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Scalability Assessment of Hybrid-Electric Technology Application to Various Aircraft Classes - an Overview of Opportunities and Challenges

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Abstract

The objective of the EU-funded research project CHYLA (Credible HYbrid eLectric Aircraft) was to identify opportunities or limitations/challenges for the applications of key radical hybrid-electric technologies and areas suitable for scaling them over different aircraft classes. This was done using a combination of conceptual aircraft design supported by sensitivity studies, credibility-based MDO and assessment of a regional operative scenario. This article summarizes the key findings from the project and presents the landscape of technology application areas. Notably, the regional and commuter classes present the largest design space with significant fuel-saving potential depending on the mission.

1. Introduction

The past decade has produced a vast number of research projects on (hybrid-) electric aviation. A large fraction of literature on this topic typically addresses single vehicle designs or studies only single vehicle classes (such as short/medium range or regional aircraft).[1,4,8,10,12,15,18,23,24,26,27,30,36] However, different combinations of novel propulsion and energy systems are expected to be applied into different powertrain architectures and different vehicle classes.

The objective of the EU funded research project CHYLA (*Credible HYbrid eLectric Aircraft*)[a] was aimed at identifing technology application areas suitable for scaling, as well as limitations or challenges for developments that arise from the different technology applications. Therefore, the ultimate objective was to construct a landscape of technology applications that provides an overview of switching points between technologies better suited to one or another class of aircraft (or CS-23/CS-25) that may arise due to top level aircraft requirements, propulsion system architecture or operations/economics.

To develop such a "landscape" of opportunities and challenges for technology applications, a framework was developed combining an energy network model[34] with a conceptual aircraft design framework[9,14] performing the initial aircraft design[13] and sensitivity studies[2] and credibility-based Multidisciplinary Design Optimization (MDO).[32,33] For the latter MDO studies, designs for various aircraft categories are optimized, taking the credibility of reaching a certain technology level explicitly into account (e.g., the confidence of reaching a certain battery performance). This required the development of a novel credibility-based MDO method.[31,35] Additionally, aircraft design was directly coupled to airline network optimization to assess operations and economics of such designs,[16] aimed at minimizing climate impact.[22]

1.1 CHYLA Background

In the CHYLA project, novel energy systems were applied to aircraft configurations and optimized to identify promising configurations in five different classes, i.e. 1) light aircraft, 2) commuter aircraft, 3) regional aircraft, 4) short-

[a]https://www.tudelft.nl/lr/chyla-project/

medium range and 5) large passenger transport aircraft. CHYLA is a collaboration between Delft University of Technology, Technische Universität Braunschweig and University of Southampton, funded by the EU H2020 program. The objective of the project is to identify the potential and challenges associated with the applications of hybrid electric powertrain technologies to aircraft of different classes. These technologies also extend to the application of different energy carriers and propulsion systems, linked to the particular powertrain architectures. To this end, the project identifies suitable technologies, suitable combinations of technologies and use an approach consisting of different phases to assess technology scalability/applicability. Additionally, economic and airline network aspects are analysed as well in a regional operative scenario.

1.2 CHYLA Approach

The approach followed in the CHYLA project is illustrated graphically in Figure 1. Multiple stages of scalability assessment have been followed in order to analyse the different radical technology applications. The development of radical aircraft feeds the conceptual design stage. These initial designs provide the input to a credibility based MDO approach, as detailed in Wahler et al.[35] During this MDO study, several aircraft were optimized for maximizing range whilst maintaining a minimum credibility level (e.g. confidence of reaching certain battery performance). This optimization is fed by a detailed energy network model, specifically designed to assess different combinations of electrical technologies to achieve required powertrain performance. The energy network model that has been developed is presented in Wahler et al.[34] During the third stage of scalability assessment, additional design sensitivity studies have been performed on the various baselines which feed the landscape that will be presented here and in detail in a subsequent article. The final stage uses the baseline designs in an airline network and operational scenario to understand the impact on operations, economics as well as airport integration.

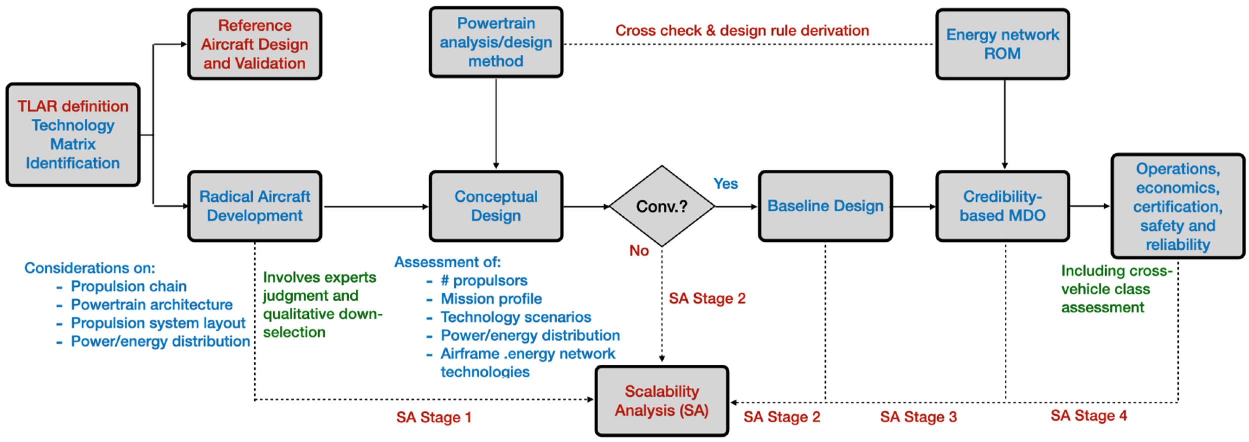

Figure 1: Illustration of the approach followed in the CHYLA project for aircraft design and scalability assessment.

1.3 Paper Outline

This article presents the activities performed over the final trimester of the project (October 2022 - May 2023). Particular focus is on the developed landscape of technology applications and switching points. Thus, this paper presents some of the final outcomes of the project, focusing on the commuter and regional aircraft classes including their use in a regional airline network.

The article consists of three main sections, each of which will briefly address the method applied for the respective studies. However, detailed descriptions of the different methods go beyond the scope of this article and the reader is referred to the specific articles discussing them in detail. The three main sections consist of an overview of switching points and the technology landscape (Section 2), an example from the credibility-based MDO study (Section 3) and a highlight from the regional operative scenario (Section 4). Section 5 summarizes the main conclusions and provides an overview of recommended areas for future studies/projects.

2. Switching Points and Technology Landscape

Key to the CHYLA project was the development of a landscape of opportunities, challenges and limitations to the application of different technologies across different classes of vehicles. An important factor in constructing such a landscape is the conceptual aircraft design, for different technologies, scaled over a range of requirements and applied in different vehicle classes. This section provides an introduction to the sizing process that was employed, the Top Level Aircraft Requirements (TLAR) that were defined and the technology assumptions that were made. Subsequently, an illustration of payload-range sweeps is presented for both commuter and regional aircraft. These analyses, plus others performed over the course of the project, ultimately allowed the construction of a technology application landscape which concludes this section.

2.1 Aircraft Requirements and Definitions

The conceptual sizing is performed using the TU Delft in-house "Aircraft Design Initiator", which consists of a series of disciplinary analysis and sizing modules combined in an aircraft sizing framework. A description of the Initiator is presented by Elmendorp et al.[9] and information on the employed overall sizing process for hybrid electric aircraft, with distributed propulsion, and its inputs is presented by Hoogreef et al.[14] The hybrid-elecric design process is based on the work from De Vries et al.,[7] where also the thrust, lift and drag decompositions account for aero-propulsive interactions leading to a set of modified equations of motion for the constraint analysis (or wing-power loading diagram). For distributed propulsion this is required, since the equations for equilibrium flight become coupled with lift and drag depending on thrust.

The analysis methods programmed in the various functions inside the Initiator aircraft design framework are regularly bench-marked against data from the open literature and comparisons are typically presented with every publication (e.g.[9,14,29]). Additionally, a separate comparison of the preliminary sizing method for hybrid electric aircraft is performed by Finger et al.,[11] where the reference case is a typical commuter aircraft (Dornier DO-228).

Instead of exploring also novel aircraft configurations, it was purposely decided not to deviate from a conventional aircraft configuration apart from elements of hybridization in order not to convolute conclusions. Most are inspired from the design of the ATR-72-600 and Dornier 228, respectively, which are also used as benchmark aircraft and for validation of the methods. The set of TLARs selected for the regional and commuter studies are summarized in table 1.

Table 1: Top Level Aircraft Requirements for regional and commuter classes.

Requirement	Unit	Regional	Commuter
Passenger capacity	–	70	19
Maximum payload	kg	7500	1805
Harmonic range	km	926	500
Cruise Mach number	–	0.4	0.32
Cruise altitude	m	7010	3658
Landing distance	m	1006	600
Takeoff distance	m	1372	700
Diversion range	km	185	150
Endurance	min	45	45
Diversion Mach number	–	0.28	0.22
Diversion altitude	m	1500	1000
Climb performance	–	17.5min to 5400 m	7.5 m/s

Tail sizing is performed using a volume coefficient approach. The selected design point is based on the criteria of maximum wing loading, which generally produces the lowest Maximum Take-Off Mass (MTOM) for conventional aircraft[28] and also minimizes MTOM for radical aircraft.[7] The sizing of hybrid electric aircraft is highly sensitive to the underlying technology assumptions made; values used for this study are listed in table 2.

An important aspect concerns the volumetric integration of energy carriers. These are located within the main wing. A study by Bonnin et al.[3] illustrates the impact that such volumetric integration may have on the sizing of hybrid electric aircraft. For a regional aircraft it is shown how distributed propulsion and battery integration have to be harmonized in order to comply with existing airport limitations (ICAO gate constraints).

Another aspect is the included powertrain model (for all types of powertrains with single or dual energy sources, see De Vries et al.[5]) which is modelled as a chain of components/efficiencies. This powertrain model is controllable

Table 2: Electric components assumptions, aligned with EU battery roadmap[b] and Clean Sky 2 Small Air Transport[c].

Parameter	**Unit**	**Value**	**Remark**
Battery gravimetric energy density	Wh/kg	340	pack-level
Battery volumetric energy density	kg/m^3	800	pack-level
Battery minimum state-of-charge	%	20	
Electromotors gravimetric power density	kW/kg	3.77	includes TMS, controllers and converters
Electrogenerators gravimetric power density	kW/kg	4.79	includes TMS, controllers and converters
Electromotors volumetric power density	kW/lt	18.2	electric drive only, ex. gearbox
Battery DC/DC gravimetric power density	kW/kg	14.85	Includes DC/DC (18 kW/kg) and cooling system (0,85 kW/kg, with 1% assumed heat rejection.
Battery TMS gravimetric power density	kW/kg	0.36	Dissipates battery heat to the outside.
Battery heat rejection	%	3	Fraction of battery power output dissipated via heat

for different flight phases for different operating modes (of a hybrid electric powertrain) and can be configured with different power control parameters (gas turbine throttle setting, supplied power ratio, i.e. by a secondary energy storage in case of a hybrid powertrain, and the shaft power ratio, which determines the power provided to the distributed electric motors). In the current article the following powertrain architectures are considered: fully electric, serial hybrid, parallel hybrid (boosting), series-parallel partial hybrid (SPPH) and direct combustion. These powertrain architectures are illustrated in Figure 2. In this figure, "F" and "BAT" refer to Fuel and Battery respectively. As for components, "GT" stands for Gas Turbine, "GB" for Gear Box, "EM" for Electric Motor, "PM" for Power Management and "P" for Propulsor. Upper-case letters are used for energy sources and powertrain components, while power paths are indicated with lower-case subscripts, with arrowheads indicating the feasible direction of the power flow.

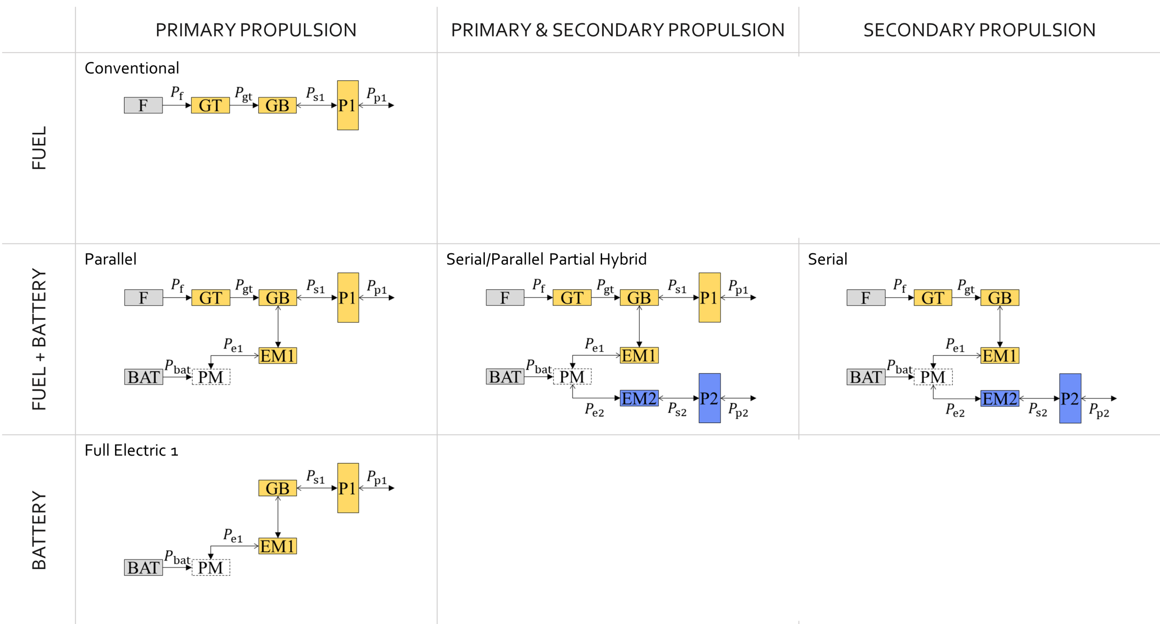

Figure 2: Notional representation of powertrain architectures, adapted from De Vries et al.[6] and Bonnin & Hoogreef.[2]

The *supplied power ratio*[7,17] is used as a power-split parameter to define how the power coming from the two energy sources is shared at the node:

$$\Phi = \frac{P_{bat}}{P_{bat} + P_f}. \tag{1}$$

[b] https://battery2030.eu/research/roadmap/
[c] https://cordis.europa.eu/project/id/945500

For the evaluation of the aircraft designs, the following Key Performance Indicators (KPIs) are considered:

- E_f: fuel energy consumed along the nominal mission, excluding loiter and diversion.
- E_{bat}: battery energy consumed along the nominal mission, excluding loiter and diversion.
- $PREE$: Payload Range Energy Efficiency, see equation 2, with W_{PL} the payload weight, R the mission range. The $PREE$ is computed with respect to the energy spent during the nominal mission, excluding loiter and diversion.

$$PREE = \frac{W_{PL} \cdot R}{E_{bat} + E_f} \tag{2}$$

2.2 Payload-Range Exploration for Commuter and Regional Aircraft

Payload-range explorations are performed for both commuter and regional aircraft, for different powertrain layouts (as presented in Figure 2). For the commuter aircraft, variations between 11 and 19 passengers were made with harmonic range varying between 300 km and 600 km. For regional aircraft, variations between fifty and ninety passengers were made, varying the harmonic range between 250 and 600 nautical miles. In the following section, the 19-seat commuter aircraft and 70-seat regional aircraft are highlighted in terms of range exploration.

The range exploration for the commuter aircraft with 19 seats is presented in Figure 3. Shown in this figure are the difference in MTOM with respect to a kerosene baseline designed for the same requirements, the difference in PREE and the difference in fuel consumption over the nominal mission. It must be noted that a complete redesign is made for every point, for every powertrain architecture (as well as the kerosene baseline). In addition, the span limit (ICAO B-gate) of 24 meter is shown to illustrate the feasibility of the different topologies in terms of size.

Four different (hybrid-) electric aircraft are compared to a kerosene baseline: a fully electric (fullE) configuration with a single main propeller per side (COM-fullE), a fully electric configuration with ten (COM-fullE-LEDP10) (five per side) Leading Edge Distributed Propellers (LEDPs), a serial hybrid with 40% supplied power ratio and a serial hybrid with 60% supplied power ratio (COM-serial-Phi40 and Phi60). Note that beyond a harmonic range of 550 km, the fully electric configurations did not converge anymore in the design point. Indicating that these become too large/heavy to be feasible. Additionally, it is worth mentioning that the CS-23 MTOM limit of 8.62 metric tons is in this case not enforced as a constraint. The impact of this constraint is indicated in the technology landscape (Figure 5).

All hybrid electric or full-electric commuter aircraft are significantly heavier than the baseline. The relative MTOM increase over the baseline increases with cruise supplied power ratio Φ^* ($\Phi^* = 1$ for full-electric aircraft) and with harmonic range. For the lowest range the MTOM increase of full-electric aircraft exceeds 75%. The LEDP version of the full-electric is much heavier than the full-electric with only main propellers (+20% for 19 pax over 500km design range), due to increased powertrain weight.

The 24-meter span limit is severely constraining the domain where full-electric aircraft could fly, though one could argue its applicability to this class of aircraft. With 19 passengers capacity, the fullE can fly only 300 km before hitting the span constraint. Here, the LEDP configuration brings a benefit: it enables a lower wingspan (smaller wing area for an identical aspect ratio) for a given set of payload and design range: a 19-pax LEDP version could fly up to 400 km before hitting the span limit. (Note that the outboard propeller was placed half a diameter inboard to not enlarge the span). Also hybrid aircraft can be significantly impacted by the span limit, as shown in Figure 3. At 19-pax capacity, any design range above 525 km is unfeasible for any of those serial aircraft, without exceeding the 24-meter span limit

All aircraft achieve better PREE compared to the baseline. For most of the design ranges, the fullE is more efficient, while the fullE-LEDP suffers from its mass penalty and is for the lowest ranges on-par with the serial-Phi60 before being outperformed by it. Towards the highest design ranges, the PREE of the fullE, serial-Phi40 and serial-Phi60 are rather similar, but the serial-Phi40 is the only that abides by the 24-meters span constraint. Since all aircraft are more efficient than the baseline, the block fuel reduction they manage is greater than their Φ^*, thus all achieve a decrease in fuel burn.

For regional aircraft, the range exploration for different turboprop architectures with 70 passengers is presented in Figure 4. The KPIs and design procedure are the same as for the commuter aircraft, except that now the 36m ICAO C-gate limit is indicated. Three different hybrid electric architectures are evaluated for this aircraft type, the SPPH, serial and parallel (boosted) powertrains. The serial (REG-serial) and boosted (REG-boostedTP) architectures contain a single propulsion chain with a main propulsor on each wing. Both architectures are evaluated for a ten percent and twenty percent supplied power ratio during cruise (Phi10 and Phi20). The SPPH architecture is evaluated for the same Φ^*, however, also variants that have one main propulsor and one wing tip mounted propulsor (WtipMP) are designed, next to configurations with one main and three LEDP propellers.

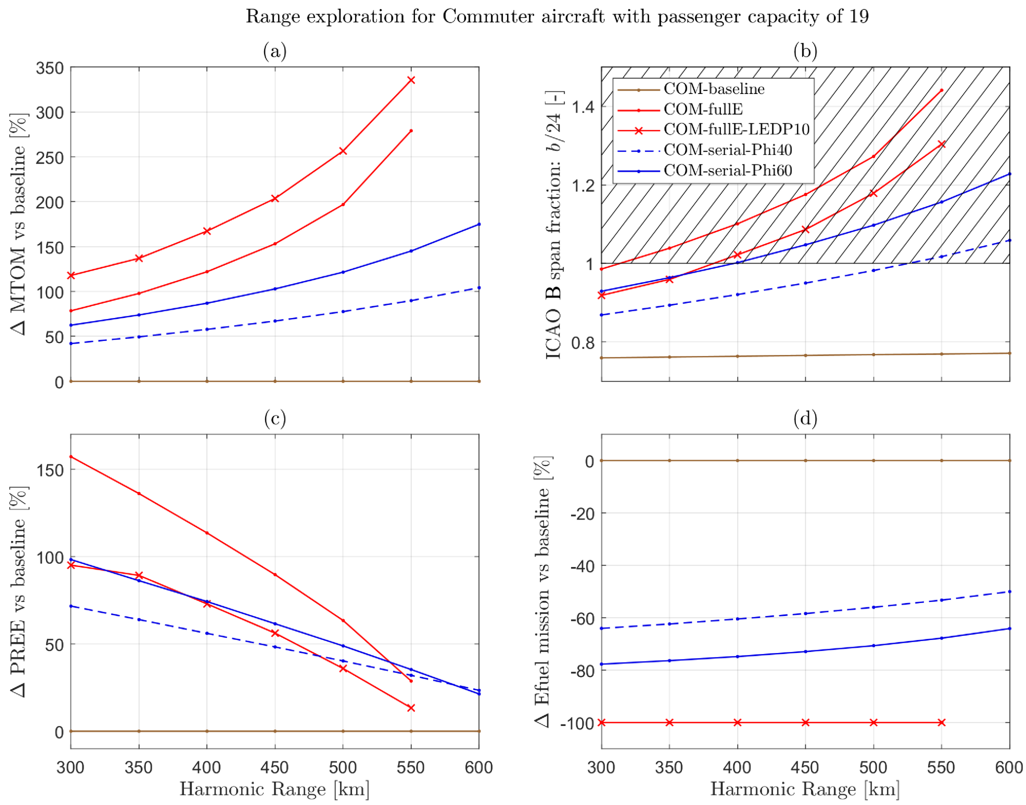

Figure 3: Range exploration for hybrid and electric commuter aircraft with 19 passengers.

A general observation concerning the variation in range for regional aircraft is that MTOM is significantly higher for all hybrid aircraft, with the relative difference increasing with range. The trend in MTOM variation with range is pseudo-linear for aircraft with Φ^{*}=0.10, but non-linearities appear clearly for Φ^{*}=0.20. The debilitating impact of hybridization on MTOM is clearly visible, with hybrid aircraft easily exceeding twice the MTOM of the baseline.

The minimum MTOM increase over the baseline is around 25%, with the SPPH aircraft being significantly lighter than the serial or parallel (boostedTP) configurations. This conclusion may seem counterintuitive as the SPPH architecture is the most complex hybrid powertrain which contains the most components and nodes. However, this design architecture enables to minimize the power loading of the EM1 (see Figure 2). In serial or parallel powertrains, the presence of a single propulsion layout requires EM1 to be either sized by the maximum GT power output case (serial) or by the battery maximum power output case (parallel). In an SPPH architecture, the primary and secondary branch can be maintained quasi-independent and therefore EM1 can be maintained relatively small. This is also synomymous for limited power conversion during mission phases, drastically reducing conversion losses. Hence, the PREE advantage of SPPH configurations (for a given Φ^{*}) over other architectures increases with range.

The PREE is mostly impacted by mass penalties induced by larger battery capacities, which can be seen when comparing identical aircraft/powertrain layouts with different Φ^{*}. The decrease in ΔPREE with range is larger for aircraft with higher Φ^{*}. ΔPREE curves intersect: aircraft with higher Φ^{*} are more efficient for lower ranges and less efficient at higher ones. However, those switching points occur at different ranges for various aircraft configurations, due to the different impact of power conversion losses.

The maximum span constraint, assumed to be 36 meters for the regional class, is an important consideration. Almost all designs become exposed to this constraint over the course of the range exploration. The most efficient configuration (SPPH) is also the lightest, such that it could be implemented on the largest domain of payload and range. For instance, the SPPH-Phi20 can match the required payload and harmonic range of the ATR-72 without being exposed to the span constraint, with a span of 34.4 meters. The wing-tip mounted propeller configuration (SPPH-WtipMP) are in both cases underperforming by a few percent compared to their SPPH counterparts with three outboard electro-motors. Besides, the secondary propulsor at the wing tip increases the physical wingspan.

Concerning the relative fuel burn, it can be seen from the curves of the serial-Phi10, that the presence of a battery

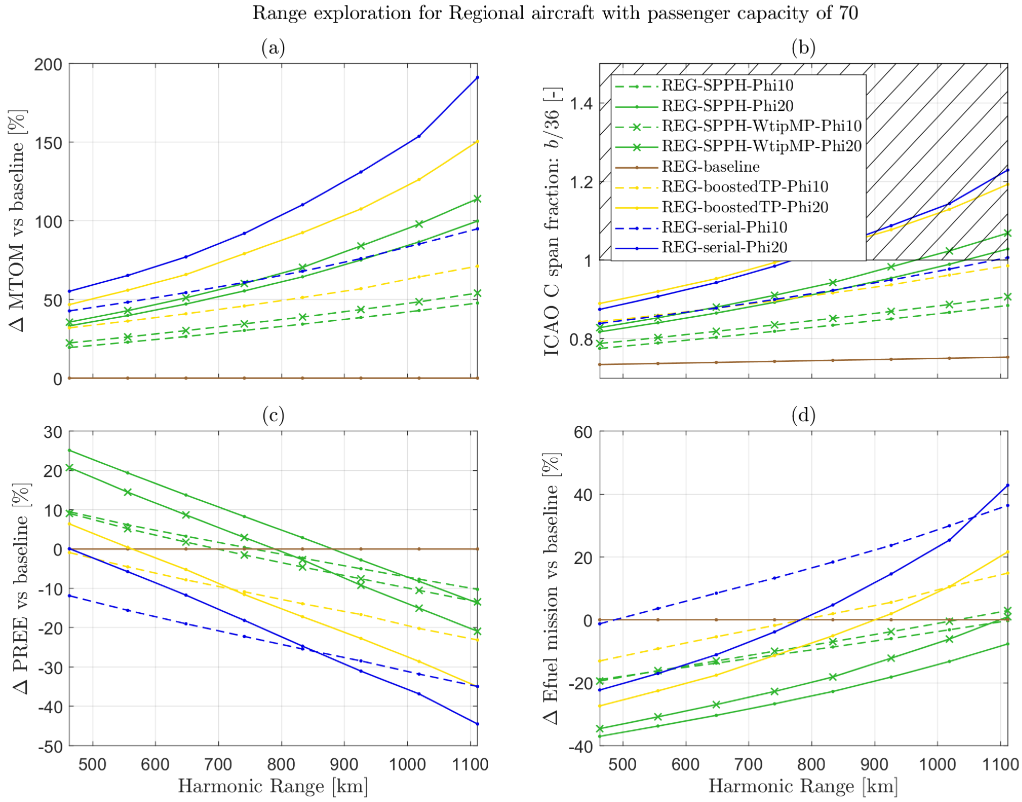

Figure 4: Range exploration for hybrid regional aircraft with 70 passengers.

does not necessarily imply a reduction in fuel burn. On the other side, the SPPH-Phi20 manages a reduction in fuel burn that can be significant and, interestingly, exceed the degree of hybridization in cruise due to the high efficiency of the powertrain when EM1 is minimized.

Although the SPPH variant seems to outperform the other architectures for the regional category, its performance in off-design conditions still has to be proven. Additionally, it is important to consider limitations for all powertrain architectures that may stem from volumetric constraints, whilst still maintaining gate constraints. More on this topic can be found in Bonnin et al.[3]

2.3 CHYLA Landscape of Technology Applications

From the various aircraft designs and sensitivity studies (including an assessment of hydrogen tank integration by Onorato et al.[21]), a landscape of technology applications can be drawn. The landscape that has been identified from the CHYLA studies is presented in Figure 5. This landscape illustrates the different feasible aircraft designs for the various aircraft classes, from general aviation to large commercial aircraft.

An important observation is that for the categories larger than regional, only liquid hydrogen combustion allows for feasible designs. For the largest category of aircraft, the fuselage length actually becomes critical, whereas for the smaller categories, generally, the wingspan becomes a limiting factor due to the increase in powertrain masses due to electrification. Hence, double-deck cabin layouts become interesting for the largest category.

The regional category is the one with the largest feasible design space, though the ICAO C-gate span limit narrows this down significantly. Φ^* should be limited between 10% and 20% for this category to remain feasible, whereas for the commuter aircraft higher supplied power ratios are possible.

Interestingly, the feasible powertrains for the commuter category are slightly different in terms of how promising they are compared to the regional class. For regional SPPH outperforms parallel (boosted) and serial hybrids. Whilst fully electric designs are still achievable for commuters, their maximum range is significantly impacted by the CS-23 weight limit. Serial hybrid commuters can fly longer ranges at significantly lower MTOM than fully electric versions. This impact of electrification is also obvious for the general aviation aircraft.

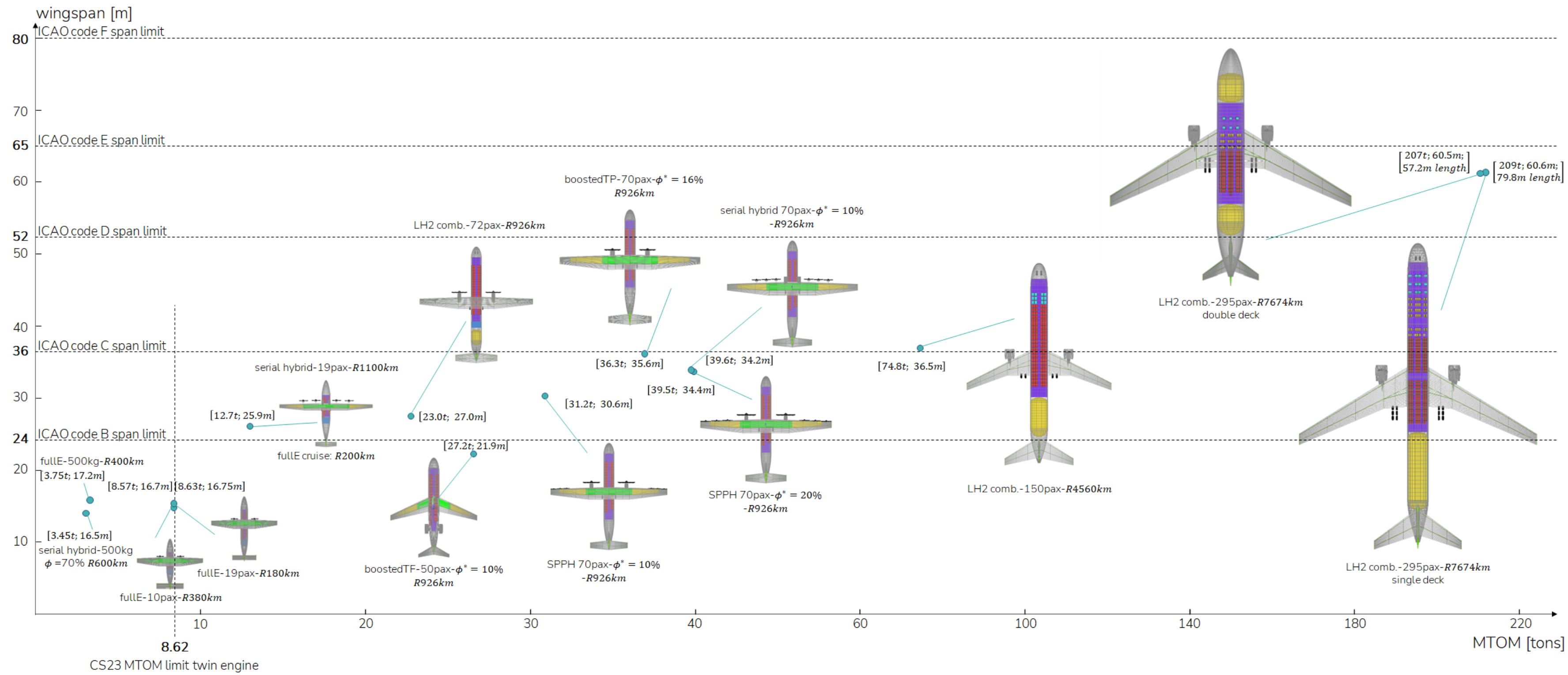

Figure 5: CHYLA landscape of aircraft technology applications, Φ^*: supplied battery power ratio in cruise.

3. Credibility-Based MDO

Technology predictions about the improvement in the state-of-the-art for aircraft designs and subsystem technologies show a large variability in achievable future performance. Hence, instead of assuming scalar values for future performance parameters, probability distributions that assign a certain change of realisation to performance improvements could be defined. In the CHYLA project, the concept of design credibility was defined as: ”The probability that at a certain time frame the technology will have reached at least a certain maturity (performance) level“. More details on credibility definition, quantification and credibility based MDO can be found in Wahler et al.[31,33]

In mathematical terms a Credibility Function (CF) that is equal to the complementary Cumulative Distribution Function (CDF) of the parameter can be defined according to Equation 3. This states that the credibility of parameter performance is large when the probability that performance of a certain technology can exceed the desired value is large.

$$CF = P(X > x) = 1 - P(x \leq X) = 1 - CDF \tag{3}$$

State-of-the-art performance of a parameter will result in very high credibility, whereas a large assumed improvement results in a low credibility. To assess the credibility of predictions for parameter performance it is necessary to construct the corresponding Probability Density Functions (PDFs) that define the probable performance range of a technology parameter for a given timeframe. The shape of these PDFs is influenced by a range of factors depending on the quality of the prediction or the inherent characteristics of the technology that is considered. An example of this concept is shown in Figure 6. This figure illustrates different possible shapes of the underlying PDFs and their resulting CFs around an expected improvement of 3.5% over the status quo.

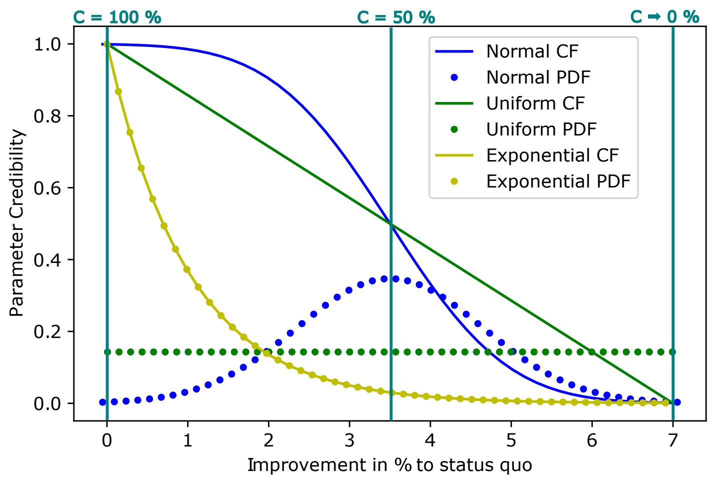

Figure 6: Credibility functions for different types of PDFs, adapted from.[35]

A vast range of technologies could be considered for credibility-based MDO. However, given the scope of the project and to remain computationally feasible, a selection of interesting technology parameters (in the project referred to as uncertain parameters) was made. These reflect technologies in which a large uncertainty in achievable performance levels is expected and which in turn may have a significant impact on the overall aircraft performance. As a baseline, converged aircraft designs from conceptual sizing are used as inputs to the optimization process (see Figure 1). In CHYLA, the following technologies were considered during the credibility-based optimization.

- Gravimetric battery energy density
- Gravimetric electric motor power density
- Volumetric electric motor power density
- Percentage of laminar flow over the main wing
- Percentage of structural weight reduction due to novel materials and production techniques

To illustrate the potential of the credibility-based MDO method, this article presents a demonstration on a boosted-turbofan aircraft for 50 passengers. The aircraft uses a parallel hybrid-electric powertrain where the gasturbine is boosted by an electric motor attached through a gearbox to the shaft. Energy is provided by kerosene combustion and a battery for the electric motor. The objective is to maximize the range of the aircraft, whilst respecting a minimum credibility level for the differenct uncertain parameters.

Figure 7 illustrates the results from the crediblity-based MDO. The reference aircraft, as obtained from the conceptual design space is plotted with its average credibility (evaluated based on the assumed technology scenario for this particular design). Three lines illustrate the achievable range and associated average credibility when optimizing only the parameter impacting the energy network (powertrain), all uncertain parameters, and an additional case where also wing geometry is optimized.

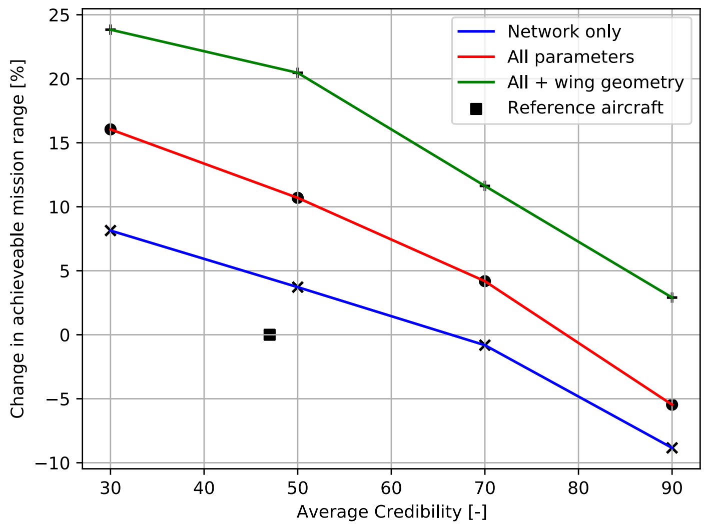

Figure 7: Credibility-mission range Pareto front for boosted-turbofan regional jet optimisations with 50 passengers.

It is clear from comparing the curves in Figure 7 that the more design variables are added to the optimisation, the better the overall performance of the resulting aircraft is. The relative change in mission range between highest and lowest credibility is ~17% for the network only case, while a relative change of ~21% can be achieved when all design variables are included. Adding also the wing geometry variables does not have this much of an impact to the relative change between low and high credibility anymore.

The impact of the actual credibility-based optimization on the uncertain parameters is more clear when inspecting the results in Table 3. In this table, the case for all parameters without optimization of the wing geometry is discussed. The influence of the wing weight reductions is clearly illustrated in the wing and structural masses in Table 3. It must be noted that the values in this table refer to the actual component performance, with the values in brackets corresponding to the credibility values. With low credibility, low masses are resulting, with the motor, battery and fuel masses showing clear trends. Improvements in motor mass are largest mass-wise when comparing high credibility data points. Both fuel and battery mass increase for lower credibilities. Thus, the reduction in wing and motor mass allows batteries and fuel volume to be larger, directly translating to longer range.

It can be observed that both motor and wing masses have the highest absolute reductions at high credibilities. The exponential distribution of the underlying structural weight reductions PDF is clearly visible. For the 90% average credibility, structural weight reduction is hardly used due to the large negative impact on credibility that a small weight reduction would yield. An initial improvement of the parameter of 3% requires a reduction in credibility of 30%, whereas an improvement of a further 3% would only require less than 20% further reduction in credibility. In terms of relative importance, the battery is the dominant parameter, whereas the volumetric power density of the electrical machines showed a very low influence at high credibility values, and even at lower allowable credibility data points it was never a limiting (or close to limiting) value.

4. Regional Operative Sscenario

The regional operative scenario considers airline operations for the Air Nostrum network, representing a typical European airline operating in a highly competitive market. For this study, a dynamic programming model was developed based on the work by Séoane-Alvarez[25] and Noorafza et al.[20]

Dynamic programming is an optimization method that decomposes a complex problem into smaller sub-problems. This approach allows for an efficient solution of problems that would otherwise be computationally infeasible. Dynamic programming can be applied to the network and fleet allocation problem. A flight schedule is built by allocating

Table 3: Credibility-based MDO results for boosted-turbofan regional jet optimisations with 50 passengers, all parameters, no wing geometry optimization.

Parameter	Reference	30% Cred	50% Cred	70% Cred	90% Cred
MTOM [kg]	33024	33046	33094	33026	33026
Structure [kg]	7334	6919	7008	7083	7182
Wing [kg]	2685	2270	2359	2434	2533
Motor [kg]	1202	403	451	582	621
Battery [kg]	8243	9309	9299	9130	9058
Fuel [kg]	1595	1756	1676	1583	1519
Area of laminar flow [%]	0 (100%)	38.9 (57%)	40.2 (53%)	37.8 (60%)	23.7 (90%)
Structural wing weight red. [%]	12 (31%)	12.2 (29%)	10.7(43%)	7.45 (62%)	4.55 (99%)
Battery grav. energy density [Wh/kg]	543.4 (12%)	533 (20%)	513 (40%)	496 (60%)	476.2 (80%)
Motor grav. power density [kW/kg]	4.0 (99%)	11.95 (20%)	10.68 (40%)	8.26 (78%)	7.73 (83%)
Motor vol. power density [kW/l]	35.2 (31%)	32.9 (39%)	23.0 (73%)	8.0 (96%)	5.0 (99%)

one aircraft at a time to the schedule, by selecting the most profitable type at each iteration for the demand that is still to be served. More details on the application of dynamic programming can be found in Proesmans et al.[22]

Profit and route matrices for each aircraft type in the fleet are constructed for the network and fleet allocation problem. The profit matrix is two-dimensional with the entire scheduling period on one axis (in this case one week) and the airports in the network on the other. To construct the profit matrix, starting from the last time instant, for each airport, all possible alternatives to reach the airport at that time instant are considered. Each alternative has an associated profit value, which may be negative if the option is not economically viable. This profit represents the maximum economic return that can be obtained from that point in the space-time network onwards. Going backwards in time, the maximum profit that can be obtained from each point in the space-time network onwards is determined.

Simultaneously, a route matrix of the same dimensions records the flown routes that, starting from that time-space instant, lead to obtaining the maximum profit. Hence, for each aircraft type, the maximum profit that can be obtained from its assignment to a weekly schedule, and all the movements that are required to achieve that profit are determined. The aircraft with the highest positive profit is assigned to the schedule. If the best possible aircraft returns a negative profit, the algorithm stops.

Subsequently, this aircraft is removed from the available fleet and the passenger demand that will be satisfied by its scheduling is removed. The algorithm starts the second iteration, subject to availability of other aircraft and demand. Eventually, the algorithm determines the total number of aircraft required and their weekly scheduling.

The dynamic programming is based on the Bellman-Ford algorithm, commonly used in the optimization of transportation systems.[19] The Bellman-Ford algorithm is a shortest-path algorithm to find the shortest path between two nodes in a graph. The algorithm works by repeatedly relaxing all edges in the graph until the shortest path distances converge. In this case, the algorithm is used iteratively to build the matrixes, finding the best path between each pair of airports, taking into account flight times, flight costs, flight revenues and other operational constraints.

For the network under consideration, the possible aircraft that can be used are presented in Table 4. These consist of three kerosene aircraft (two jet and one prop) and two hybrid-electric alternatives (one prop and one jet), which can carry similar payload. bTF-50 is a boosted turbofan aircraft (regional jet) which carries 50 passengers, bTP70-Phi16 is a 70 passenger boosted turboprop aircraft with a Φ^* of 16% in cruise.

Table 4: Database of hybrid electric and kerosene aircraft available for the regional operative scenario.

Aircraft name	Aircraft type	Seats [-]	Max range [km]	Cruise speed [km/h]	Req. runway [m]
CRJ200	KE	50	3148	786	1920
ATR72-600	KE	72	1528	510	1315
CRJ1000	KE	100	3056	830	2030
bTF-50	HE	50	926	747	1333
bTP70-Phi16	HE	70	926	450	1333

A variety of case studies was performed for the operational assessment within CHYLA. In this article we summarize these findings in Figure 8, which highlights the impact of changing emission taxation, fuel price and charging time (for hybrid electric aircraft) on emissions and profit for an airline. Note that the solutions do not necessarily serve the same routes as only profitable routes are selected by the algorithm.

In Figure 8 it can be seen that in fact the charging time has the largest impact on emissions and a low charging time is required. At low taxes, no hybrid aircraft are selected. For hybrid-electric aircraft to become competitive, relatively high CO_2 taxes are required. However, lower charging time has a significant impact on profit and emissions at the same time, as suddenly more routes become profitable. Fuel price only shifts the results but does not impact the trends.

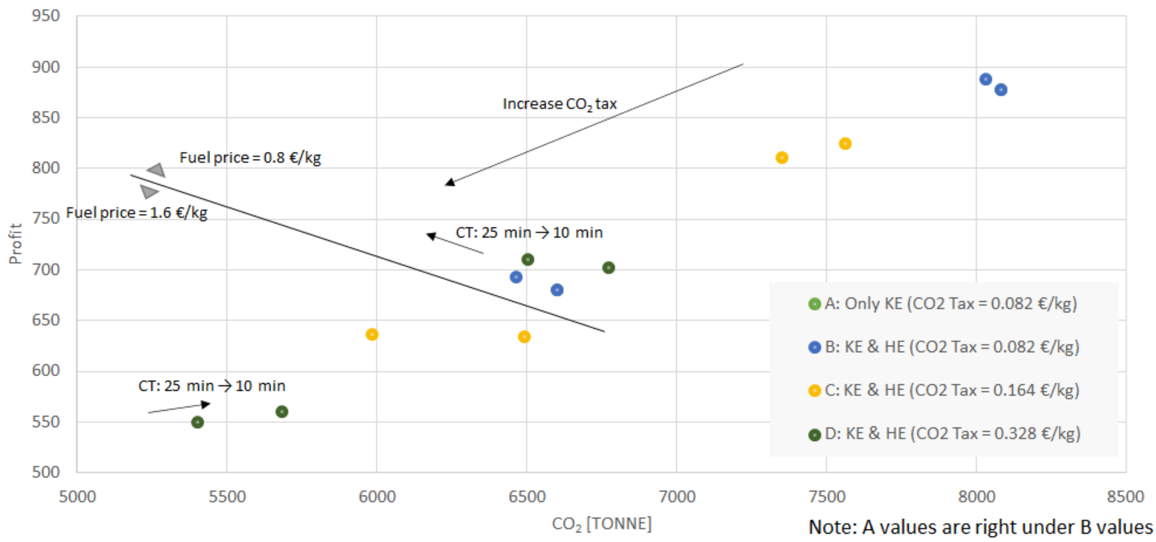

Figure 8: Regional network fleet allocation solutions varying CO_2 tax, fuel price and charging time.

Table 5 further highlights these trends. Here, it is very clear that only few hybrid electric aircraft enter a profitable fleet at low charging times and hence no emission reductions are achieved at high charging times. At higher taxation, the fleet size is decreasing as less and less routes are actually profitable to service (hence dropping total profit). The combination of hybrid electric aircraft, but certainly lower amount of flights, benefits the overall emissions.

Table 5: Results for fleet and network allocation of hybrid electric aircraft in regional network; fuel price €0.8/kg.

Scen.	**CO_2 tax [€/kg]**	**Charging time [min]**	**Profit**	**CO_2 emissions [kg]**	**Fleet size**	**Best fleet**	**% Profit**	**% Ems.**
A	0.082	25	8.78E+06	8.08E+06	41	CRJ200 (16), ATR 72-600 (6), CRJ1000 (19)	–	–
B	0.082	25	8.78E+06	8.08E+06	41	CRJ200 (16), ATR 72-600 (6), CRJ1000 (19)	0%	0%
C	0.164	25	8.11E+06	7.35E+06	36	CRJ200 (12), ATR 72-600 (5), CRJ1000 (19)	0%	0%
D	0.328	25	7.03E+06	6.77E+06	33	CRJ200 (10), ATR 72-600 (6), CRJ1000 (17)	0%	0%
B	0.082	10	8.89E+06	8.03E+06	42	CRJ200 (15), ATR 72-600 (5), CRJ1000 (19), TF-50 (3)	1%	-1%
C	0.164	10	8.25E+06	7.56E+06	38	CRJ200 (12), ATR 72-600 (4), CRJ1000 (18), TF-50 (4)	2%	-3%
D	0.328	10	7.11E+06	6.50E+06	33	CRJ200 (7), ATR 72-600 (5), CRJ1000 (16), TF-50 (5)	1%	-4%

5. Conclusions and Recommendations

All hybrid electric or fully electric commuter and regional aircraft are significantly heavier than the baseline. For commuter aircraft, a fully electric LEDP design is much heavier than a fully electric one with only main propellers (+20% for 19 pax over 500 km design range). For this category, the CS-23 MTOM limit will become critical at short ranges (~180 km) or low payload (~10 pax).

For both categories of aircraft, span limits (24 m and 36 m, respectively) can already be severely constraining the designs. With 19 passengers capacity, the fully electric commuter can fly just 300 km before hitting the span constraint. At 19 pax capacity, any design range above 525 km is unfeasible for any serial commuter aircraft, without exceeding the 24 m span limit. The maximum span constraint, assumed to be 36 m for the regional class, is impacting all powertrain layouts. The most efficient configuration (SPPH) is also the lightest; with $\Phi^* = 20\%$ it can match the required payload and harmonic range of the ATR-72 without being exposed to the span constraint, with a span of 34.4 m.

All commuter aircraft achieve better PREE due to more efficient powertrains. Since all commuters are more efficient than the baseline, the block fuel reduction they manage is greater than their Φ^*. For regional aircraft, PREE is mostly impacted by mass penalties induced by larger battery capacities, which can be seen when comparing identical aircraft/powertrain layouts with different Φ^*. The SPPH with $\Phi^* = 20\%$ manages a reduction in fuel burn that can be significant and, interestingly, exceed the degree of hybridization in cruise due to the high efficiency of the powertrain when EM1 is minimized.

From the landscape of technology applications it can be seen that for the larger categories (larger than regional), only liquid hydrogen combustion allows for feasible designs. However, for the largest category of aircraft, the fuselage length actually becomes critical. Hence, double-deck cabin layouts become interesting. For the smaller categories, generally the wingspan becomes a limiting factor on the design due to the increase in powertrain masses due to electrification.

The impact of the actual credibility-based optimization of the uncertain parameters showed that improvements in motor mass are largest mass-wise when comparing high credibility data points. Both fuel and battery mass increase for lower credibilities. The reduction in wing and motor mass allows batteries and fuel volume to be larger, directly translating to longer range.

It was concluded from the regional operative scenario that the charging time has the largest impact on emissions and a low charging time is a necessity. Relatively high CO_2 taxes are required for hybrid electric aircraft to become competitive. However, lower charging time has a significant impact on profit and emissions at the same time, as suddenly more routes become profitable.

For future work it is recommended to study the different hybrid electric aircraft in their off-design conditions. It is expected that the relative performance of the powertrains may differ, yet also that significant fuel savings compared to kerosener aircraft are possible. These off-design conditions should also be more tightly coupled and integrated to strategic airline planning to further reduce emissions.

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