. Indeed, the operational phase of helicopters occurs at lower altitudes compared to commercial airplanes (up to 5,000 meters), meaning they do not emit contrails, and the effects of nitrogen oxides (NOx) are less significant Ref. 6 & Ref. 13.
If reducing the fuel consumption has always been an economic goal for the competitiveness of helicopters, today, it seems necessary to go further in this approach.
The pillars of decarbonization for helicopters are as follows Ref. 14:

- Engine efficiency: even if the engine OEM already did significant progress on the recent engine version, there is still potential improvement. This would represent a potential efficient lever using retrofits.
- Aerodynamic efficiency of the airframe and rotor, that will permit to reduce fuel consumption, particularly in cruise speed.
- Deployment of sustainable aviation fuels (SAF), which is a powerful element to reduce CO2 emission since it does not require a renewal of the fleet, even if the availability of large volumes would be an issue.
- Introduction of electrification and hybridization. The impact of such technology would be long term since it requires a renewal of the fleet.
- Weight Saving: reducing the gross weight of a helicopter (at iso payload) is a key to save fuel consumption.

- Operation: Optimization of trajectories, speed & cruise altitude can lead to a -10% fuel gain on some missions from first estimation. However, these gains cannot be applied on all missions, due to operational constraints.

Before going into the improvement of the platform, the first step of this process consists of defining the best indicator to measure the CO2 emitted by the helicopter in operation.

This article presents the methodology for defining a CO2 metric dedicated to helicopters. The metrics used in the automotive and aviation sectors are typically based on emissions per unit distance or per pax. Helicopter missions are diverse and some of them may not include passengers, or may not have to cover a given range (aerial work for instance). Those points render the classic metrics not applicable to the fields of the rotorcraft.

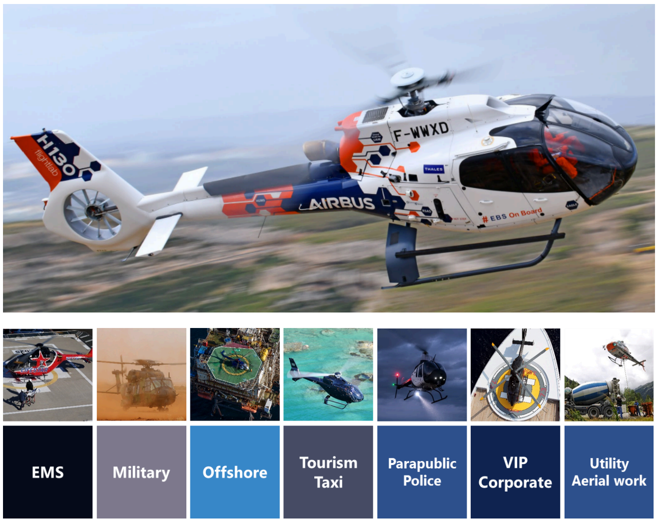

Figure 2. Helicopter: A Multimissions Aircraft

Due to its complexity and its high empty weight compared to its payload, as well as its low aerodynamic efficiency, the helicopter needs a high installed power to take-off vertically and fly quickly. Moreover, the ability to fly in hover is very energy-intensive. This is why helicopters could be erroneously considered as polluting and harmful means of transportation when compared to the automotive and rail sectors if an inappropriate metric is used.

3. PREVIOUS WORKS

CO2 Emission factor

Several CO2 metrics already exist in the transport industries, which historically grew by using thermal engines.

The common element is that the CO2 emitted during the use phase can be derived from the consumed fuel through the “CO2 emission factor”. The chemical combustion of fuel results in an amount of CO2 emitted proportional to the amount of fuel burned, according to a “CO2 emission factor”:

$$kgCO2 = Emission\ factor \cdot Fuel\ mission \qquad \text{Eq. (1)}$$

- For Jet fuel, the CO2 emission factor considered is 3.16 Ref. 8 - 1 kg of Jet fuel emits 3.16 kg of CO2 during combustion in the engine: direct emission factor.
- When considering upstream phases (kerosene production, transportation, etc.), the direct + indirect emission factor value is 3.83 kg of equivalent CO2 (kg CO2e).

In the current study, the direct and the indirect emission factor is considered to determine the amount of CO2e emissions. If the direct coefficient had been chosen, this would not have changed the final conclusion since the objective was to draw a relative positioning of the helicopters.

Automotive & commercial aviation

The automotive industry considers the quantity of CO2 emitted per kilometer for each vehicle Ref. 9.

Regarding commercial aviation, the CO2 intensity is expressed as gCO2 per Revenue Passengers Kilometers (RPK) Ref. 10 & Ref. 11.

In both cases, these metrics are not compatible with the rotorcraft mission specificities. Indeed, the CO2 emitted considered in these metrics is related to the distance travelled. That is not relevant for a rotorcraft where part of its operation consists in hovering phases.

CO2 Metric referring to useful load

Consequently, a CO2 metric specifically dedicated to helicopters has been proposed in the Ref. 9.

A usage spectrum was defined considering three main flight conditions representative of the majority of operations: hover & cruise at speed for best endurance, and cruise at the speed for best range.

The CO2 emission was calculated from the hourly fuel consumption at sea level International Standard Atmosphere (ISA) conditions.

In this reference Ref. 9, the choice was made to relate the CO2 emitted to the useful load of the helicopter. This choice is relevant since the useful load is a good indicator of the maximum transport capacity of a helicopter.

This indicator, however, relies on data that can be challenging to gather, and may not be widely applied to compare different helicopters. Indeed the useful load is the difference between the Maximum Take-off Weight (MTOW) and the empty equipped weight (EEW).

Useful load = MTOW - EEW [kg] *Eq. (2)*

The MTOW value is an indisputable public value that can easily be found in the Type Certificate Data Sheet (TCDS).

For the EEW, it is much more complex.

To compare a large range of helicopters, the configuration of these different rotorcrafts must be aligned. Aligning these configurations across an OEM's entire product range is already challenging. Indeed, the level of equipment proposed can differ largely, e.g environmental cooling system (ECS) or Auxiliary Power System (APU).

This becomes almost impossible if the final target is the comparison of helicopters from different OEMs. The reason is the knowledge of the detailed weights, what is included in the baseline empty weight or not. This is why it appeared necessary to determine a new CO2 metric for helicopters.

Additionally, the reference mission will be refined to better reflect the characteristics of the helicopter.

4. NEW CO2 METRIC DEFINITION

Several proposals of a CO2 metric dedicated to helicopters are described in the following sections. For each metric, the pros and cons are considered.

4.1 Direct CO2 emission calculation on a given mission

For a precise study based on a customer's needs, CO2 emissions can be calculated directly according to the mission profile defined by the customer.

The result will be the total fuel consumed by the helicopter on the different flight phases of the specified mission, multiplied by the emission factor:

$$CO2 = CO2\ Emission\ Factor \cdot \sum Fuel\ on\ mission\ phases \qquad Eq.\ (3)$$

Generic helicopter mission proposal:

In the frame of a more general study on CO2 emissions, it is necessary to define a reference mission that represents the main characteristics of a helicopter mission. This generic mission must take into account the following flight phases, which are typical of helicopters - Ref. 9:

- Hovering: that is the essence of helicopter flight.
- Cruise at best endurance speed (VBE): The speed at which the hourly fuel consumption is minimized. Operationally, this speed is typically used for observation or search missions (loitering).
- Cruise at optimal speed for range (VBR): The regime where the consumption per kilometer is minimized.

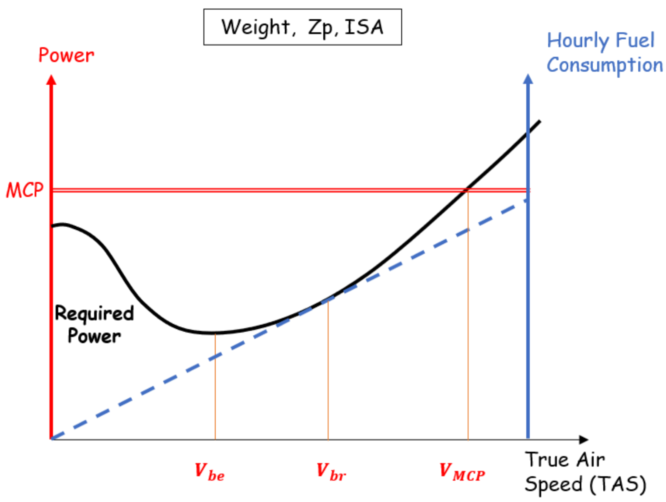

***Fig 3:** Typical helicopter power polar* Ref. 15

These flight phases are the ones defined in Ref. 9. However, the distribution of these flight phases in the reference mission is changed in the current approach. The flight profile chosen for the reference mission is as follows:

- Hover out of ground effect HOGE during 5 min.
- Cruise at VBE during 15 min
- Cruise at VBR with 100 NM of range.

Remarks:

1. This reference mission has been defined from the OEM experience with regard to the missions considered by our customers. If the order of magnitude is representative of the helicopter missions, the distribution of hours can be challenged.

2. The goal being to compare helicopters of different sizes, all the helicopters considered must be capable of performing this mission. The considered range includes helicopters with a maximum takeoff weight (MTOW) between that of the H125 (2,370 kg) and the H225 (11,160 kg) in the civil helicopter category (based on Airbus Helicopters range).
3. The first two phases are defined by a duration, and the third by a distance. This is the main difference with regards to the mission considered in the Ref. 9
4. Fuel consumption for these different phases is considered under the following conditions:
    a. Maximum Take-Off Weight (MTOW)
    b. At sea level in ISA conditions.

The CO2 emission is derived from the total mission fuel consumption which is the sum of the consumption from these three flight phases.

$$CO2(Mission)\ [kg] = Emission\ factor \cdot Fuel(Mission)\ [kg] \qquad Eq.\ (4)$$

$$Fuel(mission)[kg] = Fuel_{hover} + Fuel_{VBE} + Fuel_{VBR} \qquad Eq.\ (5)$$

As mentioned previously, the presence of a hovering phase involves that the CO2 emission related to a distance is meaningless. In the proposed approach, the CO2 emission will be related to the reference mission considered.

Results:

The kgCO2 emission results for this reference mission are presented in the figure 4 as a function of their MTOW and by considering various helicopter types from different OEMs.

The sources for fuel consumption come from commercial brochures.

The graph shows a nearly linear increase of the CO2 emission with the MTOW, and this trend remains uniform across different manufacturers.

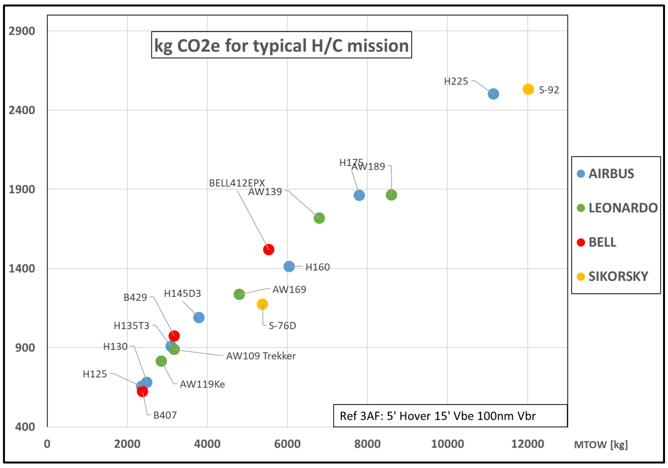

***Fig 4**: kg CO2e vs MTOW for a reference mission*

Conclusion:

This simple and pragmatical approach is appropriate for comparing CO2 emissions of some helicopters on a given mission. The comparison of the CO2 emitted by two helicopters able to perform the same mission will permit us to rank them appropriately.

However, this approach will not be adapted to compare helicopter emission in a more global approach. For instance, this indicator would systematically offer an advantage to light helicopters, which may not be able to offer the same services to the clients than heavy helicopters in terms of payload or passengers. So, the idea is to introduce a dimensionless factor in order to relate the CO2 emission to a “given service”, which naturally increases with the helicopter's carrying capacity.

Two metrics proposed in the following relate the CO2 emission to:

- Helicopter payload (cargo mission)
- Seating capacity (passengers transport mission)

4.2 CO2 Emissions on the reference mission related to the payload

This approach consists of dividing CO2 emissions on the reference mission by the helicopter's payload.

This metric will be appropriate for cargomissions e.g aerial work, logistic transport.

This method is close to the one used in Ref. 9 which considered the useful load instead of payload.

Reminder:

The useful load is the difference between the maximum takeoff weight and the empty weight. See Equation (2)

The payload excludes the crew and mission fuel weight from the useful load.

Payload = Useful load - crew [kg] - fuel mission *Eq. (6)*

As a first approach, related CO2 to payload as a metric is a fairly good indicator of the service delivered. However this approach presents some problems. Aligning empty weights is a complex exercise:

- Problems already arise when considering the range of AH helicopters. Indeed, the baseline equipment varies greatly depending on the range considered.
- This alignment becomes even more complicated if we want to compare with helicopters from other manufacturers, particularly due to an accessibility issue with components weights for non-AH products.

Results:

Despite the difficulties mentioned above, a preliminary positioning of the AH range only has been done. The kgCO2 emission on the reference mission related to payload are presented in the figure 4.1 as a function of MTOW.

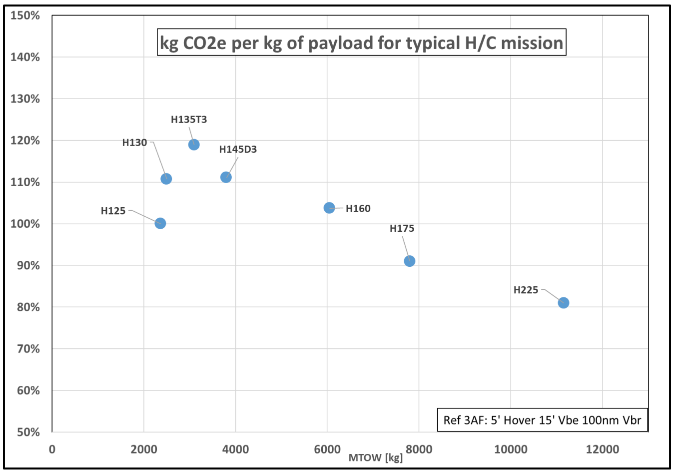

***Fig 4.1**: kg CO2e per kg Payload vs MTOW for a reference mission*

PS: Due to the data sensitivity, the results are presented using the H125's CO2 emissions per kg of payload as a reference.

Figure 4.1 shows a predominant influence of the payload over CO2 emissions, which introduces a bias into the metric's results. The payload increases more rapidly than the fuel consumption with the helicopter size i.e. max gross weight). An improvement of this metric is proposed to reduce the weighting of the payload vs fuel consumption.

Refined methodology for CO2 related to Payload:

A direct relationship exists between the payload and the Maximum Takeoff Weight (MTOW). This relationship can be considered as linear in first approximation. The MTOW has a direct impact on the required power; specifically through the induced power that increases proportionally to the MTOW to the power of 3/2.

The required power can be considered as proportional to the induced power:

$$Preq = \kappa . Pind \qquad Eq.\ (7)$$

The coefficient κ takes into account the main parameters impacting the required power computation.

$$\kappa = \frac{(1+K_{TR})}{(1-K_{MGB}) \cdot Fm} \qquad Eq.\ (8)$$

With:

- K_{TR} *The Tail rotor power is proportional to the Main Rotor power.*
- K_{MGB} *The Main Gear Box losses are proportional to the Main Rotor power.*
- *Fm The Figure of merits which is the efficiency of the Main Rotor.*

From the momentum theory, the induced power can be expressed as :

$$Pind = \frac{\left((1+K_{down}) . MTOW \cdot g\right)^{3/2}}{\sqrt{2\rho S}} \qquad Eq.\ (9)$$

With:

- *g Gravitational constant 9.81 kg/m²*
- *ρ Air Density 1.225 kg/m³ at sea level ISA*
- *S The main rotor disc area*
- K_{down} *The download coefficient due to the Main Rotor downwash on the fuselage below.*
- κ coefficient described below.

From Leishman, the fuel consumption CH is linear with the normalized requested power Ref. 12:

$$\frac{CH}{\delta\sqrt{\theta}} = B + A \cdot \left(\frac{P_{req}}{\delta\sqrt{\theta}}\right) \qquad Eq.\ (10)$$

With $\delta = \frac{P}{P_0}$ *et* $\theta = \frac{T}{T_0}$ *which takes into account the evolution of performances for different altitude z and* ΔISA*.*

As we're looking for a metric that is independent of the MTOW, and as the fuel consumption is shown to increase roughly with the payload to the power 3/2, an

exponent ⅔ is applied to the payload in the final relationship to account for its weighting.
That leads to the following CO2 metric for cargo mission:

$$CO2\ metrics_{\ cargo} = \frac{Emission\ factor \cdot Fuel\ on\ mission}{Payload^{2/3}} \quad \text{Eq. (11)}$$

Results of this metric are presented on the *figure 4.2* for AH helicopters only. It is presented as a percentage of H125.
It appears that H125 is particularly efficient according to this metric. That is not really surprising since this helicopter has been used in this field (aerial work) for years.

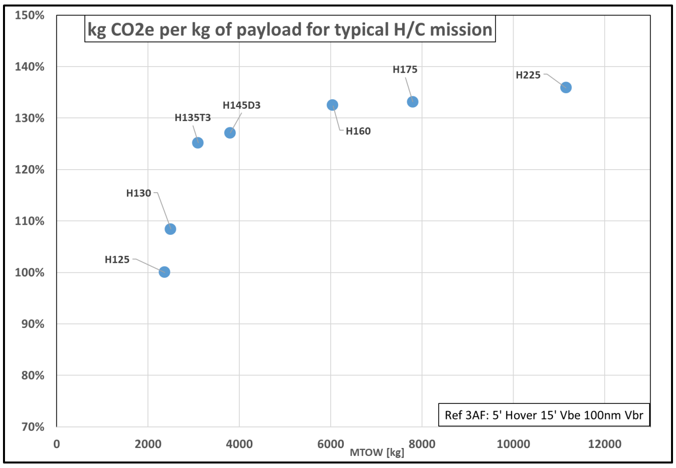

Fig 4.2*: Refined kg CO2e related to payload vs MTOW for a reference mission*

Conclusion:

- CO2 metric related to payload could be a good option for missions dedicated to cargo transport.
- The critical aspect is that the payload is based on the empty equipped weight which needs to define a reference configuration. A comparison of helicopters from several OEMs will need an agreement to transparently share the detailed weighting data regarding an aligned empty weight configuration.

4.3 CO2 Emissions on a given mission related to the number of pax

The principle of this last proposal is to refer to the cabin area on each rotorcraft as a key sizing parameter and a relevant reference for cabin capacity.Thus, this approach consists of dividing CO2 emissions on the reference mission by the pax capacity of the helicopter.

Even if this metric will be more appropriate for pax transport missions, it remains a good indicator for other missions.
The principle of this metric is similar to commercial flights that takes into account the fuselage size Ref. 16.
In order to be aligned on the seating capacity, a Standard Passenger per Surface (SPS) is introduced.
The SPS is defined by an empirical relationship: number of passengers vs. cabin area, established from numerous helicopters, from AH range and from other OEMs. This relationship allows positioning of different helicopters with the same passenger comfort standard.

	Number of seat Pax transport	Cabin area [m²] Commercial brochure
H125	5	2.6
B407	5	1.8
AW119 Ke	6	3.1
H130	6	3.0
H135T3	6	3.2
AW109 Trekker	6	3.1
B429	6	3.1
H145D3	8	4.1
AW169	10	4.5
B412EPX	14	5.0
S-76D	13	4.7
H160	12	5.7
AW139	12	5.5
H175	16	8.0
AW189	16	8.0
H225	19	9.5
S-92	19	10.2

H175 example :

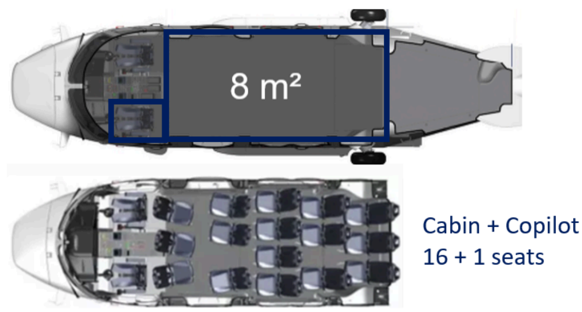

Fig 4*: H175 cabin surface example*

Based on the cabin surface area and the number of installed seats in the studied aircraft, the derived SPS rule is the following:

$$SPS = (3,016 \cdot Cabin\ area)^{0,866} \quad \text{Eq. (12)}$$

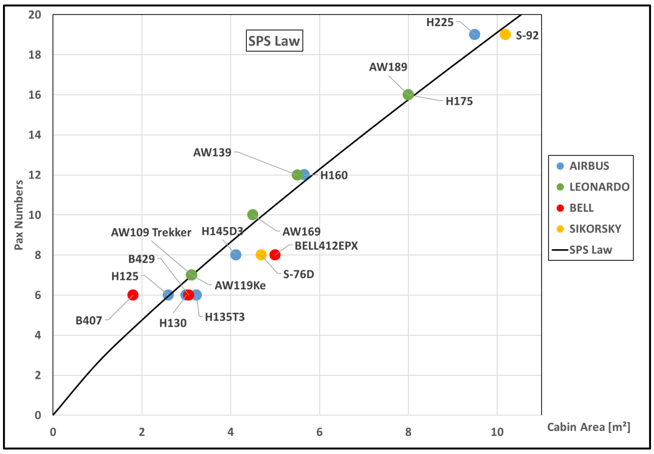

***Fig 5**: Standard Pax on Surface*

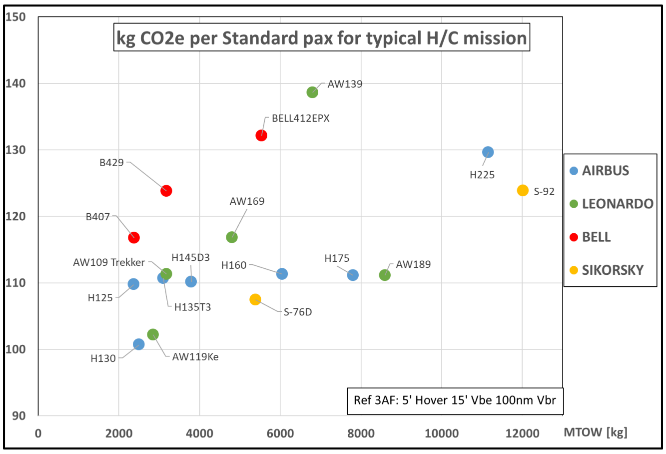

***Fig 6**: kg CO2e per SPS vs MTOW for a reference mission*

Remarks:

- The resulting SPS rule is not linear. This non-linearity reflects the differences in cabin architecture among the various helicopter ranges .
- For closed-cabin aircraft, the co-pilot's seat is added to ensure consistency with light single-engine aircraft, where this seat is already accounted for in the SPS rule.

Finally, we calculate CO2 emissions on the reference mission in relation to a standard of passengers per surface (SPS), i.e.:

$$CO2\ metrics = \frac{Emission\ Factor \cdot Fuel\ on\ mission}{Standard\ Pax\ per\ Surface} \qquad \textit{Eq. (13)}$$

The defined metric is expressed in kgCO2e per passenger per unit area, using a common comfort standard for a reference mission.

The primary advantage of this metric is that it uses public domain data, allowing for the comparison of both AH helicopters and those of other OEMs.

The results obtained are presented in the following graph:

- The positioning of the AH helicopters is quite consistent. The H130 stands out due to its favorable position, notably thanks to a large cabin size for its category.
- With its high installed power with regards to its size, the AW139 is less well-placed on this metric than other helicopters manufactured by Leonardo.
- Bell 412 is also less well-placed, notably because of its small cabin and a low VBR cruise speed which represent a disadvantage (poor fuel consumption per nautical mile).
- Regarding the heavy helicopters (H225 & S-92), the size of their cabins do not compensate for the increase of fuel consumption.

5. CONCLUSION

Aviation is engaged in the general process of reducing greenhouse gas emissions, particularly on CO2. Even if it represents a marginal part of the aviation CO2 emissions, the helicopters must also reduce their contribution.

The first step of this process consists of defining the best indicator to measure the CO2 emission.

The definition of such metrics has already been done for several means of transport, including commercial flights.

Due to the specific nature of helicopter missions, which involve hovering and may not carry passengers, standard metrics from automotive and fixed-wing aircraft industries are unsuitable.

A metric defined for helicopters was initiated in 2010, the objective of this article was to improve and extend it. This article proposes several methodologies that have been investigated for this purpose.

When the mission is well identified, the best and more relevant metric consists of comparing the quantity of CO2 emitted .

To provide a more general assessment, it seems relevant to relate the emissions to a given service, either to a transported kilogram or a transported person. Consequently, two other metrics have been proposed.

The first one dedicated to cargo missions, consists of relating CO2 to the payload. The main issue of this metric is that it relies on the empty weight configuration that is not easy to align, especially for comparison of helicopters from different OEMs. For this reason, a metric referring to raw payload derived from a reference configuration is not recommended.

The second metric refers to the cabin area on each rotorcraft as a key sizing parameter and a relevant reference for cabin capacity. More dedicated to passenger transport missions it remains a good indicator for other missions. This metric calculates a helicopter's CO2 emissions, per equivalent passenger, representing a common comfort standard across all helicopters on a typical mission. This metric has been developed using publicly available data. The inputs for this calculation are: fuel consumption at characteristic regimes and cabin surface area.

Finally, the recommended metric refers to cabin floor area as follows:

$$CO2\ metrics\ =\ \frac{Emission\ Factor \cdot Fuel\ on\ mission}{Standard\ Pax\ per\ Surface}$$

Where:

$$Standard\ Pax\ per\ Surface\ =\ (3,016\ \cdot\ Cabin\ area)^{0,866}$$

Emission factor = ***3.83***

This metric can serve multiple purposes: notably as a reference for potential future regulations and as a design criterion to reduce CO2 emissions in future helicopters.

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