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Publisher’s version / Version de l'éditeur:

Vertical Flight Society's 76th Annual Forum and Technology Display, pp. 2980-2991, 2020-10-05

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To cite this version:

Albertus Tjandra, Pierre-Marie Basset, Routhieau Vincent, Wajid Chishty, Claude Bérat, et al.. Green house gas (GHG) reduction study for the rotorcraft industry. 76th Annual Forum & Technology Display Vertical Flight Society, Oct 2020, Montreal (virtual), Canada. hal-03225084

Green House Gas (GHG) Reduction Study for the Rotorcraft Industry

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ABSTRACT

The global aviation industry adopted a set of targets to mitigate CO_2 emissions resulting from air transportation in 2009. The engine fuel burn is the main driver of CO_2 emission; hence it will be the focus of this study. Rotorcraft are designed for supporting different types of missions or operations that are different from fixed wing aircraft. For this reason, the rotorcraft strategy for addressing the carbon impact should mainly target the new emerging technologies that will assist in reducing the fuel consumption and the deployment of Sustainable Aviation Fuels (SAF). This paper presents a forecast of the contribution level that could be achieved by rotorcraft industry in CO_2 emission reduction in the period up to 2050. A projection of growth in civil rotorcraft fleet worldwide is provided as the starting point. Several new emerging technologies for both rotorcraft and engine together with the implementation scheme and their projected positive net impact on CO_2 emission level are considered. Further, the contribution from SAF deployment in rotorcraft operation is analyzed. It is generally recognized that as much as 80% reduction in overall CO_2 life cycle emission can be achieved from SAF relative to the fossil-based fuels or Conventional Aviation Fuels (CAF). However, some critical parameters used in predicting the SAF benefits remain uncertain. These pertain to fuel resources, economy, investment and policies. Therefore, consistent with previous studies, several fuel substitution scenarios are considered ranging from the most conservative to an optimistic projection.

NOTATION

3AF	Association Aéronautique et Astronautique de France
AHS	American Helicopter Society
ASTM	American Society for Testing and Materials
ATAG	Air Transport Action Group
CAEP	ICAO Committee on Aviation Environmental Protection
CAF	Conventional Aviation Fuels
CEAS	Confederation of European Aerospace Societies
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CO2	Carbon Dioxide
CRC	Coordinating Research Council
EU	European Union
FAA	Federal Aviation Administration
FOCA	Federal Office of Civil Aviation
FT	Fischer-Tropsch
GHG	Green House Gas
HEFA	Hydro-processed Esters and Fatty Acids
HP	High Pressure
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
Kg	Kilo Grams
LCA	Life Cycle Assessment
LCF	Lower Carbon Aviation Fuel
LCFS	Low Carbon Fuel Standard
LTO	Landing and Take-Off
MCP	Maximum Continuous Power
MJ	Mega Joules

MT	Mega Ton
NASA	National Aeronautics and Space Administration
NRC	National Research Council Canada
ONERA	Office National d'Etudes et de Recherches Aérospatiales
P&WC	Pratt & Whitney Canada
SAF	Sustainable Aviation Fuels
SFC	Specific Fuel Consumption
SHE	Safran Helicopter Engine
SHP	Shaft Horse Power
TRL	Technology Readiness Level
TU	Technical University
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America.

THE GHG INITIATIVE

The 3AF/VFS Green House Gases (GHG) Working Group is a Trans-Atlantic collaboration between The Vertical Flight Society (known previously as the American Helicopter Society, AHS) and the French Aeronautics and Aerospace Society (3AF) based in Paris. The 3AF was formed in 1971 with mostly technicians, engineers and researchers as their members; they are associated with major industrial partners in Europe and a founding member of the Confederation of European Aerospace Societies (CEAS).

The working group has been active for the last four years and involves technical experts from the rotorcraft and engine industries as well as researchers from national research centers such as ONERA, Bell Textron, NRC Canada, Airbus Helicopters, Pratt & Whitney Canada Corp., Safran Helicopter Engine/SHE France.

INTRODUCTION

The main objectives of the study are two-fold, first to define the CO_2 emission baseline resulting from the worldwide rotorcraft operation, and second to analyze the impact of new emerging technologies and the implementation of SAF on the reduction of CO_2 emission. This study is limited to the civil rotorcraft category based on the conventional rotorcraft design; it does not include any other types of vertical lift vehicles.

Specifically, for the urban air mobility, there are today more than a hundred design concepts which rely on electrical or hybrid powerplant driving multiple lifting and propulsive rotors in various stages of development. While the design approach is less reliant on carbon fuels, it is still premature at this time to make a reasonable CO_2 emission forecast without having a definition of the types of operation, regulation and any other restrictions that would dictate the urban air vehicle design configuration, operation and their worldwide population.

This rotorcraft initiative follows a similar effort of the 2010 ICAO/Global Aviation world-wide campaign, which was inspired by the Kyoto Protocol. This is an international treaty which extends the 1992 United Nations Framework Convention on Climate Change (UNFCCC) that commits the State Parties to reduce the level of global GHG emissions. It is based on the scientific consensus that the global warming is occurring and that it is extremely likely that human-made CO_2 emissions have predominantly caused it. The treaty was adopted in Kyoto, Japan on December 11, 1997 and entered into force on February 11, 2005 [1].

It is acknowledged that aviation CO_2 emission accounts for about 2% of the global CO_2 emission or about 13% of the CO_2 emission level from all transportation modes collectively [2]. The engine fuel burn has been identified as the primary contributor for aviation CO_2 emission as well as NOx, CO, unburnt hydrocarbon and particles. Therefore, the engine fuel consumption becomes the focus of the study.

In 2009, the aviation industry adopted a set of targets to mitigate CO_2 emissions from air transportation aiming for 1.5% improvement in fuel efficiency annually from 2009 to 2020, a cap on net CO_2 emissions from 2020 (carbon-neutral growth) and reduction in net CO_2 emissions of 50% by 2050 reference to the 2005 levels. This is also illustrated in Figure 1.

These targets are based on the four-pillar strategy considered by the aviation industry [2]:

(1) implementation of new technology including the deployment of sustainable alternative fuels,

(2) more efficient aircraft operations,

(3) infrastructure improvements including modernized air traffic management systems, and

(4) single global market-based measure to fill the remaining emissions gap.

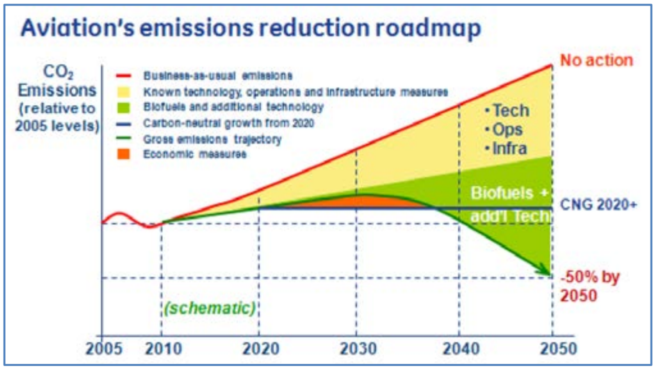

Figure 1. Aviation's Commitment [3].

Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) developed by ICAO and adopted in 2016 is an example of the fourth strategy. It is an emission mitigation approach for the global airline industry and specifically addresses the carbon emission from international air travel that exceeds the 2020 cap level. This scheme does not include rotorcraft operation.

A rotorcraft is different from an airplane in the sense that the rotorcraft is designed for supporting different types of missions or operations with an extensive utilization in hover flight. Typically, the operations for rotorcraft are unscheduled in nature, whereas much of the larger airplane operations are carried out as part of an airline's scheduled operation. The infrastructure required to support rotorcraft operation is less expensive and less extensive. For this reason, the rotorcraft industry should mainly benefit from the implementation of new emerging technologies that will assist in reducing the fuel consumption and the deployment of SAF for the purpose of addressing the carbon impact.

SAF is the term preferred in the aviation industry since the scope of SAF is broader than aviation biofuels, which only refers to fuels produced from biological resources (plant or animal materials). SAF is made by blending conventional petroleum-based jet fuel (fossil-based) with renewable hydrocarbon. They are certified as per ASTM D7566, therefore meeting the technical and certification requirements for use in commercial aircraft including rotorcraft. Feedstocks for SAF are varied, ranging from cooking oil, plant oils, municipal waste, waste gases, and agricultural residues.

SAF is known to have the biggest potential in addressing the climate change while providing a diversified energy supply and economical and social benefits at the same time.

Figure 2. SAF Life Cycle Analysis [4].

SAF offers as much as 80% reduction in overall CO_2 emission, when compared to the fossil fuels [5]. This reduction is based on a life cycle analysis, because combustion of SAF, at least for the currently approved SAF's, emits similar quantities of CO_2 as the combustion of conventional aviation jet fuels. The fuel life cycle is made up of multiple steps from the feedstock to the "final use" in an aircraft/rotorcraft (Figure 2). These intermediate steps include, for example, oil recovery including feedstock cultivation, processing, and transport/distribution of fuel. At each of these steps, CO_2 emissions are produced. The total carbon footprint of the fuel (Life Cycle Assessment or LCA) is obtained by adding all emissions from the various steps.

GLOBAL ROTORCRAFT FLEET DATA

Public data on global rotorcraft fleet published by Ascend was considered for this study [6]. The data, which is based on 2016 statistics, captures all rotorcraft registered for civil and para-public operations and includes multiple rotorcraft categories based on engine type and number i.e. piston, gas turbine; single and twin engine, and rotorcraft size i.e. light, medium and heavy.

In 2016, the worldwide population of piston engine helicopter was 10,192 units. This figure consisted of Robinson Model R44 (5,453 units or 53.5% of the total piston engine helicopter population), Robinson Model R22 (2,805 units or 27.5%), Guimbal Model Cabri G2 (153 units or 1.5%) and other unspecified rotorcraft models (1,781 units or 17.5%). It was further documented that 67% of the piston engine helicopter fleet were operated for private, business or corporate missions. The average annual flight hours for these types of mission was 200 hours. The second mission identified in their documentation was pilot training with an annual operating time of 300 flight hours in average, this mission represented about 16% of the total fleet. Aerial works and multi-purpose operation were the third mission category with an average of

400 flight hours per year and represented about 17% of the total fleet.

For gas turbine powered helicopters, the single engine light helicopter with less than 3 tons maximum gross weight had a population of 13,763 units (56%). The twin-engine light/medium category helicopter, with a maximum gross weight range less than 7 tons, had 7,519 units (31%). The last category is twin-engine super-medium/heavy category helicopter with 3,193 units (13%). The annual average operating hours for these helicopter categories were identified as 300 flight hours, 400 flight hours and 450 flight hours respectively.

Table 1 provides the summary of this global rotorcraft population based on 2016 statistics.

Table 1. Rotorcraft Population in 2016.

ROTORCRAFT CATEGORY	2016	(%)	FH/YR
PISTON ENGINE	**10,192**	---	200-400
TURBOSHAFT ENGINE	**24,475**	---	---
Single Engine	13,763	56%	300
Twin Engine Light & Medium	7,519	31%	400
Twin Engine Super-Medium & Heavy	3,193	13%	450
TOTAL	**34,667**		

This database formed the starting point to analyze baseline CO_2 emission generated by the operation of global rotorcraft fleet in 2016.

Forecast International in their study dated October 2017 [7] predicted circa 9,000 helicopter deliveries worldwide between 2017 and 2026. It is assumed that this growth rate will be distributed proportionally in all rotorcraft categories based on the 2016 composition. The resulting growth rate per rotorcraft category was considered as the base growth rate for the periods between 2017 and 2050.

Specifically, for the twin-engine light/medium and super-medium/heavy category helicopters, a growth rate correction factor was implemented to be on the conservative side. The global fleet growth rate was reduced by 50% between 2017 and 2036 and by another 50% for the period between 2037 and 2050.

At the same time, the typical aging helicopter of around 45 years of service is considered for the fleet attrition. This results in a global helicopter fleet attrition of around 35% in 2036 relative to the fleet population in 2016.

For this study, the rotorcraft classification was further simplified. Four categories were considered, the first one being the piston engine helicopter and three other categories under the gas turbine engine helicopter i.e. light, medium and heavy. The light category includes the short and long light single engine classes as well as the light twin engine class, examples are R66, Bell 505, H125, H135, Bell 429 and AW109. AW139, Bell 412, H160 and S-76 are among the helicopters grouped as medium category. The heavy category besides covering helicopters such as Super Puma and S-92 also includes the new super medium class i.e. AW189, H175 and Bell 525.

The projected population of worldwide civil rotorcraft fleet from 2016 through 2050 for piston engine and turboshaft engine categories (light, medium and heavy) was computed accordingly and is shown in Figure 3.

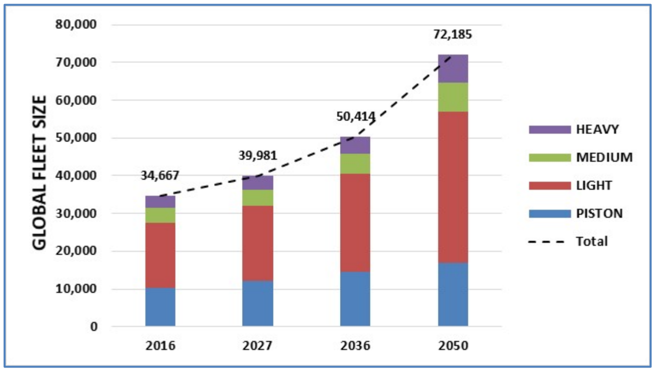

Figure 3. Worldwide Civil Rotorcraft Population Forecast.

These global fleet projections were subsequently validated using data from other reliable sources. The second source was Honeywell's publication of 20th annual turbine-powered, civilian helicopter purchase outlook dated 2018 [8]. About 3,800 helicopter units were delivered worldwide in the period of 2013-2017. Honeywell estimated between 4,000 and 4,200 deliveries between 2018 and 2022. These deliveries were projected to be distributed in North America (13%), South America (35%), Europe (22%), Africa (10%) and Asia Pacific (18%).

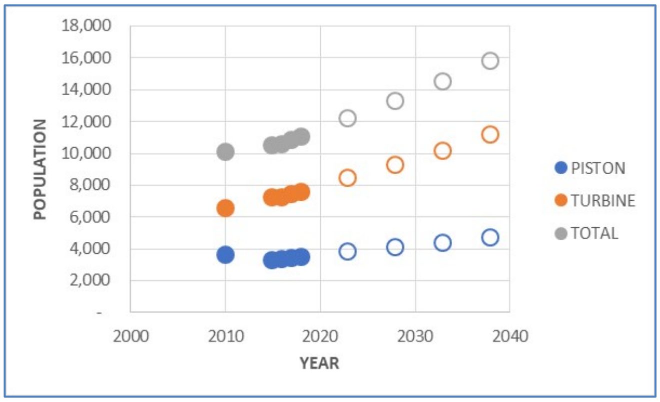

Figure 4. Rotorcraft in USA (FAA Data).

The third source was the FAA Aerospace Forecast for Fiscal Years 2018-2038 published in 2016 [9]. Both historical and forecast data of piston engine and turbine engine helicopter population operating in US airspace are presented in this reference document and shown in Figure 4. The open circles in this figure represent the forecast data.

The total US rotorcraft population in 2016 (10,577 units) was approximately 30% of worldwide population reported by Ascend (34,667 units).

It was also noted in the FAA document that the average annual growth of 165 units for turboshaft helicopter in North America is more optimistic compared to Honeywell's forecast of 104-109 units of annual delivery for the same region. For this comparison, the rotorcraft population in Canada was assumed to be around one quarter of the US rotorcraft population.

The global fleet data provided by Ascend for 2016 was considered as the initial reference for validating the data. The annual fleet growth worldwide can be estimated using the projection of new rotorcraft delivery distribution in various continents in Honeywell's publication:

GFG = (100/13) * NAFG (1)

GFG stands for Global Fleet Growth and NAFG represents the Fleet Growth in North America (USA and Canada). The rotorcraft fleet in Canada was assumed to have the same growth rate as in USA as published in the FAA Aerospace Forecast.

Since the combination of Honeywell and FAA forecast data is limited to the period until 2038, it was only possible to validate the global fleet projection for 2036. Equal growth rate for both piston and gas turbine engine rotorcraft fleet was considered. The projected global rotorcraft fleet in 2036 was finally determined as the sum of global fleet in 2016 and Global Fleet Growth (GFG).

The original global fleet estimate for 2036 conforms with the alternate projection based on data published by FAA and Honeywell within 7-9% variation. This good correlation for 2036 projection provides the confidence for further utilization of the fleet data estimate as shown in Figure 3 for the purpose of this study.

ENGINE FUEL BURN

As previously stated, the engine fuel burn has been determined as the major contributor for CO_2 emission and is therefore the primary focus in this study.

The Federal Office of Civil Aviation (FOCA) of Switzerland published a helicopter emission report [10]. Switzerland have this unique database because they must include helicopters in their aviation emission inventory. More than 1,000 helicopters routinely make thousands of sorties every year in an area of no more than 41,000 square kilometer.

Helicopter engine emissions have been measured after overhaul and the emission test data, together with the engine power rating or maximum power data, were gathered. Three helicopter categories were considered i.e. piston engine, single and twin turboshaft powered helicopters. The report [10] provides data for airport emission calculation based on LTO (Landing and Take-Off) cycles and tabulated emission data based on one flight hour in cruise at MCP (95% of maximum power) for the country's emission inventory. The engine fuel flow consumption can be reasonably assumed to be similar during cruise and hover at MCP. Hence, the one-hour flight data at MCP cruise was considered in this study.

Mathematical models are provided to determine engine fuel flow based on the engine shaft horse power data [10] and they are as follows,

Piston Engine:

Fuel Flow = 19E-12*SHP^4 – 1E-9*SHP^3 +2.6E-7*SHP^2 + 4E-5*SHP +0.06 (kg/sec)

(2)

Turboshaft Engine:

Fuel Flow = 2.197E-15*SHP^5 – 4.4441E-12*SHP^4 + 3.4208E-9*SHP^3 – 1.2138E-6*SHP^2 + 2.414E-4*SHP + 0.004583 (kg/sec) for engine with power range ≤ 600 SHP

(3)

Fuel Flow = 3.3158E-16*SHP^5 – 1.0175E-12*SHP^4 + 1.1627E-9*SHP^3 – 5.9528E-7*SHP^2 + 1.8168E-4*SHP + 0.0062945 (kg/sec) for engine with power range between 600-1,000 SHP

(4)

Fuel Flow = 4.0539E-18*SHP^5 – 3.16298E-14*SHP^4 + 9.2087E-11*SHP^3 – 1.2156E-7*SHP^2 + 1.1476E-4*SHP + 0.01256 (kg/sec) for engine with power range ≥ 1,000 SHP

(5)

The fuel burn data for different rotorcraft models were determined following the formula's above. The rotorcraft models were grouped based on their categories and an average fuel burn was then calculated for every category. The average fuel burn data with the respective list of rotorcraft models are summarized in Appendix A.

BASELINE CO_2 EMISSION

The CO_2 emission in 2016 resulting from worldwide rotorcraft operation was estimated using two methods. The first estimate was based on a simplified version which relies on the average hourly fuel consumption at MCP cruise flight for each of the four rotorcraft categories i.e. piston, light, medium and heavy. The total fuel burn for 2016 can be calculated as follows,

$$\Sigma Wf = (PH_Q * FHY_{PH} * W_{fhPH}) + (LH_Q * FHY_{LH} * W_{fhLH}) + (MH_Q * FHY_{MH} * W_{fhMH}) + (HH_Q * FHY_{HH} * W_{fhHH}) \qquad (6)$$

Where,

PH_Q, LH_Q, MH_Q, HH_Q - Worldwide population of respectively piston engine, light category, medium category and heavy category rotorcraft.

FHY_{PH}, FHY_{LH}, FHY_{MH}, FHY_{HH} - Annual flight hours for the respective rotorcraft category.

W_{fhPH}, W_{fhLH}, W_{fhMH}, W_{fhHH} - Average hourly fuel consumption for the respective rotorcraft category.

The second estimation method considered the helicopter model distribution in each rotorcraft category [6]; hence it should have a better accuracy.

For the piston engine helicopter, the following distribution was considered:

- Robinson R44 (53%)
- Robinson R22 (27%)
- Schweizer H269 (12%)
- Others (8%).

For the light category, the following distribution was considered:

- Airbus H125/EC130 (27%)
- Bell 206 (21%)
- MD500/H369 (10%)
- Bell 407 (10%)
- Bell 206L (9%)
- Airbus H120 (4%)
- Airbus H130/EC130 (5%)
- Others (14%).

For the medium category, the following distribution was considered:

- Leonardo AW109 (12%)
- Leonardo AW139 (9%)
- Bell 412 (9%)
- Sikorsky S-76 (7%)
- AS365 (7%)
- Airbus H145/EC145 (6%)
- BK117 (4%)
- Airbus H155/EC155 (2%)
- Others (44%).

For the heavy category, the following distribution was considered:

- Mi 8 (67%)
- Sikorsky S92 (9%)
- Sikorsky S70(5%)
- Kamov Ka-32 (5%)
- Airbus H215/AS332 (3%)
- Others (11%).

Furthermore, there are several new gas turbine powered helicopters that have recently entered the market such as Leonardo AW169 & AW189, Bell 505 & 525, Airbus H160 & H175 and Robinson R66. These products are not listed in FOCA database. An assessment was made primarily in terms of engine specification and MTOW in order to properly classify each of these new helicopters and integrate them within the data originated from FOCA.

Considering the annual flight hours for each rotorcraft category, the results of global rotorcraft fuel consumption in 2016 based on the first and second methods are shown in Figure 5.

The emission factor for the most common aviation jet fuels i.e. Jet A1 and Jet A is about 3.15; this factor represents the mass of CO_2 emission per unit mass of fuel burn under complete combustion assumption. For Aviation Gasoline and Jet B fuel grade, the emission factor of 3.10 is applicable [3].

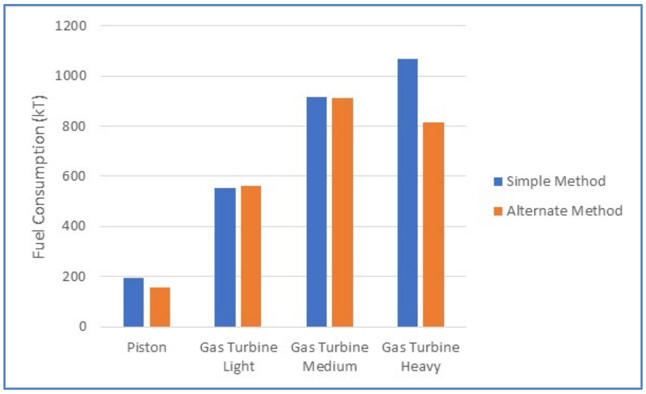

Figure 5. Rotorcraft Fuel Burn in 2016.

The annual fuel burn was then translated into the total CO_2 emission worldwide using the petroleum-based jet fuel emission factor of 3.15 and the results are presented in Figure 6.

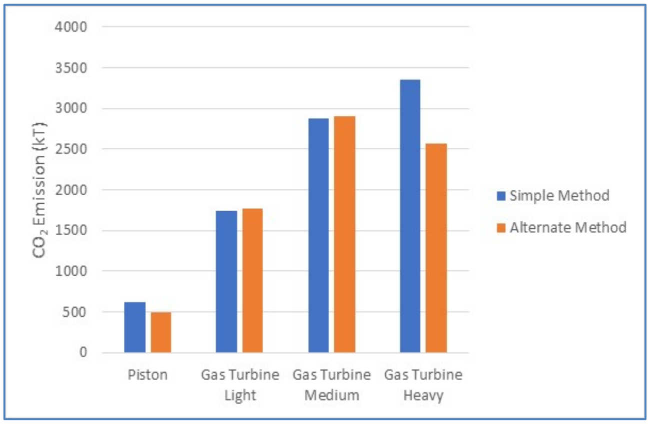

Figure 6. Rotorcraft CO_2 Emission in 2016.

The simple method appears to match the second estimation method reasonably well except for the heavy category. The difference in the heavy category was driven by the Mi-8 helicopter data; this helicopter has significantly higher population than the rest with an hourly fuel burn below the average level.

Several reference sources have published 43 gigatons per year of CO_2 emissions worldwide from all sources in 2017. As previously stated, the aviation industry accounts for 2% of the global carbon emission level, this translates to 860 million tons in 2017. The EU has estimated that about 1% CO_2 emission of the aviation industry i.e. 8,600 kilotons, is originated from rotorcraft operation.

The annual worldwide rotorcraft CO_2 emission of 7,300 kilotons (2016) based on the alternate method agrees with the EU's rough estimate mentioned above. For this reason and because of its better accuracy, further fuel burn analyses to complete this study was carried out using the alternate method.

NEW EMERGING TECHNOLOGIES

This section provides the general description of new emerging technologies both for rotorcraft and engine applications with a potential of net positive impact in reducing the carbon footprint. These technologies are mature enough and may be introduced before 2050 and are therefore included in this study.

High Compression Engines

This engine type is also known as an aero diesel engine; it relies on a lean-combustion unlike the mostly rich- or stoichiometric-combustion in a gasoline engine. The internal combustion process in diesel engines generates high gas pressures and temperatures translating into a rotary motion of the crankshaft and delivering the net torque and horsepower. The fact that high compression engine is operated using petroleum-based conventional jet fuel makes this technology more attractive.

There are several certified aero diesel engines up to 500 SHP capacity currently installed on small fixed wing propeller aircraft. However, there is no rotorcraft application identified to date.

A net reduction of 5.5% and 40% in specific fuel consumption are considered, when a high compression engine is offered as a substitute for piston engine and gas turbine engine respectively.

This aero diesel engine is superior compared to the piston engine class in all key performance parameters. However, it still has a less superior power to weight ratio when compared to the turboshaft engine. For this reason, the prospect of this technology is mainly for the light single rotorcraft application as a replacement for the piston engine.

Accordingly, this study assumed that the aero diesel engine application will be limited as substitute for the piston engine light rotorcraft category. All new helicopter in this category are considered to have the high compression engine starting from 2036. The CO_2 emission level was determined based on 5.5% SFC reduction compared to the level achieved with piston engine.

Parallel Hybrids

The concept of a parallel hybrid propulsion system has the objective of achieving shared power output from an electrical source and gas turbine engine. This solution, which is considered as the transition to a fully electric propulsion (Figure 7), offers a lower fuel consumption thus a reduction in CO_2 emission level. A fully electric solution for conventional rotorcraft is not anticipated to be ready for production before 2050, hence it is not considered in this study.

In order to achieve the production readiness, further innovation in the electrical component technologies is needed. The batteries will have to increase the specific energy in the order of 3 to 5 times. The electric motor and power converter will have to improve the power density by a factor of 3 to 5.

NASA predicts that the hybrid electric propulsion should be available in 2028 for application on the light rotorcraft category based on the record of annual progress in the battery technology [11].

For this study, the implementation of a parallel hybrid solution is restricted to light twin rotorcraft category. The extra weight to achieve the required battery capacity would not be attractive for the light single engine helicopter.

The CO_2 emission level was determined based on fuel saving relying on the maximum peak shaving strategy [12]. The battery will be sized to provide energy beyond the pre-determined peak shaving limit based on the gas turbine power rating. The battery will not be used for any energy demand below this power rating.

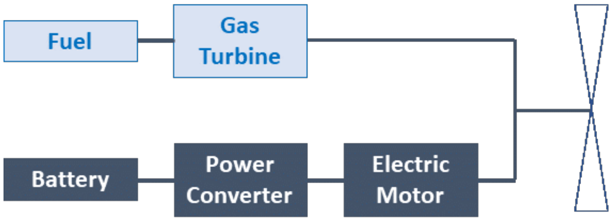

Figure 7. Hybrid Propulsion.

A fuel burn saving of 20% compared to the level achieved with the gas turbine engine in 2036 and followed by a linear improvement from 20% to 25% saving between 2036 and 2050 was assumed. This assumption is conservative in order to compensate a possible additional net weight as the result of this hybrid design approach.

The CO_2 emission analysis considered that 30% of new light twin engine helicopter will be powered with a parallel hybrid solution beginning in 2036.

Turbo-Electric Motors

Like the parallel hybrid solution, the turbo-electric motor design relies primarily on both gas turbine and electrical components (Figure 8). The design objective of the turbo-electric motor is to transform the entire thermal power from the gas turbine into an electrical power by means of an electrical generator mounted on the gas turbine engine. This will allow the gas turbine to operate mostly at its optimum SFC. Electrically powered motors will be required to drive the rotor system.

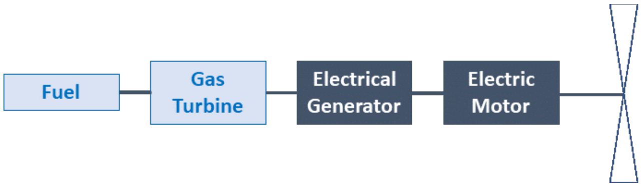

Figure 8. Turbo-Electric Motor.

The main technological challenge today is also related to the electrical components; what was previously described for the parallel hybrid solution applies for this turbo-electric motor technology.

Consequently, it is assumed in this study that the application will be limited to the light twin rotorcraft category. The CO_2 emission level was determined based on 18% SFC reduction compared to that of the current gas turbine engine.

Similar to the parallel hybrid technology, the CO_2 emission analysis considered 30% of new light twin helicopter will be powered with turbo-electric motor starting from 2036.

Hybrid Propulsion with High Compression Engines

The solution to use a high compression engine in lieu of gas turbine was considered for both parallel hybrid and turbo-electric motor solutions. The expectation is that only a low percentage (around 10%) of the new light single helicopter will utilize each of these technologies starting from 2036. The fuel saving is based on the reduction due to the transformation from gas turbine engine to high compression engine in combination with the application of electrical components. A fuel saving of 54% and 44% was considered for the parallel hybrid and turbo-electric motor respectively.

More Electric Rotorcraft

This technology primarily involves the aircraft systems through enhancement of electronic power generation to achieve more electric aircraft systems.

Further innovation efforts are still required, knowing that today's gas turbine engines offer limited power off-take capability when the power is extracted from the HP spool. This is due to the engine operability limitation as the run line will move closer towards the compressor stall line. In addition, there may be an added net weight as the result of more complex gearbox arrangement. The complexity of installation and mechanical arrangement may offset the performance benefit.

An incremental fuel burn reduction (linear) starting with 14% in 2025 to 16% in 2050 (conservative) was assumed. The CO_2 emission was calculated for all gas turbine rotorcraft categories considering 100% of new helicopter from all categories entering the service with this technology beginning in 2025.

Advance Gas Turbines

This involves an adaptation of the internal aerodynamics and thermal capability of the engine hot section through the application of technologies like advanced 3-D aerodynamics, end wall contouring, high temperature resistant hot section materials and optimized cooling flow scheme.

These technologies have already been used in different market segments such as military application and large commercial engines. The challenge for the rotorcraft engine segment is that it will require lowering the cost to make it affordable.

The accumulative effect of these technologies can provide up to 5% improvement in fuel burn. For this study, a linear scale approaching 5% by 2040 was assumed. The CO_2 analysis considered that 100% of new gas turbine engines will have the advance gas turbine technology beginning in 2020.

Alternate Cycles for Gas Turbine (Recuperated Engine)

The focus of this alternative technology is the retention of Brayton cycle, but now embodying a more complex thermodynamic system, with the inclusion of heat exchangers. In this field, near-term activities will be focused on the power uprating of current engines and the introduction of new conventional simple-cycle engines. However, it is possible that situations such as a rapid escalation of fuel cost could stimulate the development of more efficient recuperated turboshaft engines. The recuperated engine concept shown on Figure 9 including a single stage radial compressor, and axial stages for the gas generator and power turbine, is based on the most simplistic approach to yield minimum weight. A two-pass cross-counterflow recuperator is installed to the rear of the turbine exit.

A combined cost and weight reduction analysis is still required to avoid performance off-setting. Up to 25% of fuel burn reduction is achievable for turboshaft engine application [13].

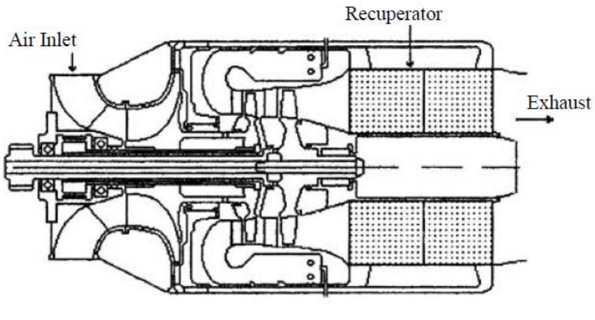

Figure 9. Recuperated Turboshaft Concept (13).

In this study, 25% step change was assumed for fuel saving in the light single/light twin segments starting in 2030 and in the medium and super medium segments from 2035. The CO_2 analysis assumed that 15% of all new gas turbine engines could be delivered with the alternate cycles of gas turbine.

Vehicle Optimization

This kind of technology aims to improve the aerodynamic characteristics of the airframe and rotor blades to reduce the overall vehicle drag and power required for the main rotor system. It ultimately translates into reductions in engine fuel burn and CO_2 emission.

The fuel savings as the result of vehicle optimization was projected to be 7%. The CO_2 analysis considered new helicopters in all categories to enter service with vehicle optimization features beginning 2036.

SUSTAINABLE ALTERNATIVE FUELS

The SAF deployment scenarios for international aviation are considered in a 2017 study by CAEP [14]. As described therein, there are uncertainties which still exist in predicting the contribution of SAF. This is based on the evaluation of 120 SAF deployment scenarios up to 2050. The global availability of resources, economic conditions, financial investments, and policy decisions required to reach the assessed levels of global SAF production are identified as the challenges.

Following the above-mentioned methodology, four categories of SAF deployment scenario are considered. It is possible that up to 100% of international aviation's CAF demand could be met using SAFs in 2050. This possibility is illustrated by the "Maximum" scenario, which is obviously the most optimistic one. As an illustration and as reported in the CAEP study, this would require approximately 170 new biorefineries to be built annually from 2020 to 2050. For comparison, recent-year global biofuel production increased by only about 70 biorefineries per year, brought about by production or consumption incentives being put in place in different world-regions.

The most conservative projection is a "Low" substitution scenario targeting 4% of international aviation's CAF demand, this would require a SAF production of about 20 MT/year in 2050.

In addition to the Maximum and Low scenario, an "Illustrative" scenario was also evaluated by CAEP, where 28% of international aviation's CAF consumption was replaced by SAF.

Further, an "Intermediate" scenario with 50% substitution is provided for information.

The LCA-based CO_2 emission factor is defined as the carbon intensity measured in $kgCO_2$ per MJ energy multiplied by the lower heating value of kerosene jet fuel. The LCA-based CO_2 emission factor for SAF varies and is heavily dependent on several variables, for example, the type of feedstock, the type of conversion processing, the land use change, etc.

For fossil-based jet fuel or CAF, the carbon intensity and the lower heating value are known to be 89 gCO_2e/MJ [15] and 42.8 MJ/kg [16]. This gives 3.827 $kgCO_2/kg$ fuel as the LCA-based CO_2 emission factor on the fuel weight basis.

In this study, SAF emission factor of 1.596 $kgCO_2/kg$ fuel is used based on California Low Carbon Fuel Standard (LCFS) that governs the SAF production from the Alt Air facility in California, which is one of the few worldwide facilities producing SAF on a continuing basis. This number of 1.596 is obtained by multiplying the lower heating value of jet fuel (43 MJ/kg of fuel burn) with the California LCFS determined Carbon Intensity of 37.13 gCO_2/MJ of energy for SAF produced using North America rendered animal fat, natural gas, hydrogen and grid electricity [17].

The ICAO CORSIA supporting document [18] provides similar information. The eligible fuels under CORSIA include both SAF and Lower Carbon Aviation Fuel (LCF), however the reference only publishes the default core LCA values applicable for the SAF conversion processes which have been approved for aviation alternative fuel production under ASTM D7566 Annexes such as Fischer-Tropsch (FT) and Hydro-processed Esters and Fatty Acids (HEFA).

The average level of carbon intensity obtained from this reference is 30.8 gCO_2/MJ, which is in the same ballpark as the level used in this study. This validates the use of SAF emission factor of 1.596 $kgCO_2/kg$ fuel.

The projected annual fuel burn data was used together with SAF emission factor to determine the CO_2 emission level for each of the SAF deployment scenarios.

RESULTS

The forecasted rotorcraft fuel burns worldwide shown for different rotorcraft categories up to 2050 assuming there is no action taken i.e. without new technology and SAF is presented in Figure 10.

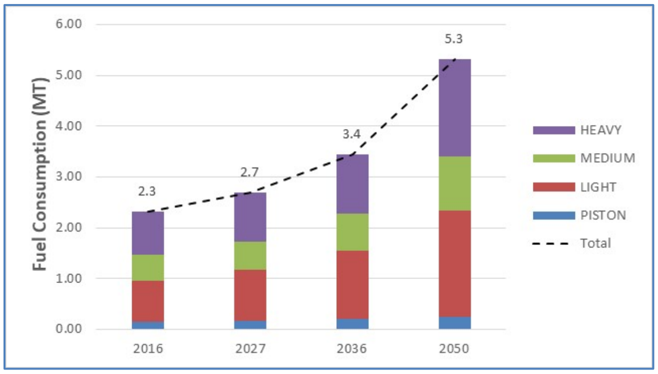

Figure 10. Rotorcraft Fuel Consumption.

Figure 11 provides the forecast of corresponding CO_2 emission distribution.

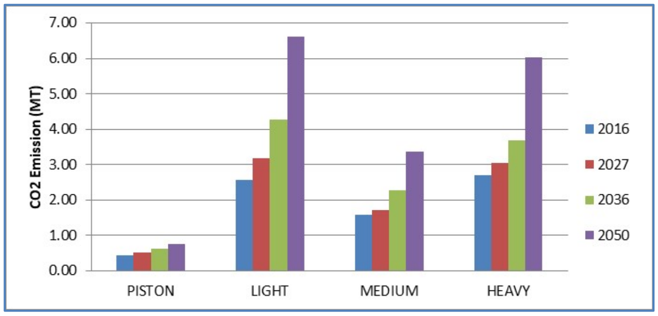

Figure 11. Rotorcraft CO_2 Emission by Class.

Finally, the CO_2 emission contribution forecast from the different rotorcraft categories is provided in Figure 12.

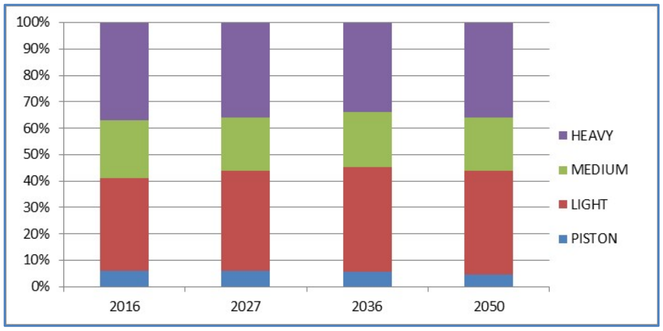

Figure 12. CO_2 Emission Distribution.

Figure 13 presents the forecast of total CO_2 emission together with the positive net effect of considering the new emerging technologies and in combination with the utilization of SAF based on four different deployment schemes.

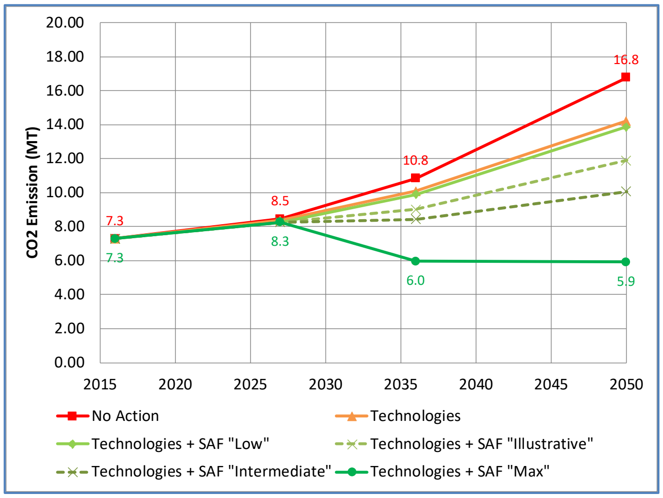

Figure 13. Rotorcraft CO_2 Emission Forecast.

CONCLUSIONS

The global civil rotorcraft fleet is expected to grow in number. The fleet growth was carefully and conservatively modelled based on projection from credible sources. The global fleet size in 2050 is anticipated to be more than double the 2016 level of 34,667 units.

If the current rotorcraft and engine technologies remain in use until 2050, rotorcraft operation may require up to 5.3MT of fuel consumption annual and this will generate 16.8MT of CO_2 emission in 2050. Light and heavy rotorcraft categories appear to be those that potentially consume the largest amount of fuel therefore generating the highest amount of CO_2 emission.

There is an opportunity for both SAF producers and rotorcraft industry to transform rotorcraft into a more environmental-friendly vehicle.

Qualitatively, the CO_2 emission forecast for civil rotorcraft has a somewhat similar pattern to the one which has been identified by the global aviation community. There are new emerging technologies that can help reduce the CO_2 emission level. The potential impact of SAF usage is more significant when the LCA-based approach is considered. This approach is consistent with what has been done by the global aviation industries.

Provided that the assumed scenarios related to the emerging technologies and "Maximum" deployment of the SAF can be materialized, one might expect to keep the annual CO_2 emission at 5.9MT in 2050. This will also help the aviation industries worldwide in achieving the target for 2050.

The low impact of new technologies on global CO_2 emissions is attributed to the long service life of a helicopter. Nevertheless, it is desirable that the rotorcraft industry continues to invest on these new technologies, even if the real benefit will not be achieved before more than 50% of the fleet is renewed.

Note that the global fleet size would be roughly doubled if the military rotorcraft population is included and this would increase the CO_2 emission level by a factor of 2.

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APPENDIX A

Fuel Burn Data

Fuel burn of ~50kg/h for piston engine helicopter was determined using the fuel consumption per hour data of the helicopter models as shown in Figure A-1.

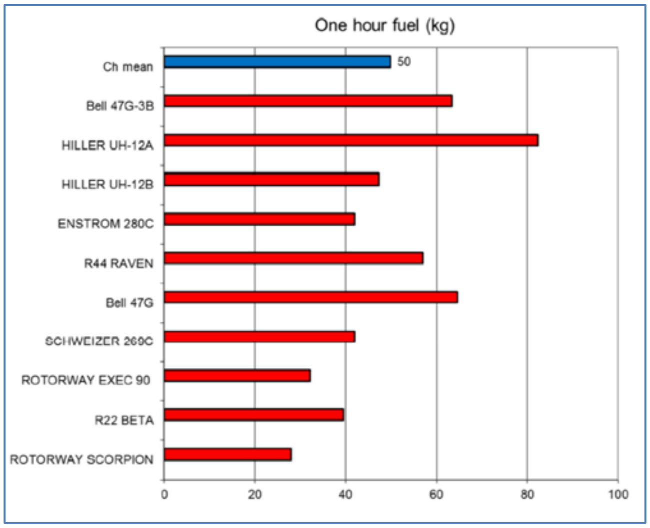

Figure A-1. Fuel Burn (Piston).

Fuel burn of ~165kg/h for light weight, single and twin gas turbine engine helicopter was determined using the fuel consumption per hour data of the helicopter models as shown in Figure A-2.

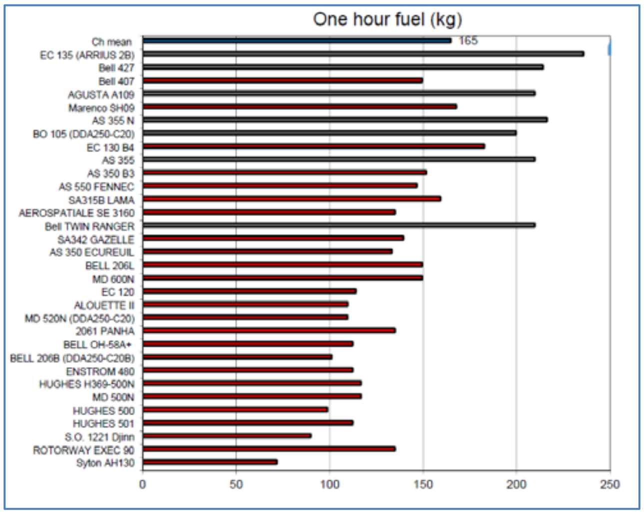

Figure A-2. Fuel Burn (Light).

Fuel burn of ~292kg/h for medium weight gas turbine engine helicopter was determined using the fuel consumption per hour data of the helicopter models as shown in Figure A-3.

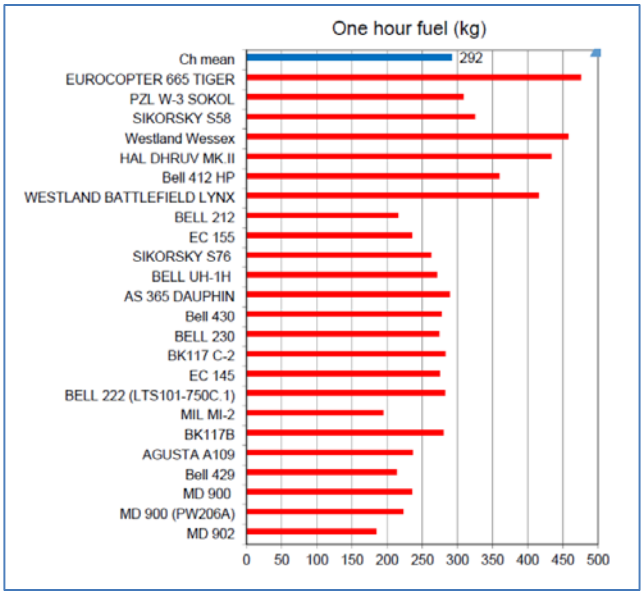

Figure A-3. Fuel Burn (Medium).

Fuel burn of ~617kg/h for heavy weight gas turbine engine helicopter was determined using the fuel consumption per hour data of the helicopter models as shown in Figure A-4.

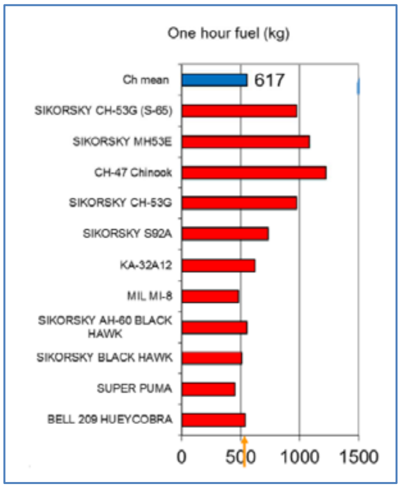

Figure A-3. Fuel Burn (Heavy).

Note that the published fuel burn data of MIL 26 helicopter is far beyond the average level i.e. nearly 15,000kg/h and therefore, it was excluded from this study.

ACKNOWLEDGMENTS

The participation and continuing contribution to allow successful completion of this research is very well acknowledged. Special thanks to the following organizations and their representatives: VFS, 3AF, Bell Textron, ONERA, Airbus Helicopters, Safran Helicopter Engines, Pratt & Whitney Canada Corp., NRC Canada.

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