Ref. Ares(2021)2243367 - 31/03/2021

FUTPRINT50

Future propulsion & integration:
towards a hybrid-electric 50-seat regional aircraft

Deliverable 2.1

Requirements and Reference Aircraft

Grant Agreement Number	875551
Project Acronym	FUTPRINT50
Project title	Future propulsion and integration: towards a hybrid-electric 50-seat regional aircraft
Starting Date	1 January 2020
Project Duration	36 months
Project Officer	Hugues Felix
Project Coordinator	Prof. Andreas Strohmayer (USTUTT)
Author(s)	Ricardo dos Reis (EMBRT) Felipe Odaguil (EMB) Evert Windels (ADSE) Yorick Teeuwen(ADSE) Jenny van der Pols (ADSE) Panagiotis Laskaridis (CRAN) Dominique Bergmann (USTUTT) Dominik Eisenhut (USTUTT) Nicolas Moebs (USTUTT)
Contributing partners	Airholding/Embraer Research and Technology Europe (EMBRT), University of Stuttgart (USTUTT), Cranfield University (CRAN), ADSE Consulting & Engineering BV (ADSE), French Alternative Energies and Atomic Energy Commission (CEA), Embraer S.A. (EMB), Baranov Central Institute of Aviation Motor Development (CIAM)
Due Submission Date	31 October 2020
Actual Submission Date	31 March 2021

“This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 875551”

Status

Draft	
Final	**X**

Type

R	Document, report	**X**
DEM	Demonstrator, pilot, prototype	
DEC	Websites, patent fillings, video etc	
OTHER		

Dissemination Level

PU	Public fully open	**X**
CO	Confidential, only for consortium members (including the Commission Services)	
CI	Classified, information as referred to in Commission Decision 2001/844/EC	

Revision History

Date	**Lead Author(s)**	**Comments**
2021-03-31	All	Final revision
2021-03-20	Felipe Odaguil (EMB), Panos Laskaris (CRAN)	Y2040, E. Mngt
2021-01-31	All	TLARS revision
2020-04-20	Ricardo Reis (EMBRT), Nicolas Moebs (USTUTT)	TLARS release

Glossary

Acronym	Full Title
ATAG	Air Transport Action Group
BTS	Bureau of Transportation Statistics
CFA	Conventional Futprint50 Aircraft
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DOC	Direct Operating Cost
EASA	European Union Aviation Safety Agency
EIS	Entry Into Service
EU	European Union
FL	Flight Level
FOM	Figure of Merit
HE	Hybrid-Electric
HEA	Hybrid-Electric Aircraft
ICAO	International Civil Aviation Organization
ISA	ICAO Standard Atmosphere
KTAS	Knots true airspeed
MTOW	Maximum Take-off Weight
NM	Nautical Mile
OEW	Operating Empty Weight
SAF	Sustainable Aviation Fuel
SL	Sea Level
STOL	Short Take-off and Landing
SUAVE	Stanford University Aerospace Vehicle Environment
TLAR	Top-Level Aircraft Requirements
TOFL	Take-off Field Length
UN	United Nations
WTP	Wing Tip Propellers

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Abstract

This document provides a reference workbook for FUTPRINT50 project. Namely, it provides: Top-Level Aircraft Requirements (TLAR) for the target aircraft class and underlying assumptions; Figures of Merit, to support aircraft design and specific technologies trade-offs; Mission priorities and Energy Management Strategies.

Additionally, the document provides, for the defined TLAR, a conceptual conventional reference aircraft configuration with entry into service in 2040. This configuration was obtained by projecting the evolution of current conventional technologies up to 2040, allowing comparison with the hybrid-electric configuration to be developed in FUTPRINT50.

1 Introduction

Aviation has been a driver for economic wealth by not only connecting millions of people, but also by providing a fast option for trade between different continents. It amplifies tourism, allowing people to experience different countries and cultures and broaden their minds. This generates economic wealth for the destination region, which is especially valuable for developing countries with a remote tourism market [1]. Apart from the many benefits created by aviation, there are also downsides, primarily concerning environmental aspects. According to different studies, aviation is currently responsible for 1–2% of human-made CO_2 emissions [1,2]. Aviation's impact on the environment is not only limited to CO_2, but also includes other forms of emissions like NO_X or noise. While emitted greenhouse gases impact the climate and contribute to climate change [3], noise is expected to influence the health and general well-being of residents in the vicinity of airports [4]. Many efforts are being pursued by governments and the aviation sector itself to reduce negative impacts, with the ultimate goal of achieving sustainable aviation.

In 2011, the European Commission presented the EU Aviation Sector's vision for the future of aviation, called Flightpath 2050 [5]. This report not only set goals for emission reductions, but also built a framework for the sector's market direction. Therefore, the vision pursued the aims of streamlining procedures and improving overall passenger experience. This included facilitating fast boarding, arriving at destinations on time regardless of weather conditions, and enabling 90% of European travelers to reach their destination from door to door within 4 h. Apart from increasing the convenience of air travel for passengers, arriving on time and improving air traffic management also contribute to reducing emissions by causing fewer deviations and less otherwise "wasted" holding time and fuel.

Roughly eight years later, at the end of 2019, the European Union (EU) introduced the next step towards a sustainable future—the European Green Deal [6], which aimed to ensure that Europe would become the first "climate-neutral" continent on Earth. Similar to Flightpath 2050, the aims of this Green Deal included setting emission targets and enforcing a circular economy. These actions were not specifically aimed at aviation, but instead aimed to cover all the sectors impacting the climate.

In addition to governmental policies, the aviation industry is also striving to become more sustainable in its own right. With the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) initiative, the International Civil Aviation Organization (ICAO), as a subsidiary organization of the United Nations (UN), is also setting emission targets for the aviation industry. From 2021 onwards, carbon-neutral growth should be achieved, as well as an increase in energy efficiency by 2% per year until 2050 [2].

In addition, the UN in 2015 defined an agenda including 17 sustainable development goals and 169 targets to be achieved by 2030: “They are integrated and indivisible and balance the three dimensions of sustainable development: the economic, social and environmental” [7]. Moreover, the UN stated that a global effort is required to end poverty, respect human rights, create equality, and other essential goals, all while protecting the environment where “humanity lives in harmony with nature and [where] wildlife and other living species are protected” [7].

According to the Air Transport Action Group (ATAG) and their 2020 Aviation Benefits report [1], aviation plays a major role in supporting that agenda. To name just a few ways in which the aviation plays a main role: Before the COVID-19 pandemic, the aviation sector supported nearly 88 million jobs across the world, including direct, indirect, induced, and tourism related jobs. In addition, aviation supported 4.1% of the global gross domestic product [1].

Aviation has many benefits compared to other transport modes. The most important involves travel times, which are usually the lowest of all available modes of travel due to the straight flight paths that are possible without deviations being needed. Even in regional markets, this often holds true, despite the short distances that need to be covered to travel across these areas. This benefit is further increased if air travel is used to get across natural barriers like mountains, lakes, or the seas between islands. Air travel allows for connecting smaller cities to the already existing transport networks with lower infrastructure costs, thereby reducing development and maintenance spending. The only requirements to cover an airline route are airports at the departure and destination locations, each with sufficient infrastructure. No roads or rails are necessary in between these airports to facilitate air travel. Furthermore, more remote regions can be reached by air travel where a fast connection by other means of transport is not economically feasible or even where the route itself is not economically feasible at all.

According to an ATR market forecast, 58% of the worldwide regional air routes network was created between 2003 and 2018 [8]. To support this growth and add more remote regions to the global transport system in a sustainable way, the vision of a regional 50-passenger aircraft will allow for connecting smaller routes or simply destinations with reduced passenger and/or cargo volumes. To fulfil this purpose, it is expected that the size of the aircraft is reasonably defined. In addition, a smaller plane allows for more connections every day, if the demand is high enough, and reduces the risk of unprofitable flights due to low passenger volume at the same time. This will lead to more travel options for European citizens and a denser transport network interconnecting Europe. However, the higher number of connections must be cost efficient, and the aircraft must have competitive direct operating costs (DOCs) in comparison to other transport modes. In regional aviation, the impact of fuel consumption is amplified. Emissions wise, besides those on air, there is the impact of fuel transport to remote regional airports. This transport also increases the costs, wich compared to hub airports, are in average higher by one third worldwide, and in some parts of Europe, even by a factor of two or more [8].

Following the vision of the European Commission within Horizon 2020, an entry into service (EIS) for 2035/2040 for a hybrid-electric 50-seat regional aircraft seems challenging but feasible.

Electrifying the powertrain offers many benefits over conventional architectures. Electric motors provide power without any local emissions. The only emissions might result from producing the electric energy required to power the motors. Furthermore, electric motors scale almost linearly regarding power and mass. This might enable the use of novel propulsion concepts like, for example, distributed (electric) propulsion, where efficiency can be increased, synergistically exploiting the interaction between the wing and propulsors.

Assuming green electric power, a fully electric aircraft would offer the lowest emissions during operations. For now, the range of such an aircraft would be limited due to the low specific energy of current battery technology. To tackle this flaw, a hybrid-electric concept combines the advantages of both worlds, i.e., the range provided by conventional fuel, and the emission reduction achieved by an electrified powertrain with higher efficiency. In addition, this concept enables new operation strategies where emissions can be managed based on different factors. In flight phases where the most harmful pollutions occur, using only the battery will allow for lower emissions of greenhouse gases and noise. Different hybrid-electric architectures offer further options for the design and operation of the aircraft. A parallel architecture allows for a power boost in high load scenarios like take-off or go-around. A serial architecture can increase redundancy or offers to replace a gas turbine with a battery pack if certification and technology requirements are met.

Apart from architectures and operation strategies related to local emissions, an additional degree of freedom is created by different energy management strategies. Having multiple energy/power sources allows for controlling the ageing of different powertrain components. With operating hours of a gas turbine building up, the battery could provide power originally produced by the turbine and vice versa. This will increase wear on the boosting component but might help the operator to optimize the maintenance schedule.

In contrast to these benefits, the hybrid-electric system will add additional components to the aircraft which increase mass and complexity. The mass penalty must be outweighed by a higher overall efficiency of the aircraft and other benefits. One is the required emission-free taxiing within Flightpath 2050, which can be fulfilled easily by the hybrid-electric aircraft (HEA). Furthermore, the added complexity will require a higher effort for certification. The HEA must achieve similar safety levels to a conventional aircraft. The different operating and energy management strategies might lead to additional redundancy. However, analysing the overall architecture and different failure scenarios is challenging.

In this context, the project FutPrInt50, which consists of 14 international partners, was formed. To address all these different challenges and to grasp the bigger picture, the project partners adapted a Systems Engineering approach [9] with a dedicated mission statement, which will be explained in the following paragraph.

In Figure 1, the V-model of systems engineering is shown. It advises to break the overall design process into different levels and, by the iterative process, each level is revised whether expectations and requirements are fulfilled or not.

The left part of the V starts with the need definition and works through to the definition of the design. The bottom side of the V-model contains the actual design, including systems and sub-systems design. The right side starts with the implementation and integration. After this, the design will be tested and validated if all goals are achieved. Finally, actual operation will commence.

The first conceptual design is created by defining and implementing the systems at a higher level, i.e., general layout, propulsion type, disruptive technologies, etc. The starting point is defined by using existing data and a comparative aircraft analysis. The results create the basis for the top-level aircraft requirements (TLARs) and initial architecture and design definition. Consequently, the first concept is verified and validated, and a first concept of operations can be determined.

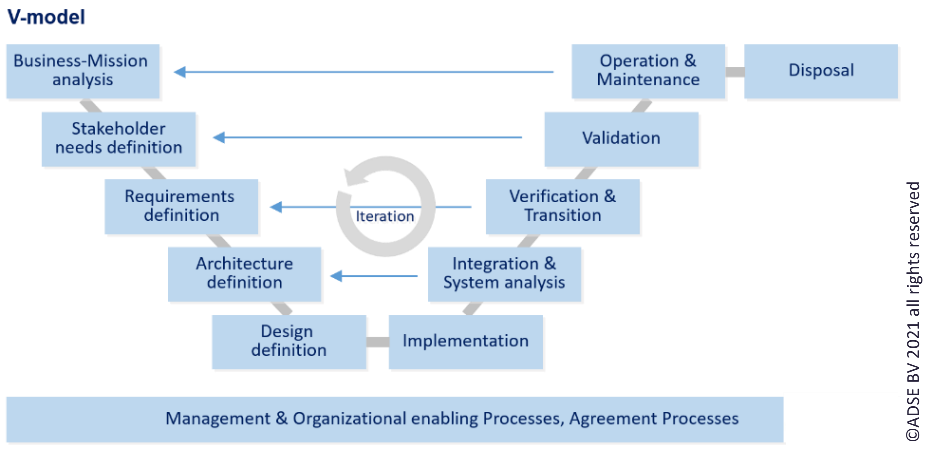

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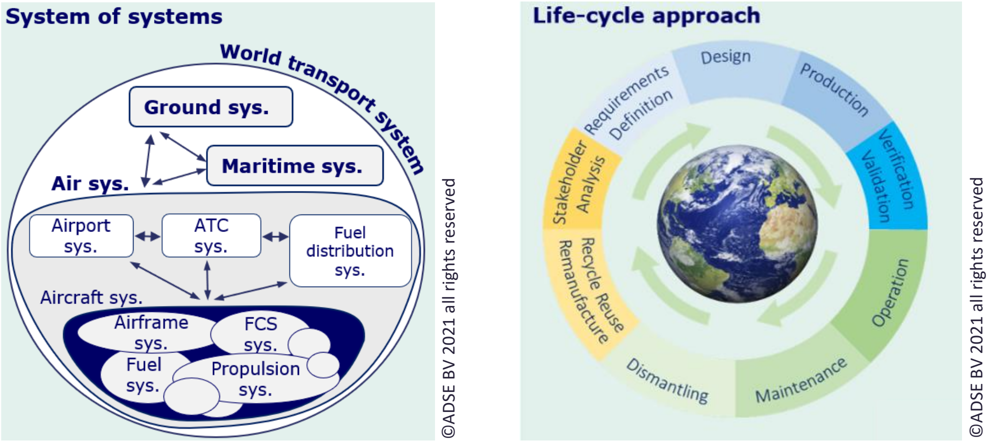
Figure 1. *V-model of systems engineering.*

During the conceptual design phase, iterations are made to identify if the initial requirements are met, as is shown in the figure. At the end of the design, the entire conceptual product is evaluated to identify if it still satisfies the initial expectations. Requirements can be re-evaluated, and stakeholders can refine their needs, as one can learn from the first concept. This iteration is important when developing new disruptive designs and technologies, as one can never create the perfect starting point during the business and stakeholder analysis. Each overall iteration brings the design to a more detailed level, eventually converging to one final design, aligned with the stakeholders.

For the FutPrInt50 project, the following stakeholders have been identified: EU citizen, authorities, operator, airport, air traffic management, supplier of energy, and the passenger. The stakeholders and their needs define the goals and requirements to make the project a success. Stakeholder interaction and analysis is required to define if the product or system to be designed fits in the overall picture. To better capture this overall picture, the product can be seen as a system within a system which is influenced by its surroundings (Figure 2a).

Taking this holistic view is important to grasp all aspects of the "larger" system and the stakeholders involved. The system of systems is one part of identifying the "larger" system, while another is the life-cycle approach shown in Figure 2b. Especially for sustainability, this shows that one should not only look at the operational period, but also all other sections of the life cycle to build a "green" solution. The needs and the requirements definition shall drive the design process to achieve a sustainable product in its life cycle, whilst still satisfying the stakeholders' needs within the systems of systems. The design decisions will drive emissions during all parts within the life cycle, which includes production, the operational phase, as well as end of life and recycling.



(a) *(b)*

Figure 2. *(**a**) System of systems and (**b**) life-cycle approach.*

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After formulating the needs and goals for the system, these could be summarized into a mission statement, used to define the system that is to be designed. The following is the current mission statement for a regional HEA:

> *"To develop a synergetic aircraft design for a commercial regional hybrid-electric aircraft up to 50 seats for entry into service by 2035/2040, to identify key enabling technologies and a roadmap for regulatory aspects. The clean sheet aircraft design shall help accelerate and integrate hybrid-electric aircraft and technologies to achieve a sustainable competitive aviation growth, as well as acting as a disruptor to regulators, air traffic management and energy suppliers."*

The clean sheet aircraft design shall:

- **have class-leading emissions and noise,**
- **include technologies that ensure (operational) safety,**
- **offer a competitive operational cost,**
- **offer operational improvements during exploitation compared to current regional aircraft,**
- **not enforce expensive changes to the current infrastructure.**

This statement not only describes the system, but also highlights the benefits for the stakeholders. Within the V-model, it represents the first two levels, the business mission analysis and stakeholder needs definition. These two provide the framework for the requirements definition represented by the TLARs.

The TLARs help to translate the abstract needs of the stakeholders to more manageable requirements on a system level. This includes specifications that should be precisely met, like the range, for example, or ones like emissions, where overachieving the goal is desirable.

The V-model requires us to validate if the requirements are fulfilled by the design. Therefore, figures of merit have been defined in the process and are shown in Section 4: they offer means to quantify the fulfilled requirements, thus create the possibility to compare different design approaches and to identify superior concepts. This is especially necessary for complex interwoven requirements like emissions and Direct Operating Costs (DOCs). On the one hand, capital cost as part of the DOCs might increase due to the higher development and manufacturing cost of a more environmentally friendly airplane. On the other hand, when emissions are taxed, this might increase the DOCs for aircraft with higher emissions.

2 Top-Level Aircraft Requirements

All defined TLARs are grouped in different categories, relating to environment, market, operations, performance and regulations [8]. This helps to evaluate the design with respect to different aspects. All requirements within these categories are explained in the following sections.

2.1 Environment

The environmental requirements are mainly derived from Flightpath 2050, all adopted requirements are shown in Table 1. Defined emission reductions for CO_2, NO_X and noise are directly implemented into our TLARs.

Table 1. Top-Level Aircraft Requirements regarding environmental aspects

TLAR (environment)	**Value**
Δ CO_2 emissions	≥ –75 % vs. ATR-42
Δ NO_X emissions	≥ –90 % vs. ATR-42
Δ Noise emissions	≥ –65 % vs. ATR-42
Emissions during ground operations	No CO_2- and NO_X-emissions
Materials used in the design	Sustainable end of life solution
Use of alternative propellants	Yes

In addition to the emissions reduction during flight, all ground operations should be performed emission-free, which includes taxiing. In general, there are two options available: Either an emission-free system is integrated into the aircraft, or the aircraft is towed by an electric truck on ground. The first option is easily fulfilled by the HEA. In comparison, a conventional aircraft would require a system solely for the purpose of emission-free taxiing. During all other mission sections, this system is dead mass that penalizes the overall aircraft performance. The second option, an electric tow truck, requires infrastructure on the ground at every serviced airport. Especially for smaller regional airports, this might limit profitability of either the aerodrome itself or the desired connection.

Furthermore, the goal is not only to reduce overall emissions during the operational phase but also during the whole aircraft life cycle. Therefore, materials used should allow a sustainable solution like recycling or reusing at the end of life. This connects to the life-cycle approach described earlier.

The final criterion is the usage of alternative propellants. This is not only limited to sustainable aviation fuels (SAF) that replaces conventional jet fuel but also specifically allows for hydrogen.

These defined environmental requirements not only would incorporate the Flightpath 2050 goals, also further political initiatives are accounted for, like the European Green Deal [6] and its aim of being climate neutral in 2050. This can be achieved by SAF or green hydrogen, using hybrid electric propulsion systems, in combination with a life-cycle approach that also considers recyclability in a circular economy. In this case there is only a minor difference for aviation between the Flightpath 2050 goals and the Green Deal.

2.2 Market

2.2.1 Size, comfort & costs

Table 2 shows all aspects related to market requirements including operator demand and passenger comfort. Aiming at the regional air traffic market, the number of passengers is set to 50. This aircraft size was chosen from an evaluation of as addressing the existing transport network and feasibility towards entry into service in the challenging range of years 2035-2040.

Table 2. Top-Level Aircraft Requirements with regard to market

TLAR (market)	Value
Number of passengers	≤ 50
Cargo capacity	≥ 500 kg
Luggage bins	≥ 0.06 m³/passenger
In-flight entertainment	Seamless connectivity
Cabin altitude	≤ 2000 m (6560 ft)
Cabin ventilation	≥ 0.25 kg/min fresh air per passenger
Cabin temperature	23 °C
Cabin humidity	10 %
Lavatory	≥ 1
Galley	≥ 1
Direct operating costs	Competitive with ground transport
Dispatch reliability	≥ 98 %

As the world is coming closer together, not only fast connections for passengers are required but also for cargo. Therefore, the cargo capacity is set to at least 500 kg if maximum passengers are on board. In addition, it should be possible to quickly convert the plane from passenger to cargo and vice versa. Furthermore, a combi-version would allow to trade some passengers for additional cargo. This allows flexibility to the operators and gives them the ability to react to different needs in different markets/regions.

In regional aviation, mostly carry-on luggage is used. This also helps with the turn-around time. To allow for enough space in the cabin, the luggage bins are sized that each passenger has 60 litres available. This is comparable to the current Embraer E-Jet E1 family and is larger than the bin size of current turboprop aircraft. Furthermore, the volume of regular hand luggage (55 x 40 x 20 cm) is only 44 litres.

No conventional in-flight entertainment will be integrated but seamless connectivity like Wi-Fi should be provided. The flight duration is rather short and connection to the internet is expected to be more essential, especially for business trips where the passenger can work during the flight. To share flight information, an app could be provided for example.

Cabin pressure is set to 2000 m (6560 ft) which complies with certification specifications (CS) that require a cabin pressure altitude of less than 2438 m (8000 ft) (CS 25.841 (a)) [11]. For the short flight time of the regional aircraft, a lower altitude is not needed. New airplanes for long routes like the Airbus A350 and the Boeing 787 are already using a cabin altitude of 6000 ft, so the trend and market requirements for regional aviation must be closely monitored.

To comply with CS-25, cabin ventilation must be designed to provide every passenger with at least 0.25 kg of fresh air per minute. The exact required ventilation capacity is closely connected to the temperature and humidity requirements. Every passenger on board is generating heat and moisture. To keep the temperature at 23 °C and humidity at 10 %, the air inside the cabin must be reconditioned which in the end defines the exchange rate for cabin ventilation.

For passenger comfort at least one lavatory must be installed. Despite the trend going to serve less warm food on-board, at least one galley is foreseen. This ensures the possibility to offer hot beverages like coffee or tea during flight.

As already described, the goal of the aircraft is not to replace other transport modes. Therefore, the DOCs should be competitive with public ground transport. A metric for comparison might be the expected ticket price for each transport. Furthermore, a comparison to car travel might be of interest, even more so as a majority of cars is expected being electric by 2040. Another important aspect which drives the DOCs of the airplane is the dispatch reliability which should exceed 98 %. This will increase utilization of the airplane for the operator and so the potential profit.

2.2.2 Network and range

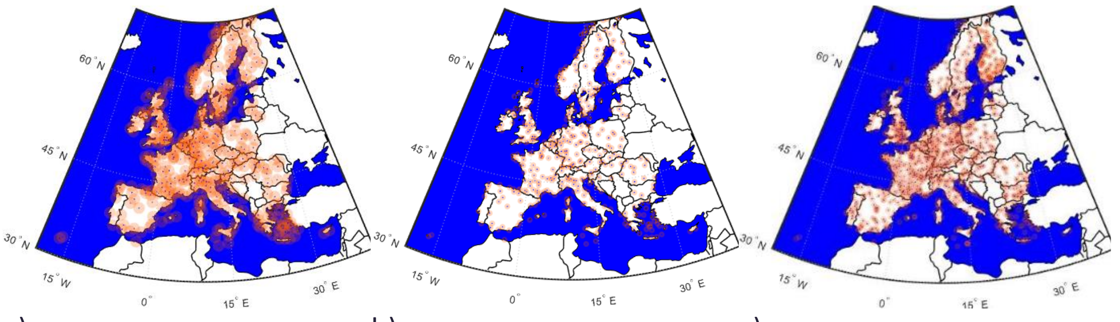
The design range of the regional aircraft is a major point concerning its future mission and purpose. Aim of a regional air travel is a closer connection of rural areas and to realize a fast connection between cities. This is connected to the Flightpath 2050 goal that "90 % of travellers within Europe are able to complete their journey, door-to-door within 4 hours" [5].

The regional flights should enable an easy and fast way to travel also on routes with lower passenger volume, like remote bus and train connections. Thereby traveling by air should work in synergy with other modals, enabling routes which are difficult or not cost-effective to realize with ground-based transport systems or add a significant and useful time differential.

At first, the coverage of airports in the EU plus Great Britain, Norway, and Switzerland is analysed (see Figure 1). This leads to a number of 414 airports with a field length of more than 1000 m (430 airports for 800 m, respectively) that have a volume of more than 15,000 passengers per year according to data of reporting airports to Eurostat from 2019 [13], excluding overseas departments. It is expected that these airports are commercially in use. Under the assumption of a 100 km catchment area around the airports, major parts of the EU are already covered. We expect that a larger catchment area does not result in any advantages for the traveller, since no time advantage is expected. Furthermore, we assumed that no emission savings can be achieved for a catchment area more than 100 km.

For regions with low transport infrastructure (no highway, no railway, mountainous regions) the catchment area must be adjusted because of a slower travel speed. Here, a more suitable radius of the catchment area for regional air traffic would be 50 km or even less from an airport. Considering this smaller catchment area, there is only sufficient coverage for metropolitan areas. These urban areas are often already connected to the regional traffic network. However, air travel can realize new and faster connections between these areas as an alternative means of transport.

However, if we consider airports or airfields in general (commercial or not) with a runway (concrete and asphalt) of at least 1000 m, a higher degree of coverage can be achieved. A study based on EU airports provided in the database of OpenAIP [14] has shown that 1112 airports and airfields fulfil this requirement (the study includes also military airfields). Taking these airfields into account, nearly all regions of the EU can be connected to a regional air traffic network. Assuming that these regions often are barely connected to a fast transport infrastructure network, this will greatly contribute to the European vision presented in Flightpath 2050.



a) b) c)

Figure 1. Coverage area of European commercial airports with an assumed catchment radius of a) 100 km, b) 50 km and c) 50 km considering all airfields of at least 1000 m runway

To allow regional travel in the EU with an aircraft in respect to the defined goals of Flightpath 2050 as well as worldwide defined climate objectives, the design range is set to 400 km and the maximum range to 800 km, respectively. It is assumed that for this range it is possible to develop an aircraft with EIS 2035/2040 reaching the global climate goals and to enable a regional air transportation system as extension of the current traffic infrastructure. To connect different regions and cities in the EU, the existing commercial airports with a field length of 1000 m or more in operation already enable 12,467 routes (distance between 350–800 km). For a field length of 800 m or more, this would result in 13,214 routes. In both cases, these connections of interest to regional flight cover approximately 15 % of the flight connections in the EU with a distance of more than 250 km (Figure 2).

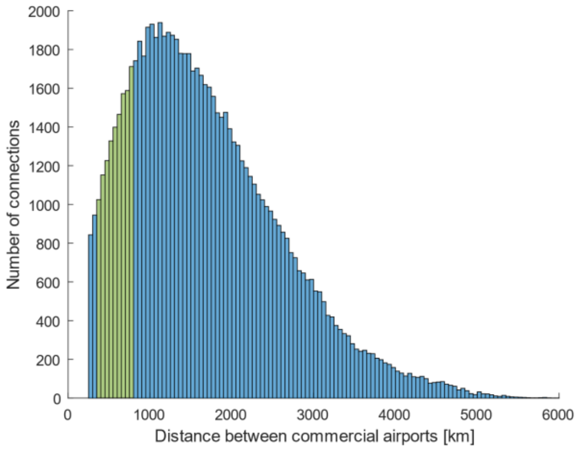
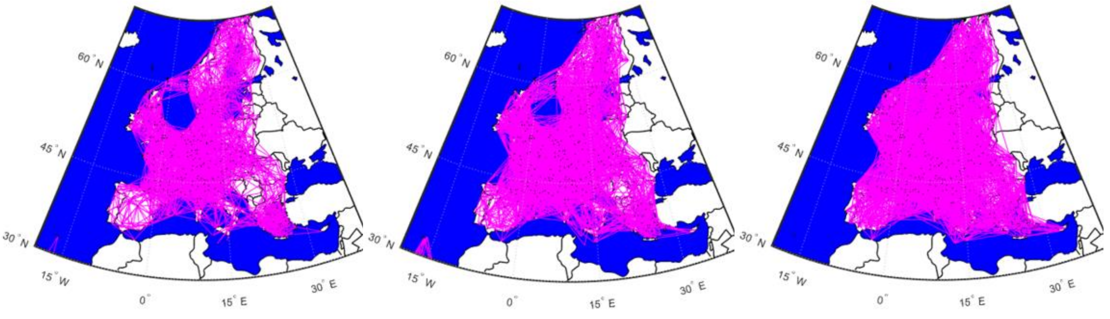


Figure 2. Number and distance of flight connections in the EU (plus Great Britain, Norway and Switzerland) concerning commercial airports in operation (blue + green) – feasible connections for regional air traffic (green). All connections of more than 6000 km are not displayed.

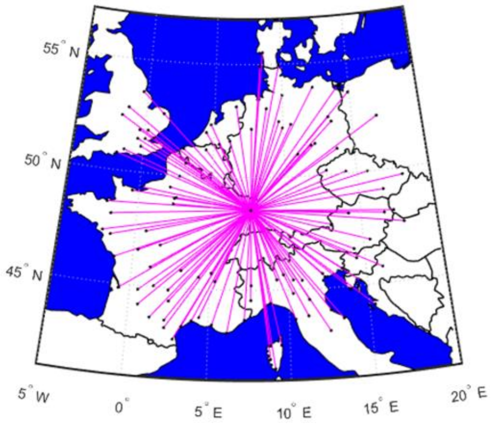
Due to the lower passenger capacity of the planned aircraft, also less populated regions could be connected to the EU traffic network even if there is a lower passenger and cargo volume demand. The availability of these air connections has been shown to play a role regarding regional development [15]. Figure 3 shows the coverage of different ranges for existing commercial airports with a field length of at least 1000 m. It can be seen that nearly all states of the EU can be covered, excluding some islands and overseas departments.



a) b) c)

Figure 3. Connections between commercial airports in operation in different distances a) 350–500 km b) 500–650 km and c) 650–800 km

The two examples in Figure 4 and Figure 5 showcase possibilities within this regional air traffic system. The first is Strasbourg, France in the heart of the EU and seat of the European Parliament. Only considering a distance between 350–800 km, 113 connections can be realized. The figure on the right presents domestic air traffic between the Greek mainland and islands. This could be an addition to current ferry connections for faster travel between the islands with a bigger distance. Therefore, the minimum flight distance was reduced to 150 km.



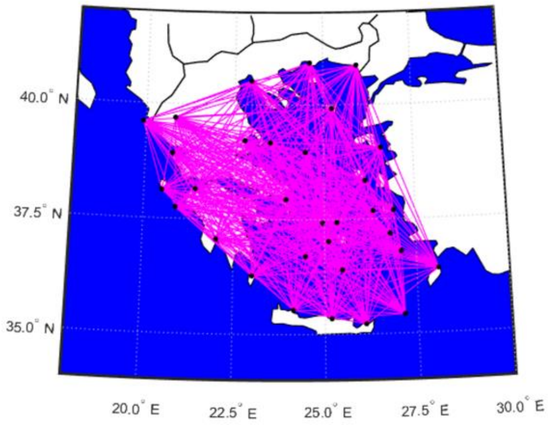


Figure 4. Example 1: Connections from Strasbourg (SXB) between 350–800 km

Figure 5. Example 2: Feasible domestic flight routes of Greece between 150-800 km

2.2.3 Reserve policy

Within ICAO Annex 6 [16], topics concerning the operation of aircraft are covered. This includes fuel requirements for a safe execution of a complete flight. It defines that the minimum amount of usable fuel should account for the following parts: Fuel required for taxiing and the overall trip including a contingency fuel for unforeseen factors. The reserves are split into fuel required to reach the alternate airport and a final fuel reserve which for a turbine driven aircraft is set to 30 minutes of holding at holding speed, 1500 ft above ground level.

The distance to the alternate and therefore required fuel is specific to the planned route. For this project, it is defined as 185 km in general which is equal to about 23 % of the maximum range. In many regions, this is expected to be enough for most regional flights. Two main events can happen that require to divert to an alternate. First, having already reached the planned destination and being required to divert to another airport, for example because the airport got closed due to an accident. Second, being en-route and the weather at the planned destination worsens requiring to divert to an en-route alternate.

For the first case, having already reached the destination and being required to divert, Figure 6 shows the number of potential alternates for airports in the EU (including Great Britain, Norway and Switzerland). Out of the 414 commercially operated airports with a field length above 1000 m, 3 have no alternate within the defined reserve distance. This yields more than 99 % of airports adequately covered. Over 90 % have more than one alternate within reach. To correctly define airports with missing alternates, airports in Serbia, Bosnia and Herzegovina, Montenegro, Kosovo, Albania, North Macedonia, Belarus and Ukraine were added in all reserve analysis. Here, the same criteria for the airport selection have been applied (field length of at least 1000 m and yearly passenger volume of at least 15,000).

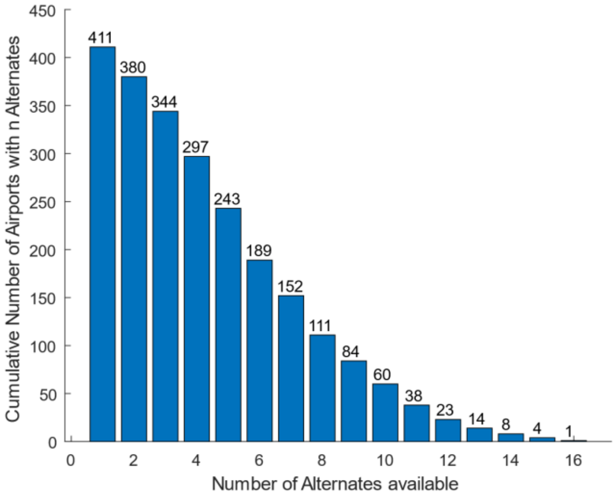


Figure 6. Cumulative number of airports that have *n* available alternates within reach by the defined reserve distance

The three airports not included are highlighted in Figure 7 with a circle representing the defined reserve distance. We can see that the airports of Lisbon (LIS) in Portugal, Flores (FLW) on the Azores and Longyearbyen (LYR) on Svalbard lack an adequate alternate airport.

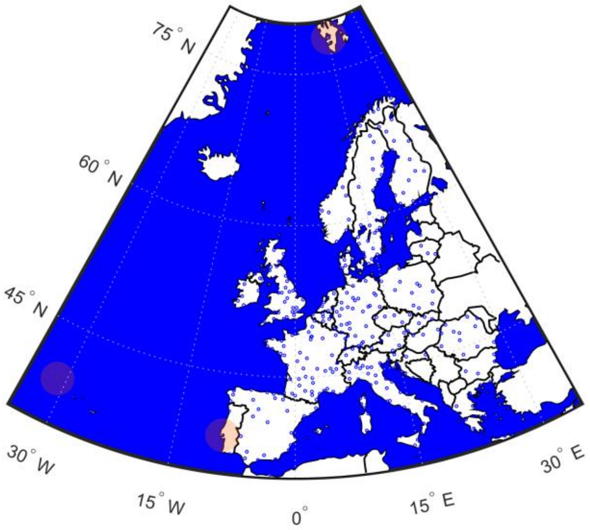


Figure 7. Airports that have no alternate in reach with the specification given in the TLARs.

The farthest distance to an available alternate is 945 km for Longyearbyen, which is longer than the maximum range of the aircraft; therefore, the airport is not relevant for the analysis. This leaves a number of 413 airports investigated in total. For the other two airports, the distance to an alternate equals 234 km for Flores and 201 km for Lisbon.

To better account for operational aspects, two safety factors are introduced for a second study. First, a safety margin should be applied in order to derive from the theoretical range of the great circle to a practical range. For this, a distance increase by 5 % was assumed. Second, a safety factor should consider adverse headwind conditions, which increase the energy required to reach the diversion airport. If a "fresh breeze" on the Beaufort Scale is assumed as the reference value with wind speeds up to 38 km/h, the flight time of an aircraft with a cruise speed of 550 km/h would be increased by around 7 % and consequently the required energy for the flight is increased accordingly.

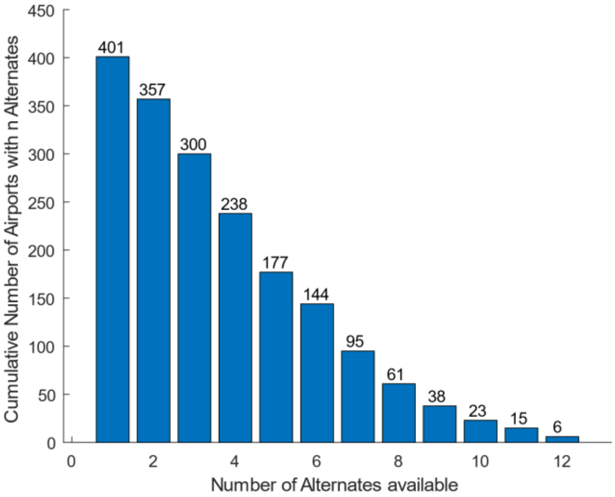


Figure 8. Cumulative number of airports that have *n* available alternates within reach by the defined reserve distance including safety factors for practical range and adverse headwind

Figure 8 shows that including safety factors the number of airports without any alternate within reach is increased by ten. With 3 %, the fraction of airports with no alternate is still small. For these twelve airports, the distances required vary between slightly over 185 km up to 263 km, again with Flores on top. This shows that even with unfavourable conditions the selected reserve policy is suitable for most airports in Europe.

It must be mentioned that some airports do have potential alternates within the defined range without being recognized in this calculation. That is because they do not meet the requirements previously set, e.g. within Lisbon's range, Beja airport (BYJ) is not serviced by any regular scheduled flights at the moment and has a yearly passenger volume of less than 15,000 passengers.

For the second case, the distance to an en-route alternate is expected to be lower than it is after having already reached the planned destination. Even when the distance to an alternate en-route is higher than the defined reserve distance, the aircraft still has the energy for the remaining trip, which then could be used to reach an alternate. In case of an HEA with different energy sources like fuel and batteries this might require that there is no single point of failure within one system part. Otherwise, if only one combustion engine and generator are installed and one component fails, the battery might not be able to provide the required energy to reach any airport.

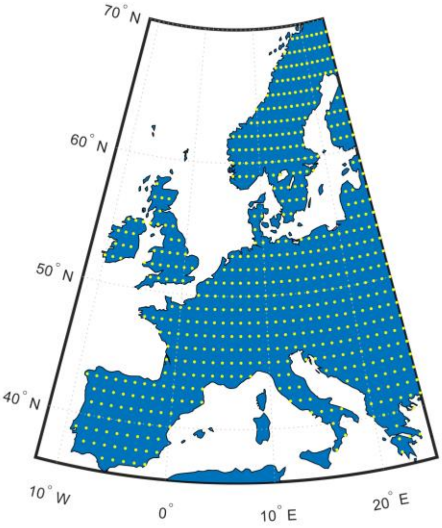


Figure 9. Exemplary visualization of investigated aircraft positions in Europe with a spacing of 1° in latitude and longitude – the calculation was carried out with a spacing of 1/60° which results in a maximum spacing of approximately 1 NM

In order to determine the distance to the nearest suitable en-route alternate airport, a mesh of possible aircraft positions over land was created expressed in latitude φ and longitude λ. Aircraft positions over sea and islands, except for Great Britain and Ireland, were excluded at this stage. The mesh applied in the calculation consists of positions with a spacing of 1/60° in latitude Δφ and longitude Δλ, which corresponds to a maximum spacing of approximately 1 nautical mile. In Figure 9, an exemplary mesh is shown with a spacing of 1° in latitude and longitude. Consequently, the shortest distance of each aircraft position to the suitable en-route alternate airports is determined by calculating the length of the great circle to each individual airport and determining the minimum value. With the data obtained, a cumulative frequency plot was created.

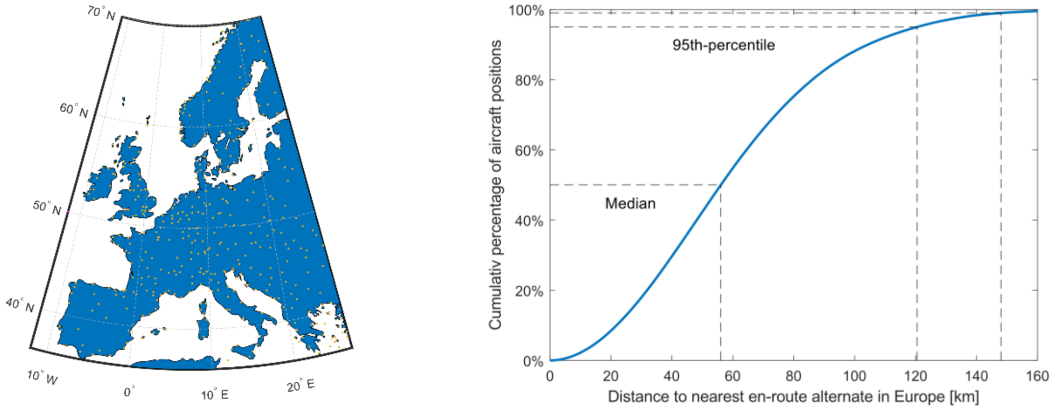


Figure 10. Possible alternate airports (left) and plot of cumulative frequency of the distance to a suitable en-route alternate with a concrete or asphalt runway (right)

Figure 12 shows the database of alternate airports on the left and the resulting curve for airports within the investigated parts of Europe featuring a concrete or asphalt runway with a field length of more than 1000 m on the right. Suitable diversion airports from 95 % of all investigated aircraft positions can be reached within 120 km. A percentage of 99 % can be reached within 148 km and the farthest distance is 198 km southeast of Madrid (38.8° N, 2.75° W).

The maximum error of the calculation is evaluated by considering the distance of a possible aircraft position which is located exactly in between the mesh of evaluated aircraft positions and can be determined to be 1.26 km [17]. For this evaluation, similarly to the first analysis, safety factors for deviations from the great circle and headwind conditions were not applied.

2.3 Operations

To ensure operational flexibility for an aircraft capable of servicing many airports and achieving high utilization, operational aspects have to be considered as top-level requirements (see Table 3).

Table 3. Top-Level Aircraft Requirements regarding operational aspects

TLAR (operations)	Value
Wingspan	< 36 m
Weather operations	All weather
Turn-around time	≤ 25 min

ICAO Annex 14 [18] defines categories by which an aerodrome is rated. The number is related to the reference field length and the letter is based on the wingspan of the airplane. For the HEA, a category 2C aerodrome is required by the TLAR definitions. The "lower" the category, the more airports are available to be serviced by the aircraft. The letter C refers to the maximum wingspan of less than 36 m. This is similar to the ATR which has a wingspan of just more than 24 m. A lower airport category seems not to be feasible as the limit for category B is 24 m. Future aircraft will likely have higher aspect ratios than the ATR and with an expected higher Maximum Take-off Weight (MTOM) for an HEA also the wing area will be increased to have a similar wing loading.

Another aspect of particular interest with respect to utilization is the weather conditions the aircraft is capable to operate in. As the goal is to design an aircraft for commercial operations, the general dispatchability should be high. Therefore, obviously the aircraft must be capable of operating in all weather conditions including ice and cold conditions, for example.

To further increase productivity, a turn-around time of no more than 25 minutes should be obtained. This is comparable to current regional aircraft like the EMB-145 or the De Havilland DHC-8-300 [19,20].

2.4 Performance

In Table 4, the TLARs regarding performance are given for a regional 50 passenger aircraft. Within the following paragraphs, each requirement and the reasoning behind it will be explained.

Table 4. Top-Level Aircraft Requirements regarding performance

TLAR (Performance)	**Value**
Design cruise speed	450–550 km/h (Mach 0.40–0.48)
Design payload	5300 kg
Maximum payload	5800 kg
Design range (design cruise speed, design payload)	400 km + reserve
Maximum range (design cruise speed, design payload)	800 km + reserve
Reserve fuel policy	185 km + 30 min holding
Range from hot & high airports (design payload, ISA +28, 5400 ft)	450 km + reserve
Range from cold airports (design payload, ISA –30)	450 km + reserve
Take-off field length (MTOM, SL, ISA, paved)	≤ 1000 m
Take-off field length STOL (SL, ISA, paved, > 80 % pax)	≤ 800 m
Landing field length (SL, ISA, paved)	≤ 1000 m
Rate of climb (MTOM, SL, ISA)	≥ 1850 ft/min
Rate of climb @ top of climb	≥ 1.5 m/s (300 ft/min)
Time to climb to FL 170	≤ 12.7 min
Maximum operating altitude	7620 m (25,000 ft)
Service ceiling for OEI (or equivalent) (95 % MTOM, ISA +10)	4000 m (13,125 ft)

The design cruise speed is set to 450–550 km/h, which is comparable to current turboprops. Reducing this speed would harm productivity of the aircraft by affecting the number of dispatches per day. Increasing it will raise the number of dispatches but more excess thrust or power is required to accelerate the aircraft. Therefore, the aircraft mass might increase which limits the benefits gained. The design payload of 5300 kg is calculated by the number of passengers multiplied with their mass including luggage, which is estimated to be 106 kg. The maximum payload of 5800 kg is defined by the design payload plus 500 kg of cargo mass.

The take-off field length (TOFL) is characterized by two values. The first one is for standard operation with full capacity, here the TOFL is defined as 1000 m. The second one is defined for short take-off and landing (STOL) to allow access to smaller airports — here a TOFL of 800 m is required for a passenger load factor of more than 80 % compared to full capacity. The exact achievable load factor for this requirement will be a result of the final design and the grade of optimization for standard operations. Additionally, both field lengths are the criterion for landing as well. This means that for the two different kinds of operations, the landing field lengths must be no greater than 1000 m and 800 m, respectively.

All these field lengths depend on the maximum lift coefficient, where a “certifiable” coefficient should be reached. “Certifiable” describes that, for example in case of high-lift distributed propulsion, the aircraft must still reach an acceptable sink rate in descent. If the thrust generated for the required lift would exceed the drag of the configuration, the aircraft would climb instead of losing altitude. In this case, energy harvesting could be beneficial for the overall aircraft. In general, if a novel high-lift system is used, it must have equivalent safety compared to current conventional technology in all possible conditions, e.g. crosswinds. To address this the National Aeronautics and Space Administration carried out initial analyses for the Maxwell X-57 and made suggestions for the design of high-lift distributed propellers [9].

The minimum rate of climb at maximum take-off mass (MTOM) in international standard atmosphere (ISA) conditions at sea level (SL) is set to 1850 ft/min, which is comparable to the ATR 42 today [10]. This ensures operational capabilities and allows the operators to service equivalent routes than current turboprop aircraft.

For the rate of climb at the top of climb 1.5 m/s or 300 ft/min is defined. This ensures the aircraft’s ability to perform manoeuvres to avoid collisions when cruising at the top of climb. This value might change in the future if airspace rules dynamics change.

The overall climb performance is defined by the time to climb to FL 170. This criterion makes the climb comparable to other aircraft (ATR 42-600: 12.7 min [10]) because power, and therefore the rate of climb, depends on altitude for air-breathing propulsion. In hybrid-electric aircraft, these losses could be countered by the battery.

As maximum operating altitude FL 250 or 7620 m is defined for a few reasons. Firstly above that altitude, a redundant air management system is required (CS 25.841) [11]. This would result in a higher system complexity and an increase in total aircraft mass. Secondly, due to the typical turboprop mission duration of one hour, a higher cruise altitude is often not required as it will result in a longer climb segment. This will not only require more power but also more fuel which might not be offset by a more efficient cruise in higher altitude. Furthermore, the passenger comfort is increased when the cruise segment takes up a significant portion of the overall flight. Lastly, it is expected that the formation of aviation induced clouds and contrails at that defined altitude and thus the climate impact of the aircraft is significantly lower [12].

The service ceiling with one engine inoperative (OEI) is set to 4000 m or 13,125 ft to overfly mountain ranges in most regions of interest to air traffic and is comparable to current turboprops [10]. This criterion is set for 95 % of MTOM and ISA +10. For the HEA, the term OEI must be adapted in relation to the selected power train architecture and propulsor configuration.

2.5 Regulatory Aspects

In general, this type of aircraft must comply with CS-25. An HEA is not fully certifiable under current regulations in place. Some gaps have already been identified. For example, a battery could be used as redundancy within a serial architecture and therefore one gas turbine might be enough for a safe design.

Also looking at novel propulsion concepts like distributed propulsion, a new definition of the OEI condition is needed. Not limited to distributed propulsion, the overall propulsion architecture will need analysis. Depending on the interdependencies of different systems and their redundancies, a similar definition might emerge. Due to the complexity of the HEA architecture, this could be individual for each aircraft or architecture.

Other aspects might be electromagnetic interference or electromagnetic compatibility due to the required power of the overall aircraft. Also relevant are voltage levels and in connection the breakdown voltage of the insulator. On the other hand, the required power and the voltage level define the current, which in the end drives the cross section of the conductor and therefore mass.

3 Mission Priorities and Reference Flight Missions

The requirements and evaluation criteria serve as a framework for the output data that will be generated in the aircraft design. Those parameters depend, e.g. on weather (ambient temperature in particular), on energy management strategies, and also on the flight route and profile. Therefore, various reference flight missions were developed in the frame of FUTPRINT50, so potential markets for the regional aircraft can be analysed:

- Design Range
- Maximum Range
- Cold Operations
- Extreme Cold Operations
- Hot and High Operations
- Mountainous Terrain
- Island Operations
- STOL Operations

For these missions, an advantageous position on the market may be anticipated for the regional HEA developed within FUTPRINT50. In regions with excellent railway systems, the regional HEA will not be able to prevail due to its limited seat capacity. However, specific markets come into play where no other means of transport can compete. This concerns routes where rough terrain or water lies in between or infrastructure like railway or road networks are less developed.

A typical mission can be represented by the route from Edinburgh, United Kingdom to Dublin, Ireland (EDI–DUB). The great circle distance for this route is 338 km. However, the distance has been increased by 7 % to account for possible headwind and 5 % for airways and navigation. All other routes presented have the same increase in distance. It leads to a design range of 380 km which represents the definition by the TLARs very well. The alternate airport for Dublin is Belfast (BFS) which is located ca. 140 km north. After adding all contingency reserves, this route represents the defined distance to an alternate airport (185 km) very well. Figure 11 shows the flight route and its altitude profile. This also includes the flight to the alternate airport and thirty minutes of loiter at 175 knots. It becomes apparent that the reserve is a significant part of the whole flight mission and must not be neglected.

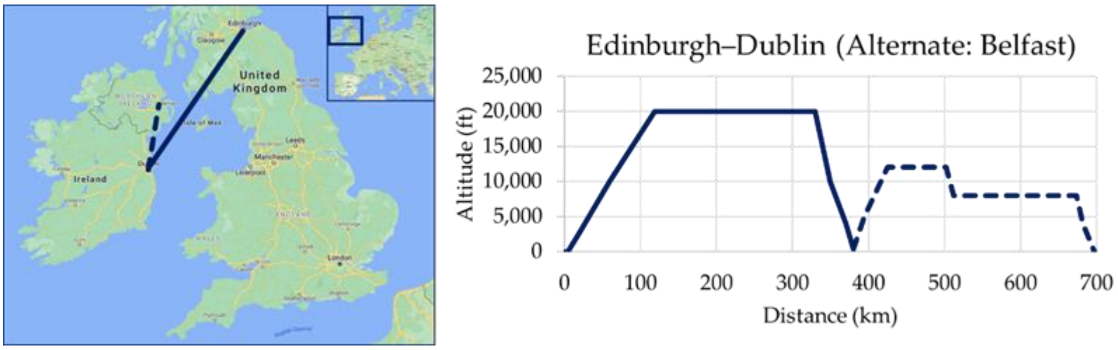


Figure 11. Exemplary flight route and profile of the design range mission EDI–DUB (Edinburgh, United Kingdom to Dublin, Ireland) (including the flight to the alternate BFS (Belfast) and a holding of 30 min)

For the investigation of low temperature impacts, a flight route in Iceland is selected. The flight from Reykjavík to Egilsstaðir (RKV–EGS) is a common route serviced by a De Havilland Canada DHC-8. The average temperature at both airports is about ISA –10.

In order to account for the effects to the powertrain in even colder temperatures, the flight route from Yakutsk to Vilyuisk (YKS–VYI) in Russia is examined. The average winter temperature can reach up to ISA –55 (–40 °C).

As mentioned earlier, the regional HEA will be able to compete on routes where other means of transport lack required infrastructure. This is also the case in the mountainous terrain from Lima to Ayacucho (LIM–AYP) in Peru. This flight route requires a steep climb right after take-off to reduce detours; this will challenge the climb performance of the aircraft design. Furthermore, a Missed Approach Procedure at an airport elevation of 2720 m is included on this route.

In order to test the TLAR for hot and high missions, the flight route from Mexico City to Acapulco (MEX–ACA) in Mexico was selected. The elevation of the airport of Mexico City is 2230 m which translates into a 20 % reduced air density compared to SL. Furthermore, Mexico City shows an average daytime temperature that lies 10 °C above ISA conditions.

Island operations describe a mission which restricts refuelling to only take place at one airport. This can be simulated by flight operations from São Tomé to Príncipe (TMS–PCP) and back. It must be noted that the distances of each leg may not be simply added up to one round trip. The need for two take-offs and climbs is expected to play a major role on the total energy required.

To account for the STOL capabilities of the aircraft, the flight route from Corvo to Horta (CVU–HOR) in Portugal was included in the list of reference missions. With a flight distance of about 270 km, both airports are located on separate islands in the Azores. The runway in Corvo offers an available take-off run distance of only 800 m. Table 5 shows a summary of the flight mission profiles selected along with each of their specific reasoning.

Table 5. Selection criteria for chosen flight missions.

Flight Mission	Route	Special Characteristic
Design Range	EDI–DUB	ca. 400 km, competing transport via 2-hour ferry
Maximum Range	TJM–NJC	ca. 800 km, 13 h by car, 17 h by train
Cold Ops	RKV–EGS	Temperature ISA –10
Hot and High	MEX–ACA	MEX: Elevation 2230 m, Temperature ISA +10
Extreme Cold Ops	YKS–VYI	Winter temperatures around ISA –55 (–40 °C)
Mountainous Terrain	LIM–AYP	After take-off: 3000 m at 80 km, 4500 m at 150 km
Island Ops	TMS–PCP	Two 200 km-legs without refuelling
STOL Ops	CVU–HOR	CVU: Runway length 800 m

4 Figures of Merit

Within the aircraft design process, numerous unique aircraft configurations are generated especially in the conceptual design phase. In order to assess those models as objectively as possible, various evaluation criteria, the so-called figures of merit, must be defined. While the TLARs described in Section 2 establish a framework of the aircraft design, the figures of merit quantify how well the design performs within the given evaluation criteria. In general, all quantifiable output parameters of the aircraft design process can serve as figures of merit. They are then utilized to rate and compare the configurations on the basis of those parameters. In Section 4.1, parameters from the aircraft design process are presented which serve as input data for the figure of merit. The more design parameters are considered, the better the assessment of the aircraft design might be. However, using a lot of parameters can also make an evaluation less transparent and more complex. Hence, a selection process for meaningful, quickly graspable figures of merit is important. This is described in Section 4.2.

While the separate parameters can compare isolated disciplines of the aircraft design, a combination of these parameters can form one aircraft-level figure of merit which rates the entire aircraft design (see Figure 12). By means of a calculation method described in Section 4.3, the aircraft-level figure of merit is constructed as a number between 0 and 1. On that scale, a better design—based on the evaluation criteria set—translates into a higher score.

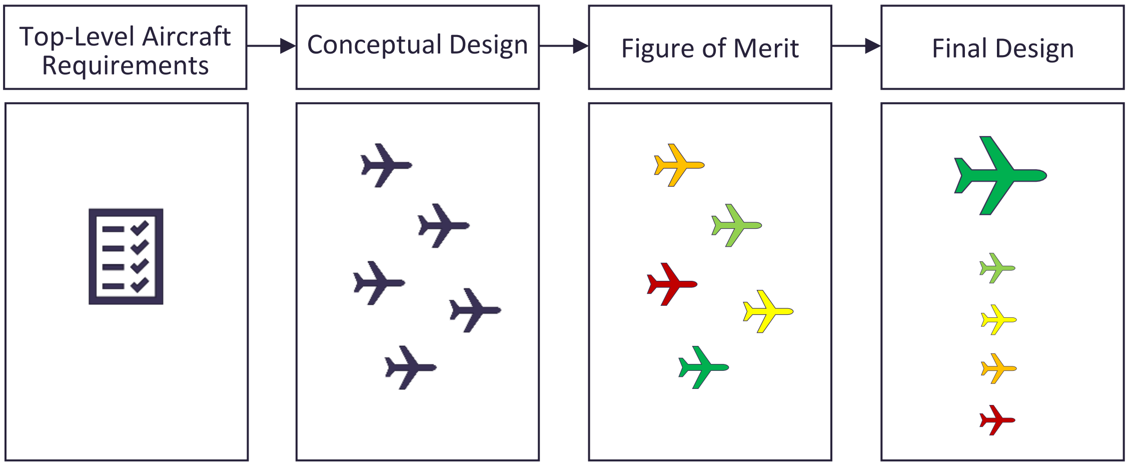


Figure 12. General application of the evaluation concept *figure of merit*

4.1 Input parameters

The figures of merit are fed by parameters from the conceptual aircraft design that serve as input data. These data are normally imported from automated design tools which calculate numerous design alternatives at once. The input parameters are divided into the following three categories: Aircraft characteristics, hybrid-electric architectures, and energy management strategies.

The first category offers input data of the selected aircraft configuration which gives information e.g. about the placement of wing, tail, and landing gear. Furthermore, all dimensions of the main components are collected to describe the geometry of the aircraft in detail. This geometric data is used to generate the component and overall masses which also play a major role within the evaluation of the aircraft design.

The hybrid-electric architecture accumulates data about the propulsion systems of the investigated designs. One important item is the degree of hybridisation which states the percentage of the electric power in regard to the total output power. Therefore, it serves as a figure which defines the architecture of the powertrain [23]. Moreover, the installation of different technologies is also described in this category. This may refer to various types of primary movers, fuels, and other technologies.

The final input data needed are the energy management strategies. Those strategies define ways to split the different energy sources like the usage of the gas turbine and battery.

4.2 Identification of the Figures of Merit

To find the most suitable figures of merit, all parameters generated in the aircraft design are processed through different criteria [9]. These criteria form a filter that excludes figures of merit that do not affect the overall evaluation of the aircraft in a significant way and are, therefore, discarded. The filter comprises four criteria:

1. Limitations that are defined by TLARs
2. Design parameters that are fixed
3. Parameters that do not change significantly between different designs
4. Parameters that are expressed through higher-level ones

The first criterion discards figures of merit that do not influence the assessment because of limitations by the TLARs. An example for this criterion is the parameter of aviation induced cloudiness. As shown in Section 2, a maximum operating cruise altitude of 25,000 ft was chosen for the regional aircraft developed within the FutPrInt50 project. Since aviation induced cloudiness is mainly expected to form in altitudes higher than that [16], this figure of merit can be discarded.

Fixed design parameters act as second criterion. Some parameters must remain unchanged during a design process. For example, the maximum range is a hard requirement stated by the airlines. Falling short of it is not an option. However, exceeding it will make the design not necessarily better either; the design may become less efficient on shorter ranges because of an increased operating mass empty.

The third criterion filters out parameters that do not change significantly. This may be valid for parameters that only vary in case of major technology changes. Switching from conventional jet fuel to hydrogen will impact the ground handling and servicing for every aircraft design similarly. This is why it can be neglected.

The last criterion discards any figure of merit that can be expressed by a higher-level one. As an example, cruise speed is often defined as a figure of merit because it can have an influence on the number of possible dispatches. However, it is also interconnected with fuel consumption and many other characteristics. All of those aspects can be combined within the DOCs.

Additional parameters in regard to the entire life cycle like CO_2 emissions of the production or end-of-life phase are not considered.

This selection process leads to seven figures of merit listed in Table 6, divided into three categories. These seven meaningful parameters evaluate the quality of the regional HEA developed within FutPrInt50 and can be used as a basis for the assessment of future concepts in this aircraft category. The separate figures of merit will be explained in more detail in the following sections, grouped per category.

Table 6. Summary of figures of merit selected in the frame of FutPrInt50.

Environmental Aspects	Airline Desirability	Introduction of Hybrid-Electric Aircraft
CO_2 emissions	Direct operating costs	Development risks
NO_X emissions		Certification challenges
Noise emissions		Production aspects

4.2.1 Environmental Aspects

The Environmental Aspects that are chosen for the figures of merit compare to the goals set in Flightpath 2050. As the CO_2 emissions of an aircraft strongly depend on fuel flow, the energy management strategy and the level of hybridisation will be made visible here. Another environmental figure of merit is the emission of NO_X. It can mainly be lowered by improving the combustion characteristics of the engine. While its atmospheric effect is important to consider due to ozone forming, it is also a relevant pollutant in the vicinity of airports [22].

The same issue corresponds as well to the noise emissions. Noise is a very important aspect in order to ensure the health and well-being of citizens living close to airports. Although noise is difficult to analyse in the early design process, engineers can roughly estimate it by focusing on components protruding from the aircraft profile like landing gear or flaps. Another key element is the positioning of propulsion components and potential shielding like a ducted fan would offer.

Major contributions to these aspects can be provided by an optimum energy management strategy which is adaptive to the current state of operation. This offers the potential to reduce emissions overall or just in particular flight segments close to the ground.

4.2.2 Airline Desirability

Operators are the main drivers for aircraft specifications, and appealing to them is of major importance for every design. Since cost is an essential parameter in the airline industry, the DOCs are the main driver of the Airline Desirability.

$$DOC_{\text{Total}} = DOC_{\text{Capital}} + DOC_{\text{Maintenance}} + DOC_{\text{Energy}} + DOC_{\text{Fees}} + DOC_{\text{Crew}}$$

The DOCs are divided into five segments which consist of capital costs, maintenance costs, energy costs, crew costs, and (navigation) fees. They can be given in different units: Per flight, per year or per 100 available seat kilometres. Nowadays, the capital costs claim around one third whereas the remaining sections each split up to one sixth of the total costs [24]. With the introduction of disruptive propulsion technologies however, this distribution might shift. In the following, the costs are broken down into detailed descriptions which makes the impact of using hybrid-electric powertrain technology more conceivable:

$$DOC_{\text{Capital}} = DOC_{\text{Structure}} + DOC_{\text{Systems}} + DOC_{\text{Equipment}} + DOC_{\text{Powertrain}}$$

The capital costs represent the acquisition costs of new aircraft. The costs of airframe structure, aircraft systems and equipment can be expressed as a function of the operating mass empty [25]. The last term of the equation consolidates all components of the hybrid-electric powertrain, namely gas turbine and battery as well as electric motors, electric cables, inverters, converters and rectifiers. Additionally, a spare parts factor is introduced which gives the opportunity to consider the effect that electric components need fewer replacements than e.g. the gas turbine [23].

To transform the unit costs into yearly costs, all DOCs listed in this equation are multiplied by factors for depreciation rate, interest rate, insurance rate and a residual value factor [25].

$$DOC_{\text{Maintenance}} = DOC_{\text{Maint Material}} + DOC_{\text{Maint Personnel}} + DOC_{\text{Maint gas turbine}}$$

The DOCs of the maintenance contain material costs which are needed for repairs and replacements. In addition, the maintenance personnel for inspections and repairs is included. Furthermore, a separate term for gas turbine maintenance is used as different dependencies apply [26]. Maintenance costs in general are expected to decrease just slightly as—despite the less complex electrical system—hybrid-electric powertrains combine two different system. Those two effects nearly balance each other out [26].

Energy Costs

$$DOC_{\text{Energy}} = DOC_{\text{Fuel}} + DOC_{\text{Electric energy}} + DOC_{\text{Carbon pricing}}$$

The energy costs are highly dependent on many parameters like cruise speed or energy management strategies, all of which are defined by the reference flight missions. They contain costs for jet fuel or hydrogen an electric energy for charging the batteries and potential supercapacitors. Furthermore, additional liabilities could emerge through carbon pricing. As they are directly proportional to the fuel spent, this will be kept in the energy group.

$$DOC_{\text{Fees}} = DOC_{\text{Navigation}} + DOC_{\text{Landing}} + DOC_{\text{Ground handling}} + DOC_{\text{Environmental taxes}}$$

The DOCs that arise from the fees that are due for using the airways (navigation fees), for using the airport (landing fees) and for using the ground services (ground handling fee). Additionally, environmental taxes may be put in place in the future.

$$DOC_{\text{Crew}} = DOC_{\text{Pilots}} + DOC_{\text{Flight attendants}}$$

The last bracket of the costs that result from operating an aircraft are the labour costs for flying personnel. This contains the salaries of the pilots and flight attendants.

Beside operating costs, the potential of generating income is an important aspect for airlines as well. Here however, it is assumed to stay the same as seat capacity and passenger comfort remain unchanged. Though, it may be included in further enhanced models within the following work packages.

4.2.3 Introduction of Hybrid-Electric Aircraft

The figures of merit in the category Introduction of Hybrid-Electric Aircraft cover the risks in development as well as the expected challenging certification process and overall production aspects. The first item represents the risks for the manufacturer developing the HEA. This includes challenges that might occur in the design process of not only the overall aircraft but also of all required components and subsystems. To address these topics, an estimation is made in relation to the technology readiness level of identified key technologies.

Certification is the second part within this category. Currently, EASA’s CS-25 offers no guidelines how to certify hybrid-electric aircraft. By assessing the complexity of the system, an estimation can be made about the amount of testing required for certification. Furthermore, adding novel propulsion concepts like distributed electric propulsion will increase complexity even more and therefore require additional verification.

Lastly, the selection of material and the application of processes also impose risks on different designs. Again, the newer and more complex the technology, the higher the overall risk for unforeseen difficulties in production. All these criteria are difficult to quantify and must oftentimes be objectively estimated by the engineer.

4.3 Calculation of the Aircraft-Level Figure of Merit

With the selected figures of merit, a new process becomes necessary: The separate figures of merit presented before must be merged into one single aircraft-level figure of merit which evaluates the entire aircraft configuration [9]. This helps by comparing different concepts and identifying which of the designs is the most promising one for further development. The scheme of this method is shown in Figure 13.

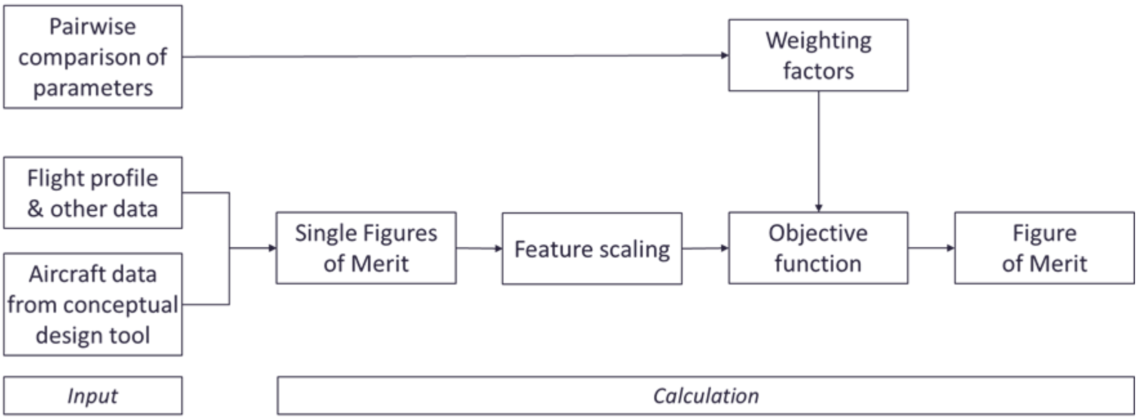


Figure 13. Calculation method for the figure of merit

The first step of the calculation method consists of combining two major input data. The design tool provides all required aircraft data like dimensions, masses, and aerodynamics. Further input contains data about the flight profile, energy management strategies, ambient conditions, etc.; this depends on the chosen reference mission. The following module *Single Figures of Merit* calculates the seven single figures of merit that were previously selected. As those separate figures of merit are all given out in their individual unit, they need to be feature scaled so they can be combined into one. Feature scaling is a method which removes all units and resizes all the different values of the figures of merit onto a rating scale. This is done by analysing all values of each parameter and assigning the scores 0 and 1 to the lowest or highest value. The remaining values are scaled correspondingly. However, it is important to note that the lowest score does not necessarily coincide with the lowest value. This is because a lower value in emissions, for example, will lead to a higher score on the assessment scale.

Furthermore, the resulting equation also consists of weighting factors. They are mostly generated by a pairwise comparison in a table. In the case of the different emissions of greenhouse gases however, the parameters are weighted by their different impacts on the environment. This constructed equation forms the so-called objective function. It consists of weighted and normalized parameters which are then combined into the aircraft-level figure of merit. The flexibility of this weighting allows us to identify designs with different focusses, for example, prioritizing environmental aspects over costs or vice versa. In the end, various sets of weighting factors can be applied, where each set represents a specific focus that shall be analysed.

This process leads to a single number, which represents the figure of merit on the aircraft level. This number will then be used to assess all the aircraft designs that need to be compared.

Dividing the parameters into different categories and sticking to that strict workflow has the advantage that the structure of the figures of merit is established in a modular way. For example, a function of power, specific fuel consumption, and time quantifies the CO_2 emissions, which merge into the environmental aspects. So, the modular approach allows for building a figure of merit that consists of others, merging into the single aircraft-level figure of merit. This means that if any outcome of a figure of merit is unclear, it is always possible to go one level deeper to understand the characteristics of that specific figure of merit. This provides transparency, traceability, and plausibility. Another advantage of the modular approach is the simple implementation of modifications. When an additional figure of merit is identified, it can be added by changing only one module of the entire workflow. This allows an easy integration of figures that were previously discarded – it is also thinkable to select a modular approach within the code. For example, the maximum altitude or cruise altitude could be analysed and based on this value, contrails are included or discarded in the environmental aspects.

After all calculations, the separate figures of merit can be shown on a radar chart (see Figure 14 on the left). This allows a quick evaluation of the aircraft design subject to all separate figures of merit. The bar chart on the right gives the opportunity to quickly capture the score of the different evaluation categories and the overall aircraft-level figure of merit. Therefore, the figure of merit method helps to find the best design out of many different concepts.

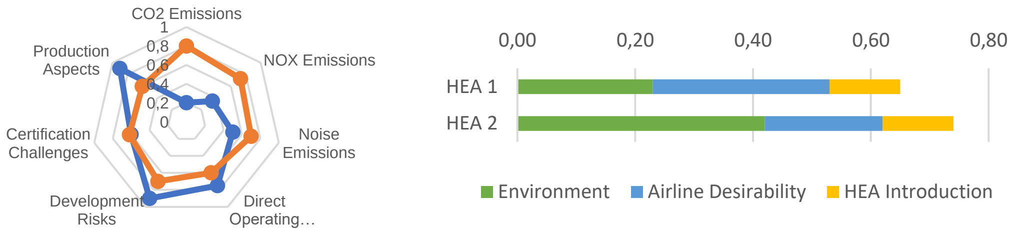


Figure 14. Charts visualizing separate figures of merit and aircraft-level evaluation.

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5 Energy Management Strategies

5.1 Introduction

In the case of hybrid-electric aircraft, several energy sources and power distribution paths are available. Energy management strategies can be used to explore and optimize how the available energy onboard the aircraft can be used. Energy management strategies can be incorporated at design as well as at operational level. For this reason, a multi-level optimization approach is proposed. Selected energy management strategies can be used to compare and assess the potential designs during the design space exploration phase. In this case the impact of an energy management strategy on the design and selection of the architecture and the sizing of the aircraft will be evaluated. An example may be the desire to eliminate net emissions or carbon emission during the climb phase of the mission. Such a decision is likely to define the architecture (use of batteries or fuel cells in the case of zero net emissions as well as hydrogen fuelled gas turbine) as well as the size of the energy storage and the distribution system. Furthermore, the energy management strategies will be used during the operational evaluation of the selected designs. For fixed aircraft size, propulsion architecture and energy sources different energy management strategies would be used to assess how the design can meet changing mission objectives and priorities as well as optimize the overall utilization of the energy available.

5.2 Background and General Observations

Energy management strategies can be characterized by three main parameters:

- Degree of electrification in terms of power: electric power available over total power available
- Degree of hybridisation in terms of energy: electric energy stored over total available energy
- Utilisation or Activation factor: a dynamic parameter that denotes where and how the available energy is used.

In terms of Degree of Hybridisation (energy), it must be noted that different optimums can be achieved including

- Minimum mission energy
- Minimum fuel consumption

These two parameters in the case of a hybrid-electric aircraft are different. Although overall energy and overall efficiency is very important, reduced fuel consumption can have a major impact in terms of tail-pipe emissions and as such should be considered separately. Preliminary studies have confirmed that minimum energy results to a lower degree of hybridisation in terms of battery (lower battery mass) while minimum fuel consumption results to a higher degree of hybridisation (increase battery mass) for a given battery specific energy. The variation between these two optimums can be significant and the overall saving can also vary significantly, for example a 20% reduction in fuel may be translated to only 5% reduction in energy and in some extreme cases it may be possible to have fuel savings in excess of 25% while the overall energy saving may be close to zero or it may even be negative, i.e. increased energy consumption relative to a conventional state of the art design. The main reason for this variation is the extra mass of the hybrid-electric system due to the increased mass of the batteries that can lead to increased energy consumption. The actual variation depends on the size of the aircraft and the mission considered. The smaller the aircraft and the shorter the range the smaller the variation between these two optimums.

In this context, in order to reduce fuel consumption and tail pipe emissions an increase in the size and take-off mass of the aircraft may be required to allow for more energy to be stored in batteries and increase the degree of hybridisation in terms of energy. However, it also needs to be noted that there is a limit to the desired increase in maximum take-off mass and the re-scaling capability of the aircraft as there is a snowball effect. This would mean that the extra mass would require extra energy which in turn will increase the mass of the battery. As the mass of the aircraft increases the extra energy stored in the batteries is used to carry the mass of the batteries rather than reduce the fuel consumption. This snowball effect is more pronounced at full electric and high degrees of hybrid designs. This effect can be mitigated by the following measures:

- Increase specific energy and specific power of electrical components and batteries
- Increase aerodynamic efficiency – through distributed propulsion including wing tip propellers and boundary layer ingestion
- Increase the ratio of the operating empty weight of the aircraft over the maximum take-off weight of the aircraft.

The latter parameter is driven by the structural efficiency of the aircraft and is of particular interest in the case of a hybrid-electric or full-electric aircraft because it allows for more energy to be stored for a given maximum weight. In terms of energy management preliminary studies also suggest that using the fuel first can improve overall system efficiency. Using the fuel first would result in a lighter aircraft with reduced thrust requirements when the electric energy will be used. As such, the effective utilization of the energy stored in the batteries will increase.

In terms of energy management strategies, it should also be noted that for a given amount of energy stored in batteries not all phases are the same. Comparing climb with descent for example could give different results. If a relatively low degree of hybridisation is used, using the available energy stored in batteries during the descent phase may be more beneficial, the following factors will contribute to that effect:

- Descent requires moderate levels of power and energy and as a result a given amount of energy will constitute a higher percentage of battery energy relative to the energy requirements for the descent rather than the climb. As such the impact will be more noticeable
- The gas turbine is operating at very low efficiency during descent and the overall efficiency benefit will be more noticeable
- There is no need to oversize the electrical and energy storage components – even moderate levels of power/energy can meet the requirements at descent and potentially even eliminate fuel usage.
- In the case of a regional aircraft the energy used during the descent phase is still a significant portion of the total energy and can account for 20% of the total mission energy leading to significant savings.

Despite the advantages of using electric energy during the descent phase there are still significant benefits when considering high power operations such as climb and take-off. Using electric power during these phases can:

- Reduce life consumption of the gas turbine: reduced temperature will reduce creep life and oxidation life while reducing power setting variations (variations in rotational speed and temperature/pressure) will reduce damage associated with fatigue and cycling loading. Regional aircraft are characterized by cycle loading.
- Reduce NO_X emissions – NO_X emissions increase with engine overall temperatures and pressures which in turn are required to increase overall efficiency
- Reduce gas turbine degradation by operating the engine at lower power setting and reducing fouling and erosion
- Improve stage performance including take-off distance, take-off at high elevation and hot conditions, increase rate of climb.
- Electric power can be used to overcome the effect of engine ageing and engine degradation/deterioration improving operational flexibility as well as time on wing and minimizing disruptions

The latter can be very beneficial. Time on wing is driven by the following parameters:

- Life limited parts – components are classified as critical parts if their failure can lead to loss of life, i.e. a catastrophic failure. In the case of twin-engine aircraft any failure that cannot be contained within the engine is classified as a catastrophic failure and the component is classified as critical component. Shaft and discs are typical critical components because their failure is very difficult to contain within the engine. Blades on the other hand are not usually classified as critical components because the casing can be designed to contain them if they fail. Critical parts have a predefine limit in terms of life. This is a hard limit and

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does not depend on the condition of the component. Once the limit is reached the component needs to be replaced regardless of its condition. Electrification can affect this limit at the design phase of the engine and can increase the life of life limited parts when used at high power settings
- Performance degradation/restoration: while in operation the power/thrust of the engine will deteriorate due to degradation. As the engine is certified for a fixed output the degradation needs to be compensated by increasing the turbine entry temperature of the engine to keep the output constant. There is a limit to how much this temperature can be increased during operation and when this limit is reached the engine needs to be removed from operation and its performance needs to be restored/recovered. In the case of a hybrid-electric system, once this limit is reached the electric part of the architecture can be used to supply the additional output and compensate the reduction of the output from the gas turbine without exceeding the temperature limitations of the engine, thus increase time on wing.
- Soft life of components: components like blades and stators, linings, etc. that are not classified as life limited parts can be replaced based on their condition. Since there is no hard limit the decision to replace the component is driven by the condition of the component and this is called soft life. A hybrid-electric system can allow for reduced temperatures and stresses at high power levels to preserve life of such components and extend operations.

Which one of the above engine removal drivers dominates depends on the type of engine/aircraft and its operational requirements? Usually the driver is related to the ratio of mission hours to cycles which relates how many hours each mission lasts. This is usually a fleet average. For high values of hours to cycles ratios – i.e. long-range aircraft – the main driver is usually soft life or performance restoration. In the case of low values of hours to cycles ratios, engine removal is driven by life limited parts. In the case of regional aircraft, the ratio is close to 1. This means that each mission lasts around 1 hour. In most cases the removal will be driven by life limited parts or performance restoration (frequent take-off and landings consume the fatigue life and also lead to increase degradation). For a regional aircraft the gas turbine is expected to last for 6,000-8,000 cycle or hours (they are the same as the ratio is close to unity). For comparison a medium range aircraft is expected to complete around 25,000 hours or 15,000-10,000 cycles/missions. The target in terms of cycles or hours also needs to be accounted when comparing the life of batteries. Typical targets are currently around 1,000-1,500 cycles which is significantly lower than the life of gas turbine.

5.3 Practical Considerations

Before considering the various energy managements strategies some practical items may need to be taken into consideration:

- The requirements for e-taxiing may have a detrimental effect on the design of the gas turbine. Gas turbines are subjected to start-up and shutdown procedures. These procedures are employed to ensure the integrity of the engine and avoid sudden variation in the tip clearance. To cope with sudden start-up and shutdown procedures future engine need to have increased tip clearances and actively manage these clearances to ensure that performance targets as well as mechanical integrity requirements are met. Inclusion of active tip clearance control will increase the cost, weight and complexity of the engine
- Gas turbines are affected by altitude variations: increase in altitude reduces power output but increases efficiency. For a conventional gas turbine, the engine will be sized at take-off conditions and the maximum efficiency will be at the top of climb. A typical variation of efficiency throughout Take-off, climb and cruise will be around 3-5% with efficiency at top of climb reaching its maximum of around 38%. Fuel cells will also be affected by variations in altitude. Power output will reduce due to reduce airflow and power required to drive the air compressor. Efficiency will also reduce due to the additional power required for the compressor. On the other hand, electrical components although they are affected by temperature their power output and efficiency are not as sensitive as in the case of gas turbines.
- One of the main challenges associated with fuel cell is the heat generated. For a fuel cell sized at 1 MW power output and 50% efficiency – typical for a fuel cell-500 kW of low-grade heat will be generated. Low-grade heat implies a relatively small temperature difference between the heat source and the heat sink and in the case of a fuel cell this difference could be around 50-100 degrees. Cooling and thermal management requirements of fuel cells for airborne applications may be very challenging.
- When considering operational aspects, it may be necessary to consider recharging or replacing batteries at the end of the mission. Furthermore, it may be beneficial to add or remove batteries depending on the mission flown. As such for a given aircraft the degree of electrification (power) and hybridisation (energy) may depend on operational variables rather than design parameters/variables.
- When sizing hybrid-electric systems, emergency operations and diversion requirements also need to be considered. Based on preliminary analysis it may be more beneficial to consider using a conventional system for the diversion mission and for the reserves, and only use electric power during the main mission.
- Using the gas turbine to recharge batteries may seem like an attractive option but is not efficient, defies the purpose of green and sustainable aviation and can lead to 10-15% reduction in efficiency. On the other hand, it may be necessary to comply with operational targets and in other cases it may allow for emission-

free phases, i.e. zero emission descent or zero-emission climb, etc. without oversizing the electrical system.

- When considering selected operation of the gas turbine – i.e. on-off operation and only use at certain phases of the mission profile the following aspects also need to be considered:
    - Altitude relight can be challenging/hazardous – extra power required from motor. May become a limitation of hydrogen fuelled gas turbine
    - Electric final approach and landing may not be possible as high-power outputs may be required in the case of aborted landing and turn around. In such a case, batteries may need to be sized for take-off requirements as it may not be possible to restart the engine
    - Starting and shutdown sequence: Extra care needs to be taken when shutting down the gas turbine – casing shrinks down faster than disks and blades and the rotor may be damaged.
    - In terms of thermomechanical fatigue and oxidation most damage takes place during shut-down. Rapid shut down damages the metal and the Thermal Barrier Coating:
        - As blades and Thermal Barrier Coatings cool down, they shrink and lose their ductility leading to cracks/failures
    - Low power settings may introduce hot corrosion
- Energy Management Strategies need to be related to:
    - Specific Missions
    - Scaling/Redundancy and Certification including reserves and diversion strategies
- Gas turbines may scale better than the electrical side of the system and it may be preferred to size the gas turbine for emergency cases such as one engine inoperative, aborted landing and turn-around, diversion. This approach may affect the energy management strategies and it may be necessary to use the gas turbine during take-off and landing for example.

5.4 Energy Management Strategies

As previously mentioned energy managements strategies will be related to mission priorities and also the specific architectures selected by the consortium. The mission objectives and priorities include:

- Minimum Fuel Consumption
- Minimum Energy Consumption
- Noise and Emissions (CO_2 and NO_X)
    - Zero Tail pipe emissions: Fuel Cell and Batteries
    - Zero Tail pipe CO_2: Batteries, Fuel Cells & Hydrogen gas turbine
- Operational Availability/Flexibility: Hot-Cold Weather, Altitude or Weight considerations

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- Maintenance costs

It must be noted that the following aspects will not be considered as part of the energy management strategies. They will be captured however in some specific cases during the modelling and simulation phases of specific components.

- Alternative energy sources can be used for transients:
  - Preserve gas turbine life
  - Improve gas turbine efficiency even when hybrid-electric power is not in use – reduced tip clearance

When considering elimination of tail pipe emission during a specific phase the following may also need to be considered:

- Priorities in eliminating certain types of emissions during each phase may be a challenging task:
  - NO_X may be more important at lower altitudes due to health hazards
  - Carbon emissions may be more harmful at higher altitude in terms of global warming potential

The above mission objectives can be related to the following operational aspects and system attributes as shown in figure 14.

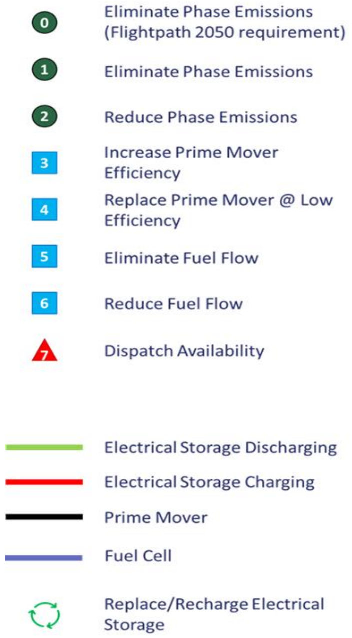

Figure 15: Hybrid-electric architectures attributes and mission priorities

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Architecture 1.a: Partially Turbo-electric Architecture with 2 Gas turbines, 2 Wing tip Propulsors and batteries. Two separate and independent energy/power paths as shown in Figure 15.

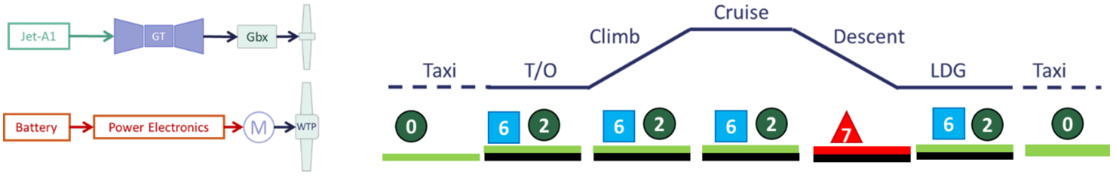

Figure 16: *Architecture 1.a and resulting Energy Management Strategy*

A highly efficient and simple architecture. As the two energy/power streams are independent and are not interconnected they need to operate continually and in parallel throughout the mission profile. This eliminates the need for a generator/alternator but imposes additional challenges in terms of the diversion mission and emergency operations as the electrical side of the system needs to be sized for these conditions as well. At an extreme case the electrical system could be sized for the main mission and if a diversion mission needs to be flown the Wing Tip Propellers (WTP) will be locked and the mission will be completed with the use of the gas turbines alone. That would mean that the engines need to be oversized to account for the additional drag from the WTP propellers and extra fuel would need to be stored on board. Despite the increase in drag and weight it is likely that the additional weight resulting from the above approach will be less than the weight of the batteries if the electrical system and batteries are also sized for the diversion mission.

Given that both systems need to operate continually it will not be possible to have an emission-free phase. Several options are available for sizing the system in terms of the degree of electrification (power) and hybridisation (energy). Benefits will be similar throughout the mission profile and would include reduction of fuel usage and carbon emissions. Depending on the sizing strategy NO_X emissions could reduce, stay the same or in some cases increase. These aspects are discussed below. Furthermore, during the descent phase energy can be harvested by the wing tip propellers. The amount of energy to be harvested depends on the drag produced and the allowable rate of descent. During this phase the engine will operate at idle conditions. To comply with Flightpath 2050 requirements, electric taxiing has been adopted so batteries need to be sized for these requirements at the end of the mission profile.

Battery sizing based on constant percentage of power/thrust throughout the mission profile: the degree of electrification will be determined by the total amount of energy that can be stored onboard and the details of the mission profile – mainly the range and cruise altitude. For an aircraft similar to the ATR42 and a 300 NM mission around 20-30% of the power throughout the mission profile can be supplied by the electrical system and the batteries, assuming a specific energy of 500wh/kg for the batteries. The percentage will drop to 10% for longer mission and/or operations without refuelling. Rescaling the aircraft using advanced designs (i.e. reduce OEW/MTOW to 0.5 from 0.63) could lead to a 50% degree of electrification. A 70-passenger retrofit could also meet this requirement leading to significant fuel reduction benefits by ca. 25-30%. Several options exist for the sizing of the gas turbine:

1. The gas turbines could be kept the same and operate at lower power setting. Such an approach would reduce development costs, NO_X emissions, life consumption and maintenance costs. However, the gas turbine will be operating at reduced efficiency. The penalty in terms of gas turbine efficiency would be around 5-10% and would be more noticeable during the cruise and descent phases.
2. Gas turbine could be resized by keeping the same mass flow. The turbine entry temperature would reduce along with NO_X emissions, life consumption and maintenance costs. Efficiency will also reduce as in the case above.
3. Size of gas turbine could be reduced by keeping constant turbine entry temperature, resulting to a smaller engine with increased efficiency. High NO_X, life consumption and maintenance costs. Furthermore, tip losses at the end of the high-pressure compressor may limit overall pressure ratio and efficiency and the use of a centrifugal compressor may be required.

Battery can be sized to provide a constant amount of Power/Thrust throughout the mission profile: In this case the percentage of thrust will vary. Typical variations for an ATR42 type of aircraft would be 10-20% at take-off, 15-30% at top of climb and around 30-50% at cruise. Minor impact on the design/sizing of the gas turbine – the engine will be sized at take-off where the percentage is relatively small therefore there will not be significant changes. Efficiency of gas turbine will reduce as the engine will be operating at lower power setting. NO_X, and life consumption will also reduce. Drop in gas turbine efficiency will be more noticeable at the cruise section and could be up to 5-10%. Significant reduction in mission NO_X- 50-60% could be achieved compared to baseline aircraft. Benefit will come from reduced temperatures and fuel flow.

Battery can be sized for constant gas turbine power: in this case the objective would be to eliminate large variations in the operation of the gas turbine. No real benefit can be achieved. Cycling loading and damage due to fatigue – both mechanical and thermomechanical – could be reduced however the engine will still be subjected to some degree of cycle loading but at reduced amplitude. For this the gas turbine would be sized at cruise and the power setting/turbine entry temperature would be reduced at take-off and climb. Overall NO_X emission and life consumption in terms of creep will also reduce along with gas turbine efficiency. The engine can also be sized at climb conditions and be allowed to operate at slightly higher temperatures. Creep life consumption would increase but this can be compensated by the reduced fatigue damage.

Finally, a variable degree of electrification could be adopted depending on the range of the mission and specific mission objective/priority that needs to be addressed.

Architecture 1.2 – Architecture 2, 5 and 6. The following architectures can share the same energy management strategies as all three combinations can be fulfilled provided that batteries and electrical components are properly sized: operation of gas turbine alone, operation of electrical system alone, hybrid-electric operation. The architectures are shown in Figure 16.

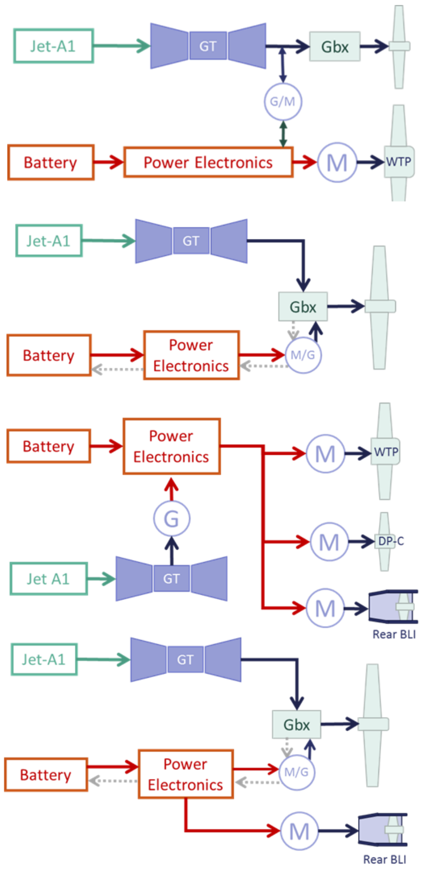

Figure 17: Alternative hybrid-electric architectures

The ability to operate each side of the system separately implies that fuel consumption and tail pipe emissions can be eliminated at one or more phases of the mission profile. The energy management strategies will therefore be driven by the design and sizing requirements of the gas turbine and the subsequent sizing of the electrical side of the system. In this context the following option have been considered:

Gas turbine sized based on cruise requirements: the energy managements strategies are shown in Figure 17 below.

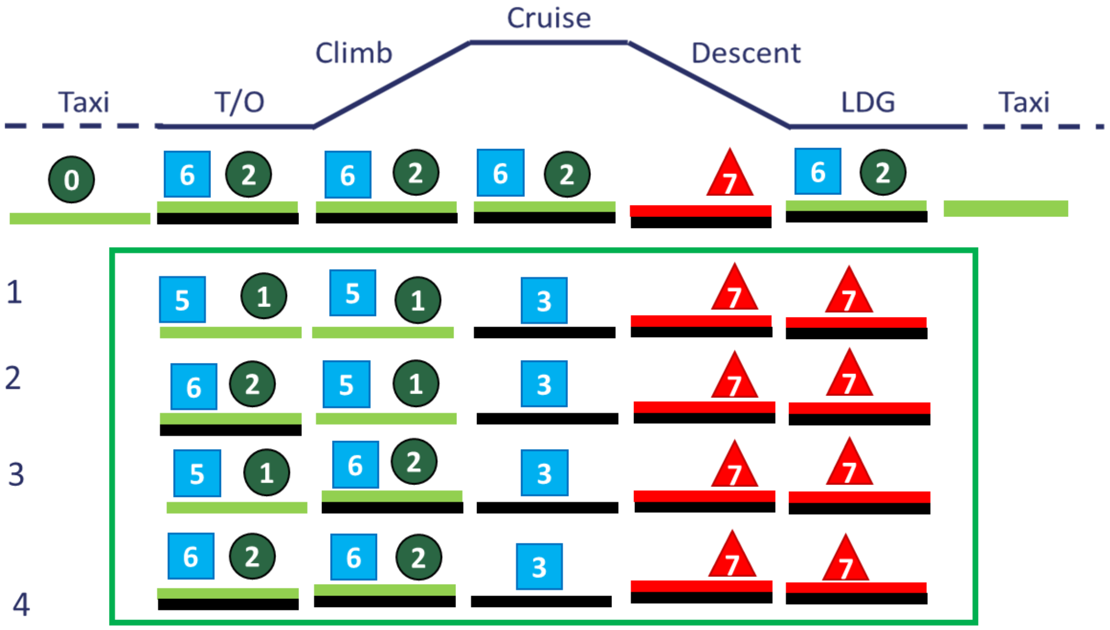

Figure 18: Energy Management Strategies with Gas Turbine sized and Cruise

Strategy 1 in particular can be very attractive as it could eliminate tail pipe emissions during the take-off and climb sections. The gas turbine will be used at cruise and during descent and landing. During descent energy can be recovered by using some of the propellers in regenerative mode. If additional energy is required – for example to account for a second mission with no recharging services- the gas turbines can also operate at higher power setting to charge the batteries if the energy harvested through the propellers is not enough. Landing could be completed by operating in a hybrid mode. Although strategy 1 can eliminate all tailpipe emissions at take-off and climb it is likely that overall emissions, fuel and energy consumption will be higher compared to other energy management strategies due to the high levels of power required at cruise and climb and the subsequent operation of the gas turbine to recharge the batteries. Overall, it is also expected that NO_X emissions will increase at cruise and descent. Gas turbine life consumption is likely to reduce and overall efficiency at cruise can increase by resizing the gas turbine and allowing it to operate at higher temperatures – at the expense of NO_X emissions. NO_X emissions will also increase during descent and landing phases as well. Strategies 2 and 3 can be used to eliminate fuel consumption and emissions during climb and take-off respectively. Overall performance and outcome will be similar to strategy 1 but with reduced weight of batteries as less energy/power will be required. Overall an increase in NO_X during cruise, descent and landing will be expected. In the case of long missions and lower levels of hybridisation – or reduced battery specific energy a hybrid approach can be adopted for the take-off and climb. The engine can be sized for cruise requirements to increase efficiency. Reduced core size could result in low compressor efficiencies due to high tip clearance losses and a centrifugal compressor may be a preferred option. If the mass of the batteries is constant then the gas turbine may operate at low levels during descent and landing sections reducing NO_X, however there will still be an increase of NO_X during cruise.

The energy management strategies that have been identified when sizing the gas turbine for the take-off requirements are shown in Figure 18.

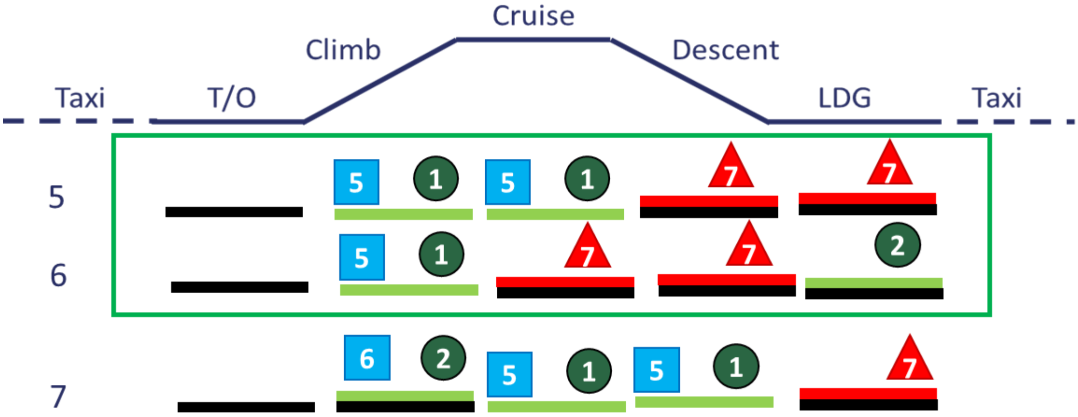

Figure 19: Energy Management Strategies with Gas Turbine Sized at Take-off

For a short mission, strategy 5 could be incorporated to eliminate tail pipe emissions at climb and cruise. Energy can be harvested from the propellers during descent and the gas turbine can also be used to recharge the batteries during descent. Strategy 5 can be a very effective strategy leading to significant reductions in fuel consumption and environmental impact. The strategy can be implemented in the case of a 200-300 NM mission but will be difficult to use for longer ranges. In addition to reduce fuel consumption and emissions, the lifetime and maintenance requirement can also reduce. NO_X during the descent phase are likely to increase however overall emissions are likely to significantly reduce. For longer ranges strategies 6 and 7 can be used instead. Strategy 6 is likely to be very inefficient, leading to an increase in overall emissions and gas turbine lifetime. Strategy 7 is also attractive as it can eliminate emissions during cruise and descent. It is also likely to have the largest reduction in fuel consumption and can lead to high values of overall propulsion and aircraft efficiency.

As in the case of Architecture 1, a hybrid-electric approach with both the electrical and gas turbine sides of the system operating in parallel throughout the mission profile is also possible. Degree of electrification at each phase can be customized to meet specific mission objectives and priorities.

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Architectures 4 - Figure 19 offers the potential for zero carbon tail pipe emissions and in some special cases even zero tail-pipe emissions throughout the mission profile.

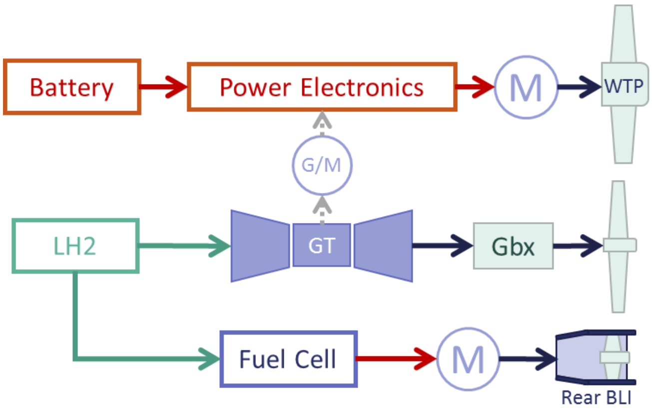

Figure 20: Architecture 4: Hydrogen Gas Turbine with Fuel Cell and Batteries

The energy managements strategies are shown in Figure 20. The first strategy is a special case. A single, hydrogen powered gas turbine may be installed for emergency cases and longer and/or diversion missions. For shorter 200-300 NM missions it may be possible to use the fuel cell and an appropriately sized electrical system to eliminate all emissions.

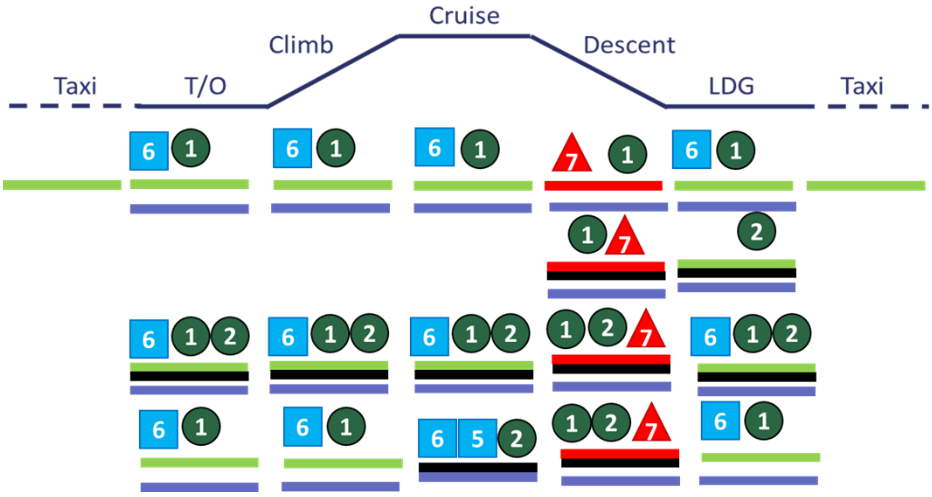

Figure 21: Energy Management Strategies for hybrid-electric Architecture Utilising Hydrogen fuelled Gas Turbine, Fuel Cell and Batteries

During the descent phase the electrically-driven propellers will be used to harvest energy and recharge the batteries. The output from the fuel cell can also be used to that effect. In this case the fuel cell would be sized to provide around 30-50% of the power required at cruise and would operate at constant power output of ca. 0.5-0.7 MW. The remaining power will be provided by the electrical system. Variation of

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this strategy could include the use of the gas turbine during descend and landing. Alternatively, a hybrid strategy where the gas turbine, fuel cell and batteries are utilized simultaneously throughout the mission profile could be incorporated. Such a strategy will result in zero carbon emissions, reduced engine NO_X and reduced gas turbine emissions. However, the maintenance requirements for the fuel cell and the electrical components also need to be considered. Utilisation of all energy sources will reduce the power setting of the gas turbine and its efficiency. An alternative strategy maybe to combine fuel cell with gas turbine. In that case, it would be preferable to use the gas turbine during the cruise section for minimizing NO_X emissions. Alternatively, in terms of efficiency and overall fuel consumption it may be more beneficial to use the gas turbine at take-off and climb sections

Architecture 9 and the resulting energy management strategies are shown in Figure 21. The architecture can result in zero tail pipe emissions however sizing the fuel cell and addressing the thermal management requirements may be rather difficult. In light of this the first strategy where the power is shared between the batteries and the fuel may be the preferred option in terms of overall system mass and can reduce the cooling requirements required for the Fuel Cell.

Figure 22: Energy management strategies for hybrid-electric architecture with fuel cell and batteries

6 Conventional Reference Aircraft

6.1 Introduction and key emission result

It is recognized that the projected evolution of technologies will be insufficient to achieve the environmental goals of Flightpath 2050. To better ascertain the potential that hybrid electric propulsion aircraft can bring, a reference aircraft configuration – using advanced conventional technologies – was developed as a benchmark. ATR42 was assumed as representative of the current operational *state-of-art* for this class of aircraft.

The results are provided as reference, due to the inevitable uncertainties related with technology evolution and necessary simplifications on the analysis. They are thus a good guideline for the order of magnitude for improvement expected, if only conventional technologies are incorporated into future aircraft configurations. From the analysis in this section,

A 39% reduction in CO_2 emission was calculated for this configuration.

In the following sections a detailed description of methodology and assumptions follow. The analysis was made using the SUAVE framework [27]. This will be released in open source form (LGPL) in a dedicated FUTPRINT50 github page in order to allow replication and further exploitation for hybrid electric modifications and benchmarking.

6.2 Design Methodology

The development of this conventional reference aircraft is important because it will be used as a benchmark for the alternative hybrid-electric configurations. Its development consisted of three steps:

1. Calibration: adjustment of models to reproduce an existing aircraft performance;
2. Modification: application of changes envisioned for a conventional aircraft for a future EIS;
3. Evaluation: assessment of the modified aircraft.

Next chapters will detail each step and an assessment regarding operating cost will be given in the end.

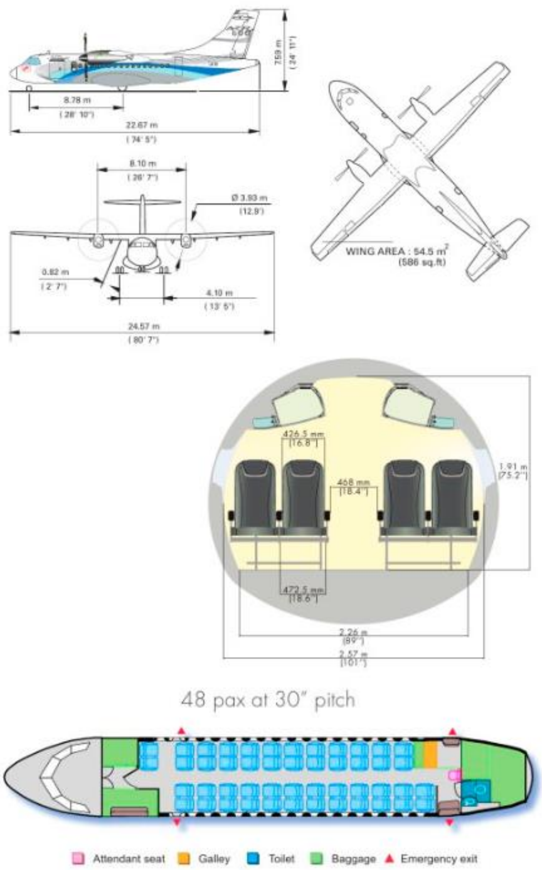
6.3 Calibration

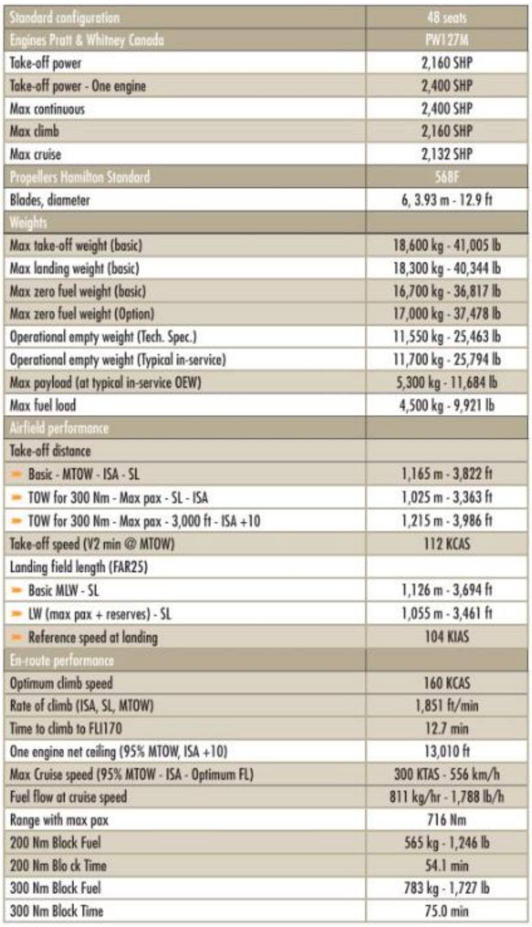
The first step in this process was the calibration of the methods with data of an existing aircraft in order to have a realistic baseline to apply the modifications envisioned for an EIS 2035/2040 aircraft.

Currently, the most similar aircraft in operation to the object of study in this project is ATR42-600. Public data (**Figure 23** and **Figure *24***) of this aircraft was used to calibrate the drag polar and the engine performance. No methods were used to estimate operational weights. They were considered as given on the available data. Furthermore, only en-route performance was assessed, and no airfield performance was evaluated. Before and during the calibration process, some assumptions had to be made as they were not explicitly presented:

- Time to climb to FL 170: take-off @ ISA, SL, MTOW
- Range with max pax: cruise @ 25kft, 240KTAS
- 200 nm Block Fuel/Time: cruise @ 19kft, 300KTAS
- 300 nm Block Fuel/Time: cruise @ 23kft, 300KTAS

It is important to highlight that data presented in **Figure 23** and **Figure 24** have distinct assumptions for fuel reserves and OEW.





Standard configuration	48 seats
Engines Pratt & Whitney Canada	PW127M
Take-off power	2,160 SHP
Take-off power - One engine	2,400 SHP
Max continuous	2,400 SHP
Max climb	2,160 SHP
Max cruise	2,132 SHP
Propellers Hamilton Standard	568F
Blades, diameter	6, 3.93 m - 12.9 ft
Weights	
Max take-off weight (basic)	18,600 kg - 41,005 lb
Max landing weight (basic)	18,300 kg - 40,344 lb
Max zero fuel weight (basic)	16,700 kg - 36,817 lb
Max zero fuel weight (Option)	17,000 kg - 37,478 lb
Operational empty weight (Tech. Spec.)	11,550 kg - 25,463 lb
Operational empty weight (Typical in-service)	11,700 kg - 25,794 lb
Max payload (at typical in-service OEW)	5,300 kg - 11,684 lb
Max fuel load	4,500 kg - 9,921 lb
Airfield performance	
Take-off distance	
▬ Basic - MTOW - ISA - SL	1,165 m - 3,822 ft
▬ TOW for 300 Nm - Max pax - SL - ISA	1,025 m - 3,363 ft
▬ TOW for 300 Nm - Max pax - 3,000 ft - ISA +10	1,215 m - 3,986 ft
Take-off speed (V2 min @ MTOW)	112 KCAS
Landing field length (FAR25)	
▬ Basic MLW - SL	1,126 m - 3,694 ft
▬ LW (max pax + reserves) - SL	1,055 m - 3,461 ft
▬ Reference speed at landing	104 KIAS
En-route performance	
Optimum climb speed	160 KCAS
Rate of climb (ISA, SL, MTOW)	1,851 ft/min
Time to climb to FL1170	12.7 min
One engine net ceiling (95% MTOW, ISA +10)	13,010 ft
Max Cruise speed (95% MTOW - ISA - Optimum FL)	300 KTAS - 556 km/h
Fuel flow at cruise speed	811 kg/hr - 1,788 lb/h
Range with max pax	716 Nm
200 Nm Block Fuel	565 kg - 1,246 lb
200 Nm Blo ck Time	54.1 min
300 Nm Block Fuel	783 kg - 1,727 lb
300 Nm Block Time	75.0 min

Assumptions for en-route performance:
- Max optional TOW & LW
- Payload: max pax
- OEW: typical in-service
- Pax weight: 95 kg (including baggage)
- Reserves: 5% trip fuel + 30 min hold + 100 Nm diversion
- Taxi: 4 min

Figure 23: ATR42-600 specification [28].

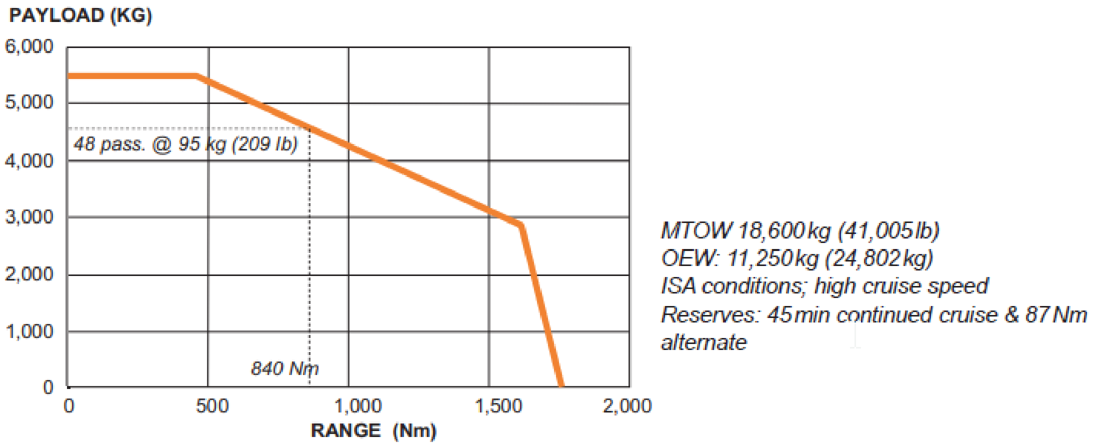


Figure 24: ATR42-600 payload x range [29].

The aerodynamic model considered follows Eq. 1.

$$C_D = C_{D0} + \Delta C_D + \frac{C_L^2}{\pi \cdot AR \cdot e} + k \cdot \frac{T}{0.5 \cdot \rho \cdot V^2 \cdot D^2} \qquad \text{Eq. 1}$$

where:

T: Thrust [N]

ρ: air density [kg/m^3]

V: airspeed [m/s]

D: propeller diameter [m]

Parasite drag (C_{D0}) was calculated with semi-empirical methods available in SUAVE, which depend basically on wetted area and form factor. The parameters that were calibrated to match the performance data were:

- Drag increment by flight segment (ΔC_{D0})
- Oswald efficiency factor (e)
- Thrust disk loading coefficient factor (k)

The component proportional to thrust disk loading was added to account for propeller slipstream interference on wing parasite and induced drag and for an eventual additional trim drag, since ATR42 has co-rotating propellers.

Engine performance data (power, fuel flow and residual jet thrust) was derived from a model generated in the program GASTURB[1]. Power for each engine rating was adjusted according to **Figure 23** and fuel flow was calibrated to match block fuel data.

ATR42-600 is equipped with Hamilton Standard F568 propellers. Its efficiency was extracted from a study by [30]. The propeller map is presented in **Figure *25***. For simplification purposes, fixed efficiencies were considered for cruise, climb and descent to simulate the aircraft mission performance.

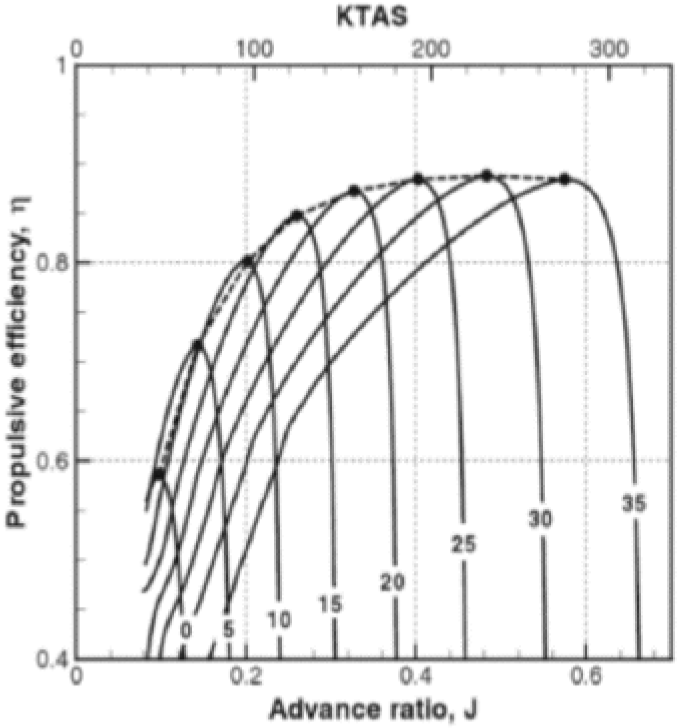


Figure 25: Hamilton Standard F568 propeller map [30]. (Advance ratio is normalized by π)

Calibration was performed manually until a satisfactory convergence was achieved. Final values are presented in **Table *7*** and the comparison with the reference values are presented in **Table *8***. All monitored parameters are within approximately 1% difference, except for block time. **Figure *26*** shows the comparison in terms of payload x range.

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[1] https://gasturb.de/

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Table 7: Aerodynamic parameters calibrated values

Parameter	Value
ΔC_{D0} (climb)	0.0000
ΔC_{D0} (cruise)	0.0027
ΔC_{D0} (descent)	0.0100
e	0.93
k	0.023

Table 8: Calibrated aircraft performance comparison

Parameter	ATR42-600	Calibrated model	Difference
Rate of climb (ISA, SL, MTOW)	1851 ft/min	1838 ft/min	-0.7 %
Time to climb to FL170	12.7 min	12.6 min	-0.7 %
Range with max pax	716 nm	724 nm	1.1 %
200 nm Block Fuel	565 kg	565 kg	0.1 %
200 nm Block Time	54.1 min	55.3 min	2.3 %
300 nm Block Fuel	783 kg	785 kg	0.3 %
300 nm Block Time	75.0 min	77.8 min	3.8 %

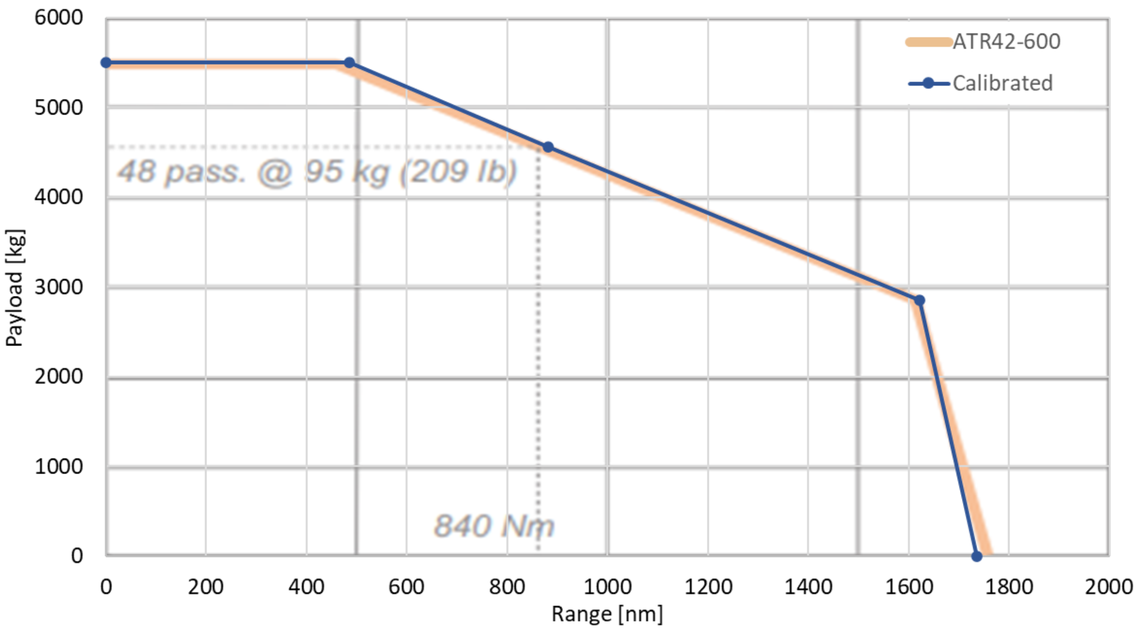

Figure 26: Payload over range calibration comparison

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6.4 Specific conventional improvement projection

This chapter describes the changes introduced over the ATR calibrated model to consider for improvements envisioned for this future aircraft, for now on called CFA (Conventional FutPrInt50 Aircraft). This aircraft is meant to be used as a reference for comparison with the alternative configurations and was developed with the mindset of incremental improvements that would be feasible for a future EIS, i.e., no introduction of disruptive technologies was considered. Moreover, the configuration is the same as on ATR42-600: high wing, two turboprop engines under the wings and T-tail.

The next sessions will detail the modifications on the main disciplines.

6.4.1 Aerodynamics

With respect to aerodynamics, two improvements were proposed: increase on wing aspect ratio and decrease of aircraft excrescence drag.

Although ATR42 wing already has a relatively high aspect ratio of 11, there were and will be improvements on materials and design methodologies that could increase its value. Here, it is proposed a value of 13.4.

The other point that can be further improved is the excrescence drag. Besides the 27 drag counts that were added during the calibration for cruise, there is another 13 drag counts for miscellaneous that were calculated by the methodologies implemented on SUAVE. It was considered a reduction of 25% or 10 drag counts to account for improvements on manufacturing tolerances, processes and sealing of gaps.

Furthermore, the factor applied to the thrust disk loading coefficient was also decreased from 0.023 to 0.020 to account for better propeller-wing integration design methodologies.

6.4.2 Propulsion

Engine performance model was generated in GASTURB based on the requirements in **Table *9***. A 2-shaft turboprop was adopted with the cycle parameters presented in **Table *10***.

Table 9: Engine performance requirements

Condition	Parameter	Regime
Altitude = 0 m; MN = 0.0; ISA	2,160 hp	NTO
Altitude = 0 m; MN = 0.0; ISA + 20°C	2,160 hp	APR
Altitude = 0 m; MN = 0.25; ISA + 20°C	2,160 hp	RTO
Altitude = 2,500 m; MN = 0.25; ISA + 25°C	1,850 hp	RTO
Altitude = 4,000 m; 195 KTAS; ISA	1,740 hp	MCT

Altitude = 3,000 m; MN = 0.3; ISA	1,870 hp	MCL
Altitude = 6,400 m; MN = 0.45; ISA	1,510 hp	Max Cruise
Altitude = 7,620 m; MN 0.50; ISA	0.32 lb/(h*hp)	Cruise

Table 10: Engine cycle parameters

Parameter	**Value**
Take-off power	2,160 hp
Compressor pressure ratio at design point	24
Burner exit temperature at design point	1,750 K
Engine air mass flow at design point	4,55 kg/s

Besides that, it was considered a power extraction of 20 hp from the high-pressure spool and a fresh airflow of 13.75 pounds per minute for each engine with a minimum bleed pressure of 25 psig. It decreased cruise specific fuel consumption from 0.32 to 0.35 lh/(h*hp).

6.4.3 Weight

Due to the lack of real data on ATR42-600 weight breakdown, no weight calibration was performed. For CFA OEW definition, it was considered the following assumptions:

- Inclusion of a fly-by-wire system
- New certification requirements
- Extended usage of advanced materials
- Higher propeller diameter
- Higher wing aspect ratio
- Higher engine power density

It is known that some of these assumptions might increase and others decrease OEW, so, for simplicity's sake, CFA's OEW was considered the same as ATR42-600, i.e., 11,700 kg.

MTOW was defined as the minimum weight to comply with TLAR. The requirement that sized MTOW was the maximum range at cruise speed and design payload with a minimum value of 800 km plus reserve. It resulted in an MTOW of 18,100 kg, which is 500 kg lighter than ATR's.

6.5 Evaluation results

The integration of the models and the simulation of the aircraft performance was made using SUAVE, an open source Python based framework. Basically, in order to run a simulation, the user must define the following:

- Vehicle: aircraft dimensions, propulsive network, design weights.
- Configurations: modifications to the vehicle attributes to be applied on different flight phases.
- Mission: flight profile setup.

Most of the vehicle dimensions follow ATR42-600, expect for the wing that follow the assumptions described in the previous chapter and the vertical tail which had its area increased by 10% to 13.7 m^2 due to the more outboard position of the propellers. Based on this, semi-empirical models implemented in SUAVE are used to calculate the aircraft parasite drag and to generate a surrogate model for the aircraft lift.

The propulsive network comprises the gas turbine model previously described and a propeller model with fixed efficiency.

Different configurations were created for each flight segment (climb, cruise and descent) in order to be able to specify the correct engine regime and to add the specific additional drag from the calibration.

Flight profile comprises the segments listed in **Table *11***. Flight segments 4 to 7 represent the reserve profile, which is 185 km to an alternate plus 30 minutes holding. For each segment, a method available in SUAVE was used. For climb and descent segments, a given throttle setting, in this case equal to 100%, and a given true airspeed have to be defined. Besides that, the user must set the initial and the final altitudes. As we want a climb/descent at constant calibrated airspeed, these segments had to be broken into several segments, each of them with an average true airspeed corresponding to the desired calibrated airspeed.

For cruise, the user must set the distance and the speed, and the method adjusts throttle. Although the user can also set the altitude, this is not usual as it automatically is taken from the last segment. In most cases, a high-speed cruise of 300 KCAS was set and cruise performed at 25.000 ft, unless this mission segment represents less than 1/3 of the mission range. In this case, cruise altitude is decreased.

For the reserve profile, all segments are performed at 160 KCAS which is close to the speed of maximum aircraft aerodynamic efficiency.

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Table 11: Mission profile setup

	Segment	Method	Obs.
1.	Climb	Constant_Throttle_Constant_Speed	160 KCAS
2.	Cruise	Constant_Speed_Constant_Altitude	300 KCAS; 25,000 ft
3.	Descent	Constant_Throttle_Constant_Speed	160 KCAS
4.	Climb	Constant_Throttle_Constant_Speed	160 KCAS
5.	Cruise	Constant_Speed_Constant_Altitude	160 KCAS; 11,000 ft
6.	Descent	Constant_Throttle_Constant_Speed	160 KCAS
7.	Hold	Constant_Speed_Constant_Altitude	160 KCAS; 1,500 ft

In order to simulate a mission, the user must provide the aircraft take-off weight and as it does not have an automatic check on available fuel, it is recommended to implement a convergence loop to guarantee that the simulation is feasible and/or that it covers the desired range.

Table 12 shows a comparison between TLAR and the obtained values for the requirements which could be assessed and Figure 27 compares the payload x range for CFA and ATR42-600. It is important to note that both curves were calculated using the same reserve fuel policy of 185 km plus 30 min holding and ATR42-600 curve was generated using the calibrated model. Table 13 lists the points that define the payload x range chart.

A maximum usable fuel of 3,000 kg was considered. Considering that ATR42-600 is able to carry 4,500 kg, this value seems feasible even though CFA has a higher aspect ratio wing. Besides that, it is enough to outperform ATR42-600.

Table 12: TLAR comparison

Requirement	Target	Result
Design cruise speed	450-550 km/h	557 km/h
Design payload	≥ 5300 kg	5300 kg
Maximum payload	≥ 5800 kg	5800 kg
Maximum r (cruise speed, design payload)	≥ 800 kg + reserve	874 km
Rate of c (MTOW, SL, ISA)	≥ 1850 ft/min	1864 ft/min
Rate of c (maximum operating altitude)	≥ 1.5 m/s (300 ft/min)	3.6 m/s
Time to climb do FL170	≤ 12.7 min	9.9 min
Maximum Operating Altitude	7620 m (25,000 ft)	7620 m

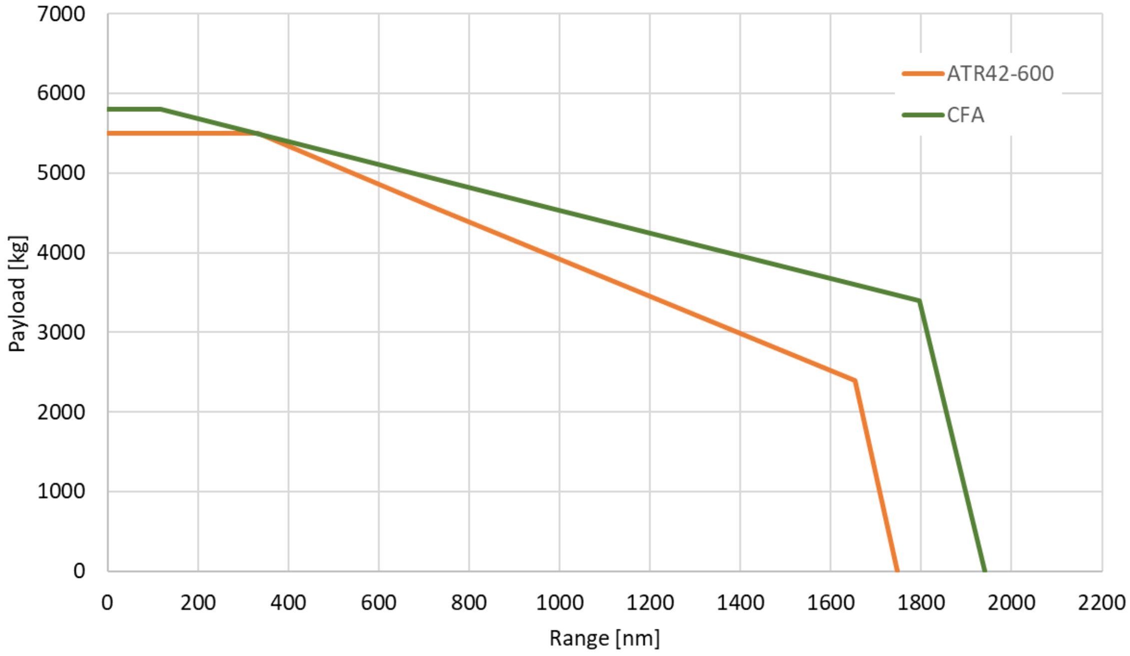

Figure 27: CFA payload x range chart (fuel reserves for 185 km plus 30 min holding)

Table 13: CFA payload x range data (fuel reserves for 185 km plus 30 min holding)

Payload [kg]	**Range**	
	[km]	**[nm]**
5800	218	118
5300	874	472
3400	3324	1795
0	3595	1941

Figure 28 shows the mission profile for the design range mission (400 km plus reserves, 5300 kg payload, 557 km/h cruise speed). Altitude was limited to 23,000 ft in order to keep cruise segment with a reasonable distance. Climb and descent segments present some irregularities on some parameters due to the approximation needed to simulate a constant calibrated airspeed profile. It shows an L/D at cruise of 13.7, reaching more than 17 on the segments with lower speeds.

Figure 29 shows the drag breakdown for the same mission. During climb, total drag starts at about 500 drag counts and goes down to 450 drag counts due to decrease of the portion associated with thrust disk loading. At cruise, total drag is around 324 drag counts.

Table 14 shows the mission performance results for each flight segment and Table 15 brings some additional results.

Figure 30 show the aircraft 3-view and Figure 31 a realistic view.

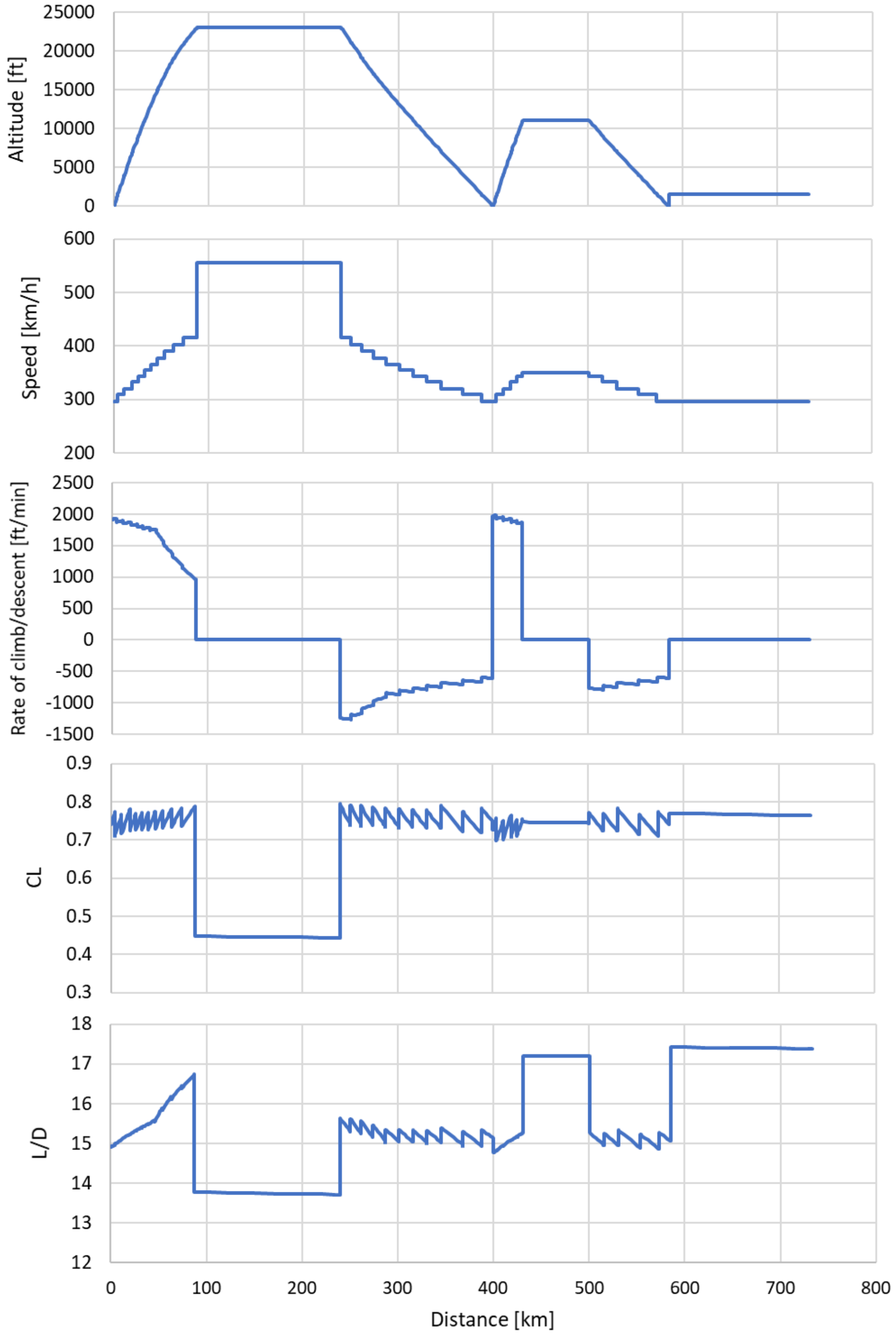

Figure 28: Design range mission profile

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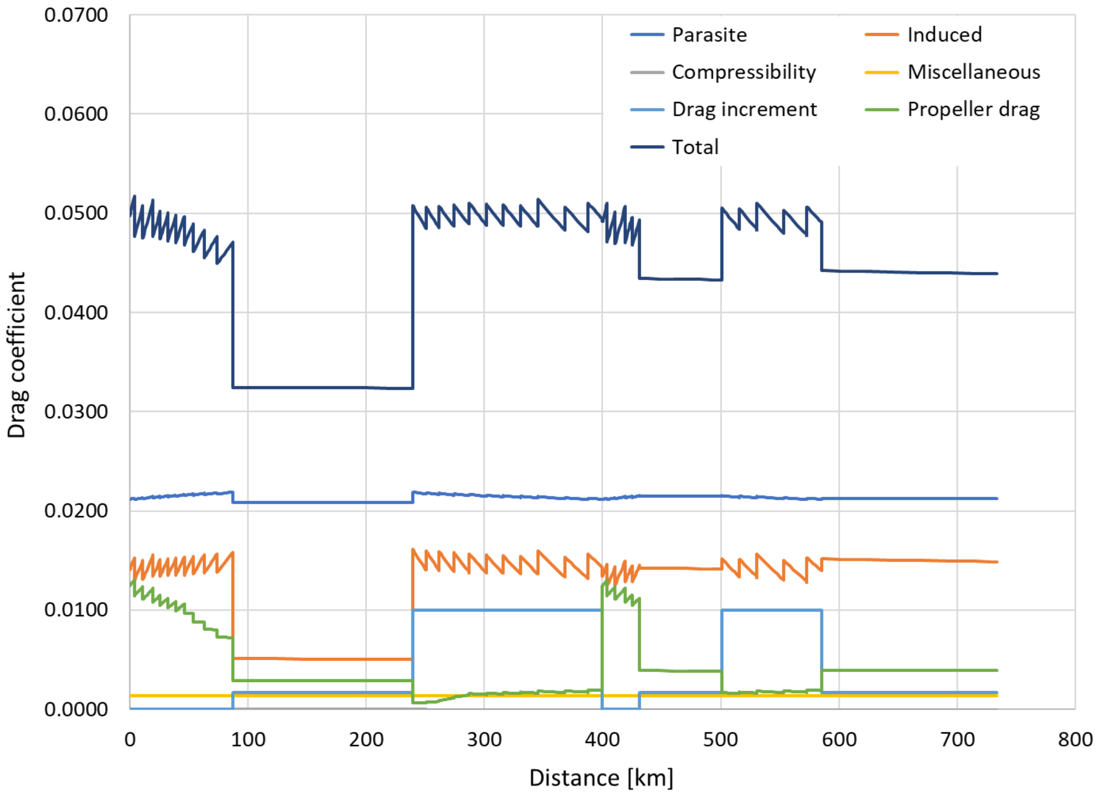

Figure 29: Design range mission drag breakdown

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Table 14: Design range mission performance by segment

	Segment	Fuel [kg]	Time [min]	Distance [km]	Specific range [km/kg]
	Climb	148.1	14.6	87.4	0.590
	Cruise	125.8	16.4	152.1	1.209
	Descent	103.1	27.8	160.4	1.557
	Total	**377.0**	**58.8**	**400.00**	**1.061**
Reserve	Climb	64.2	5.9	31.2	0.486
	Cruise	60.2	11.9	69.3	1.151
	Descent	66.9	15.8	84.1	1.257
	Alternate	**191.3**	**33.6**	**184.6**	**0.965**
	Hold	152.5	30.0	148.2	0.971
	Total	**343.9**	**63.6**	**332.8**	**0.968**

Table 15: Design range mission results summary

BOW	11700	kg
Payload	5300	kg
Mission fuel	377	kg
Reserve fuel	344	kg
TOW	17720	kg
Rate of climb (start)	1917	ft/min
Rate of climb (end)	966	ft/min
Time to climb to FL170	9.6	min
Cruise fuel flow	459.5	kg/h

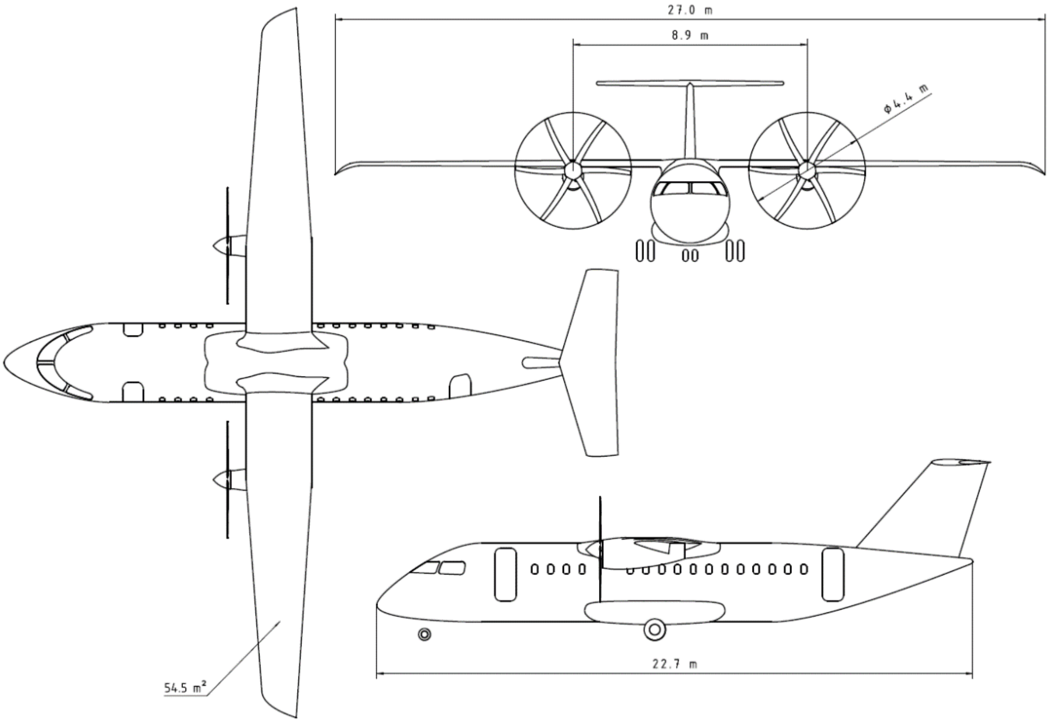

Figure 30: CFA three side view

Figure 31: CFA realistic view

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6.6 Operating cost

Besides a performance reference, an operating cost reference was also provided. To do this, a databank provided by U.S. Bureau of Transportation Statistics [32] was used. The databank used for this analysis was Form 41 Schedule P-5.2 and it contains detailed quarterly aircraft operating expenses for large certified U.S. carriers. The data available and its classification are presented in Table 16.

This analysis consisted on evaluating the expenses history of turboprop powered aircraft over the years for which there was a reasonable amount of data. In order to make a fair comparison throughout the years, cost values are presented in 2019 U.S. dollars to account for inflation according to GDP deflators provided by U.S. Bureau of Economic Analysis [33] and presented in Table 17. Furthermore, to account for fuel price fluctuations, jet fuel cost was normalized to 2019 jet fuel price of 2.0 U.S. dollars per gallon, which history is shown in Figure 32.

Figure 33 shows the total expenses for the relevant years as well as the breakdown highlighting the most relevant sources of cost. Figure 34 shows the same data in relative values and Figure 35 shows an average distribution through 1990 to 2012.

From ATR42-600 en-route performance presented in Figure 23 and considering jet fuel price of US$2.0/gallon, it is possible to estimate fuel expense of US$ 409/flight hour and from CFA simulations an estimate of US$ 251/flight hour is reached, which represent a reduction of 39%. As CO2 emissions are linearly proportional to fuel, this is the same expected reduction for CO2 emissions.

Applying this reduction to the fuel portion of DOC and keeping the other expenses unchanged, the DOC breakdown presented in Figure 36 is obtained. It means a total DOC of US$ 1673/flight hour.

Table 16: Form 41 Schedule P-5.2 categories description [32].

Category	Account	Description
Flying Operations	51230	Pilots and Co-pilots
	51240	Other Flight Personnel
	51281	Trainees and Instructors
	51360	Personnel Expenses
	51410	Professional and Technical Fees and Expenses
	51437	Aircraft Interchange Charges
	51451	Aircraft Fuel
	51452	Aircraft Oil
	51530	Other Supplies
	51551	Insurance Purchased – General
	51570	Employee Benefits and Pensions
	51580	Injuries, Loss, And Damage
	51680	Taxes – Payroll
	51690	Taxes - Other Than Payroll
	51710	Other Expenses
Direct Maintenance	52251	Labour – Airframes
	52252	Labour - Aircraft Engines
	52431	Airframe Repairs
	52432	Aircraft Engine Repairs
	52437	Aircraft Interchange Charges
	52461	Materials – Airframes
	52462	Materials - Aircraft Engines
	52721	Airworthiness Allowance Provisions – Airframes
	52723	Airframe Overhauls Deferred, Credit (-)
	52726	Airworthiness Allowance Provisions - Aircraft Engines
	52728	Aircraft Engine Overhauls Deferred, Credit (-)
Depreciation	70751	Airframes
	70752	Aircraft Engines
	70753	Airframe Parts
	70754	Aircraft Engine Parts
	70755	Other Flight Equipment
	70758	Maintenance Equipment and Hangars
	70759	General Ground Property
Amortization	70741	Developmental and Preop. Expense
	70742	Other Intangibles
	70761	Capital Leases - Flight Equipment
	51470	Rentals

Table 17: U.S. GDP deflators [33].

Year	GDP deflator
1984	47.12
1985	48.61
1986	49.59
1987	50.81
1988	52.61
1989	54.67
1990	56.71
1991	58.63
1992	59.97
1993	61.39
1994	62.70
1995	64.02
1996	65.19
1997	66.31
1998	67.06
1999	68.03
2000	69.55
2001	71.07
2002	72.20
2003	73.54
2004	75.52
2005	77.87
2006	80.23
2007	82.38
2008	83.98
2009	84.62
2010	85.61
2011	87.40
2012	89.07
2013	90.64
2014	92.32
2015	93.19
2016	94.17
2017	95.94
2018	98.25
2019	100.00

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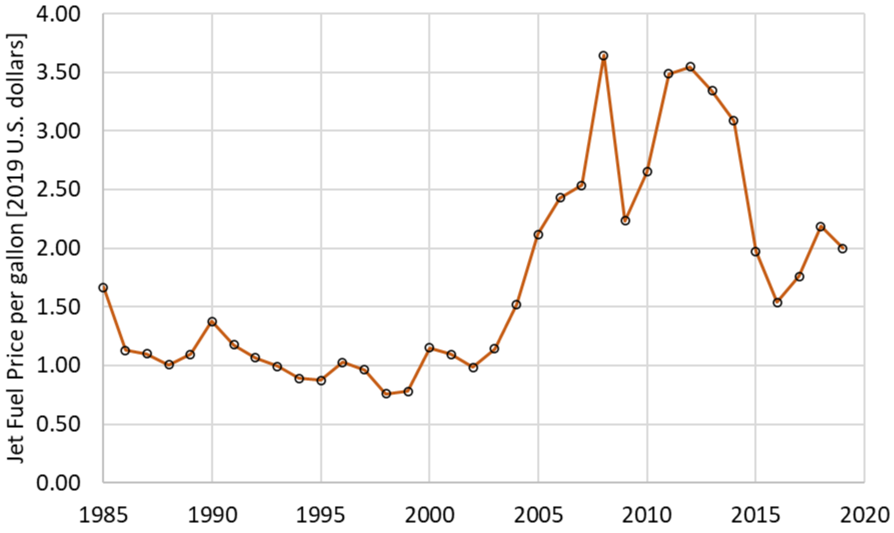

Figure 32: Jet fuel price history in 2019 U.S. dollars [33][34]

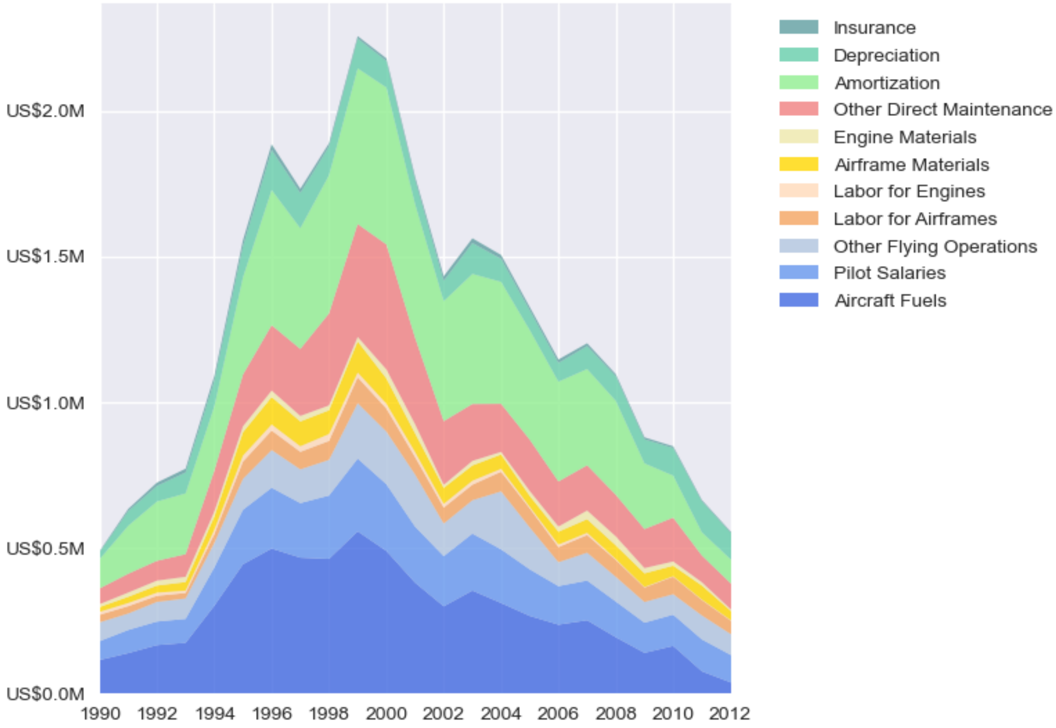

Figure 33: Turboprop direct operating cost history (values in 2019 U.S. dollars and jet fuel price of US$2.0/gallon)

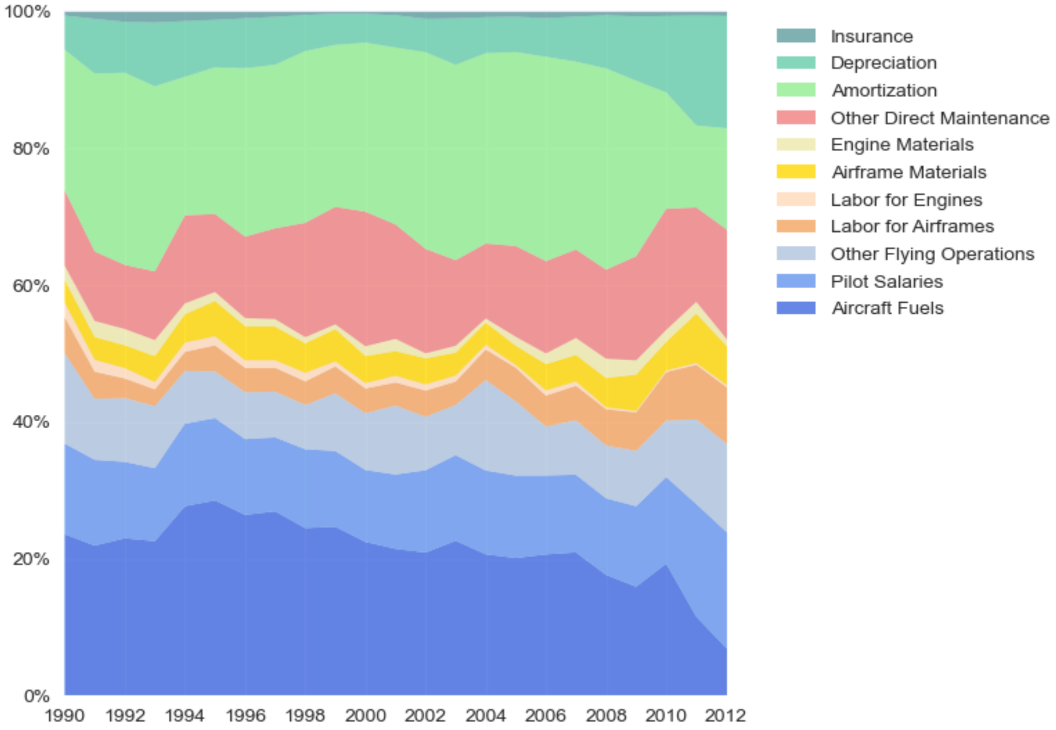

Figure 34: Turboprop direct operating cost history distribution considering jet fuel price of US$2.0/gallon

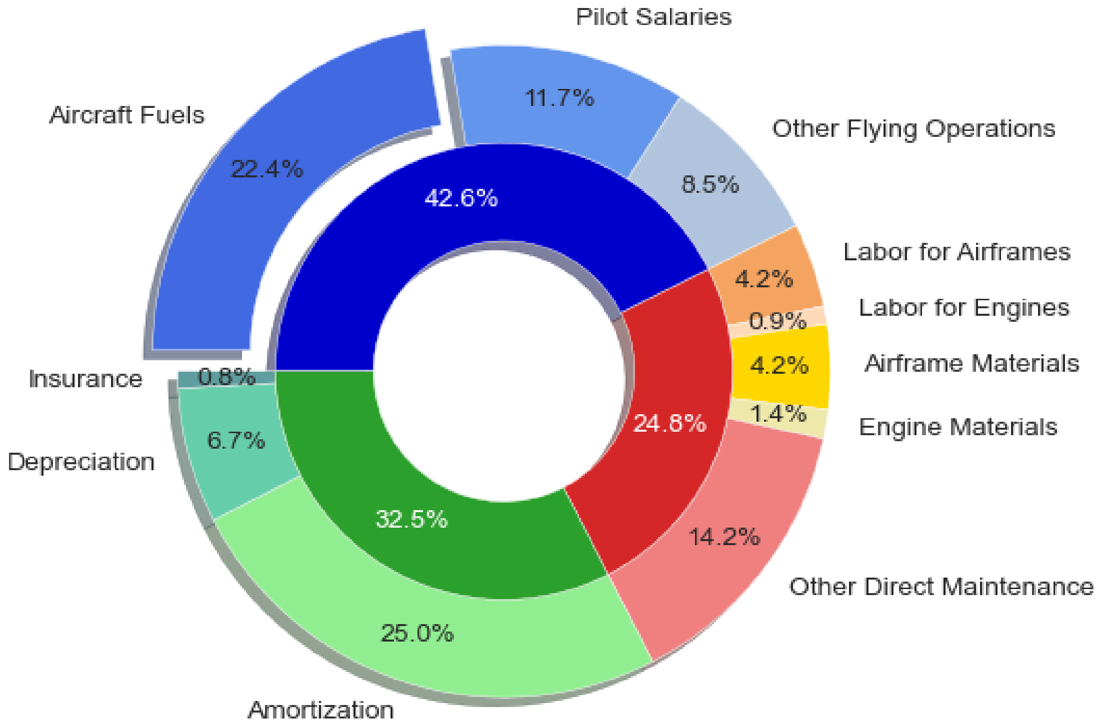

Figure 35: Average turboprop direct operating cost breakdown considering jet fuel price of US$2.0/gallon

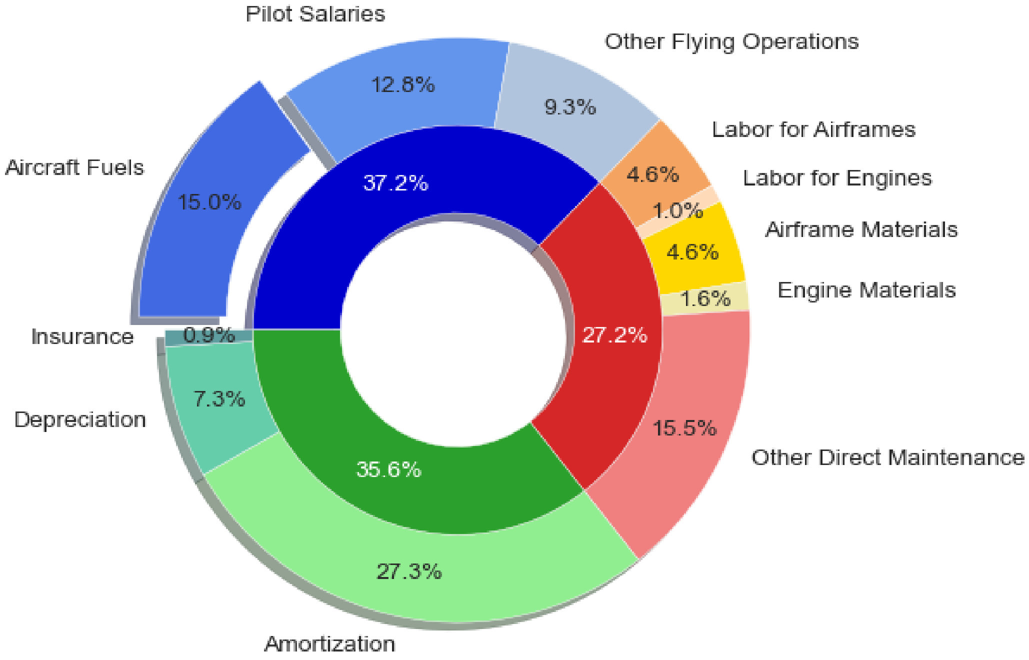

Figure 36: CFA direct operating cost breakdown considering jet fuel price of US$2.0/gallon

7 Final Considerations

Top Level Aircraft requirements were developed with primary focus on replacing the current regional aviation network with hybrid electric aircraft. It is expected that the availability of such new aircraft will foster the densification of such a network due to environment and cost efficiency.

To better support the aircraft design studies across different operational realities, a set of reference missions was assembled.

Figures of Merit were developed to support trade-offs, namely allowing an understanding of those related with environmental, desirability and feasibility.

For the Y2040 conventional reference aircraft, a 39% reduction in CO2 emissions was forecasted under improvements in conventional technologies.

This material in this document constitutes a reference for developments in FUTPRINT50 but extends beyond it. It is envisioned that other research lines in key themes for regional hybrid electric aviation can refer too (e.g., missions, TLARS) ensuring coherent and relatable discussions for the advancement of the topic.

Due to the predicted knowledge advancement during the project (either due to internal or external developments), a revision is planned for the last year of FUTPRINT50.

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