A Methodology to Evaluate Electric Environmental Control System Impact on Aircraft Drag and Mission Performance

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Due to strengthening of environmental constraints and current industrial competitiveness, the airplane manufacturing industry is urged to turn towards an increase use of sustainable energy sources. A prominent concept is airplane electrification, either of the engine or various non-propulsive systems. In this paper, electrification of the Environmental Control System (ECS), which is used for cabin pressurization and electronic devices cooling, is analyzed. The objective is to develop a calculation method which allows to study the impact of ECS electrification on the aircraft mission performance, by taking into account the ambient air extraction impact on the aircraft drag. The method can be used at early design, for a complete aircraft mission, and is based on penalty analysis methods to convert the system performance impacts into fuel weight delta. In this paper a conventional and a fully electrified architecture are compared for a short-medium range aircraft. While the electrical ECS architecture is shown to be more advantageous with respect to the engine performance alone, preliminary studies using the presented method indicate that a conventional ECS architecture is more adapted regarding the overall aircraft mission fuel performance.

I. Nomenclature

AMS = Air Management System
CC = Combustion Chamber
CD = Cold day weather condition
C_d = Drag coefficient (-)
CMP = Compressor
D = Drag (kg)
D_s = Specific diameter (-)
d_{cmp} = Compressor diameter (m)
ECS = Environmental Control System
GB = Gearbox
HD = Hot day weather condition
HP = High pressure
HX = Heat exchanger
H_{ad} = Adiabatic head ($J.kg^{-1}$)
IP = Intermediary pressure
IPS = Ice Protection System
ISA = International standard atmosphere
k_i = Conversion factor
MF = Mass flow rate ($kg.s^{-1}$)
Noz = Nozzle
N_{cmp} = Rotor rotational speed (rpm)
N_{pax} = Number of passengers (-)
N_s = Specific rotational speed (-)
P = Power (kW)
p = Pressure (Pa)
Pri = Primary
R = Air gas constant ($J.kg^{-1}.K^{-1}$)
r = Lift-to-drag ratio (-)
Sec = Secondary
T = Temperature (K)
TO = Take-off
TRB = Turbine
TSFC = Specific fuel consumption ($kg.N^{-1}.s^{-1}$)
W = Weight (kg)
ΔD = Drag variation (kg)
ΔW = Weight variation (kg)
ΔP = Power variation (kW)
α = Security factor (-)
γ = Heat capacity ratio (-)
ρ = Density ($kg.m^{-3}$)
τ = Phase flight time (min)

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II. Introduction

The reduction of airplane emissions is of utter importance to aeronautical industry due to its current global environmental footprint and the impact this will have on the future competitiveness on the market. For example, in the United States, NASA has published a roadmap concerning the definition of a technology portfolio to deal with energy efficiency and environmental challenges for 2025-2030 timeframe with aggressive performance targets [1]. Likewise, in Europe, a study was requested by European Parliament in 2015 from Policy Department A for the Committee on Environment, Public Health and Food Safety (ENVI) to evaluate necessary investment into the aviation sector to severely reduce its emissions [2]. The OEM's is strongly encouraged to develop new technologies to decrease its carbon footprint. Aircraft electrification is a potentially suitable solution to reach this goal. Concerning the propulsive system electrification, there are typically six possible hybrid-electric propulsion architectures [3]. An exhaustive review of fixed-wing airplane concepts with electric, hybrid or turboelectric propulsive systems is given by Brelje and Martins [4].

The electrification also concerns the airplane non-propulsive systems. In a conventional aircraft the power extracted from the engine is transformed into four types of power available to the non-propulsive systems: pneumatic, hydraulic, mechanical and electric. The systems electrification commonly implies powering the conventional hydraulic and pneumatic systems electrically, in order to remedy for their typical drawbacks in terms of negative impact on engine efficiency, difficulties to detect and manage fluid leakage and their sizable pipe networks [5]. The electrical power can be supplied either by an electric generator which extracts mechanical power from the engine shaft or by an independent rechargeable battery. The electrification can have major repercussions on the system architecture, not necessarily. The Ice Protection System (IPS) illustrates the first case. Actually, the piccolo tubes blowing hot air at the wing leading edges are replaced by electric heating resistance or piezoelectric elements [6]. On the contrary, the modifications due to Environmental Control System (ECS) electrification will influence only the minor subsystems upstream of the ECS pack.

As currently applied on the B787 [8], the studied unconventional system in this paper is the fully electric ECS. However, if there is ambition to move towards All Electric Aircraft concept, the scientific community rather advice to firstly go through the intermediary More Electric Aircraft. Indeed, the entire airplane electrification still required maturation of enabling technologies such as power electronics, control, cooling requirements and batteries (power densities) [9].

The objective of the paper is to develop a calculation method to evaluate the impact of ECS electrification on the aircraft mission performance for a short-medium range airplane. This criterion to conclude about the electric ECS interest is the fuel weight delta relative to conventional aircraft on-board fuel weight. Firstly in this paper, a general description of ECS system is part III, followed by a review of the ECS models found in the literature. Then, part IV outlines the methodology developed in the current work, which aims to encompass all the elements related to ECS electrification at first order level, by accounting for the component/subsystem modifications impact only. The respective components' impact is expressed in terms of system weight, system power consumption and system drag deltas. These deltas are translated into block fuel using penalty analysis method developed by Moir and Seabridge [11]. The performance evaluation is carried out relative to a baseline airplane with a conventional ECS. Part V, presents the application case, the Airbus A320 with a fully electric ECS. The study is performed for two flight missions with extreme ambient temperature conditions. In order to assess the methodology robustness, two parametric studies are carried out with the mission range and the airplane passenger capacity as free variables. Finally, part VI proposes a way to generalize the method, along with potential improvements for the presented work.

III. State of the Art

A. ECS Overview

1. General architecture

ECS refers to aircraft equipment in charge of maintaining a comfortable environment for human beings, along with ensuring avionics cooling and protecting the aircraft against ice accretion on wings leading edge. Temperature and pressure conditions are important for the passengers, as human beings are sensitive to these conditions, whereas the electronic systems operation is mainly sensitive to humidity level. It means this system has to provide air flow regulated with respect to different constraints, which depend on the target application. ECS is typically broken down into the following sub-systems (Fig. 1):

1) *Air Bleed System*, which extracts the flow from a source,
2) *Air Management System* (AMS), which regulates temperature and pressure to constant values at the pack inlet and potentially at the wing Ice Protection System (IPS) inlet if the system is not electrified,

3) *ECS pack* (common to any ECS architecture), which adapts thermodynamic properties of the extracted air to meet the requirements form the cabin and the electronic devices,
4) *Air Distribution System* (common to any ECS architecture), which conducts the air to the necessary compartments.

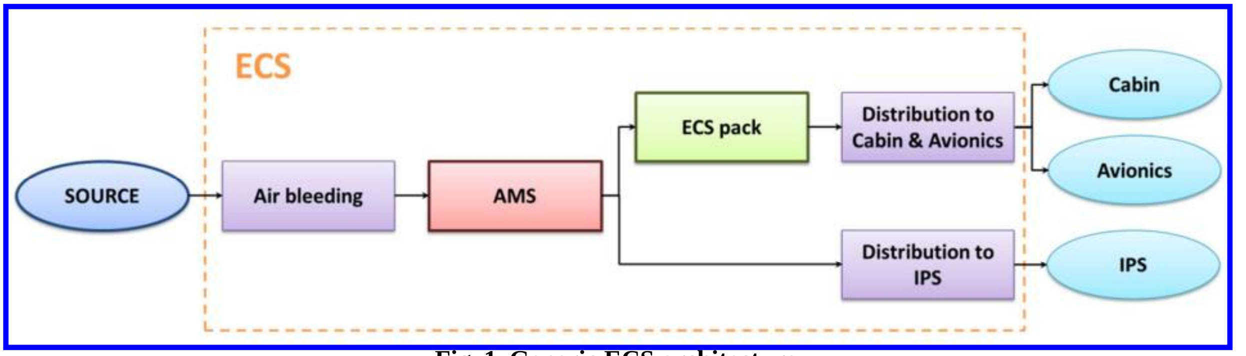


Fig. 1 Generic ECS architecture.

2. Conventional ECS

In a conventional ECS, the air is bled from two engine compressor ports, usually named high pressure (HP) port from a high pressure compressor stage and intermediary pressure (IP) port from a low pressure compressor stage. Because temperature and pressure at the ports evolve significantly over the mission and to limit the engine fuel consumption penalties implied by the air offtake, the bleed ports position is differently optimized for different flight phases: the air is mainly bled at IP port during take-off, climb and cruise and at HP port during descent, landing and taxiing. These two groups of flight phases are respectively distinguished by high and low required engine thrust levels, which have an impact on temperatures at the compressor bleed ports. However, despite this optimization, about 2 to 5% of the engine fuel consumption due to ECS is unavoidable. The non-negligible pressure losses in discharged valves notably contribute to make ECS the biggest non-propulsive power consumer [12].

Concerning management of the extracted air properties, AMS is in charge of regulating air at a temperature of 450 K and a constant pressure between 200 and 300 kPa. The temperature should not exceed the given value in order to avoid thermal damage of the pack components. Simultaneously, it should not be lower than this value, in order to ensure good IPS operation. The pressure is kept at a constant value to ensure continuous optimal pack operation.

3. Fully electric or hybrid ECS

The full ECS electrification means using ambient air instead of air bled from the engine. The Air Bleeding System is therefore composed of a vanned duct which guides the ambient air to the AMS to be pressurized and heated up to the levels required at the ECS pack inlet. Since ECS electrification often comes together with IPS electrification, it loosens the previously mentioned lower temperature constraint for the electrical AMS. However, the pack performance is dependent on the inlet temperature, so regulation must be ensured.

The common definition of hybridization implies having both the engine bleed air and the outside air available to the ECS. It is then possible for the hybridization ratio to vary along the mission. This definition is described as “in parallel” hybridization. As previously studied by Parrilla [14], it is also conceivable to bleed air from other engine ports than from the high pressure compressor, meaning from the low pressure compressor only, or from the fan. The ECS requires then assistance with an electrical driven compressor to provide the same pressure levels at the ECS pack inlet. This technological solution is called “in a series” hybridization. Parrilla [14] developed a 0D design methodology to study this concept with NPSS (Numerical Propulsion Simulation System). According to the results, air bleeding from a low pressure compressor stage only seems to be promising solution for a regional jet aircraft.

A successful ECS electrification has been already carried out on the long range B787 Dreamliner. Boeing estimates a block fuel saving of about 3% for this airplane size due to ECS electrification [8]. For the other aircraft ranges, there is no experience that would allow to draw conclusions on viability of electrical subsystem architectures. Even if the non-negligible pressure losses in conventional ECS promise potential performance gain with electrification, the latter causes an increase of the on-board weight for electricity production and an additional drag due to outside air extraction. These elements render the overall performance evaluation rather complicated even without taking into account concrete technological constraints (e.g. need for electronics cooling).

B. ECS Modeling

ECS modeling methods found in the public domain literature offer a purely thermodynamic assessment without considering the weight influence; they do not estimate the generated drag due to auxiliary inlet addition or they only take into account cruise flight phase. Dollmayer and Carl have developed a 0D model to evaluate the impact of non-propulsive systems on the mission fuel mass of an aircraft at early design by using SYSFUEL simulation tool [13]. They considered three contribution factors from each secondary system: their mass, their power consumption and their drag impact. From values of these parameters and an engine model run at a specific operating point, the mission fuel mass is calculated iteratively taking into account aircraft systems requirements, the necessary fuel mass flow and aircraft weight. The wing area and the mission range can be then recalculated. Later, Chakraborty and Mavris introduced a more exhaustive iterative model which estimates the three factors based on pre-sized aircraft aerodynamic and propulsive performance data and critical weights as a function of the ECS performance data [15]. In the current paper, the focus is rather on definition of a preliminary sizing method to evaluate the factors of interest for a specific airplane and a specific design flight mission. An engine model is used to obtain performance data of the engine, which is designed without considering non-propulsive system power extraction.

Since the three factors have different natures, it is necessary to define a unique criterion which relates the parameters with each other in order to be able to compare architectures performance. The chosen approach is to use penalty analysis methods to deal with the parameter comparison developed by Moir and Seabridge [11]. They established three equations to evaluate the fuel weight increase due to system weight, system power off-take and system drag. The selected criterion is therefore the fuel weight variation due to architectural differences between the conventional architectures and the one studied in this work. Long et al. [16] used this method to analyze and compare two fully electric ECS architectures, with and without an energy recovery unit (an additional cabin pressure outflow valve that contributes to thrust recovery [17]). With the system addition, calculated for cruise only, a reduction in block fuel weight was observed. The proposed correlations of Long et al. for moto-compressor weight estimation are applied in the current work, and the results are completed with works of Baljé [18] to estimate the ECS compressor diameter during early-design.

Concerning the definition of ECS design requirements, Maggiore et al. [19] have developed a method to size and evaluate electric ECS performance. The required air mass flow rate in the cabin is estimated by calculating the aircraft thermal power balance. The input data for the assessment are aircraft sizing characteristics and extreme environmental conditions that can be tolerated by the airplane. Their goal is to size different ECS components and the results are successfully compared with CFD calculation. A similar tool is presented in this paper to evaluate the ECS global power needs.

One of the parameters to estimate is the induced drag of an air intake used for electric ECS. Rütten and Krenkel [20] have developed a method to compare the aerodynamic effect of two different air intakes ("flush" and "scoop") on global airplane performance. The air intake performance evaluation is based on ESDU 86002 [21], which outlines semi-empirical models to estimate the air intake drag and the pressure loss between the entry plane and the inlet throat; the model inputs are the mission operating point description and air intake axial position on the fuselage. The authors conclude that without an ECS system model this method cannot be used to choose an optimal air intake type. The two air intakes have opposite behavior with respect to generated exterior drag addition and internal pressure loss. However, for the current work, it was important to make a choice since it is necessary to know the internal geometry of the air intake in order to carry out system performance evaluation. Therefore, an air intake which generates less pressure drop in selected, because it allows to minimize the error made by neglecting the losses in the pipe upstream of the electric-driven compressor.

IV. Methodology Outline

A. Input data

1. Aircraft definition

At early design, ECS sizing requires that the user has knowledge of airplane geometry, the passenger number and the cabin temperature need. In addition, the current method requires geometrical data to size the auxiliary inlet for an electric ECS and aircraft aerodynamic data, in order to perform a complete performance calculation of an aircraft mission. The complete list of necessary data is provided in part V.

2. Flight mission definition

The flight mission is divided in several short flight segments during which the data of interest are assumed to be constant. They are the operating points of the mission. The method allows both to size sub-systems and to estimate their mission performance. For the sizing, two missions with extreme weather conditions have to be defined. The first mission is mainly characterized by exceptionally hot outside temperature, high flight speed and maximal number of passengers; the second mission is characterized by very low outside temperature, low flight speed and few passengers. This way, ECS operation at all possible flight conditions will be ensured since common operating points will always fall within the envelope defined by these two extremes.

The extreme temperatures are commonly defined in official documents such as from the National Research Council [22] (Fig. 2). The cruise Mach number is fixed arbitrarily. For the second mission, it is supposed that the aircraft is filled up to about one third of its passenger capacity.

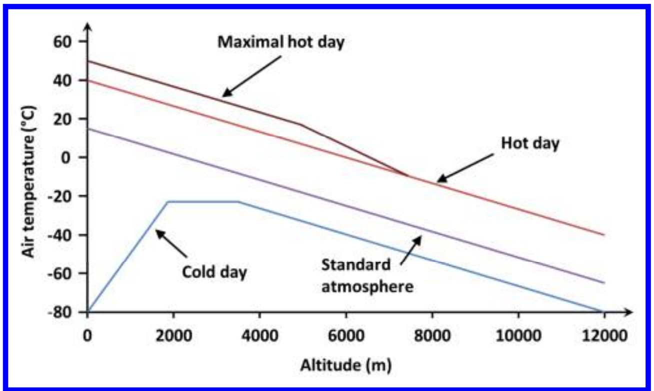
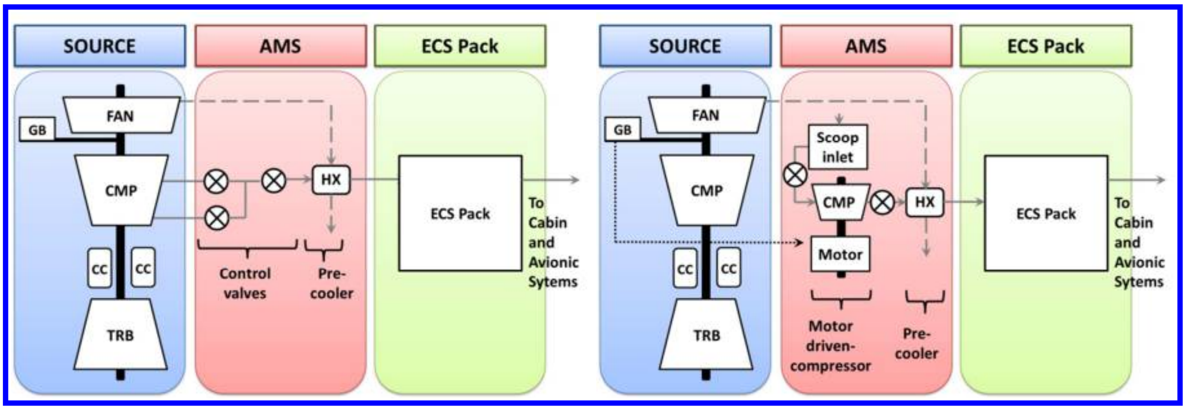


Fig. 2 Typical temperature design conditions for a civilian aircraft, taken from [22]

3. Geometry definition

In order to study how the full ECS electrification influences the aircraft performance, an assessment of the structural differences between the new and the conventional ECS is performed. The ECS pack architecture is not changed despite electrification, whereas the AMS architecture is completely modified. The air taken at an engine compressor stage port is replaced by ambient air compressed by a motor-driven compressor. To run the motor, mechanical power is provided from the engine shaft (Fig. 3).



(a) **(b)**

Fig. 3 (a) Conventional ECS, (b) Electrical ECS

B. Mass flow rate requirement

All the ECS architectures are sized for the cabin air requirements over a flight mission, and this calculation is independent of the ECS geometry. A method for calculating the necessary mass flow for the cabin is proposed here. Three different conditions have to be met for the passenger comfort and the fuselage structural constraints due to difference of pressure inside and outside of the aircraft.

The first condition is the minimal mass flow rate imposed by certification requirements (EASA *CS-25 or FAA Part 25)*. For civil aircraft, the minimum fresh air flow rate is 0.55 lb/min/passenger (0.00416 kg/s/passenger). This value has to be multiplied by the number of passengers to calculate the first minimal mass flow rate requirement.

$$MF_{ventilation} = 0.00416 * N_{pax} \tag{1}$$

The second condition is the mass flow rate to ensure a correct pressurization of the fuselage. On the one hand, to correctly refresh air inside the cabin, some air has to be injected and the same proportion has to be discharged outside the aircraft to maintain the cabin pressure. The mass flow rate to provide is therefore proportional to aircraft discharge surface. On the other hand, during descent phase, the cabin has to be progressively re-pressurized. For the passenger comfort, the maximal speed of re-pressurization is 11 mbar/min. The mass flow rate to re-pressurize the cabin is proportional to this speed and the cabin volume. The required mass flow rate is the sum of these two contributions.

$$MF_{pressurization} = MF_{leakage\ compensation} + MF_{re-pressurization\ during\ descent} \tag{2}$$

The third condition is the mass flow rate to ensure the required cabin temperature. For this calculation, it is necessary to fix the blown air temperature and to estimate the total thermal power exchanged throughout the cabin. The first parameter is an input; the second parameter can be divided in four contributions: the thermal power exchanged through the fuselage walls, the metabolic thermal power produced by passengers, the thermal power dissipated by the electrical loads (light, avionics and entertainment) and the solar radiation [19].

$$P = P_{walls} + P_{metabolic} + P_{electric} + P_{solar} \tag{3}$$

$$MF_{temperature\ control} = \frac{P}{c_p(T_{cabin} - T_{blown})} \tag{4}$$

At each operating point, the required mass flow rate is therefore the maximum of the three calculated values, which ensures that all the constraints are respected. In addition, a safety factor α (>1) is added to the calculation.

$$MF_{required} = \alpha * \max(MF_{ventilation}, MF_{pressurization}, MF_{temperature\ control}) \tag{5}$$

C. Engine bleed removal

To calculate the impact of the electrification in comparison to the conventional configuration, it is necessary to take into account the weight of the removed components related to engine bleed and the required pneumatic power in the conventional AMS.

Three valves are used in the conventional ECS. The high pressure valve (HPV) and pressure reduction valve (PRV) perform regulation of the compressor stages downstream pressure. A third valve, named flow control valve (FCV), is used to control the mass flow rate. The first component is purely pneumatically actuated, and the two other valves employ electronic controllers for regulation [23]. For a fully electric ECS, only two valves are required because there is only one air extraction path (vs. two engine bleed ports). The pressure valve can be supposed to be lighter in an electric ECS since it would be subjected to lower temperature and therefore would not require the same materials as the conventional ones. Manufacturer engine bleed air valve data sheets [24] indicate an order of magnitude of 2~3 kg for the weight of one conventional valve without electronics. However, the equivalent data was not found for valves adapted for electrical ECS use. Therefore, the valve weight modifications are not taken into account in the proposed methodology. Results of an example study (presented in part V) show than this weight component is negligible for the calculation at early design.

Conventional pneumatic ECS is characterized (and often criticized for that) by significant energy loss as a consequence of necessity to bring the high temperature and high pressure air from the engine to moderate conditions at the ECS pack. The temperature drop is taken into account in the calculation of the power loss in the AMS. To calculate this power, the presented method uses a 0D engine model developed in PROOSIS [25] an object-oriented 0D gas turbine system simulation software. The engine (schematic given in Fig. 4) is an in-house developed cycle based on public domain data on CFM56 engine, which powers families of short-medium range airplanes such as A320 and B737. Additional bleed ports on high pressure compressor have been introduced for non-propulsive systems air off-take. Since the model is 0D, the bleed ports are characterized by enthalpy loss fractions in the compressor element, ranging linearly between 0 at the compressor inlet and 1 at the compressor exit. The ports at 75% and 100% of the enthalpy have been chosen in this model to simulate to IP and HP engine bleed ports.

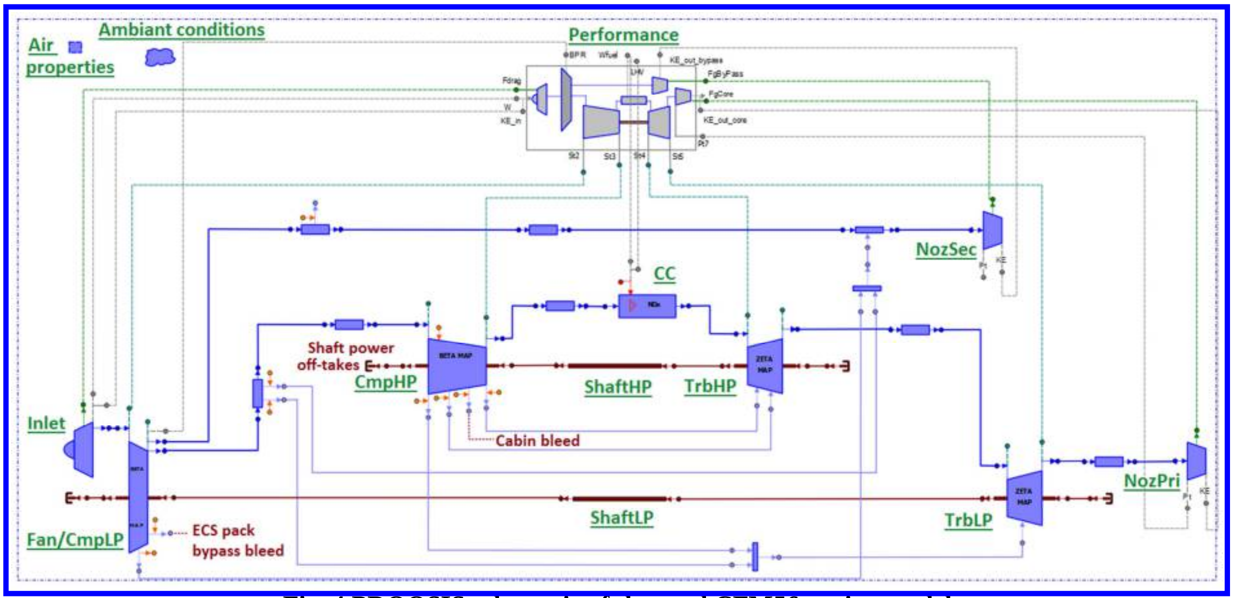


Fig. 4 PROOSIS schematic of the used CFM56 engine model

In the developed method, it is supposed that the control valves and the pre-cooler are capable of maintaining the temperature at 450 K at AMS outlet. If the temperature at the IP port is higher than 450 K, this value is chosen for the power calculation. If this temperature is lower, the value at the HP port is used:

$$T_{ref} = 450K \tag{6}$$

$$T_{IP} \rightarrow \begin{cases} > T_{ref} & \rightarrow \quad T_{inlet} = T_{IP} \\ < T_{ref} & \rightarrow \quad T_{inlet} = T_{HP} \end{cases} \tag{7}$$

$$\Delta P_{pneumatic} = MF_{required} * c_p * (T_{inlet} - T_{ref}) \tag{8}$$

Motor-driven compressor addition

To calculate the impact of the electrification, it is also necessary to take into account the weight of the additional electrically driven compressor and the required shaft power for the motor. Power electronics and a cooling system are also required for the motor operation, but they are not taken into account here. Since the geometry of the pipes between the scoop inlet and the moto-compressor is usually not defined during early sizing, it is not possible to properly estimate the pipe pressure drop, and therefore the motor inlet pressure. By imposing a generic pipe form, an analytical relationship depending on the mass flow rate or a fixed penalty factor could be used. The AMS required compression ratio is taken to be the ratio between the pack inlet needs and the ambient total pressure.

The pack inlet requirement in this method is a fixed value of 250kPa for the pressure and a fixed value of 450K for the temperature. By assuming an isentropic compression, the required thermodynamic properties at the compressor outlet have to reach the following values:

$$\begin{cases} T_{ref} = 450K \\ p_{ref} = 250\ kPa \end{cases} \tag{9}$$

$$T_{outlet,isentropic} = T_{inlet}\left(\frac{p_{ref}}{p_{inlet}}\right)^{\frac{\gamma-1}{\gamma}} \rightarrow \begin{cases} > T_{ref} & \rightarrow \quad \begin{cases} p_{out} = p_{ref} \\ T_{out} = T_{outlet,isentropic} \end{cases} \\ < T_{ref} & \rightarrow \quad \begin{cases} p_{out} = p_{inlet}\left(\frac{T_{ref}}{T_{inlet}}\right)^{\frac{\gamma}{\gamma-1}} \\ T_{out} = T_{ref} \end{cases} \end{cases} \tag{10}$$

By assuming there are no losses through the moto-compressor shaft power extraction, it is possible to calculate the required power for the system at any operating point of the mission:

$$\Delta P_{shaft} = MF_{required} * c_p * \left(\max\left(T_{ref};\ T_{outlet,isentropic}\right) - T_{inlet}\right) \tag{11}$$

Additionally, the weight due to moto-compressor is taken into account. With the correlations used by Long et al. [16], the maximal required power for the motor, along with the compressor diameter can be converted into system weight increase:

$$\begin{cases} W_{motor} = \dfrac{P_{max}}{k_1} \\ W_{cmp} = 2 * \left(k_2 * {d_{cmp}}^3\right) \end{cases} \tag{12}$$

$$\begin{cases} k_1 \in [2; 2.05]\ (kW/kg) \\ k_2 \in [1070; 3220]\ (kg/m^3) \end{cases} \tag{13}$$

$$\Delta W = W_{motor} + W_{cmp} \tag{14}$$

Since the two missions with extreme weather conditions are supposed to be the limiting cases of the flight envelope for the ECS, the maximal power for the motor and the maximal compressor pressure ratio are assumed to be attained during these missions. For the motor, the maximal ΔP_{shaft} of the characteristic operating points of the two missions is P_{max}. For the compressor, the pressure ratio reaches 14 in the studied case. A compressor with two radial stages is therefore necessary; during early design, the stages are assumed to be identical, with the same compression ratio. The diameter is chosen with Baljé's method [18] to optimize the stage efficiency for the design point using the N_sD_s diagram:

$$\begin{cases} N_s = \dfrac{N_{cmp} * \sqrt{MF/\rho}}{{H_{ad}}^{3/4}} \\ D_s = \dfrac{d_{cmp} * {H_{ad}}^{1/4}}{\sqrt{MF/\rho}} \end{cases} \tag{15}$$

To neglect the compressibility effects, the use of the N_sD_s diagram is completed by checking that the estimated tip Mach number M_{atip} is inferior to or near 1 [25]. The efficiency optimization for design point is proposed here without assuming any constraints on the maximal tolerated motor speed or the maximal compressor size.

$$Ma_{tip} = \frac{d_{cmp}}{2}\left(N_{cmp}\frac{2\pi}{60}\right)\sqrt{\gamma RT} \tag{16}$$

D. Air cooling system

In a conventional ECS, a heat exchanger commonly referred as "pre-cooler" performs temperature regulation at the pack inlet. This component is also necessary in an electric ECS because the moto-compressor cannot regulate both pressure and temperature. To calculate the electrification impact in comparison to conventional ECS, it is necessary to take into account the weight difference for this component between the two architectures.

In a conventional ECS, the typical weight of a heat exchanger is about 10-15 kg [12]. The weight variation is expected to be lower than this pre-cooler weight and is therefore considered as negligible during early design. This assertion is confirmed by results in part V.

E. Auxiliary air intake addition

To quantify the impact of the auxiliary air intake addition for an electric ECS, the induced drag of this component is taken into account. Two types of auxiliary air intake are used in the aviation. The "flush" inlet type has no parts outside the aircraft fuselage and the geometry inside the fuselage is a NACA profile. The generated drag is thus minimized, but its internal geometry produces non-negligible pressure losses. On the other hand, the "scoop" type inlet has its inlet section outside the aircraft facing the external flow directly. The drag and pressure loss behavior of this inlet type is opposite to the flush inlet. Based on the ESDU 86002 [21], an air intake can be sized early and the generated drag coefficient increment can be estimated for any flight point. The drag coefficient increment is normalized with the intake area whose value is obtained through the sizing. As explained in part III, the scoop geometry is chosen in the current method to minimize the error produced by neglecting the pressure drop between the air intake inlet and the motor driven-compressor.

As for the moto-compressor, it is supposed that the sizing cases are evaluated by calculating all operating points of the two missions with extreme weather conditions. The approach is to pre-size the auxiliary air intake at each flight point and to select the biggest inlet area to ensure that all air intake mission points can be operated. It is then possible to calculate the generated drag at any mission point. The result is given as an increment of the drag coefficient, so in order to retrieve the drag variation for a mission operating point, this value has to be multiplied by the whole aircraft drag coefficient. In the current work, only the cruise drag coefficient has been found in literature and it is assumed to be constant over the mission.

F. Fuel weight estimation

As previously explained, the values of system weight, system induced drag and system power off-take can be converted into fuel weight with the fuel penalty analysis method [11]. In addition to the three deltas: ΔW, ΔP and ΔD, the formulas require two other aircraft parameters: the thrust-specific fuel consumption TSFC and the lift-to-drag ratio r. The TSFC can be calculated with the PROOSIS engine model. As for the drag coefficient, the mission lift-to-drag ratio is fixed at a constant value found in the literature. The last new parameter in this formulation is the mission time τ. The mission is therefore divided in several flight phases.

Fuel weight increase due to system weight is given by [11]:

$$\left(\Delta W_{fuel}\right)_{\Delta W} = \Delta W * (e^{TSFC*\frac{\tau}{r}} - 1) \tag{17}$$

Fuel weight increase due to system drag is given by [11]:

$$\left(\Delta W_{fuel}\right)_{\Delta P} = \frac{r}{TSFC}\Delta P * (e^{TSFC*\frac{\tau}{r}} - 1) \tag{18}$$

Fuel weight increase due to system power off-take is given by [11]:

$$\left(\Delta W_{fuel}\right)_{\Delta D} = r * \Delta D * (e^{TSFC*\frac{\tau}{r}} - 1) \tag{19}$$

The complete workflow of the presented method for ECS electrification impact assessment is given in Fig. 5.

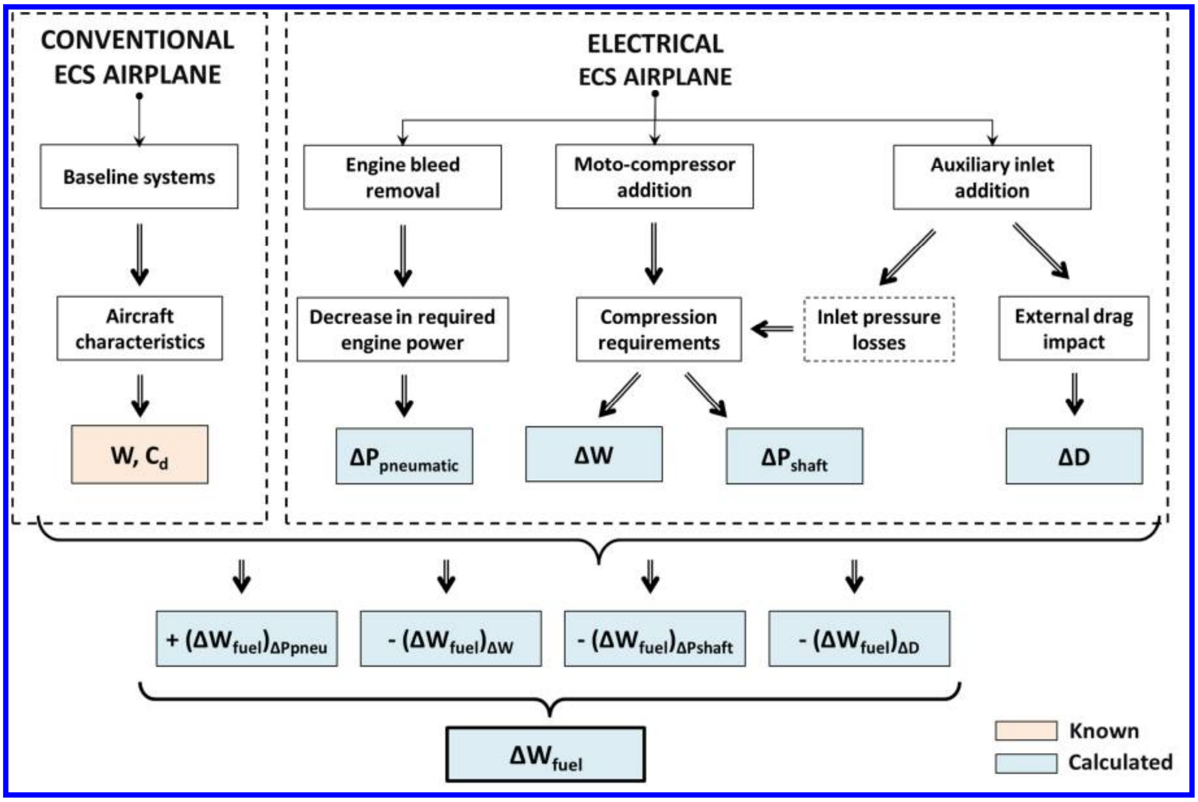


Fig. 5 Method for ECS electrification impact assesment

V. Results

A. Baseline mission

The test case for first application of the method is an A320-type airplane with a fully electric ECS. The reference engine for the calculation is CFM56. The mission range is fixed to 1500 km. The first mission is named “Mission HD” (hot day) and is defined with very high outside temperatures (“Maximal hot day” on Fig. 2). It lasts 85 min. The maximal Mach number is 0.77. The second mission is called “Mission CD” (cold day) and is characterized by low temperatures (“Cold day” on Fig. 2). It lasts 100 min. The Mach number evolution in this case is chosen to be lower than for the hot day mission in order to minimize the required power from the ECS due to thermal exchange through the fuselage walls. The maximal Mach number for this mission is 0.72. For both missions the thrust law is extrapolated from CFM56 engine reference data for maximal take-off (117.9 kN) and cruise (21.7 kN). All the required inputs are introduced in Fig. 6 and Table 1.

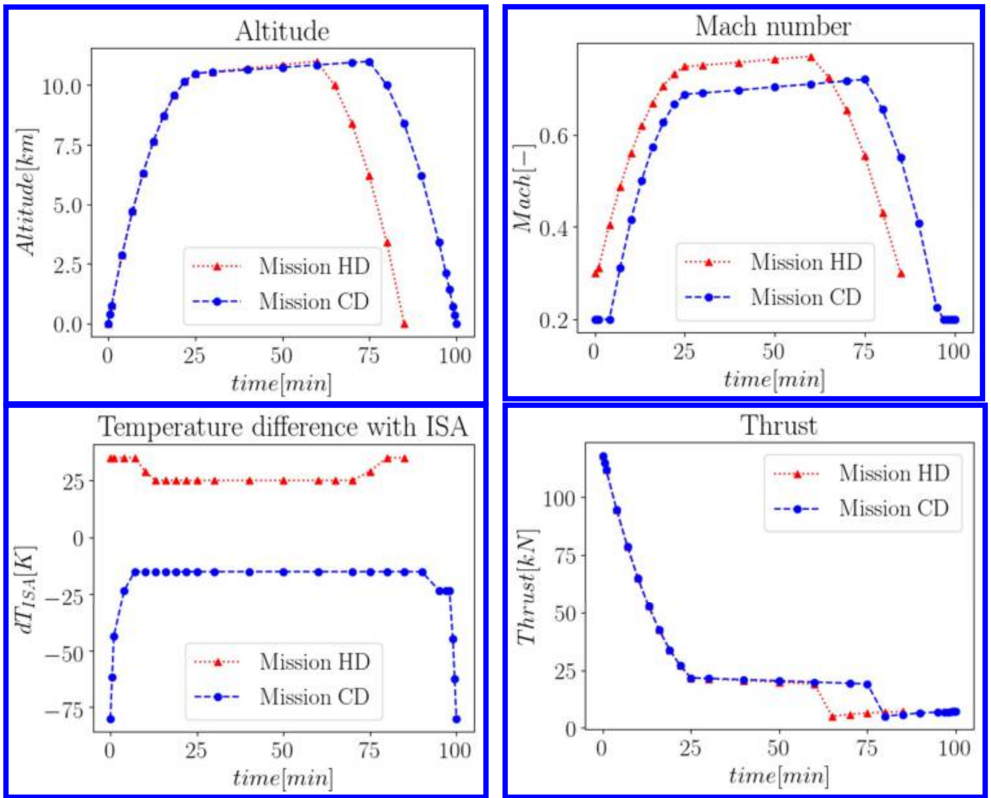


Fig. 6 Aircraft input mission

Table 1 Aircraft input data

Airplane characteristics	Mission HD	Mission CD	Scoop inlet characteristics	Mission HD	Mission CD
Cabin volume (m^3)	430		Inlet shape	circular	
Glazed surface (m^2)	9.14		Lip profile	elliptical	
Air discharge surface (m^2)	0.0016		Overall length (m)	0.2	
Wall exchange coefficient (W/ m^2/K)	0.7		Diverter height (m)	0.05	
Maximum number of passengers (-)	162		Throat aspect ratio (-)	4	
Mission characteristics	**HD**	**CD**	Inlet location along the fuselage (m)	10	
Cabin required temperature T_{cabin} (°C)	24	24	**Cruise characteristics**	**HD**	**CD**
Cabin blown temperature T_{blown} (°C)	-15	30	Lift-to-drag ratio r (-)	17.43	
Number of passengers N_{pax} (-)	162	33	Drag coefficient C_d (-)	0.03092	

Results for the intermediate parameters are provided for the four ECS sizing points: take-off ('TO') and cruise for both "Mission HD" and "Mission CD", respectively named TO_HD, Cruise_HD, TO_CD, and Cruise_CD (Table 2).

Table 2 Mission flight point results

Operating point	TO_HD	Cruise_HD	TO_CD	Cruise_CD
Altitude (km)	0	11	0	11
Mach number	0.3	0.77	0.2	0.72
ΔT_{ISA} (K)	+35	+25	-80	-15
Thrust (kN)	117.9	21.7	117.9	21.7
Time τ (s)	60	600	30	300
$MF_{required}$ (kg/s)	0.573	0.368	0.359	0.289
$\Delta P_{pneumatic}$ (kW)	161.8	32.0	61.7	42.6
ΔD (kg)	78.2	125.6	48.0	134.4
ΔP_{shaft} (kW)	69.7	77	86.4	66.5
$\Delta W_{moto\text{-}compressor}$ (kg)	51.3	51.3	51.3	51.3

The four operating points for the two compressor stages are located in the N_sD_s diagram with a common diameter and different rotational speeds (Table 3, Fig. 7). In order to limit the tip Mach number, the points are located at the left side of the area of best efficiencies.

Table 3 Results with N_sD_s method

Operating point	TO_HD	Cruise_HD	TO_CD	Cruise_CD
Rotational speed (krpm)	40	48	50	48
Diameter (m)	0.15	0.15	0.15	0.15
N_s	0.83	0.89	0.47	0.71
D_s	3.18	2.87	5.41	3.45
Axial tip Mach number Ma_{tip}	0.80	0.98	1.06	1.03

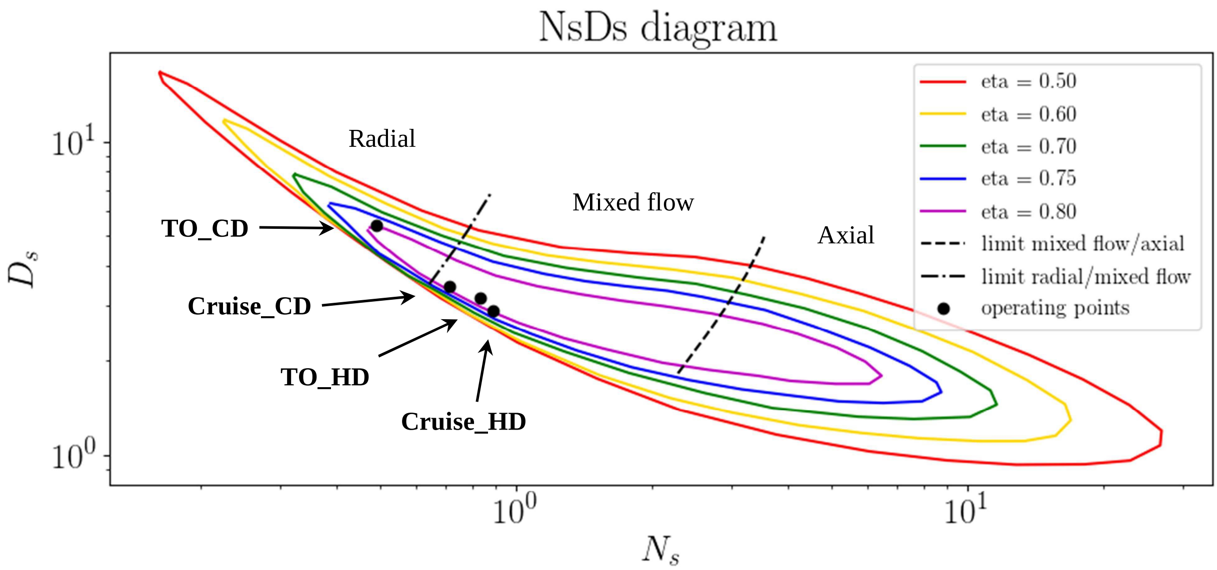


Fig. 7 NsDs diagram, taken from Baljé [18], with current operating points

The global fuel weight results for the two defined missions are presented in Table 4. The different contributions to fuel weight are distinguished and then summed.

Table 4 Mission global results

	Mission HD	Mission CD
$(\Delta W_{fuel})_{\Delta Ppneumatic}$ (kg)	-150.5	-98.2
$(\Delta W_{fuel})_{\Delta D}$ (kg)	+127.7	+112.2
$(\Delta W_{fuel})_{\Delta Pshaft}$ (kg)	+126.1	+89.0
$(\Delta W_{fuel})_{\Delta Wmoto-compressor}$ (kg)	+3.4	+3.1
$(\Delta W_{fuel})_{global}$ (kg)	+106.7	+106.1

According to the obtained results, the use of an electrical ECS architecture implies more fuel penalty than the conventional ECS for the two defined missions. By comparing the different terms, the drag impact is the main contributor to the penalty during the two selected missions; the power off-take of the pneumatic architecture is higher than the electric architecture power off-take for both missions, which means the electric ECS is more advantageous with respect to the engine performance. However, the induced drag in the auxiliary air intake is so significant than the global fuel weight penalty is higher with the new architecture. The impact of the moto-compressor weight (~50kg) is rather negligible relative to the other contributions. It can be also concluded that the assumption that control valve and pre-cooler weights variation (order of magnitude of 2kg) are also negligible during early design is reasonable.

B. Parametric studies

1. *Influence of the mission range*

For the two defined missions, the range is modified by increasing the duration of the cruise at 11,000 m. This study allows calculation of a mission for which the cruise phase is dominating. The error made by supposing the two cruise characteristics (thrust-specific fuel consumption TSFC and the lift-to-drag ratio r) to be constant during the entire mission is less significant in this study. However, another engine model adapted to longer mission range should be used. The corresponding Mach numbers for this flight phase are still 0.77 for the "Mission HD" and 0.72 for the "Mission CD". The results for the fuel weight terms are introduced in Table 5 and Table 6 and are graphically represented on Fig. 8. The particular percent difference between the respective effects of pneumatic and electric power off-takes, summarized in Fig. 9, is calculated as follows:

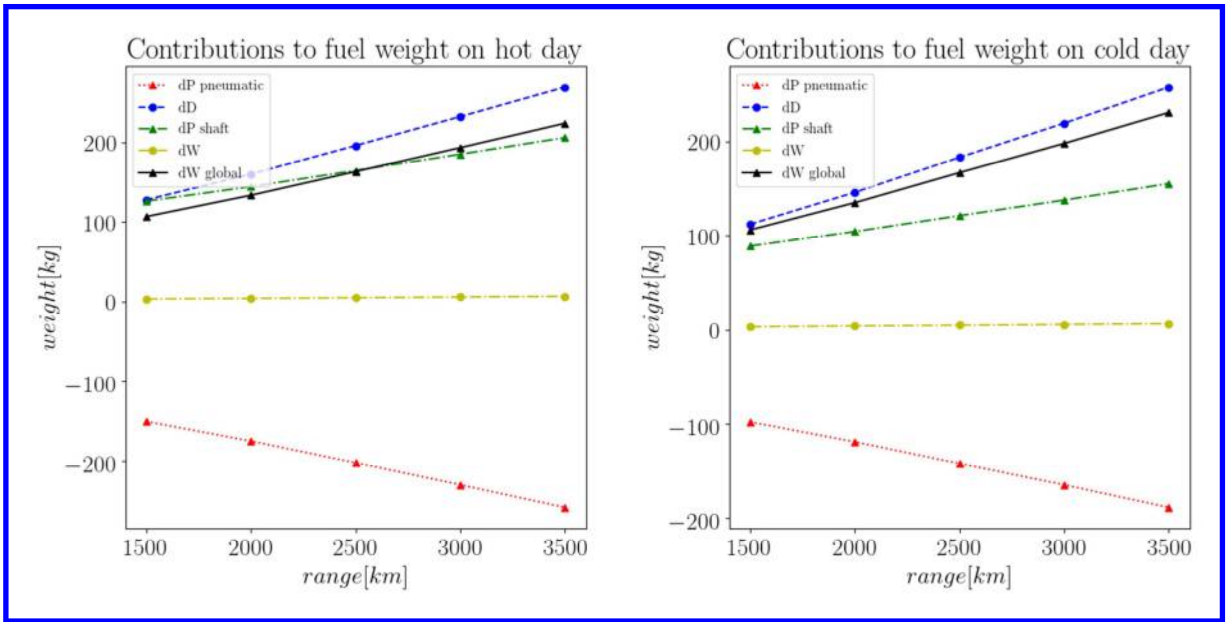
$$difference = \frac{\left(\Delta W_{\Delta fuel}\right)_{\Delta P_{shaft}} - \left(\Delta W_{\Delta fuel}\right)_{\Delta P_{pneumatic}}}{\left(\Delta W_{\Delta fuel}\right)_{\Delta P_{shaft}}} \tag{20}$$

Table 5 Mission HD: Influence of the mission range

Range (km)	**1500**	**2000**	**2500**	**3000**	**3500**
Time increase (min)	0	22	46	70	94
$(\Delta W_{fuel})_{\Delta Ppneumatic}$ (kg)	-150.5	-175.0	-202.2	-229.8	-257.9
$(\Delta W_{fuel})_{\Delta D}$ (kg)	+127.7	+160.0	+195.8	+232.1	+269.0
$(\Delta W_{fuel})_{\Delta Pshaft}$ (kg)	+126.1	+144.3	+164.5	+185.0	+205.8
$(\Delta W_{fuel})_{\Delta Wmoto-compressor}$ (kg)	+3.4	+4.2	+5.0	+5.9	+6.8
$(\Delta W_{fuel})_{global}$ (kg)	+106.7	+133.5	+163.1	+193.2	+223.7

Table 6 Mission CD: Influence of the mission range

Range (km)	**1500**	**2000**	**2500**	**3000**	**3500**
Time increase (min)	0	25	52	78	105
$(\Delta W_{fuel})_{\Delta Ppneumatic}$ (kg)	-98.2	-119.3	-142.3	-164.9	-188.7
$(\Delta W_{fuel})_{\Delta D}$ (kg)	+112.2	+146.1	+183.3	+219.6	+257.9
$(\Delta W_{fuel})_{\Delta Pshaft}$ (kg)	+89	+104.4	+121.3	+137.9	+155.4
$(\Delta W_{fuel})_{\Delta Wmoto-compressor}$ (kg)	+3.1	+3.9	4.7	+5.5	+6.3
$(\Delta W_{fuel})_{global}$ (kg)	+106.1	+135.1	+167.0	+198.1	+230.9



(a) **(b)**

Fig. 8 Different terms contributing to the calculated fuel weight (a) on "hot day", (b) "on cold day", with mission range variation

For all studied ranges, the conclusions are identical to the main mission. The use of the electrical ECS architecture is less advantageous than its conventional equivalent with respect to the aircraft performance. However, from the engine point of view, the shaft power off-take is less penalizing than the pneumatic power off-take.

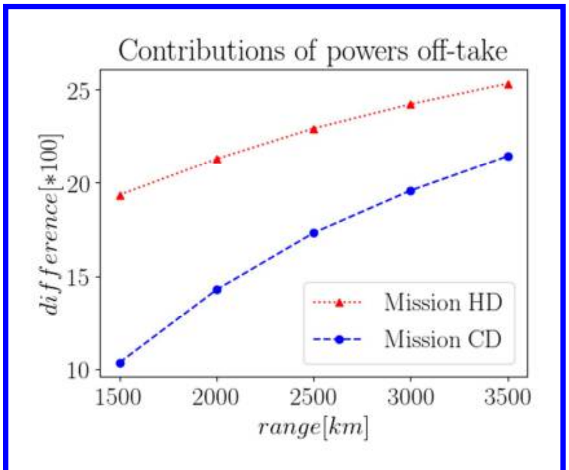


Fig. 9 Influence of different power off-takes on mission fuel weight

For both missions, the difference between the engine penalties due to the mechanical power and the pneumatic power off-takes increases as the mission range rises. The results indicate that the use of an electric ECS is less detrimental for the engine and this result is particularly visible when the mission range increases.

2. Influence of the aircraft size

For the two missions, the aircraft passenger capacity is multiplied by two. Concerning the aircraft characteristics, the cabin volume, the glazed and air discharge surfaces and the maximal number of passenger are multiplied by two; the other input parameters stay constant. All calculations except the engine model are computed again. The auxiliary air intake and the moto-compressor are re-sized. The results are presented in Table 7.

Table 7 Influence of the aircraft passenger capacity

	Mission HD		Mission CD	
Number of passengers	162	324	162	324
$(\Delta W_{fuel})_{\Delta Ppneumatic}$ (kg)	-150.5	-281.5	-98.2	-196.7
$(\Delta W_{fuel})_{\Delta D}$ (kg)	+127.7	+165.1	+112.2	+122.8
$(\Delta W_{fuel})_{\Delta Pshaft}$ (kg)	+126.1	+257.7	+89.0	+177.9
$(\Delta W_{fuel})_{\Delta Wmoto\text{-}compressor}$ (kg)	+3.4	+6.5	+3.1	+6.0
$(\Delta W_{fuel})_{global}$ (kg)	+106.7	+147.8	+106.1	+110.0

As it was observed for the previous conducted studies, the electric ECS architecture is less adapted with respect to block fuel optimization; on the other hand, less power is taken from the engine. However, in opposition to the other presented studies, the drag impact on fuel weight is less significant in this case than the shaft power off-take for the moto-compressor for both missions.

VI. Conclusion

The purpose of the presented paper is to provide a methodology for early design evaluation of a non-conventional ECS impact on the aircraft mission performance. The principle is to consider a reference ECS architecture and to analyze all the geometrical differences between the conventional and other architectures. The methodology could also be adapted to compare two new architectures between each other. For the ECS sizing, two specific missions have to be defined with extreme ambient conditions to limit the potential flight envelop. Then the method can be applied to a specific mission chosen within this envelope. Various approaches have been developed to estimate the influence of ECS components modifications in terms of weight, power off-take or additional drag. The values are then converted into block fuel impact using the penalty analysis method.

The method is then applied to a fully electric ECS case for a short-medium range airplane, comparing it to a conventional one. The used aircraft missions are the same two missions on which the ECS sizing is based. The results indicate that that the conventional architecture is more adapted to minimize mission block fuel, but the electric architecture is more advantageous with respect to the engine performance. Parametric studies on the mission range and airplane passenger capacity provide the same conclusions concerning the aircraft performance.

The paper provides guidelines on how to quantify the impact of a non-conventional ECS on aircraft performance during an early sizing phase. Although the accuracy of the presented results themselves can certainly be improved, the present methodology enables to draw global trends regarding both the engine performance and the whole aircraft performance. Several ways of improvement can be considered in future work:

(i) The first one directly addresses the conventional ECS modeling, provided that more complete data can be found about this system geometry and performance. In order to be more consistent, a similar level of modeling also needs to be provided for the studied non-conventional ECS, in particular concerning the weight estimation of the modified components and the new ECS geometry definition, among others the exact shape of the air intake, the complementary pipe system (and the associated pressure drop), and the compressor description.

(ii) Then, the PROOSIS engine model can be improved with realistic bleed port locations and possibly calibrated with experimental results.

(iii) Furthermore, variable aircraft lift-to-drag ratio and drag coefficient values should be used over the whole mission.

(iv) Moreover, the ECS specifications themselves should be updated, in relation with the systems expected to be electrified. For example, if the Ice Protection System (IPS) is electrified, the temperature specifications at the pack inlet must be adapted.

Finally, the non-optimization of the electric ECS, the associated airplane and engine partly explain the present conclusions in favor of conventional ECS use. Indeed, during the early sizing of a non-conventional ECS, both aircraft and propulsion models should be iteratively updated, accordingly to the changes in global airplane architecture. For this reason, ongoing research at ISAE-SUPAERO is focusing on coupling the involved tools and methods in order to enable a more integrated design process.

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