FutPrInt50 Academy

Regional Aircraft Hybridization

TECHNICAL REPORT

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Abstract

This technical report aim to show the potential benefits of a turbo propeller hybridization for a regional 50 seats aircraft by modifying it in a hybrid powertrain concept, analyzing it within the fly mission, flight phases and power involved in. The double turbo propeller Bombardier Dash8 Q400 is taken as a reference for this report. The main geometrical features of this civil aircraft shown in figure 2 are reported in figure 1 [1]:

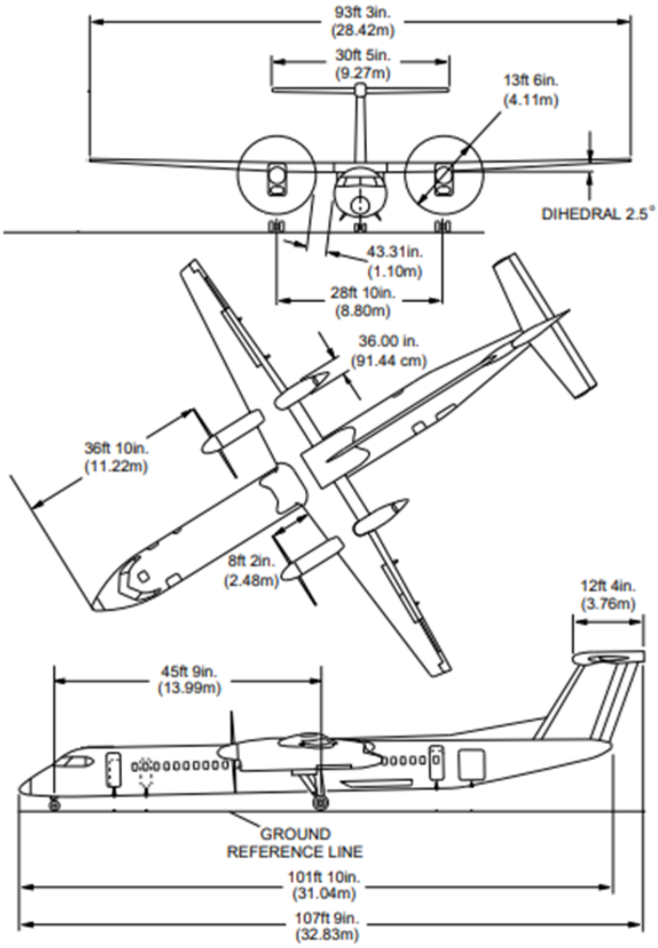


Figure 1: Main aircraft geometrical dimensions

Figure 2: Bombardier / De Havilland Dash8 Q400

The main feature that brought to the choice of this aircraft are the following:

- Good aerodynamics efficiency;
- Powertrain efficiency;
- 78 passengers' capacity;

Since, hybridization integrates an electric powertrain with a conventional combustion engine to provide the necessary power, the resulting system combines the low CO_2 emission benefits of the electric propulsive system with the extended range and high-power density of the turbogas propeller. The main drawback of this system is the increased mechanical and electrical complexity, the need to introduce a power management system and, above all, the overall weight increase. Accepting the reduction of the maximum passenger on board, little changes have to be made to integrate the hybrid propulsive system, thanks to the larger structure of the Q400.
In order to generate the adequate amount of electrical power, an exhaust heat gas recovery system and wing solar PV panels technology are integrated to make the project feasible. Results, assumptions and calculations are taken thorough literature, research papers and podcasts to supports decisions, however many of them are not investigated to in deep for the sake of simplicity that this report is intended to. All the sources used for this work are reported in the bibliography below at the end of the document

INTRODUCTION

In a world society connected and globalize, nowadays the main biggest challenge is to continue to evolve and maintain our technology level while respecting and live in harmony with our planet, which has unfortunately entered in a phase of great negative climate change. Finally, assuming that the biggest culprit for this change is human intervention, people began to raising for the climate change awareness. In a transportation point of view, our tech improvement in thermal conventional engine seems have reach an asymptote mainly caused by old by fuel technology and cost/feasibility.
Through the years aeronautical industry represents a high technology forge and research center for new materials, structures, aerodynamics and turbine powertrains, most of all due to the properties of the flight physics itself where it is possible only through an indispensable lightness, low drag and high propulsive power necessary to support its dynamics.
Flight sophistication may evolve through multiple disciplines fused and deriving from other sectors such as, one above all, the automotive: in fact, facing new technological challenges too, automotive industry is looking to other types of energy vectors such hydrogen, full and hybrid electrification.

THE ENERGY PROBLEM AND SELECTING THE PROPER TECHNOLOGY

As mention above, hydrogen and battery/full electrification are the actually most used alternative solutions for power generation in the transport sector beside of traditional fossil fuels.
Hydrogen is the lightest and most common element in nature with a higher specific heat value of 120-142 MJ/kg compared to 44-46 MJ/kg of petrol/gasoline and 43 MJ/kg of jet fuel (which makes it interesting from an energetic point of view). However, its production requires an

important consumption of energy to separate it from the compounds in which it occurs in nature. Different classifications are associated with the energy source used for its production (hydrogen color chart):

-Very High carbon emissions:

- **Black Hydrogen**: from coal (like grey hydrogen) with no CCS;
- **Brown Hydrogen**: from Lignite (like grey hydrogen) with no CCS.

-High carbon emissions;

- **Grey Hydrogen**: made from natural gas in a process called steam reforming (no CCS);

-From Medium to High carbon emissions;

- **Turquoise Hydrogen**: from pyrolysis, instead of CO2 as gas a solid carbon by-product is generated;

-From Zero to very low carbon emissions;

- **Green hydrogen**: produced through electrolysis by using renewable electricity;
- **Blue hydrogen**: like grey, brown, and black, but with CO_2 stored underground through 'carbon capture and storage' (CCS) technique;
- **Pink Hydrogen**: like green hydrogen (electrolysis) but solely using energy from nuclear power;
- **Yellow Hydrogen**: like green hydrogen (electrolysis) but solely using energy from solar power;

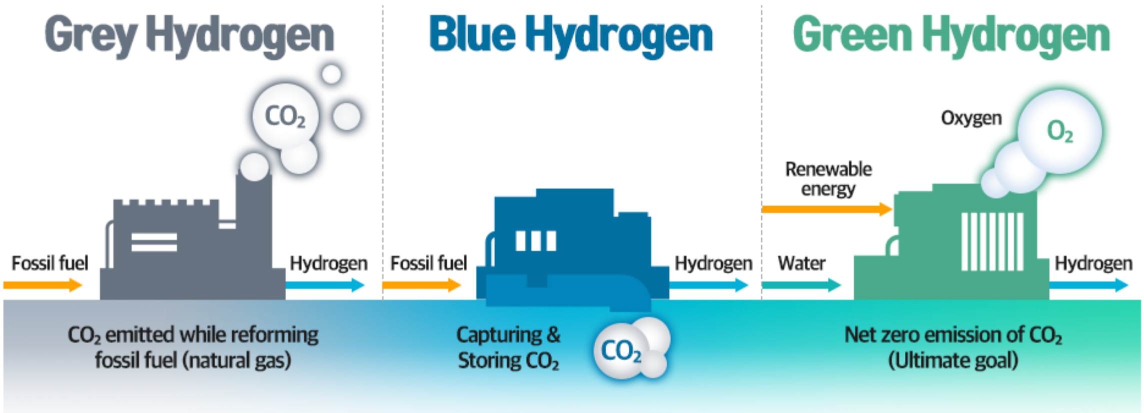


Figure 3: The three main technologies to produce hydrogen

Technologies that use coal and methane as starting compound to obtain hydrogen (currently 71% of total production starts from methane and 28% coal) without CCS involve high CO2 emissions and do not contribute to reducing the greenhouse effect. In order to reduce the environmental footprint, green hydrogen and its variants are the only ones considered in this report (hydrogen produced by splitting the water molecule with electricity supplied from renewable sources).

Another important aspect to take into account is the energy consumption and consequently CO2 emissions of the production chain, including compression, liquefaction, transport and its final storage in high resistance tanks. In addition, the transport phase (by road or rail) represents a very dangerous issue, compared to traditional fossil fuels due to the explosiveness

of hydrogen. If it can be avoided by imagining to transport it in pipes or to centralize its production on site in proximity to the use where production and consumption overlap, by not taking into consideration the cost of the resulting infrastructure, the problem is then only transferred to the final user machine (in this study the aircraft itself) which must necessarily have special high-light-resistance tanks.
Many other technological limitations such metallic hydrogen embrittlement, high combustion temperatures etc., represent others limitations to discard hydrogen as a de-carbonized fuel.
However, also the full-electric conversion is not a simple task due to the heavy weight of the electrical components that are necessary to obtain the same power produced by the two Pratt and Whitney PW150A engine installed on the Q400 (4'056 kW each). To generate and convert this power purely by electric propulsion, multiple electric motors are needed and to store this energy the necessary batteries would have a mass of 25'420kg (as can be seen in table 1 and 2) basing on a TLAR flight mission (Top Level Aircraft):

ENGINE DATA			
Pratt and Whitney PW150A			
Max Thermodynamic power [ESHP]	Max Mechanical Power [SHP]	Max Prop RPM [RPM]	Max Shaft power [kW]
6680	5071	1020	3781

Table 1: Engine main power parameters

Available Power	[SHP]	[kW]	X2 [kW]
100%	4056	3025	6049
112%	4580	3415	6830
125%	5071	3781	7562

Table 2: ICE Engine power calculations

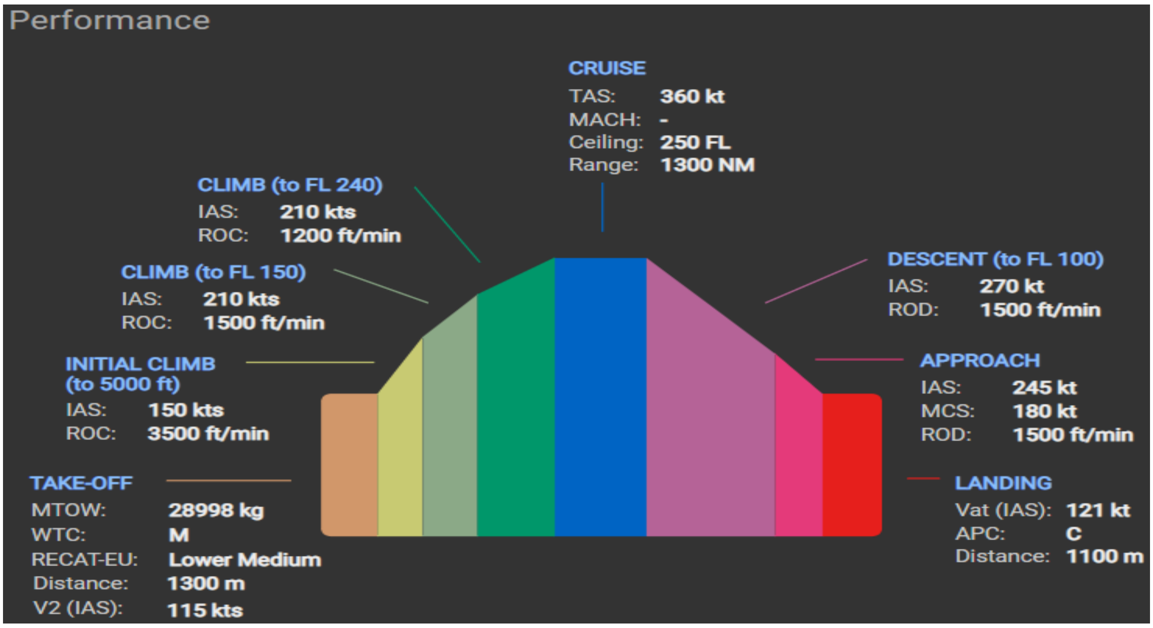


Figure 4: Usual flight envelope

The TLAR mission here considered is a flight from Malpensa Airport (LIMC) to Bari Airport (LIBD) which consist in a range of 450 nm (833 km) with an altitude range of 25'000 ft. The total fuel consumptions is estimated using the online tool of Fuel Planner website (www.fuelplanner.com) as shown below:

Fuel quantity for Bombardier Dash 8 Q400

	Fuel	Time
Fuel Usage	1006 kgs	01:27
Reserve Fuel	687 kgs	00:44
Fuel on Board	1693 kgs	01:49

Provided by Fuelplanner.com (http://fuelplanner.com/)

Figure 5: Standard fuel usage

The flight envelope was estimated considering the aircraft used power in the different flight phases for the total duration of the phase, as reported in the table 3:

Flight Phases	Setpoint Power	Power Mode	TOTAL Available Power	Instant Engine power	X2	Time	Time	Used Power	Area
[-]	[%]	[-]	[%]	[kW]	[kW]	[min]	[h]	[kW]	[kWh]
Start	0	0	0	0	0	0	0	0	0
Taxing / Push Back	5	NTOP	90	136,107	272,215	5,000	0,083	272,215	22,685
Take off	90	NTOP	90	2449,933	4899,866	9,000	0,150	4899,866	326,658
Initial Climb	40	MCL	90	1088,859	2177,718	12,000	0,200	2177,718	108,886
Climb FL170	38	MCL	90	1034,416	2068,832	15,000	0,250	2068,832	103,442
Climb FL240	70	MCL	90	1905,503	3811,007	23,000	0,383	3811,007	508,134
Cruise	50	MCR	69	1043,490	2086,980	62,000	1,033	2086,980	1356,537
Descent	20	MCR	70	423,445	846,890	78,000	1,300	846,890	225,837
Approach	40	NTOP	90	1088,859	2177,718	85,000	1,417	2177,718	254,067
Landing	80	NTOP	90	2177,718	4355,436	90,000	1,500	4355,436	362,953
TOTAL Calculated Capacity	-	-	-	-	-	-	-	-	3269,199
Reserve	-	-	-	-	-	40,000	0,667	2177,718	1451,812
Corrective Factor	-	-	-	-	-	1,250	-	-	1814,765
TOTAL Requested Capacity	-	-	-	-	-	-	-	-	5083,964

Table 3: Flight capacity calculations

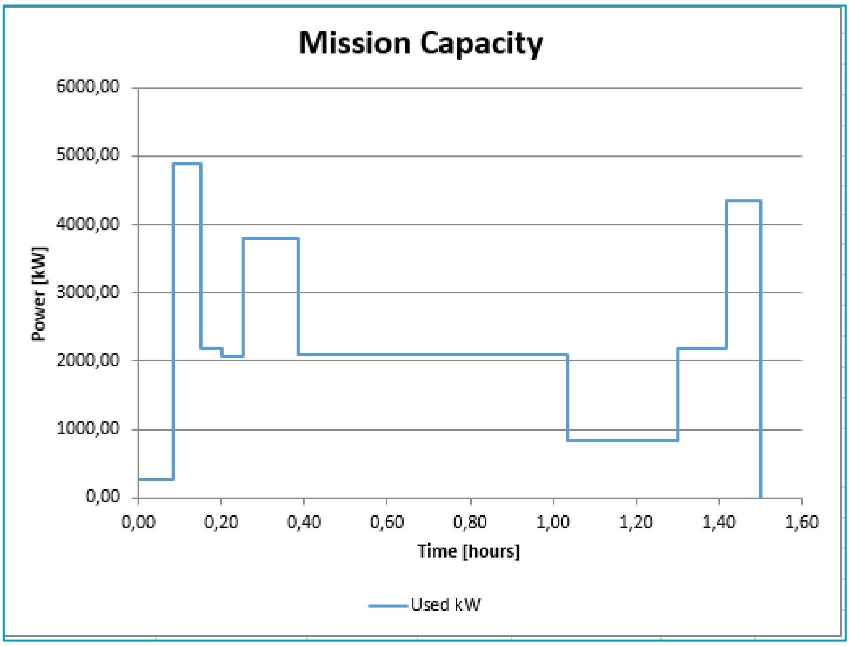


Figure 6: Capacity flight mission graph

Using the 3'269kWh consumed power and divided it for Jet A1 energy density of 11'990 Wh/kg and multiplying it for 0,25 system efficiency factor, 1'090 kg of fuel are necessary to complete the mission with standard engine. This value is consistent with the aircraft real consumption calculated with the previous online software, confirming the previous results obtained for the full-electric conversion.

FUEL CONSUMPTION VERIFICATION				
Reserve	1515	lbs	687	kg
Jet A1 energy density	11,99	kWh/kg		
Fuel energy Capacity	8237,13	kWh		
TOT mission energy capacity	3269,20	kWh		
Supposed ICE system efficiency	0,25	-		
Supposed regular fuel consumed	1090,64	kg		

Even using smaller batteries in hybrid configuration, the weight of the batteries and the quite small recharge cycles will continue to play an important role: actually, the state of the art power densities for modern batteries is around 200Wh/kg. Considering the power density of traditional jet fuel, in order to maintain the same propulsion power, big and heavy batteries have to be chosen, preventing a full conversion of the aircraft. [2].
Another possible option to reduce CO_2 emission, is to substitute the traditional jet fuel with an alternative E-fuel to power the system. The E-fuel is produced through the electricity generated from renewable energy sources ("Green" Hydrogen) using water and CO_2 present in the air: in simple terms, CO_2 is retrieved from the air using direct air capture (DAC) technique and combine it with water to produce syngas through high-temperature co-electrolysis (or combination of low-temperature alkaline electrolysis with Reverse-Water-Gas-Shift reactor, like Synhelion manufacturing process).
Once syngas is obtained (mixture of H_2 and CO) is converted into hydrocarbons in a Fischer-Tropsch reactor producing synthetic crude oil that will be refined into synthetic kerosene.
Moreover, E-fuels are called with the name of "drop-in fuels" because they can be easily mixed with traditional fuels in any percentage and they are compatible with modern internal combustion engines, providing the necessary power (usually E-jet fuels have heat value of 44.1MJ/kg).
Existing fuel transport, distribution and refueling infrastructures can be easily switched without any special adaptations, allowing to reduce emissions over the entire life cycle (depending on the raw material, production method and distribution chain used).

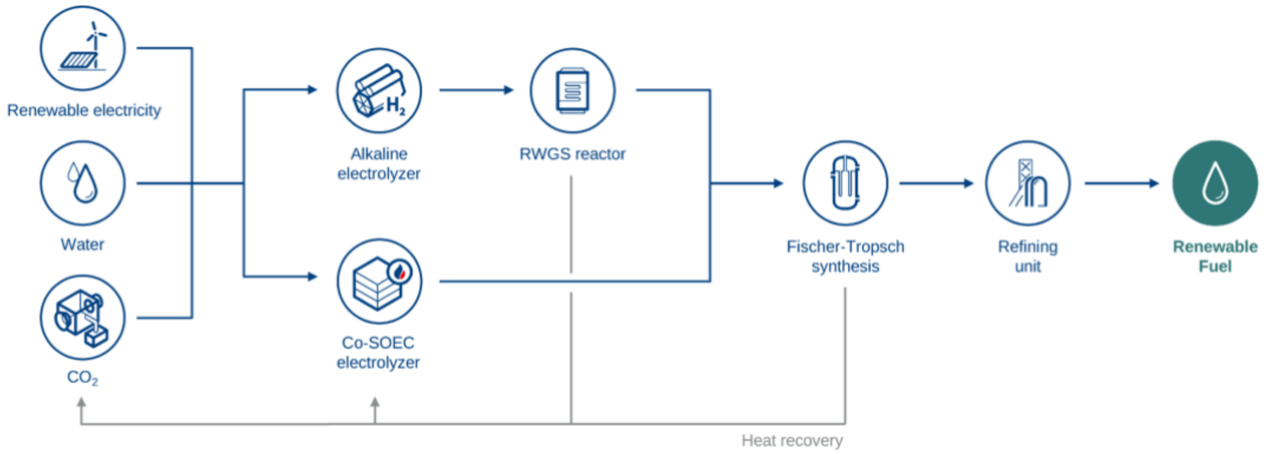


Figure 7: Usual production flow of E-fuels

To storage the energy, commonly batteries are used, but the process of charging and discharging can only last usually around 3'000 cycles. Another important point that must be taken into account, is the cooling of the thousands of cells composing the battery which have to dissipate the generated heat of the internal reaction.
Moreover, recycling and production are also very important aspects: while industry standardization is highly required for recycling, the cells package from the form factor is why many 12-volt car batteries have a similar form factor.
For all these characteristics, even if they are different from batteries for operation and package, a super capacitors solution is preferred.
Super capacitors are governed by the same fundamentals as the conventional capacitors, but utilizing different construction technology to achieve greater capacitances and energy densities.
Compared to batteries, they have counterparts such linear discharge voltage and low power density (20Wh/kg), but with a much greater life (1 million cycles or 30'000 hours). High load currents and great temperature performance are another aspect which better comply with flying integrated hybrid system. [3]. Unfortunately, with today's state of the art supercapacitors cannot be adopted for this report, so a usual battery pack arrangement is adopted. To obtain less fuel consumption, two different solutions are integrated in this project:

-Installing on the top of the wings solar PV panels to capture solar irradiance and transform it into electrical energy by using new technology high efficiency solar cells that only weight 0,58kg per square meter;

-Implementing an Organic Rankine cycle (O.R.C.) to recover part of the thermal energy dissipated from the two main aircraft engines at the exhaust.

HYBRID ARCHITECTURE AND LOGIC

Today's aircraft powertrains are powered by internal combustion engines (I.C.E.), while in the automotive industry, during the last twenty years I.C.E/hybrid electric powertrain became a valid option to reduce CO2 emissions and consumptions.

Hybrid technology could be also an opportunity for the aviation industry to reduce the environment footprint and, in the meantime, provide the same huge power needed for flying. [4]

At actual state of art, there are three main hybrid integration architectures: serial, parallel, and "mixed". Generally speaking, series configurations are simpler but with low power/weight ratio, while mixed and parallel configuration on the other hand present more complexity, better power/weight ratio and greater efficiency at constant speed.

As best configuration, a "mixed" configuration is chosen in this project to combines the two previous architectures and achieve a global better efficiency.

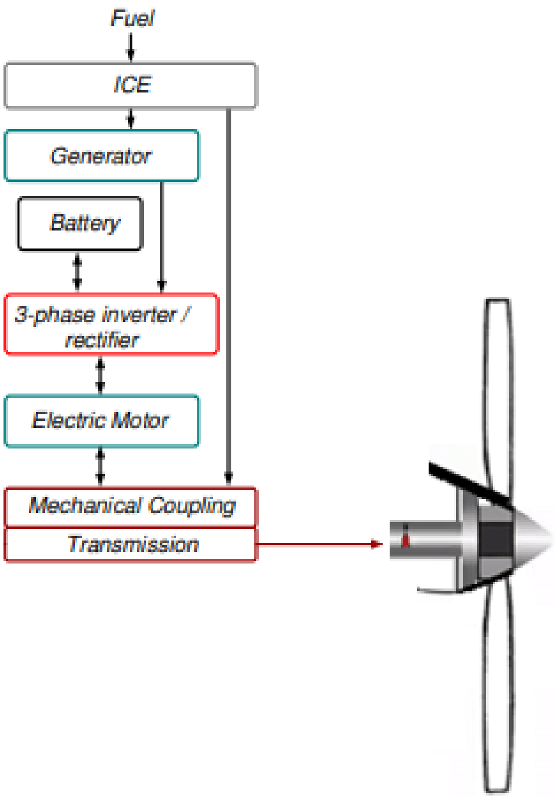
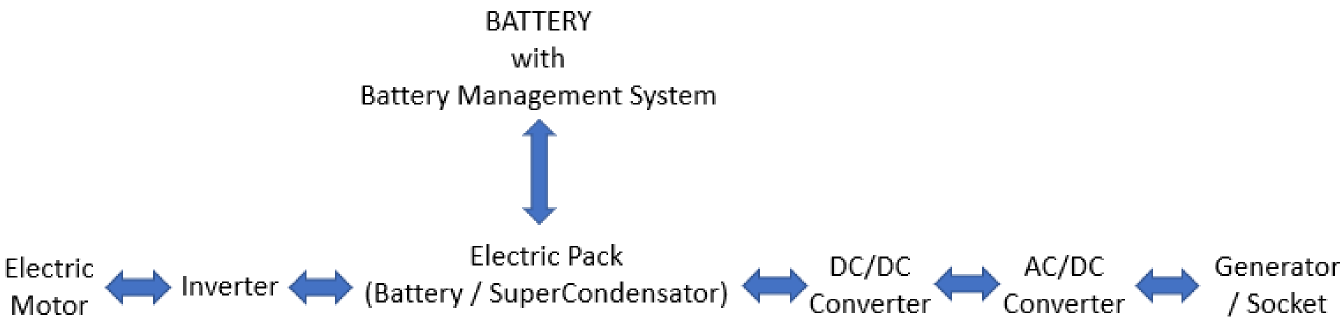


Figure 8: Proposed Hybrid Architecture

Mechanical coupling can be performed by a planetary gear in order to combine the power generate by the I.C.E. and the electric motors and let them operate in a specified working range improving their efficiency. A three-phase inverter must be installed to drive the electric motor based on power needs.

This configuration design is also better than others architectures in aeronautical turbo-propeller applications where the ICE operates at a datum design point for the majority of the time: turbine is set to a quasi-steady desired power output and control the thrust propulsion by maneuvering the pitch of the blades of the main propellers (figure 9).

In addition to this, a full functional system would comprehend all the components below:



The design of the system requires very complex calculations and design iterations, so in order to keep this report as easy as possible, the design will be limited only to the inverter, that is the component with the highest weight (which is the main indicator beside power for the feasibility of the project).
As shown later, the required capacity power for the hybrid architecture is 7'101,18kW and, assuming an efficiency of the inverter of 80%, the related capacity is 10kVA.
A commercial inverter of this size will weight around 170kg.
As for battery/super capacitors problem encountered in the previous paragraph, inverters and power technologies have a large gap to close to become a valuable architecture for aviation.
To answer to this problem, Gallium nitride (GaN) could increase electronic performance by potentially reduce energy losses with a lower volume/weight cost.
European Union is currently funding GaN4AP project plans to make GaN based electronics the primary technology in devices for all power conversion systems [5].

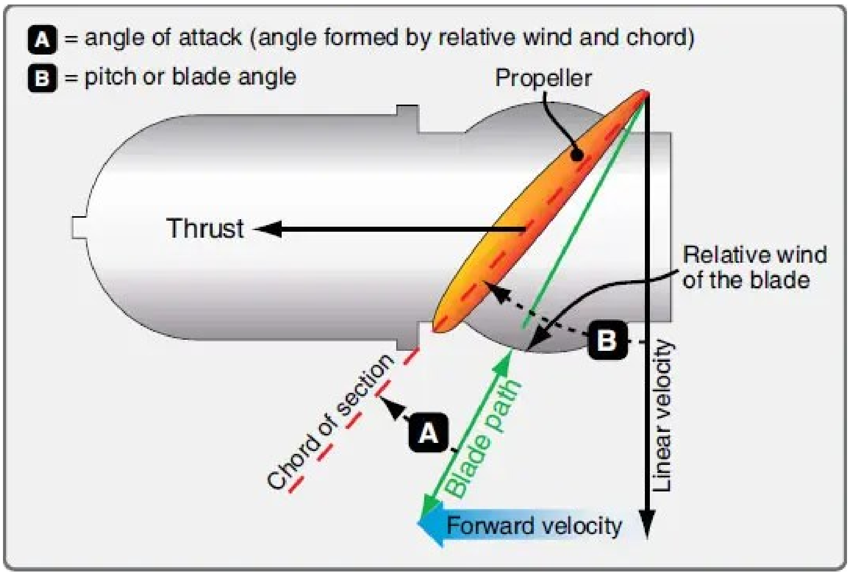


Figure 9: Blade pitch control, Google Scholar

In the proposed design, the electric motors give auxiliary power to ICE during high power consumption flight phases (takeoff, climb and approach). During taxing phases, the necessary power could be given totally by the electrical motors with really low emission and noise.
In this hybrid configuration, the modified Q400 operative modes are summarized in the following table and explained below:

TAXING	FULL ELECTRIC
TAKEOFF	HYBRID
CLIMB	HYBRID
CRUISE	ICE
DESCENT	HYBRID
APPROACH	HYBRID

-Taxing strategy: 100% electric propulsion with strong reduction of noise and emissions;

-Take-off strategy: hybrid power generation with around 10% electric and 90% I.C.E. (this percentages have been chosen to use a reduced battery capacity in order to contain the total weight of the system);

-Climb strategy: hybrid power generation with around 20% electric and 80% I.C.E.

-Cruise strategy: 100% I.C.E. During this phase the ORC generated power is completely used to charge the battery.

-Descent/Approach and Landing strategy: hybrid power generation with around 20% electric and 80% I.C.E. During this phase, the electric motors are maintained operative in case of emergency situation where the power from I.C.E. may not be available.

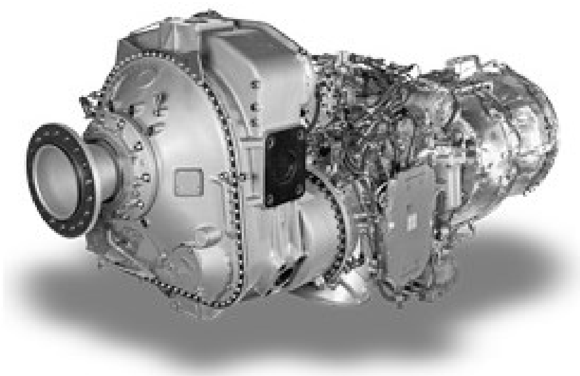
Here below is represent a schematic grade of hybridization and power involved in each condition:

Standard		Hybrid			
ICE	ICE	ICE	ICE	EV	EV
Used kW	Area kWh	Used kW	Area kWh	Used kW	Area kWh
272,21	22,68	0,00	0,00	272,21	22,68
4899,87	326,66	4409,88	293,99	489,99	32,67
2177,72	108,89	1742,17	87,11	435,54	21,78
2068,83	103,44	1655,07	82,75	413,77	20,69
3811,01	508,13	3048,81	406,51	762,20	101,63
2086,98	1356,54	2086,98	1356,54	0,00	0,00
846,89	225,84	592,82	158,09	254,07	67,75
2177,72	254,07	1742,17	203,25	435,54	50,81
4355,44	362,95	3919,89	326,66	435,54	36,30
	TOTALS	19197,80	2914,90	3498,87	354,30

Table 4: Hybridization grade calculations for each flight phase

MODIFIED GAS TURBINE SYSTEM AND ORGANIC RANKINE CYCLE

The standard Pratt & Whitney PW150A engines mounted on the Q400, have two double-stage centrifugal compressors which are powered by two independent axial turbines. The engine also has a reverse flow annular combustor and an offset reduction gearbox. All engine fuel flow is controlled by FADEC - Full Authority Digital Electronic Control with a nominal fuel consumption of 0,263 kg/kWh. [5]



In order to hybridize this engine, an exhaust gasses heat recovery system has been used with an Organic Rankine Cycle system: that system can be integrate in the main powertrain, for example at the end of the nacelles. The electrical power generated by the ORC is used to charge a battery system that gives energy to electrical motors mounted directly on the primary I.C.E. output shaft, as represented in the figure 10:

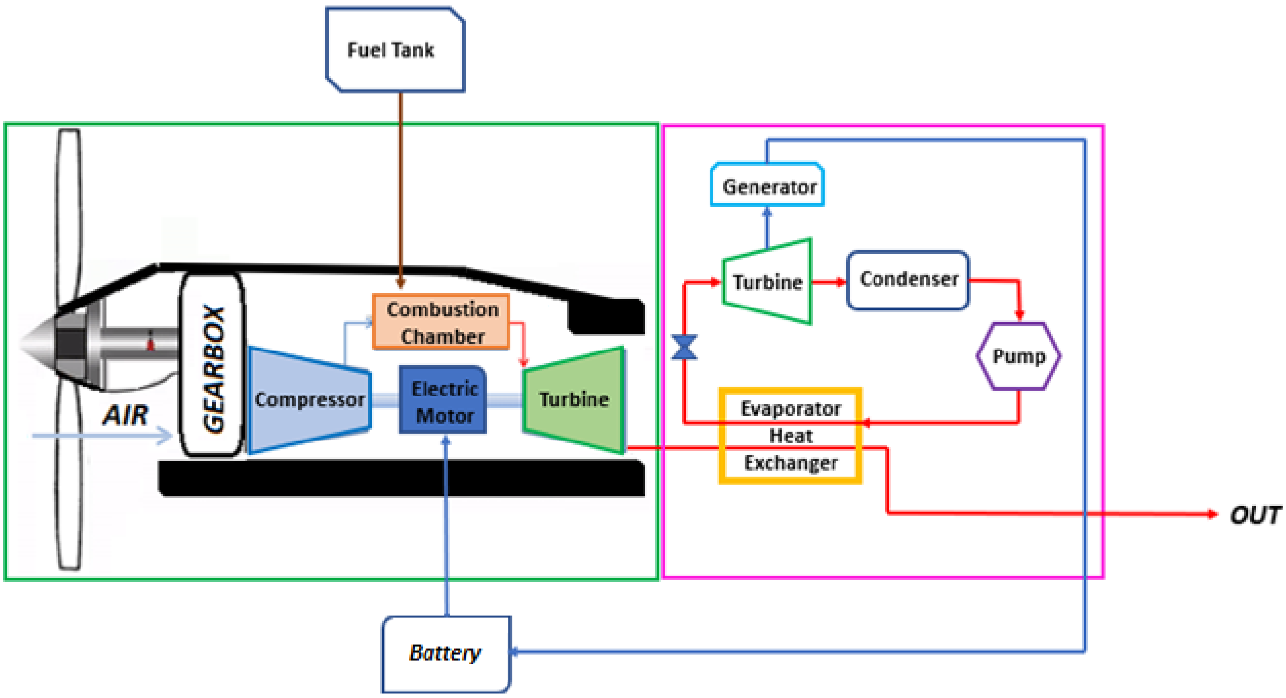


Figure 10: Proposed hybrid scheme

To simplify the installation and functional scheme, the electrical motors can substitute the native starter generator of the main powertrain. The ORC working fluid is an organic fluid with a high molecular mass and a low temperature boiling point, that allows to recover the heat exhaust gasses from the I.C.E. turbines. The heated organic gas is than expanded in an additional turbine to obtain mechanical power that is finally converted in electrical energy by a generator and stored inside the battery system.

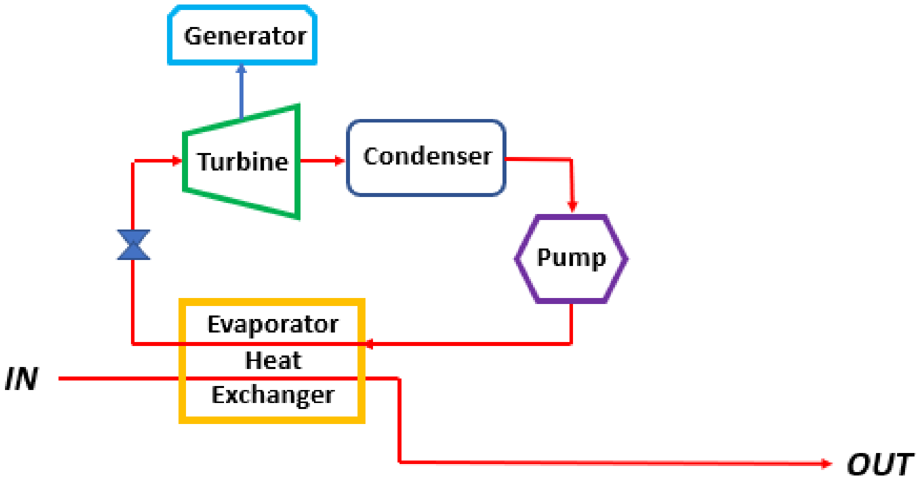


Figure 11: O.R.C. system in detail

The main components of the system are:

-Evaporator (or heat exchanger): to recover the heat from turbine exhaust gases through the evaporation and over-heating of the ORC working fluid. A thermal efficiency of 85% is assumed for the heat recovery (Qrecover = 0,85 x Qavailable from exhaust gases). The presence of the HRS will increase the outlet pressure of the gases from the I.C.E. turbines, reducing the efficiency of the engines and the available power. For sake of simplicity this aspect will not be consider in the present report but must be keep in mind in case of further development of the design.

-Turbine and generator: generate the additional mechanical power through the expansion of the working fluid. Is coupled with a generator to produce electrical power. The mechanical efficiency of the turbine is assumed to be 90%. The electrical efficiency conversion of the generator is assumed to be 98%;

-Condenser: the working fluid is condensed using external air. Since cooling temperature depends on the flight altitude, the assumed condensation temperatures are:

FLIGHT PHASE	EXTERNAL AIR TEMPERATURE
TAKEOFF/APPROACH	25 °C
CLIMB/DESCENT	5 °C
CRUISE	-27 °C

A thermal efficiency of the condenser of 85% has been assumed (like for the evaporator). A possible installation on the aircraft nacelle is represented by the configuration in figure 12 [6]:

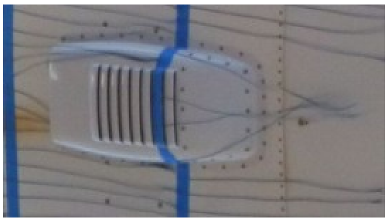


Figure 12: Heat exchanger with inlet air duct configuration (Google scholar)

It is also interesting to note that also the I.C.E. available power is affected by the altitude and air density reduction, while the output power of the electrical motor is less variable with temperature and can be assume to remain constant [25];

-**Pump:** increases the pressure of the condensed working fluid

The working fluid has particular thermodynamics propriety that allows it to reach phase changes between liquid and gas state at certain temperatures. To not interfere with the system, the fluid must have no effect on other materials (for example must not be corrosive), easily detectable in case of leaks, must be miscible with oil (used to lubricate the compressor), must not react with air humidity to operate correctly (water formation can froze at low temperatures restricting the flow passing surfaces or produce corrosive acid), and has to be a stable compound. [7] [8]
The selected working fluid for this study is the R1233zd that is suitable for O.R.C. application on I.C.E. with a medium exhaust gas temperature of 700°C.

The ideal O.R.C. is composed by these transformations:

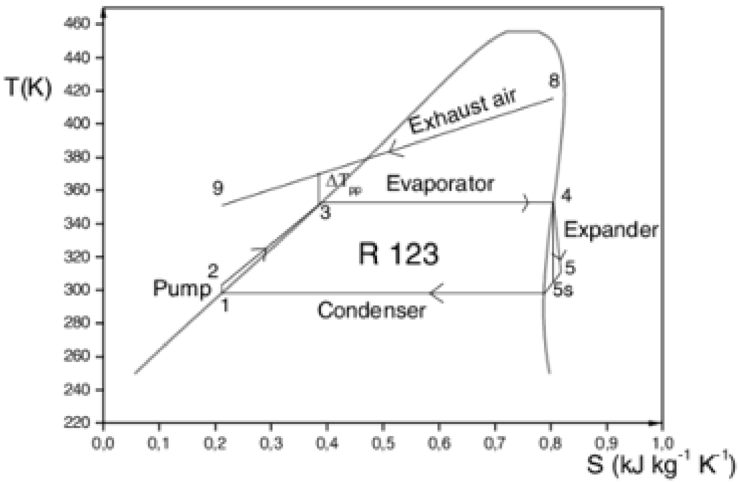


Figure 13: O.R.C. ideal with an example of R123 T-s diagram

-Isobaric evaporation (3 – 4) fluid is vaporized at constant pressure through the heat recovery (no pressure drop is considered inside the heat exchanger);

-Isentropic expansion (4 – 5s) fluid (gas phase) pass through the turbine (thermal to mechanical energy conversion);

-Isobaric condensation (5s – 1) fluid (gas phase) condensed until saturated liquid state;

-Isentropic compression (1 – 2) pressure of the fluid raised up until a value suitable for turbine operation. [9]

- Isobaric heating of liquid fluid (2 – 3): fluid temperature is increased to the boiling point at the cycle working pressure through heat recovery from exhaust gases

Using the specifications of PW150 engines such as gas mass flow and turbine outlet temperature, O.R.C. system performance can be evaluated through Matlab Simulink model base (figure 15).

CALCULATIONS AND ANALYSIS

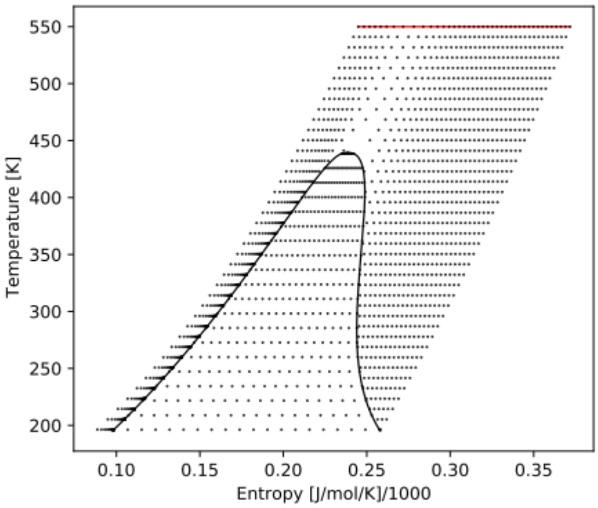


Figure 14: 1233zd R gas T-s diagram

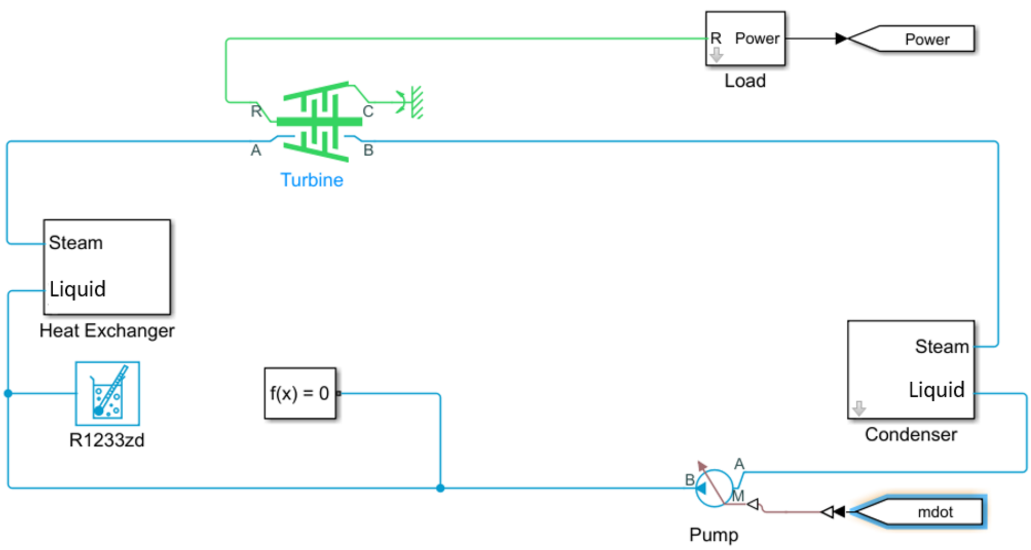


Figure 15: Model

Running the model by taking into account all the thermodynamic equations involved in to calculate the main values of the O.R.C. system a result of 346,78kW of electric power is recovered (for both I.C.E. engines). This result is affected by the many approximations that it was necessary to introduce due to the need for simplification.
Below, an estimation of the total weight of the additional installed components is reported:

-Heat exchanger and condenser: 40kg each for a total of 80kg for one engine and so 160kg for both Q400 turbines;

-Generator and Turbine: 25kg each for a total of 50kg for one engine and be 100kg for both Q400 turbines;

-Pump: 10kg for one engine and 20kg in total;

-Working fluid: 20kg for all the systems.

Considering all the additional components, the resulting total weight increment is 300kg.
In addition to that, structural mass of the aircraft has to increase to take into account the changes suitable for the new system mounted into the nacelles and their ancillaries: for this consideration, an additional weight increase of 20kg is considered, neglecting the impact on aerodynamics of the structural modification.

Despite that the electric pack, electrical motors, solar panels and ancillaries for the electrical hybrid architecture (such as charge controllers, inverters, ecc) weights have not be considered, this final value can already be a promising result, comparing it to the experimental system of EGTS (Electric Green Taxing System) already developed for aircrafts' electrical traction. This system, which allows aircraft to taxi and pushback without requiring the main engines, weights at least 300kg and can accelerate the aircraft to 37 km/h.

ELECTRIC DRIVE, ELECTRIC PACK SYSTEM CHARATERISTICS AND LOGIC

A Solar PV panels system mounted on the top of the wings, in order to have the last part of recovered energy is proposed. The Sun irradiates the Earth with approximate 84 terawatts of power as sunlight radiation, which makes solar energy an inexhaustible and clean source of energy. Solar panels absorb sunlight radiation and convert it into electricity by elemental units through the photovoltaic effect. More angled the sunlight arrives, more air mass through the atmosphere they encounter attenuates their radiation and the consequent energy recovered. The Solar radiation spectrum is reported below:

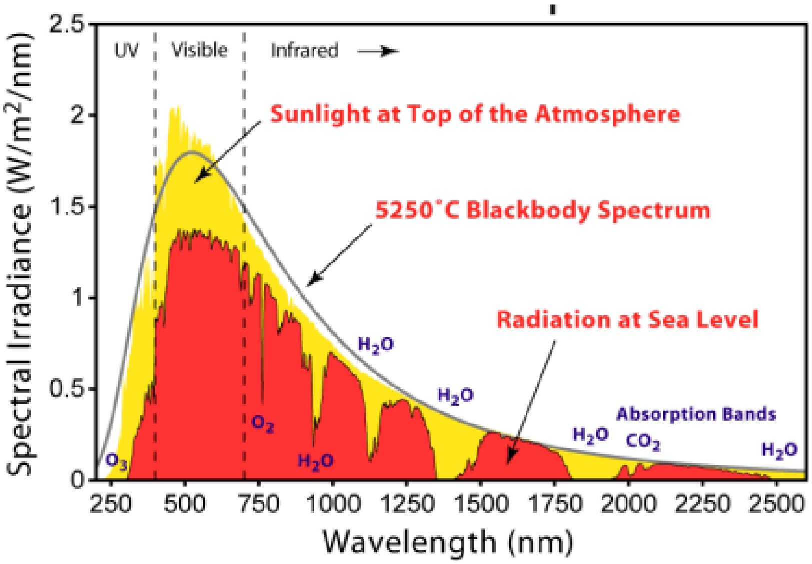


Figure 14: Solar radiation spectrum, yellow top of the atmosphere, red at sea level [10]

As for the majority of electrical machines even the solar panels can be affected by high temperature but, however, they also need to be exposed to the sun in order to generate energy. Depending to the solar cell technology and materials, this effect can have a significant role with cell surface working temperature. Cause wing area is a critical aspect for aircraft, special flexible solar panel can be mount directly in the composite wing by gluing / incapsulating them directly on the structure.

Figure 15: Solar impulse wing panels, always taken as reference technology

While standard crystalline cells are fragile (they have a glass protection), flexible thin-film technology uses a thin film of encapsulated cells with plastic in combination of new technology triple-junction compound. For reference, Sharp obtained a conversion efficiency of 32.65% with these thin film / junction cells (composed by multiple p-n junctions based on the wavelength absorbance capacity) with a mass of only 0,58kg per meter.

Combining the previous efficiency of 32,65% with the useful mounting area on the wings equal to the 40% of the total available (many sections of the wing have the presence of mechanism, maintenance point, ecc), the entire useful wing area eligible for the installation of PV panels will be 25 m².

During an ideal day hour in standard conditions, the energy produced would be 8'162Wh (8,162kWh) with a nominal power of 8'162W. The following values are assumed for the solar system:

Solar Cell efficiency 20%;

Cruise solar irradiance 700W/m^2;

Taxing solar irradiance 165W/m^2;

Climb solar irradiance 500W/m^2;

Descent solar irradiance 420W/m^2.

SOLAR EXTRACTION POWER						
MODE	**Solar irradiance**	**Time**	**Time**	**Efficiency**	**Energy Extracted**	
n	**[W/m2]**	**[s]**	**[h]**	**[%]**	**[kW/m2]**	**[kWh]**
Ground Time	165	3360	0,93	0,200	0,11	0,103488
Taxi	165	300	0,08	0,200	0,01	0,000825
Climb	500	1080	0,30	0,223	0,12	0,036126
Cruise	700	2340	0,65	0,223	0,37	0,2374281
Descent	420	1680	0,47	0,223	0,16	0,07342944
Mission Power Generated for 1 m^2					**0,65**	**0,35**
Mission Power Generated for all system (25 m2)					**16,32**	**8,70**

Table 5: Solar PV system calculations

Generating 8,70 kWh during the proposed day mission.

As well for the ORC system, solar PV panel uses many subs system such charge controller, ecu's ecc. but to remain simple as possible, they are all assumed in the electric traction pack calculations.

Since now all the power are calculated, this recovered energy has to be stored: studying an electric pack system to maintain acceptable weights and suitable power profile flat rated like strategy, an installation on the root of the wing like the standard aircraft mount auxiliary (Long Range) fuel tank is proposed as shown in the picture below:

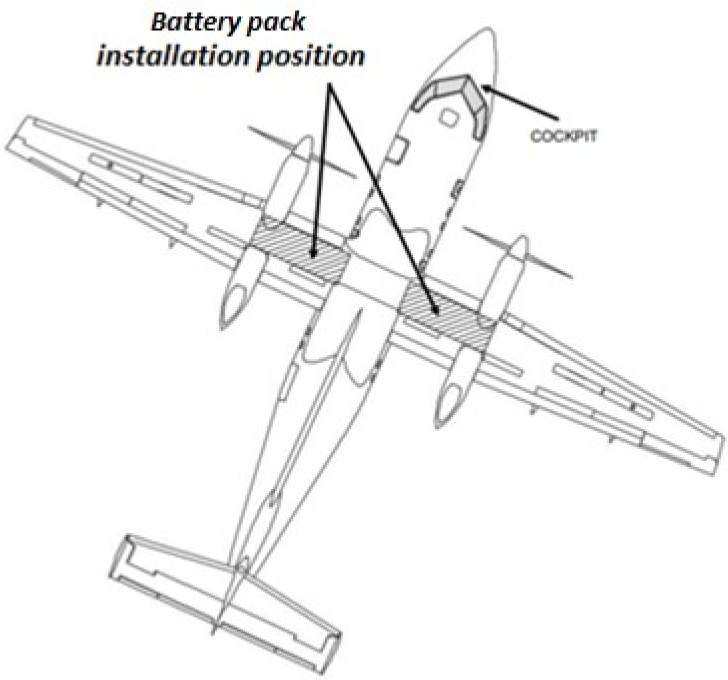


Figure 16: Battery pack installation position

That position allows to use a capacity of 2'450 liters and an admissible weight of 1'970 kg without take into account any modification on the aircraft structure.
In addition, this is a "privilege" position because it is located in the middle of the fuselage, avoiding any major variation of the center of mass, and it is in a central position from the powertrains simplifying the hybrid arrangement.
The total energy capacity required for the flight mission previously calculated leads to the final definition of the electric pack and relative characteristics: for the design is proposed to use a new battery technology developed by Novac SuperCap startup that developed a new shapeable battery pack to adapt it into different surfaces and volumes.
Here below is represent the main manufacture scheme with the estimated battery mass:

Estimate Battery mass	
1771,513	kg

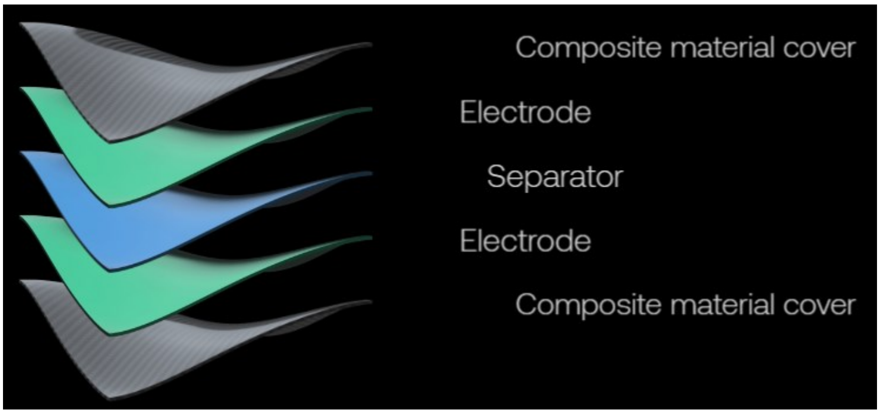


Figure 17: Novac pack design

In order to assist the ICE of the aircraft, an electric motor (two mounted in series for each PW150 turbine) of Siemens manufacture model SP200D is chosen, with the following characteristics:

Max power 255kW;

Continuous power 204kW (x4=816kW);

Mass 50kg (x4=200kg);

Continuous Torque 1500Nm;

Length 300mm (x2=600mm);

Diameter 418mm.

Figure 2018: Siemens motor model SP200D

The installation inside the main turbine required a lot of re-engineering even if it's more efficient than others solutions.
To have as much as possible a simple installation scheme, the motors can be used as E-starter generator instead of the native starter generators or they can be installed between the gearbox and the main propeller (fig.8). Therefore, the four motors have a total power of 816kW operating at a voltage of 800V. As a result, a special electrical interface is required:

Figure 21: High voltage cables

Assuming to use high power transmission cables of Prysmiangroup EV manufacture to distribute the electrical power, the cables will connect the battery pack directly to the electric traction motors.
By evaluating the distance between motors and the pack itself, it is assumed a length of 4,5 meters to cover the distance, multiplying the result for the three phase poles of each motor.
Total length and weight of the power cables is shown below:

POWER CABLES				
Number of cables	Lenght	Total lenght	Mass per cable	Total Mass
[n]	**[m]**	**[m]**	**[kg/km]**	**[kg]**
12	4,5	54	2232	120,528

Table 6: Power cables calculations

The last aspect to take into account is the battery charging and discharging strategy: to ensure battery life, a depth of discharge of 85% is assumed while the remaining 15% can be used in emergency situations (also it has to implement a bi-directional electrical redundant connection for safety aspect) while during the cruise phase the power recovered by the ORC it will be used to recharge the batteries.
For the discharging phase a charge-sustaining strategy will be adopted to maintain the State of Charge (SoC) of the battery at a certain level by ensuring always to have an adequate reserve of energy in case of emergency.

CONCLUSIONS

In conclusion, the resulting final consumption is calculated with the contribute of all power generated by ORC, solar panels and standard engine power with JetA1 density in combination of the original amount of fuel consumed. As a recap we can resume these values:

ORC Power generated, 346.78kW (in total for the two engines);
ORC mass, 320kg;
Electric motor mass, 200kg
Cable mass, 120kg
Solar power, 8,7kW;
Solar mass, 80kg (assumed);
Battery mass, 1771.51kg;
Inverter, ancillaries (assumed) ecc. mass, 100kg;
Jet A1 mass for standard mission = 1100kg;
Jet A1 mass capacity max in the standard aircraft configuration = 5320kg;
Engine standard power: 6050kW (in total between the two engines)
Fuel consumption standard I.C.E., 0,263kg/kWh

Combining them with the values in fig.11, it is calculated the resulting consumption:

Calculations of saved consumption		
Liters consumed standard flight	1090,64	kg
Liters consumed by hybrid flight	972,44	kg
Liters saved hybrid flight	118,20	kg
Liters to correct for increased mass	98,73	kg
Liters saved hybrid flight	1,78	%

Table 7: Saved fuel calculations

The mass increasing resulting to the correlated modify of the aircraft will be 2591.51kg compared to an increase of total installed power of 355,48kW.
By calculations, this proposed mix hybrid design could reach a 1,78% decrease in fuel mass consumption, but at a cost of a 13.15% mass increasing in an ordinary flight weight of 19'685kg. In addition to that, using e-fuel as main fuel, we will have a decrease of 5% of CO_2 emissions and a slight decreasing in particle emissions (-80%) [11].

Although in this report the suppose calculations are including a large number of assumptions such no friction, irreversibilities ecc., the project has certainly proved there are a lot of promising technology for energy recover, deserving a more in-depth study and investigation. In addition, new emerging technologies in organic fluids and solar cells, as well for batteries, super capacitors ecc., are rapidly growing and promising a much more satisfying results for the future.

Personal author note:

I thank my supervisor, colleagues involved in and my university to support me in this challenge, as well for the entire organization of Futprint50 for giving me the opportunity to confront myself with this project and challenges.
Even it is only a very first study of feasibility, this allows me to get involved with a very interesting thematic, a real-world challenge to find a valuable way to switch on an electric / hybrid conversion of an aircraft.
If on one side sustainable and clean technology is dramatically require to face today's environmental concerns, on the other hand there is no doubt that the high power required to fly and to sustain itself dynamics play a decisive role for the success of alternative power technologies in these applications.
In the past such great personality as scientists, engineers, devoted their lives and passions to find a solution for everyday problems by looking for innovative methods.
Today, we have such a best young people and talented engineers who work hard with the same dreams and goals: for that reason, in this study I've tried to include startups and ideas

that I found in my searches that are a result of hard and passionate work on the development of new power technologies.
There is no doubt that today the current mass production tech is not yet ready (or at least at sufficient level of research) to replacing the current ones, but only through continuous research and efforts we could achieve the present challenges.
Surely in the meantime, we will certainly have to change also the way we see the world, adopting more sustainable lifestyles and energy saving by avoiding incorrect behavior, since the only kilowatt saved is one that we have not consumed.

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