DOI: 10.13009/EUCASS2022-7371

Preliminary study of the impact of using hydrogen with a fuel cell for aircraft propulsion in an existing platform

DE FRUTOS Victor M.⋆† and PARRA Juan R.⋆ and BORDONS Carlos⋆ and ESTEBAN Sergio ⋆
⋆ Universidad de Sevilla
Sevilla, Spain
victormdefrutos@gmail.com · juan.ramon.parra.vilar@gmail.com · bordons@us.es · sesteban@us.es
†Corresponding author

Abstract
In the pursue of truly achieving the decarbonisation of air transport, several initiatives have been launched within the aeronautical industry with very different approaches. Despite that many studies have been conducted over the last years, including trials with demonstration flights for fuel cell-based aircraft platforms or for burning hydrogen propulsion, these studies have never gone beyond prototype status. One of the most promising presented alternatives is the incorporation of hydrogen technology in the power plant of flying platforms in order to reduce the carbon footprint. Two ways are contemplated for the introduction of hydrogen technology in the power plant of an aircraft: the burning of hydrogen in a combustion engine and the use of a fuel cell to generate energy to fly. Prior to consider the hydrogen utilization as an alternative, it is necessary to evaluate the impact that such technology might have in aircrafts utilization. The greener option for hydrogen utilization is using a fuel cell as the outcome of the energy production is only water. It is considered in this paper that this impact could be evaluated in the analysis and comparison of the PL (Pay Load) vs. R (range) diagram between two platforms: a traditional platform with engines as Power Plant and a modified platform from that original one using fuel cells and electrical motors as power plant. This article presents a comparison analysis between both platforms by presenting a methodology using preliminary study focused on the cruise phase as it is the more relevant phase to evaluate the range of the aircraft. The direct application of this methodology to a case study will give to the reader the level of the impact of the new technology introduction. Then the optimization in a computational code of this methodology will permit to perform sensitivity studies and to establish metrics and objectives to reduce the impact in the aircraft utilization because of this new technology.

1. Introduction

In the pursue of truly achieving the decarbonization of air transport, several initiatives have been launched within the aeronautical industry with very different approaches. Despite that many studies have been conducted over the past years, including trials with demonstration flights for fuel cell-based aircraft platforms, (see [4] and [5]) or for burning hydrogen propulsion (see [6]), these studies have never gone beyond prototype status. With the establishment of the Clean Skies for Tomorrow initiative (CST) in 2019, 60 companies in the World Economic Forum's Clean Skies for Tomorrow Coalition (see [2]) partnered with the objective to accelerate the deployment of sustainable aviation fuels (SAF) on the path to net-zero emissions by 2050 and working together to power global aviation with 10% SAF by 2030, many efforts and resources have been dedicated to go beyond the prototype phase. Among those, it can be pointed out that in September 2020, Airbus presented three ZEROe hydrogen-fuelled concepts aiming for commercial service by 2035 (see [3] and [1])

One of the most promising presented alternatives is the incorporation of hydrogen technology in the power plant of flying platforms in order to reduce the carbon footprint. Two ways are contemplated for the introduction of hydrogen technology in the engine plant of an aircraft [20]: the burning of hydrogen in a combustion engine and the use of a fuel cell to generate energy to fly. Prior to consider the hydrogen utilization as an alternative, it is necessary to evaluate the impact that such technology might have in aircrafts. The main objectives sought in this paper are:

1. To provide a methodology that allows to evaluate the impact of the introduction of hydrogen fuel cell technologies by means the comparison between the performances of the existing platform and the derivative (modified platform hereafter).

DOI: 10.13009/EUCASS2022-7371

2. To develope a computational tool to apply the methodology systematically to different aircraft configurations and flight profiles while conducting sensitivity studies to analyse and optimize the new propulsion system. It would be key to identify different levels of power source hybridization that might be required in order to minimize performance degradation, and how the different hybridization strategies might help to improve the two previous objectives.

In order to obtain these objectives, the paper presents a mathematical methodology that provides a preliminary sensitivity analysis that will allow to conduct assessment of the suitability and impact that an alternative hydrogen based fuel cell propulsion system might have in existing aircrafts when the carbon-based fuels propulsion system is replaced by hydrogen fuel-based propulsion systems. The study uses an existing tactical transport platform as a benchmark following several assumptions:

1. Both platforms, traditional and modified, have the same physical envelope. This means that the aerodynamic characteristics are the same on the traditional and modified platform.
2. The size and integration of the new power plant system could be done on the current platform envelope only affecting to the mass of the propulsion system.
3. For the modified platform, the removal of the current power plant and the installation of the new hydrogen-based power plant is considered, so the operational empty weight is affected.

The sensitivity studies evaluate how the performance is affected by the different considered hybridization power plants, while uses different metrics to evaluate the viability of the proposed power alternatives, and to propose the best configuration. The Maximum Take-off Weight (MTOW) would give the flyable limit for the modified platform: if the modification for introducing the new power plant based on hydrogen results in an aircraft weight higher than the MTOW of the traditional platform, as long as the aerodynamic behaviour is the same, the modified platform will not take off. Therefore, the MTOW will limit the hydrogen and propulsion system and would be the starting point for the impact evaluation. This preliminary study helps to pave the way for the use of hydrogen and hybrid electrical/hydrogen systems for propulsion in future aircraft designs.

2. Comparison methodology

The aim of this chapter is to provide a useful methodology to compare the two platforms with different propulsion systems, a conventional fuel engine and a modified to include an alternative propulsion system based on hydrogen. Firstly, it is started considering a propulsion system based on a fuel cell so that it could be put in the scenario of zero-emissions with the only outcome of the propulsion system the water. It is considered then purely electrical propulsion. In this sense it could be compared and evaluated a preliminary impact of the introduction of this new propulsion system in the aviation business. Secondly, it is needed the knowledge of the weights of the aircraft. Essential relations to consider are:

$$\boldsymbol{ZFW = OEW + PL} \tag{1}$$

$$\boldsymbol{TOW = OEW + PL + FW} \tag{2}$$

$$\boldsymbol{MZFW = OEW + MPL} \tag{3}$$

Where, ZFW is zero fuel weight, MZFW is the Maximum zero fuel weight, OEW is Operational Empty weight, PL is Pay Load, MPL is the maximum Pay Load, FW is Fuel Weight and TOW is Take-off Weight of the Aircraft. It is considered the modified platform as a platform equal to the traditional one (original one) except for the propulsion system in which it is assumed that the engines are removed from the aircraft as well as the corresponding systems that make the engines work (piping, valves, installation parts, etc) and it is superseded by the new power plant system based on fuel cells. As a result, the OEW of the modified platform would change because of the different weight of the power plant. Typically, the weight per kW installed of the fuel cell is higher than the state-of-the-art engines then the OEW of the modified platform will be higher than the original one. The following assumptions are considered:

1. Both platforms, traditional and modified, have the same physical envelope. This means that the aerodynamics characteristics are the same on the traditional and modified platform.
2. The size and integration of the new power plant system could be done on the current platform envelope and only the mass changes.
3. For the modified platform, the removal of the current power plant and the installation of the new hydrogen-based power plant is considered, so the operational empty weight is affected.
4. It is considered a simple mission consisting of: take-off, climb, cruise, descent and landing. This paper is focused on cruise phase which represents the most variable phase in terms of weight.

DOI: 10.13009/EUCASS2022-7371

5. It is considered negligible the mass variation between take off and cruise, so it is considered that the starting cruise mass for both platforms is the same.
6. Cruise altitude is the same in both platforms.
7. Take off power is put aside of this calculus and will be faced in future studies.
8. Hydrogen weight is taken as fuel weight. Water as outcome of the fuel cell is exhausted to ambient.
9. Comparison is done for turbo-propeller A/C for simplicity.

Then the resulting modified aircraft would have new weights with regards OEW and FW (hydrogen). Hereafter it is depicted with the suffix 1 the original platform and with the suffix 2 the modified platform.

$$\mathbf{OEW^* = OEW_1 - (1 + \eta_{inst,eng})\ x\ N_{eng} W_{eng}} \tag{4}$$

$$\mathbf{OEW_2 = OEW^* + W_{PWP,2} + W_{HSD}} \tag{5}$$

$$\mathbf{TOW_2 = OEW_2 + PL + FW} \tag{6}$$

$$\mathbf{W_{HSD} = E_{cruise} / k_{HSD}} \tag{7}$$

$$\mathbf{W_{PWP,2} = W_{FC} + W_{PDU} + W_{e-motors}} \tag{8}$$

$$\mathbf{W_{PWP,2} = N_{Stacks} \cdot W_{stack} + P_m / k_{PDU} + P_m / k_{e-motors}} \tag{9}$$

Where N_{eng} is the number of the engines installed on the original aircraft, W_{eng} is the dry weight of one engine, $\eta_{inst,eng}$ is a coefficient that takes into account the Aircraft installation related to the engine (valves, piping, pumps, etc), $W_{PWP,2}$ is the weight of the new power plant system, W_{HSD} is the weight of the hydrogen storage device calculated via E_{cruise} (energy needed for the entire cruise phase) and K_{HSD}, coefficient that put in relation the weight of the system with the energy to be stored. W_{FC} is the weight of the fuel cell system with N_{Stacks} and W_{stack} are the number of stacks installed and the weight of a single stack respectively. W_{PDU} is the weight of the Power distribution system and K_{PDU} is the coefficient that estimates the weight in relation to the power needed. $W_{e-motors}$ is the weight of the electrical motors estimated to be installed and $K_{e-motors}$ is the coefficient that estimates the weight in relation to the power needed.

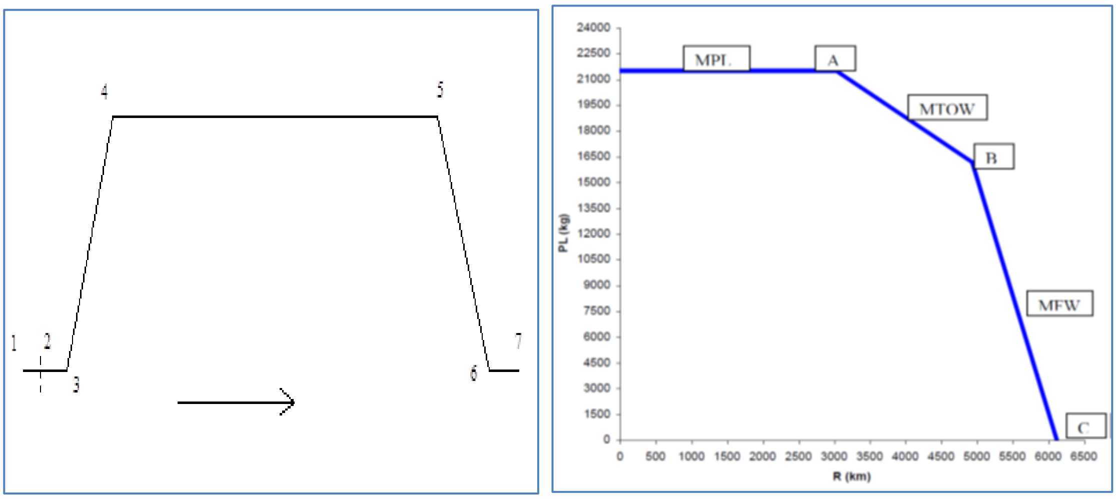
The calculation of the new power plant weight will be based on the required power based on the mission profile. It is also needed to include other contributors to OEW as the Power distribution Unit, electrical motor or the Hydrogen storage device. The hydrogen storage system selection is key for the analysis, and while currently two storing hydrogen methods are considered (gas and liquid (cryogenic)) this paper considered only a gas stored system.

The methodology proposes an iterative process that evaluates if it is possible to fly with the new power plant using the mass as the stop criteria. For a given geometry, the MTOW (maximum take-off weight) defines the maximum A/C weight for taking-off hence it will be used as stop criteria for some cases and to limit the new power plant mass. For simplicity, results presented in this paper will only consider the Cruise phase for the sizing of the power plant which will allow to evaluate the preliminary impact of the change from power plant based on hydrocarbon fuel to hydrogen-based power plant. A good metric to evaluate the impact that the different plants have on the Aircraft (A/C) performance is the available maximum Range (R) for a given Payload (PL), which can be seen in the commonly used PL vs R diagram, where R is the range of the aircraft considered as the distance covered by the aircraft in the mission.

Despite the modified platform uses purely electrical propulsion, we can use similar formulation (ref. [7], [13]) than the original A/C to calculate the range since we assume that the outcome of the propulsion system (the water) is exhausted to the ambient, which results in an associated loss of mass all along the mission. Conceptually both platforms are

DOI: 10.13009/EUCASS2022-7371

variable mass systems: the original one burning hydrocarbon fuel and the modified one consuming Hydrogen for electrical generation.



(a) (b)

Figure 1. (a) Typical Aircraft mission. (b) Typical PL vs R diagram with the limitations in MPL, MTOW and MFW

A typical PL vs. Range diagram can be seen in Figure 1(b), where it is important to highlight that:

- Point A corresponds to limitations of MTOW and MPL.
- Point B corresponds to limitations of MTOW and MFW.
- Point C corresponds to PL =0 and MFW limitation.

To go on with the methodology, it is recalled that in cruise it is assumed:

$$\gamma \sim 0 \quad (10)$$

$$\dot{x}_e = V \quad (11)$$

$$V_a = 0 \ \rightarrow h = cte \quad (12)$$

$$T - D = 0 \quad (13)$$

$$L - nW = 0 \text{ (n=1, cruise)} \quad (14)$$

$$\dot{m} + \varphi = 0 \quad (15)$$

Also,

$$\mathrm{T} = D = {}^{1}\!/_{2}\,\rho V^2 S_w C_D \quad (16)$$

$$W = L = {}^{1}\!/_{2}\,\rho V^2 S_w C_L \quad (17)$$

$$C_D = \frac{D}{{}^{1}\!/_{2}\,\rho V^2 S_w} \quad (18)$$

$$C_L = \frac{L}{{}^{1}\!/_{2}\,\rho V^2 S_w} \quad (19)$$

$$C_D = C_{D0} + kC_L^2 \quad (20)$$

DOI: 10.13009/EUCASS2022-7371

With γ the angle between the x body axe of the aircraft and the horizontal reference, ρ is the air density at aircraft altitude, T is the Aircraft Thrust, D is the Aircraft drag, L is the aircraft lift, W is the aircraft weight, V_a is the ascensional speed, x_e is the distance run by the aircraft, V is the aircraft speed, n is the load factor, $\dot{m}$ is the mass rate variation of the aircraft during the flight, and φ is the fuel consumption. Additionally, S_w is the wing area, C_L is the lift coefficient, C_D is the drag coefficient, C_{D0} is the parasitic drag coefficient and k the induced drag coefficient.

Considering $TOW_1 = TOW_2$, weight in cruise in 1 es equal to weight in cruise 2 and the same geometry:

$$\mathbf{V_{Cr1}} = \mathbf{V_{Cr2}} = \boldsymbol{V} = \sqrt{\frac{2 \cdot \boldsymbol{W}}{\boldsymbol{\rho} \cdot \boldsymbol{S} \cdot \boldsymbol{C_L}}} \qquad (21)$$

Where V_{cr} are the cruise speed for the platforms under study. As mentioned before, it will be applied the methodology for turbo-propeller aircrafts, thus need to satisfy:

$$\boldsymbol{P_u - P_d = 0} \qquad (22)$$

$$\boldsymbol{P_m = P_u \,/\, \eta_p} \qquad (23)$$

$$\boldsymbol{P_u = P_d = {}^1\!/_2\, \rho V^3 S_w C_{D0} + k \frac{W^2}{{}^1\!/_2\, \rho S_w V}} \qquad (24)$$

where P_u is the useful power driven by the platform for flying, P_m is the power provided by the motor/engine to the propeller shaft and $\boldsymbol{\eta_P}$ is the efficiency of the propeller. Accordingly, P_d is the drag power. Following ref [8]:

$$\boldsymbol{\eta_P = \eta_P(N, V, \beta_{0.75}) \sim \mathrm{cte}} \qquad (25)$$

Where, N is the rotational speed of the propeller and $\beta_{0.75}$ is a propeller parameter defined as the angle between the blade chord and the propeller plane. Then, P_u is only dependant of geometry, V_{cr} and Weight, so in the end, P_u should be the same for both the original and modified platform.

$$\boldsymbol{P_{u,1} - P_{u,2} = 0} \qquad (26)$$

Considering the actual state of the art, the cruise power should be covered by a finite number of stacks of fuel cells. Considering Figure 2, the formulation for the power installed on the modified A/C is given by:

$$\boldsymbol{P_{FC} = N_{stacks} \cdot P_{Stack}} \qquad (27)$$

$$\boldsymbol{P_{in,FC} = \frac{P_m + P_{BoP}}{\eta_{FC} \cdot \eta_{loss}}} \qquad (28)$$

$$\boldsymbol{P_{BoP} = P_m \cdot \eta_{BoP}} \qquad (29)$$

DOI: 10.13009/EUCASS2022-7371

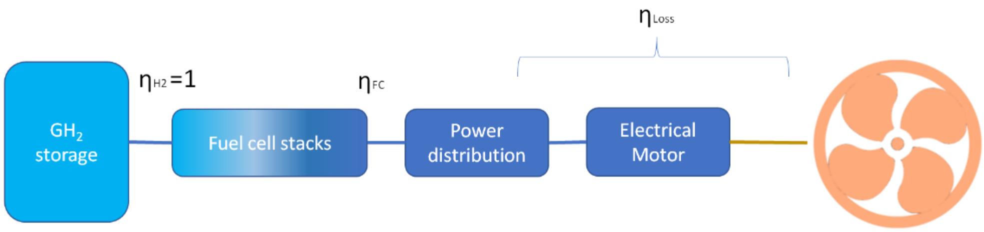


Figure 2. Power chain in the modified platform

Where $P_{in,FC}$ is the inlet power to the fuel cell system, P_{BoP} is the power used for the balance of plant of the fuel cell, calculated as a proportional to the P_m with the coefficient η_{BoP}. The efficiency coefficient that takes into account the loss in the power chain is η_{loss} and η_{FC} is the global efficiency of the fuel cell. Following the reference [9], it is calculated the Fuel flow (FF) to go into the fuel cell as:

$$\boldsymbol{FF} = \frac{\boldsymbol{P_{in,FC}}}{\mathbf{HHV}_{\boldsymbol{H_2}}} \tag{30}$$

With HHV_H being the Hydrogen Higher Heat Value,

$$\boldsymbol{HHV_{H_2}} = \mathbf{141,86}\ \boldsymbol{MJ/kg} \tag{31}$$

The value of the energy stored in the hydrogen (Higher Heat Value, HHV_{H2}) differs from ref. [9] as it is taken from ref [11]. With (30) and the cruise time, it is possible to foresee the quantity of hydrogen needed to perform the cruise phase in the modified platform assuming the fuel flow constant as well as the energy needed for cruise phase:

$$\mathbf{E_{cruise}} = \boldsymbol{P_{in,FC}} \cdot \mathbf{t_{cruise}} \tag{32}$$

$$\mathbf{FW} = \mathbf{FF} \cdot \mathbf{t_{cruise}} \tag{33}$$

The cruise time (t_{cruise}) will be used as the iteration variable and the stop criteria the mass limit of the original platform (i.e. MTOW for points A and B of PL vs R) such that when the A/C mass satisfies the criteria, a valid solution of the problem is found. Integral performance it is required in order to obtain the PL vs R diagram. Consider both platforms as mass varying systems, the do need to comply with (15):

$$\dot{\boldsymbol{m}} + \boldsymbol{\varphi} = \mathbf{0} \rightarrow \frac{\boldsymbol{dW}}{\boldsymbol{dt}} - \boldsymbol{c_p} \cdot \boldsymbol{P_m} = \mathbf{0} \tag{34}$$

$$\dot{\boldsymbol{m}} = \frac{\mathbf{d}\boldsymbol{W}}{\mathbf{d}\boldsymbol{t}} \tag{35}$$

With c_p representing the specific consumption coefficient, calculated as per equation (36)

$$\mathbf{c}_{\boldsymbol{P}} = \frac{\boldsymbol{FF} \cdot \boldsymbol{g}}{\boldsymbol{P_m}} \tag{36}$$

Following the methodology in [7] and [13]and considering that $(dx_e/dt) = V$, yields

$$\frac{\mathbf{d}\boldsymbol{x_e}}{\mathbf{d}\boldsymbol{W}} = \frac{-\boldsymbol{V}}{\mathbf{c}_{\boldsymbol{P}}\boldsymbol{P_m}} \tag{37}$$

DOI: 10.13009/EUCASS2022-7371

$$\frac{\mathbf{d}t}{\mathbf{dW}} = \frac{-\mathbf{1}}{c_P P_m} \qquad (38)$$

Integrating (37) and (38) between initial and final weight yields respectively the range and endurance of the A/C. Equations (37) and (38) do need the dependency with the mass variation and for that it is necessary to define the selected operational law. It can be demonstrated [7] that the maximum range is obtained when the A/C flies with α=const. at the given base speed. The base speed is the speed in which thrust is equal to minimum drag ($T = D_{min}$) with a load factor n=1. This speed corresponds to the speed for maximum efficiency (E_{max}) or optimal lift coefficient (C_{Lopt}) so the flight is with α= const. = $\alpha_{CL,opt}$. It is also found the same conclusion in reference [13]. This yields to the Breguet formulation:

$$x_e = \frac{\eta_P E_m}{c_P} \cdot Ln\left(\frac{W_i}{W_f}\right) \qquad (39)$$

For simplicity, for preliminary calculations, W_i is selected as TOW and W_f as landing weight (LW), assumed also for preliminary calculations as:

$$\mathbf{LW = TOW - FW} \qquad (40)$$

This allows that PL vs R diagram for the modified platform could be built considering that in Figure 1(b):

- Point A corresponds to limitations of MTOW and MPL.
  - Iteration variable: cruise time. Stop criteria $MTOW_1 = MTOW_2$.
- Point B corresponds to limitations of MTOW and MFW.
  - No iteration needed. Cruise time is established by means MFW. Cruise power is established by means $MTOW_1 = MTOW_2$.
  - Also, MFW_2 is reached so PL_2 will change.
- Point C corresponds to PL =0 and MFW limitation.
  - Iteration variable: cruise time. Stop criteria: MFW_2 established by the sizing of the fuel tanks.

The summary of this methodology is shown from Figure 3 to Figure 5. The calculation process is different depending on the point of the curve PLvs R to be calculated but mainly in point A and C is an iterative process with the cruise time as main variable and with a stop criteria based on a mass parameter of the A/C. Point B is calculated directly without iteration. A brief and general explanation of the iteration proces could be:

1. Starting point: estimating PL, selecting the mass criteria to stop then iteration process and taking A/C_1 data
2. Calculation of the Cruise Power of the original Platform and motor power needed.
3. Calculation of the Fuel Cell installation power.
4. Weight calculation for Power plant. Including power distribution unit and electrical motor.
5. Hydrogen fuel flow calculation.
6. Setting the variable: cruise time.
7. Calculation of the FW (hydrogen)
8. Calculation of the Cruise Energy
9. Calculation of the weight of the Hydrogen storage device.
10. Calculation of the new OEW_2
11. Calculating TOW_2.
12. Delta function: function to compare the mass parameter of the A/C with the stop criteria.
13. Checking stop criteria
14. Stop criteria satisfied: in point A calculus of LW2. In point C, checking $TOW_2 = TOW_1$ estimated at the beginning.
15. Stop criteria not satisfied. Variation in cruise time
16. For point A, checking the secondary condition (cruise time >0). For point C outcome from the process calculating LW.
17. Feedback loop: variation of key parameter and go to step 1.
18. Solution found: PL_2 and R_2.

DOI: 10.13009/EUCASS2022-7371

As it was mentioned before, it is needed to change the stop criteria depending on the point to be calculated and then the weight limit applicable. It is also highlighted that in the methodology, it is supposed a modular installation in fuel cells stacks and hydrogen containers, such that a variable number of stacks and hydrogen containers weight are selected according to the required selected flight conditions. Exception is found in the calculation of the point C with maximum fuel weight, in which it is needed to assume from the beginning a size of the hydrogen fuel system (storage and hydrogen fuel weight). In this way, decisions have to be taken to estimate the maximum Fuel weight and Hydrogen Storage Device weight: for instance using a storage pressure (300 bar, gas storage / 700 bar, gas storage/ liquid storage) or the location in the A/C: wings, cargo, both. In the end, Hydrogen storage device weight could be calculated as a fix value regarding the volume available in the platform or as part of the iteration process considering in both calculus the same value of energy / kg stored. Figures from Figure 3 to Figure 5 are showing a summary of the calculation process of the methodology.

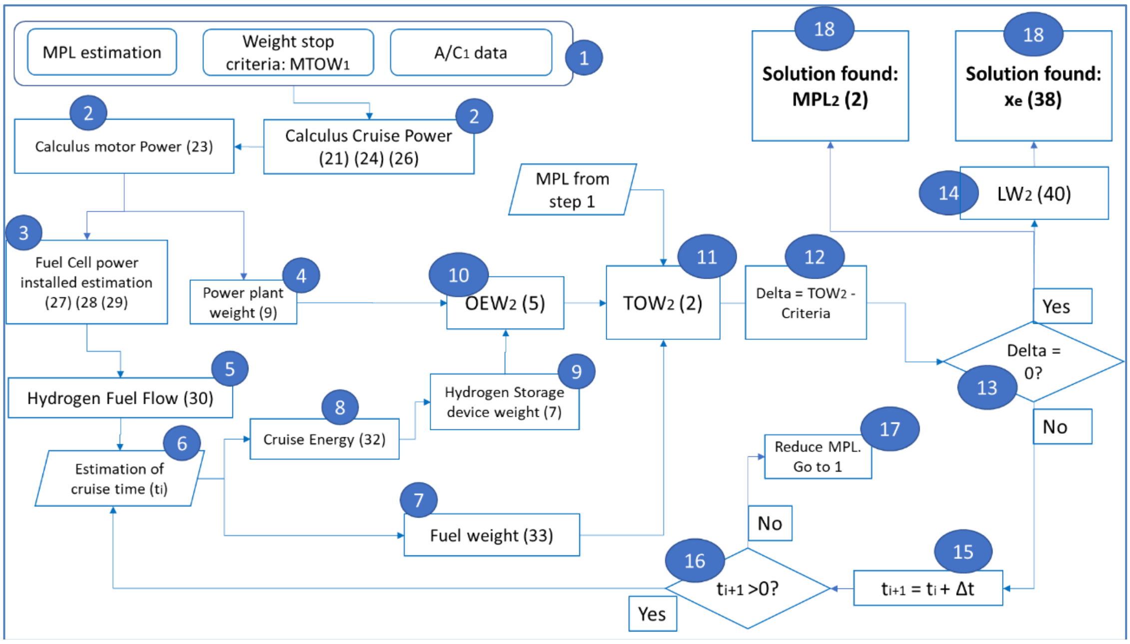


Figure 3. Summary of the methodology process for point A.

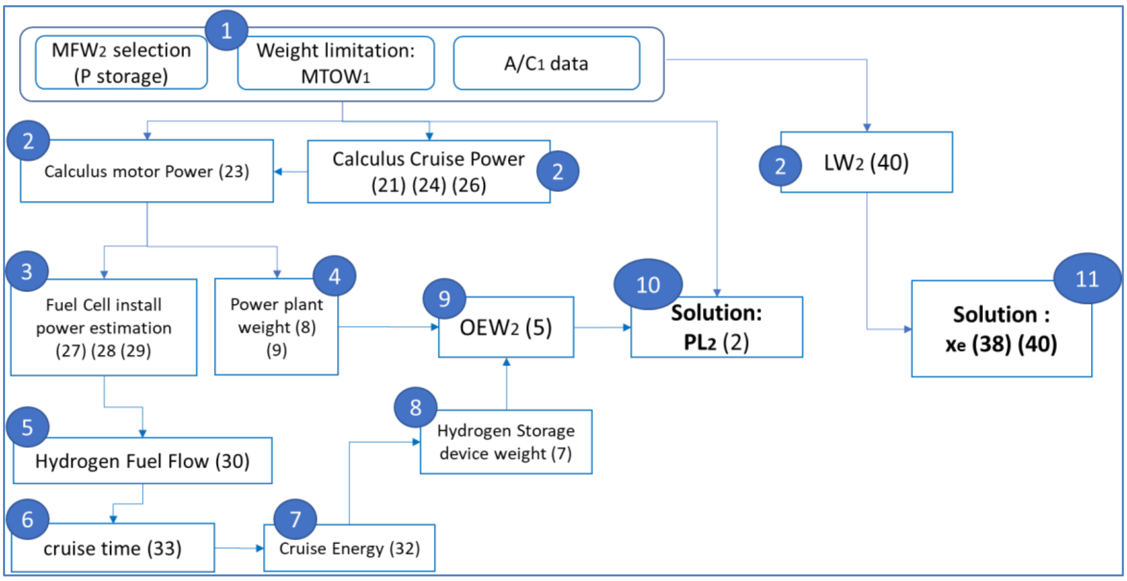


Figure 4. *Summary of the methodology process for point B.*

DOI: 10.13009/EUCASS2022-7371

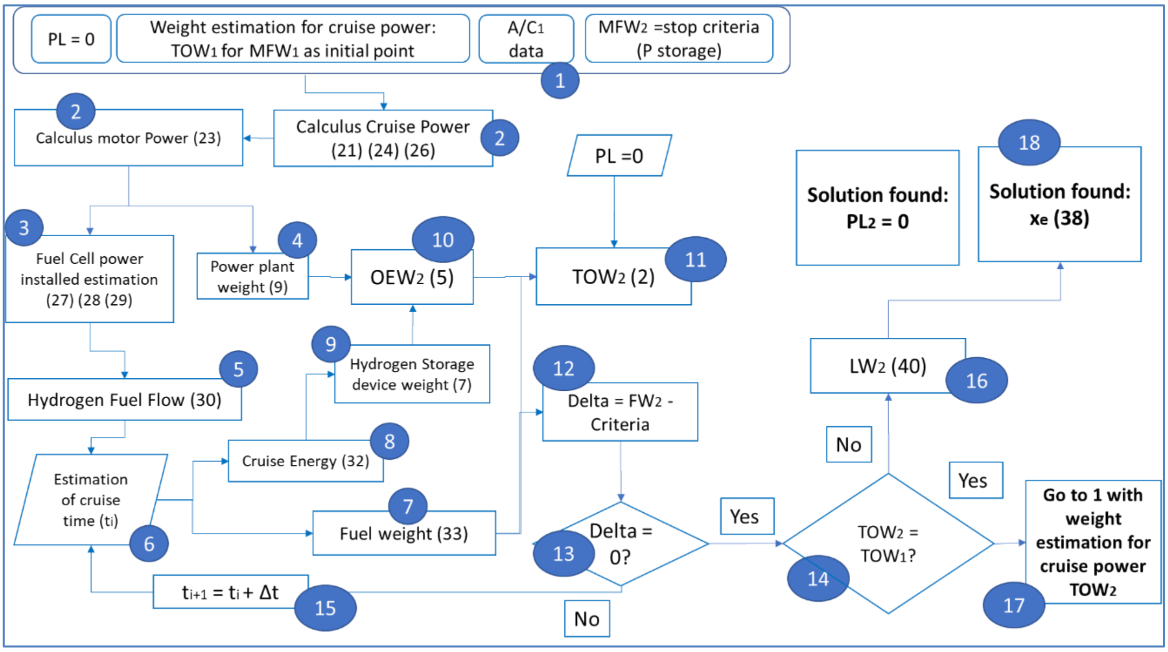


Figure 5. *Summary of the methodology process for point C.*

This methodology provides a valid solution for a modified platform with a configuration of the new power plant based on Fuel cells that is flyable (that could be modular and variable depending on the point to be calculated) and the associated maximum range. The direct comparison of the PL vs R diagram in the original platform and the modified platform will give the impact in the A/C utilization because of the introduction the new technology.

3.Study Case

This chapter applies the method to a specific aircraft case as proof of concept. In the following chapters, a refined and optimized version of the method is presented implemented in Matlab (R) [12] so that extended sensitivity performance studies can be conducted.

The methodology is applied to a similar A/C to an existing one in the cluster oflight-medium size medium range transport aircraft. Using preliminary design techniques and taking public data from existing A/Cs of the same category (references from [14] to [19][18]), it is considered for the original platform, data shown in Table 1. It is important to remark the assumptions for hydrogen storage: in the case of MFW limitation, hydrogen is stored in containers inside the original wing fuel tanks with a fill factor of the original fuel tanks volume of 90%, and the hydrogen containers storage pressure is taken 300 bar.

Table 1. Estimated data for the original platform (1)

MTOW	**ZFW**	**OEW**	**MPL**	**MFW**	**dry Weng**	**P MTO**	**P TO**	**Cp eng**	**N engines**
kg	**kg**	**kg**	**kg**	**kg**	**kg**	**kW**	**kW**	**m^{-1}**	
21000	18500	11450	7050	6468	484	2178	1973	8,92273exp-07	2

Additionally, it is considered for the original platform, cruise altitude (h_{cr}) 25000 ft, wing surface (S) 60 m^2, propulsion efficiency in the propeller (η_p) 0,9 and the aerodynamic efficiency in cruise (maximum efficiency for the case) could be estimated and for the case study it is selected E_{cr}=13,6 and the corresponding C_{Lopt} =1 .

For the calculations of the modified platform and the new systems to be included, it is considered data from Table 2.

DOI: 10.13009/EUCASS2022-7371

Table 2. Data for estimating the modified platform new power plant

k_{PDU}	k_{HSD}	$k_{e\text{-}motors}$	$\eta_{inst,eng}$	η_{p}	η_{FC}	η_{loss}	η_{BoP}	P stack	W Stack
kW/kg	kWh/kg	kW/kg	%				%	kW	kg
4	1.84	4.5	10	0.9	0.55	0.91	7	100	260

Following the methodology described, it is obtained the PL vs R diagram (Figure 6) which shows the impact of the A/C utilization with the new technology.

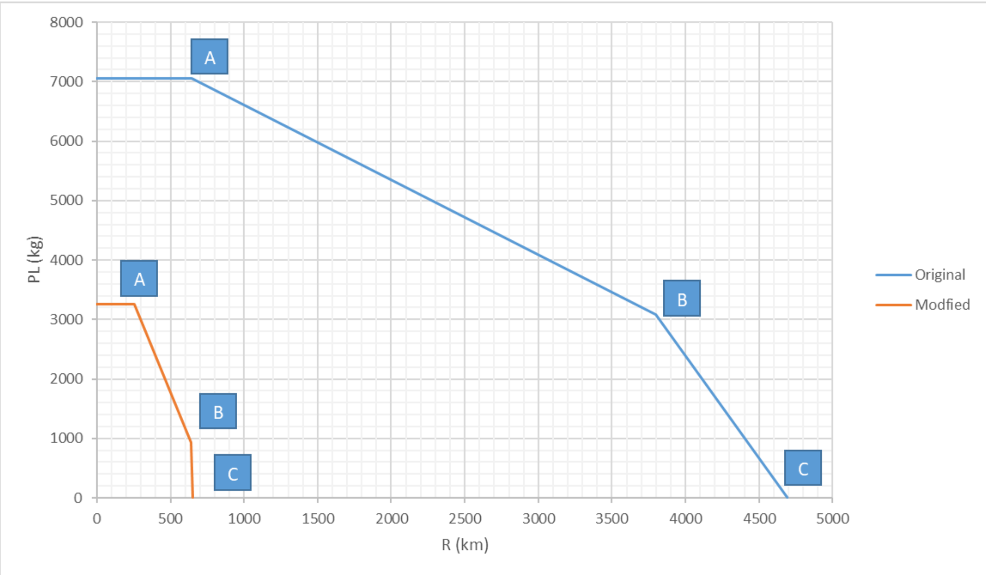


Figure 6. Impact of the new technology in A/C utilization

As it is shown in Figure 6 the impact in the A/C utilization is big. In the MPL zone of the diagram (from R=0 to point A) it is experienced a reduction in the MPL that the platform could carry for the mission. The reduction is big in terms of weight (close to 50%) and a slightly higher percentage it is found in distance (around 60%). In the MTOW limitation (from point A to B in the diagram), it is observed that the reduction in range (distance) is higher nearly 80% in relation to the original platform meanwhile the reduction in PL is lower than previous part of the curve (near 40%). This tendency is maintained in the MFW limitation (from points B to C) with higher gradient of decrease. Regarding the curve of the modified platform itself, it is curious to observe the high gradient of decrease in range in the MFW limitation. It means that reducing the PL in that zone does not involve a significant benefit in terms of range for the aircraft what did not happen in the original platform with the current state of the art in propulsion. This could be explained because of the low contribution of FW in the A/C weight (it is remined that the fuel is hydrogen). Obviously in this study it is shown a worse case scenario in which we only use Fuel Cell for propulsion (no emissions scenario). Points of improvement could be faced, and several intermediate curves of more solutions could be depicted in Figure 6 between these two curves. It would depend on the strategy of the hybridization, the state of the art of the technology for power distribution, electrical motors, fuel cell and hydrogen storage.

4. Computational implementation of the methodology

In the previous chapters it was developed a methodology to evaluate the impact of the replacement the current state of the art for propulsion by a new fully green proposal for propulsion based on fuel cells. In this chapter it is developed and optimized the methodology to find more accurate results and to be able to perform sensitivity studies which could help to establish technology targets and hybridization strategies. It is used MATLAB programming environment (R2021b) [12] for the computation of the methodology. The computational tool developed, is focus on point A and B of the PL vs R diagram. The presented tool looks for the zero of a function which compares certain mass of the A/C and a stop criteria (depending on the PLvs. R point) with cruise time as iteration variable. The main function mentioned is shown in (41).

DOI: 10.13009/EUCASS2022-7371

$$\boldsymbol{y(t_{cruise}) = TOW - TOW_{criteria}} \quad (41)$$

The main equation (41) focus on the TOW characteristics since as it is shown in equations from (21) to (29) it will be maintained the same power and cruise speed for both platforms (original and modified) so the same cruise initial conditions are shared between them with the same aerodynamics. The target is to maintain the original platform weight (TOW_criteria) that is known for each studied platform. As a result of looking for zeros of the function in (41), many possible cruises for the modified platform could be extracted from the tool . A swap in the inlet parameters can be done to study the impact in those cruises.

All the previous hypothesis, methodology and configuration parameters have been divided in different program functions. Main function is used to extract data useful for further analysis.

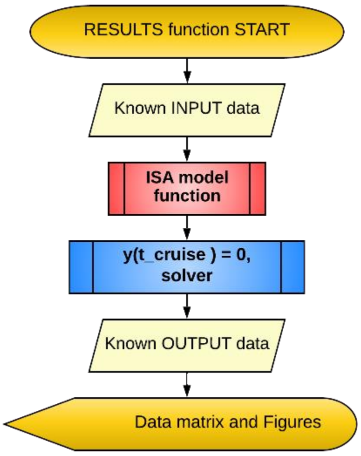


Figure 7. Blocks diagram for the main program

To obtain the density, it is supposed an ISA model with parameters values as specific gas constant 287 m^2/(s^2 k), ratio of air specific heats 1.4, variation of temperature with altitude coefficient -6.5e-3 K/m, Tropopause altitude 11000 m, temperature at sea level288.15 K, pressure at sea level 101325 Pa. As output data, it is calculated different configuration values for the derivative platform as:

- Maximum cruise time.
- Fuel cell, storage system, distribution system and maximum fuel weights.
- Number of fuel cell stacks.
- Turbo-propeller power.
- Payload available (weight and volume).
- Density of stowed hydrogen fuel.
- Aerodynamic forces and efficiency.

These data are processed to obtain useful postprocessed data for analysis as range (with constant speed), excess power, speed for maximum range/minimum excess power/zero payload. To obtain the roots of $y(t)$, it is used two different root-finding algorithms. Firstly, it is supposed that the studied function is continuous and that it has solutions within real numbers, namely there is a $t = t_{cruise}$, with t_{cruise} real and positive, such that $y(t_{cruise}) = 0$.

DOI: 10.13009/EUCASS2022-7371

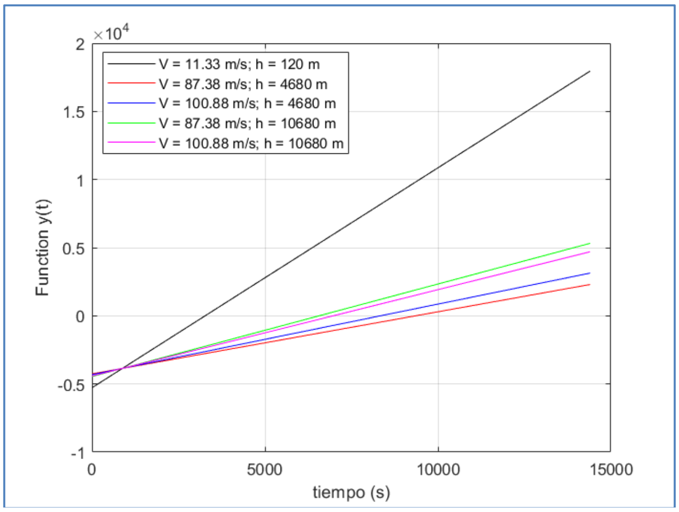


Figure 8. zero of the main function with bisection method for different cruises.

Code uses a bisection method at first to approximate the range of root values. As it can be seen in Figure 8, this method is enough to find zeros of the equation; nevertheless, Newton's method has been implemented to accelerate convergence and to prepare the code for future improvements. Hence, each method is used to find every root, they are strung together in the code using two independent functions as it can be seen in Figure 9.

Detailed block diagram

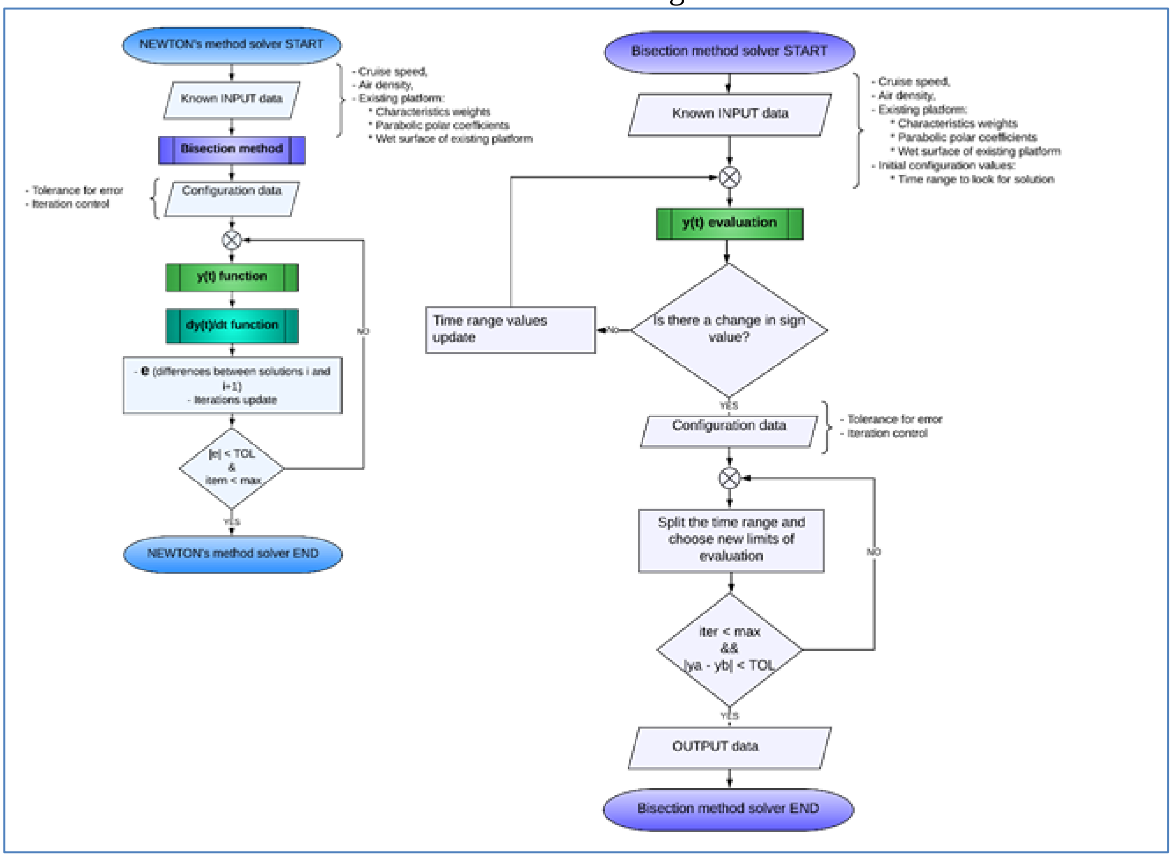


Figure 9. Detailed block diagram of the computation

A point of improvement included in the tool is the estimation and optimization of the location of the hydrogen storage devices to increase the performances in the modified platform. Maintaining the envelope of the original platform in the modified one involves that the volume is limited and all new systems need a specific volume to be integrated in the modified platform. Hence, some hypothesis about new system integration must be clarified. It is supposed that

DOI: 10.13009/EUCASS2022-7371

volume of usual fuel will be replaced completely by hydrogen fuel and, additionally, part of hydrogen fuel storage as well as the fuel cell stacks could be located on the cargo of the platform because of payload losses. A configuration parameter (PL volume for fuel storage ratio) is used to control that volume. To understand which is the impact of the payload change, it is estimated four different situations with a specific value of maximum payload: 0 kg, 1200 kg, 3000 kg, 5000 kg (see Figure 10 (a), (b), (c) and (d) respectively)

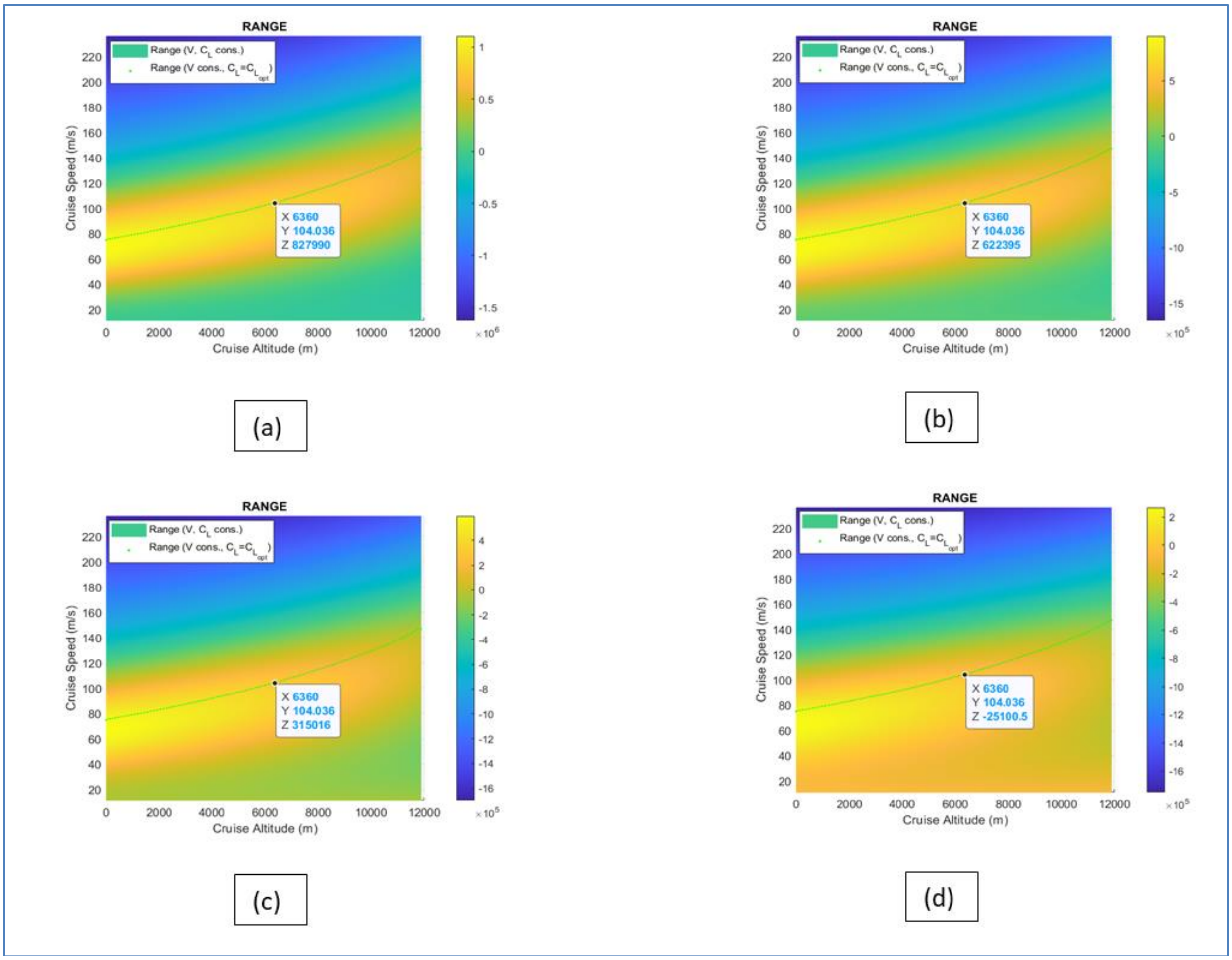


Figure 10. Possible cruises in the four cases of PL supposed.

As it is shown in Figure 10 varying the PL maintaining fixed the couple, V,h could give to us many possible cruises with different configurations of fuel cell stacks as outcome which could help to prepare the mission if it is thought a modular propulsion system.

For each subfigure in Figure 10, they are represented a large number of possible configurations depending on the flight conditions (V, h). Using as test range the values [0-235 m/s] for speed and [0-12000 m] for altitude, a weights distribution between different internal systems is estimated for each flight condition. This defines a configuration of the platform that can be characterized by its performances, its range. One point on the maximum efficiency line is quoted to illustrate the numerical value of the magnitude. Range is decreasing as it is supposed to be from Figure 10(a) to Figure 10(d). To highlight that in Figure 10(d) the range is negative, which means that the fly is not possible under those conditions**.** Hence, increasing payload weight decrease possible flying conditions for the new platform that can be quantified.

The tool is now under development in order to be able to do sensitivity studies considering among other variations, the location of the fuel storage devices considering all the hydrogen only in the wings or considering also part of the cargo for hydrogen storage, or the storage hydrogen pressure. It would lead to improvements in the modified A/C performances.

5. Conclusions and next steps.

DOI: 10.13009/EUCASS2022-7371

The hydrogen utilization for propulsion with a fuel cell, is possible regarding only the cruise phase for a low-medium range aircraft. However, the penalty in the utilization of the aircraft is high. It is needed to decide if one would pay that penalty in order to get a fully green aircraft transportation business. It is also concluded that the new power plant weight is more important than the fuel (hydrogen) weight regarding the range of the aircraft. Indeed, it is found that decreasing the PL in the scenario of MFW is not getting a significant advantage in range. Anyhow, one could take the advantage of the decreasing in PL to use the vacant in the cargo to put there more fuel containers and then increasing the fuel carried and so the range (to be evaluated with the tool developed). This methodology could be applied to whichever the aircraft was to evaluate if the utilization of the fuel cell is possible in that type of aircraft. Metrics then could be extracted to determine the maximum size of the aircraft for which this fuel cell technology is flyable.

It is only considered in this paper the cruise phase as the most important flight phase that contributes to the aircraft range. It should be taken as first shoot for the evaluation of the impact in aircraft utilization the introduction of this new technology for power plant. Nevertheless, the sizing phase for a power plant is the take-off, so these results will be worse when one took into account the take-off phase in the problem. In that case some considerations could mitigate the situation as the hybridization or the evolution of the state of the art in the technologies associated to the hydrogen storage and electrical generation and distribution. These considerations could lead that in the application of the methodology, one could be able to draw different PL vs R curves that would fall between the ones extracted from this paper in the case study chapter and with a link to the emissions targets it would be possible to select the proper strategy for the power plant to be installed. Smart hybridization strategy is key for put into the market this technology and getting the goals established for emissions reduction.

Applying this methodology to other segments of the market (long range, patrol, drones, etc) will provide a view of the more suitable platforms in which we could think to have a fully green exploitation of the business. On the other hand, it could show targets of emission reduction to the rest of the platforms pointing to the most suitable hybridization strategy.

Integration of the fuel cell performance with altitude in the model could provide more conclusions about the introduction of this technology and hybridization strategy. Finally, it is needed to see the modifications in the aircraft design needed (i.e. regarding aerodynamics or main aircraft elements) to optimize the mentioned platform with regards the new propulsion system.

Acknowledgments

This research has been supported by grant PID2019-104149RB-I00 funded by MCIN/AEI/ 10.13039/501100011033, and grant RTI2018-101519-A-I00 funded by MCIN/AEI/ 10.13039/501100011033 by "ERDF A way of making Europe"

References

[1] International Transport Forum. Decarbonising air transport: Acting now for the future. Policy Papers No. 94, OECD Publishing, Paris-0678, International Transport Forum, July 2021.
[2] World Economic Forum. "clean skies for tomorrow leaders: 10% sustainable aviation fuel by 2030". https://www.weforum.org/press/2021/09/clean-skies-for-tomorrow-leaders-commit-to-10-sustainable-aviation-fuel-by-2030/, 2021. Accessed: 2022-03-09.
[3] BBC Henderson, Caspar. "the hydrogen revolution in the skies", 2021.
[4] Robertson, David. Boeing tests first hydrogen powered plane. https://www.thetimes.co.uk/article/boeing-tests-first-hydrogen-powered-plane-bwlfbjf6wrh, April 2008. Accessed: 2022-03-09.
[5] The Engineer. Fuel cell aircraft hy4 makes maiden flight. https://www.theengineer.co.uk/fuel-cell-aircraft-hy4-makes-maiden-flight, September 2016. Accessed: 2022-03-09.
[6] Boeing PhantomWorks. "boeing unveils unmanned phantom eye demonstrator". https://boeing.mediaroom.com/2010-07-12-Boeing-Unveils-Unmanned-Phantom-Eye-Demonstrator, 2010. Accessed: 2022-03-09.
[7] Gómez Tierno, M.A., Pérez Cortés M., Puentes Márquez, C. 2014. Mecánica de Vuelo, 2ª Edición. Ed. Garceta
[8] Egbert Torenbeek. Synthesis of subsonic airplane design. 1976, Delf University Press.
[9] Andrew Mackay, Jason Hill, Kaushik Rajashekara. Modelling of Fuel Cell APU Utilisation for Aircraft Applications. 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit 25 - 28 July 2010.
[10] Johannes Brombach, Arno Lücken, Brice Nya, Martin Johannsen, Detlef Schulz. Comparison of Different Electrical HVDCArchitectures for Aircraft Application. 2012, IEEE
[11] https://www.aeh2.org/

DOI: 10.13009/EUCASS2022-7371

[12] MATLAB, R2021b, © 1984-2021 the Mathworks, Inc
[13] Anderson, J. Jr., Aircraft Performance and Design, McGraw-Hill 1999
[14] C295 brocuhre. https://web.archive.org/web/20081209080517/http:/eads.com/xml/content/OF00000000400006/4/64/677644.pdf. Accessed: 2022-06-01
[15] C295 platform public information. https://web.archive.org/web/20100405222641/http:/www.airbusmilitary.com/Tactical/TactC295.aspx. Accessed: 2022-06-01
[16] Restricted Type-certificate data sheet nº AESA 01/17 for CN-235/C295. https://www.seguridadaerea.gob.es/sites/default/files/aesa-01_17hd.pdf. Accessed: 2022-06-01
[17] ESA Type-certificate data sheet nº EASA.A.084 for ATR42 ATR72. https://www.easa.europa.eu/sites/default/files/dfu/TCDS%20ATR_EASA%20A%20084%20Iss%2009_1.Feb%2021%20corrected%20per%2010.Feb%20%5Bmarked%5D.pdf . Accessed: 2022-06-01
[18] ATR72 brochure. https://www.atr-aircraft.com/wp-content/uploads/2022/06/ATR_Fiche72-600-3.pdf. Accessed: 2022-06-01
[19] EASA Type-certificate data sheet nº IM.E.041 for engine PW100 engine series. https://www.easa.europa.eu/downloads/7725/en. Accessed: 2022-06-01
[20] Fuel Cells and Hydrogen 2 Joint Undertaking, Hydrogen-powered aviation : a fact-based study of hydrogen technology, economics, and climate impact by 2050, Publications Office, 2020, https://data.europa.eu/doi/10.2843/471510. Accessed: 2022-06-01