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Overview and preliminary results of the Scalability Investigation of hybrid Electric concepts for Next-generation Aircraft (SIENA) project

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Abstract. This paper presents an overview and preliminary system architecture evaluation results of the project SIENA developed under the European Union Clean Sky 2 Program Thematic Topics. The ambition of the project is to accelerate the development of novel aircraft propulsion technologies by identification of technologies that are scalable across different aircraft categories. One of the main tasks within this process is the aircraft-level evaluation of the various system architecture and technology options. For this, a conceptual aircraft design software developed at Politecnico di Milano, and an aircraft on-board systems design and analysis method developed at Collins Aerospace Applied Research and Technology are combined. Utilizing these joint capabilities, the paper presents system architecture performance studies for two aircraft categories, a regional turboprop (ATR 72) and a short/medium-range turbofan (A320neo). The studies compare novel propulsion system concepts, for which kerosene is replaced with hydrogen as the main energy source on board, against traditional reference systems. In this context, two future technology scenarios are considered reflecting conservative and optimistic assumptions, respectively.

1. Introduction

The ambitious climate goals of becoming net-emission free in commercial aviation by the year 2050 as proposed in the "Destination 2050" report call for radical technology advancements for the next generation of commercial aircraft [1]. The introduction of (hybrid-) electric propulsion systems is one of the most promising concepts to achieve these goals. In recent years, alternative propulsion concepts have been broadly investigated in the aviation sector by various entities from industry, research, and academia. While full-electric propulsion systems are already flying today in aircraft of the General Aviation (GA) category [2, 3], this is not feasible for large commercial aircraft in the short-term due to a variety of technological challenges such as the energy density of batteries, power density of electric motors and converters, and the complexity of thermal management [4]. For these aircraft, combinations of hybrid-electric propulsion (HEP) and aero-propulsive coupling technologies are considered as well as novel thermal management systems and the utilization of alternative fuels such as hydrogen [5, 6].

Since there are almost innumerable design options for electric propulsion architectures, it is important to carefully investigate the design space early in the process using conceptual design and analysis tools. However, due to the complexity of grasping this large design space at once, many projects are mainly focused on designing solutions for specific applications, e.g., single aircraft classes and operational profiles. This results in the development of multiple configurations in parallel. While these configurations are optimized for their specific applications, it is often hard to find similarities/commonalities in the technologies and system architectures. This results in a lack of re-usability and can prevent stakeholders from investing in the development of novel technologies. Additionally, regulatory aspects and the impact on the infrastructure (e.g., airports) are often not investigated in detail. Another aspect is that the current focus of the HEP research is on smaller aircraft categories as they are expected to enter the market in a shorter time frame. However, more than 95% of greenhouse gas emissions from commercial aviation is produced by short/medium-range and long-range aircraft [7]. For these categories, one of the most promising solutions appears to be a replacement of conventional fuel with hydrogen for direct combustion. Furthermore, the current research focus on smaller aircraft categories comes with the main drawback that it does not capture the potential of technology scalability across a wider range of aircraft. This raises the question whether technology tradeoffs or a deviation from an optimal design point enable such scalability.

The Clean Sky 2 funded project SIENA has the ambition to include scalability into the design process resulting in solutions that are scalable-by-design rather than optimized for a specific application. The aim is to build upon experience from the development of electric propulsion systems for small aircraft and transfer this experience towards larger aircraft. The project considers three main aspects in this regard,

- a technology evaluation, in which the possible design space is explored resulting in a variety of candidate architectures, which are subsequently analyzed in detail,
- an aircraft operations and economic analysis, where the impact on the airport infrastructure and the economic feasibility are investigated,
- and a certification impact study consisting of a review of relevant existing regulations and a regulatory gap analysis and requirement applicability.

While the three streams are highly interdependent and executed in parallel, this paper is focused on the technology evaluation. Section 2 gives an overview on the methodologies developed to perform the evaluation, section 3 shows preliminary results for two aircraft categories, different system architectures and technology scenarios, and section 4 provides a short summary and conclusion.

2. Methodology

To perform the technology evaluation within the SIENA project, an integrated vehicle design and systems evaluation methodology is required, which is enabled by combining the aircraft systems design and analysis capabilities at Collins Aerospace Applied Research & Technology (ART) Ireland with conceptual aircraft design capabilities at the Department of Aerospace Sciences and Technologies (DAER) of Politecnico di Milano (PoliMi). The following subsections first give an overview on both parts before shortly describing how the two are harmonized while protecting all intellectual property (IP) and IT regulations of the involved partners.

2.1. Vehicle design methodology

In the context of assessing novel propulsive configurations, a tool that can evaluate how choices in the architecture of propulsive systems affect the overall aircraft design is crucial. PoliMi's DAER has developed the Hyperion (HYbrid PERformance SimulatION) software [8], which calculates the aircraft weight breakdown, geometry, and the power characteristics of the propulsion system including conventional combustion engines as well as electric propulsion systems, depending on the targeted configuration. Hyperion computes the outputs blending data from statistical regressions and from the modular modeling of subsystems. Currently, the tool is applicable to propeller-driven aircraft with either conventional, hybrid-electric, or fuel-cell-electric propulsion and to turbofan-driven aircraft burning either jet fuel or hydrogen.

Hyperion requires general inputs regarding the propulsive configuration of the aircraft (jet or prop, energy sources), the design mission (cruise speed, range, payload, take-off, and landing runway length), and aerodynamic parameters (lift coefficients, sweep, drag penalties for gears and flaps). Additionally, specific information on the propulsion system is needed. These include bypass ratio, overall pressure ratio, and turbine entry temperature for jet engines, specific power densities for electric components like motors and fuel cells, and specific energy densities for batteries. Furthermore, Hyperion also considers the applicable regulation for the targeted aircraft (either EASA CS-23 or CS-25), which together with the prescribed performance, allow to draw the sizing matrix plot, which defines the design point as a function of power loading W_{mto}/P_s (or T/W_{mto} for jets) and wing loading W_{mto}/S.

Given the innovative architectures considered, it is not possible to size the aircraft from a single regression based on historical data; rather, each component needs to be sized independently, considering the inherent coupling of the aircraft sizing problem. Once the propulsive components (electric motor, fuel cell, jet engine) and the energy storage components (batteries, hydrogen, cryogenic tank) are sized, it is possible to size the non-propulsive airframe mass, which excludes the engines, recurring to regressions based on comparable aircraft. Note that for aircraft storing hydrogen, a correction to account for the fuselage extension to accommodate the hydrogen tank is additionally performed. An iterative procedure computes an initial guess for the mass breakdown, which is then corrected with a time-marching simulation based on flight mechanics equations. This simulation takes as input the required performance along a mission that is divided into take off, climb, cruise, descent, approach, go around, climb, diversion cruise, decent, loiter, approach and landing. The last part is necessary to ensure compliance with the applicable Aircraft Operation regulations.

2.2. Systems design methodology

Collins Aerospace ART Ireland has developed a proprietary in-house aircraft power platform modeling software, which enables detailed sizing and analysis of the entire aircraft on-board systems architecture. Besides modeling traditional architectures with bleed-air-powered pneumatic systems and hydraulic power systems, the software can also account for more- (MEA) and all-electric aircraft (AEA) configurations. The software, as originally described in [9], accounts for different technology selections and model fidelity choices for each aircraft subsystem (multi-fidelity approach). Based on this, the tool calculates the power flow of the aircraft by dividing the different systems into power sinks (power-consuming systems), power distribution/transformation systems (e.g., electric power system, hydraulic power system), and power sources (e.g., engine accessory gearbox, auxiliary power unit generator).

The core of the software with respect to the investigations relevant for this paper is the electric power distribution system module. The module is based on an object-oriented generic systems architecture in which the different power distribution components (e.g., electric motors, power converters, batteries, etc.) can be connected to each other almost arbitrarily depending on the architecture at hand.

Each electric load coming from outside the system boundary is assigned to the corresponding component(s) in the power distribution system (e.g., an electric motor providing shaft power to a propeller shaft). The interconnections among the power system components – i.e., which components are connected to each other, where they are located, and how the loads are distributed among them throughout the flight mission – is defined via so-called energy ports. Each port is unique and defines the connection between exactly two components.

Based on the mission-dependent load requirements, the entire energy network is calculated iteratively using a power balance algorithm. During this calculation, the energy state of each component is determined for every segment of the flight mission. For each of the power distribution system components, there are two essential models to consider in this context, an efficiency model calculating the input power of a component based on the output power required by the component/load up-stream and additional conditions of the current flight state (e.g., flight speed and altitude); the model also calculates the heat load resulting from the efficiency losses, and a mass model calculating the weight of a component based on its power/energy requirements. Here, it is also possible to consider critical design cases such as hot day take-off or failure cases such as one-engine-out.

The electric power systems module also contains a thermal management system (TMS). Here, the iterative nature of the power balance calculation becomes clear. The heat loads resulting from the efficiency losses of the power distribution components are transferred to the thermal management system, which, in turn, is powered by the electric power system. Thereby, it imposes an additional load to the electric power distribution system for the next iteration step.

Note that the component models are currently largely based on constant efficiencies and power/energy densities. However, some components like the fuel cell [10] and the thermal management system [11] utilize parametric models from literature with a higher level of detail. Note that it is planned to include more sophisticated models based on in-house tools at Collins in the future to increase the level of fidelity.

2.3. Harmonization of the vehicle design and systems design methodologies
To evaluate the impact of different system architecture and technology choices on vehicle level, it is necessary to couple the vehicle design with the systems design and evaluation in a closed design loop. IP and IT regulations of the partners involved prevent any direct exchange of source code or software, making remote exchange of input/output data currently the only option. While there are different ways to enable an automated data exchange between tools located at different entities (e.g., via remote execution environments), the data exchange within the scope of SIENA is currently performed manually via a data sharing platform hosted by PoliMi.

Figure 1 provides an overview of the design process approach for the system architecture studies presented in this paper, starting with the conceptual aircraft (A/C) design performed at PoliMi. In the first step, the design mass breakdown of the aircraft is calculated based on the top-level aircraft requirements (TLAR), some design decisions, as well as an initial guess for the on-board systems mass. Subsequently the sizing mission is simulated, as already presented in section 2.1. The result is a converged aircraft data set which is fed into the on-board systems sizing and evaluation method at Collins Aerospace ART. Here, the detailed systems weight breakdown is determined and the required power for each segment of the mission profile is analyzed. This information is then fed back to the overall aircraft design process at PoliMi to update the overall aircraft results.

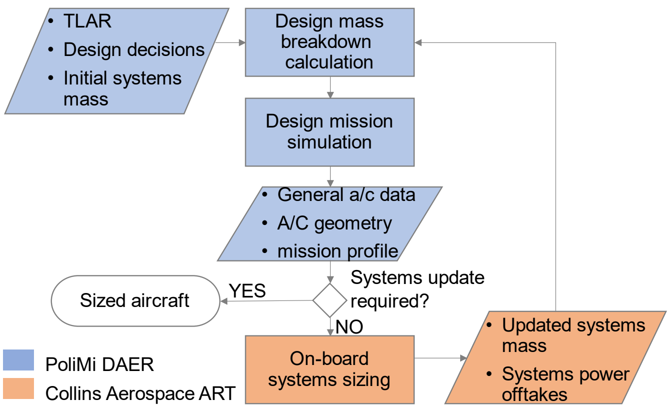


Figure 1: Aircraft and systems design process

While this process could be performed until a certain convergence criterion is satisfied, in the scope of this work, the iteration is only performed once. The studies revealed that the initial guess of the overall aircraft design was already sufficiently accurate to allow a termination of the process after one iteration. Note that this can of course be different depending on the architecture at hand and the given fidelity of the implemented models. It is therefore always necessary to check the deviation in the results for each iteration step and choose whether an update of the systems data is required.

3. Results
One of the main ideas in the context of the project SIENA is to investigate different technologies to identify opportunities and gaps for future research and development. While it is planned to do this for arbitrary system architectures and various technology scenarios (for individual components or entire system groups) in the future, the results presented in this paper are focused on demonstrating the general analysis capabilities for a limited number of cases. In order to provide insight into the effect of future

technology development on aircraft performance, two future technology scenarios have been identified as presented in Table 1:

- Conservative future scenario: the technology values are based on conservative assumptions. Most of the values are equal to the predictions for the year 2030. Hence, this case reflects a scenario that neglects technology advancements beyond 2030.
- Optimistic future scenario: the technology values are based on optimistic future assumptions. Most of the values reflect the predictions for 2050 technology advancements.

Table 1: Component parameter constants and assumptions

Component	Parameter	Unit	Value	
			conservative	optimistic
E-motor	Efficiency		0.95	0.97
	Specific power	kW/kg	11.1 [13]	16.45 [13]
Power converters	Efficiency	-	0.97	0.99 [15]
	Specific power	kW/kg	9 [12]	19 [15]
Battery	Efficiency	-	0.95	0.95
	Specific power	kW/kg	2.275 [13]	5.619 [13]
	Specific energy	kWh/kg	0.35 [13]	1.87 [13]
Fuel cell	Specific power	kW/kg	4.8 [13]	8.8 [13]
	Efficiency[1]	-	0.54 – 0.6 [10]	0.54 – 0.6 [10]
Thermal management	Pump efficiency	-	0.8075 [11]	0.8075 [11]
	Specific pump power	kW/kg	0.333 [14]	0.333 [14]
	Specific fluid & duct weight	kg/m	3.25 [14]	3.25 [14]

Within the scope of the SIENA project, various electric system architectures have been investigated for five aircraft categories ranging from the General Aviation size to wide-body long-range transports. For the sake of conciseness, the results presented in the following sections are limited to two aircraft categories, a regional turboprop (ATR 72), and a short/medium-range turbofan (Airbus A320neo).

3.1. Regional turboprop (ATR 72)

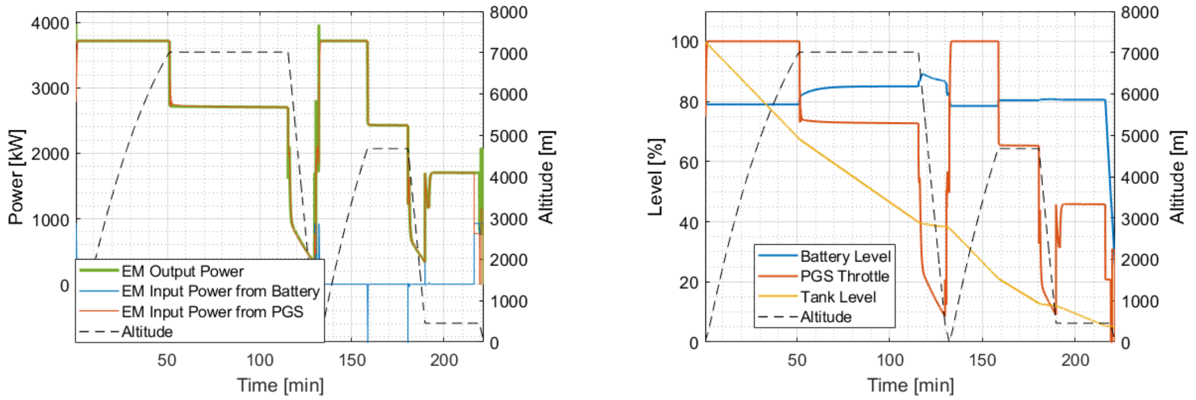
Four system architectures have been investigated for the ATR 72,

- a reference case with conventional turboprop and state-of-the-art on-board systems: *conv.*,
- a conventional turboprop with more electric on-board systems: *conv. MEA*,
- a liquid-hydrogen-powered (LH2) fuel-cell-electric (FCE) configuration with conservative technology assumptions: *LH2 FCE cons.*,
- and a liquid-hydrogen-powered fuel-cell-electric configuration with optimistic technology assumptions: *LH2 FCE opt.*

Note that each of the architecture options, a fully converged aircraft design iteration has been performed. For the two hydrogen-based configurations, a 540 V DC power distribution grid is considered including all necessary conducting and converter components as well as thermal management. Additionally, a battery is used during different segments of the flight mission as an assist to the fuel cell. The more electric systems configuration (*conv. MEA*) has been included to ensure a fair comparison against future technology advancements independent from electric propulsion.

Figure 2 provides an example of the mission performance results for the FCE configurations showing the altitude and power profile as well as the power management (i.e., power split between fuel cell and battery) throughout the mission. Given that energy is stored both in batteries and hydrogen, it is worth mentioning the power management setup: batteries provide a boost to the fuel cell for the take-off run. During cruise flight the fuel cell is used exclusively, and the battery is recharged until it has enough stored energy to allow the completion of the flight.

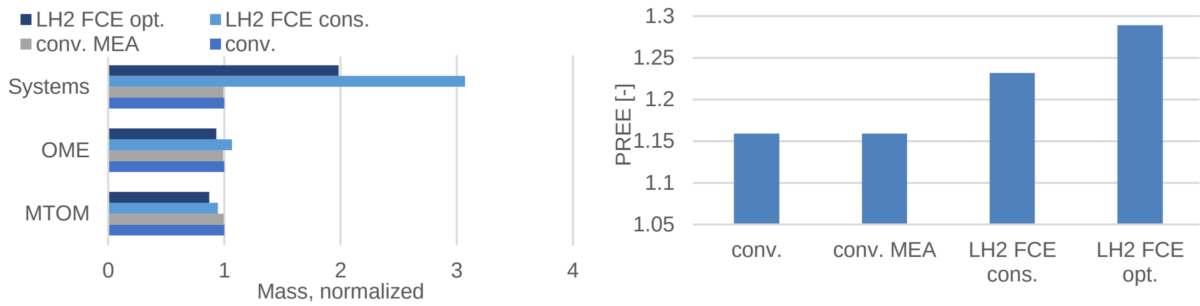
[1] Note that the efficiency values of the fuel cell vary with output power and are based on a proton-exchange membrane fuel cell (PEMFC) model adopted from [10].



a) Altitude and power profile b) Power management

Figure 2: Exemplary mission performance results for the FCE ATR 72 (conservative assumptions)

Figure 3 compares the four investigated system architectures in terms of mass properties and mission performance. Note that the mass numbers have been normalized with the *conv.* configuration as the baseline.



a) Aircraft mass properties b) Mission performance

Figure 3: Comparison for the different ATR 72 system architectures

Due to the short mission and the low cruise speed, the ATR 72 requires a relatively low total mission energy. Therefore, the novel system architectures have an MTOM that is comparable to that of the conventional baseline enabling a fair comparison between the masses of the propulsive components, as, considering that performance requirements are maintained, also the required power remains in the same range. Due to the substitution of the main energy source from kerosene to hydrogen and the additional use of a battery, the aircraft performance comparison cannot exclusively be performed based on fuel mass, as it is often done in traditional aircraft-level studies. Therefore, in Figure 3 b), the metric payload range energy efficiency (PREE), also sometimes referred to as revenue work per energy (RWE), is used, which is the ratio of the payload weight multiplied by range over the total energy stored on board:

$$PREE = \frac{m_{Pl} \cdot g \cdot R}{LHV \cdot m_f + E_{batt}} .$$

Considering the ATR 72 architecture studies, this overall efficiency metric combines many effects at the same time. On the one hand, due to the increased powertrain efficiency of the FCE architectures, the thrust-specific power consumption is lower than that of the conventional ones. Additionally, hydrogen has a three times higher energy density than kerosene, resulting in less fuel mass to be carried on the mission. On the other hand, the heavy cryogenic fuel tanks come with an increase in structural weight. Furthermore, the tanks need to be positioned in the rear-fuselage section resulting in a disadvantageous variation of the center of gravity during the mission and an extension of the fuselage, which adds aerodynamic drag.

3.2. Short/medium-range turbofan (Airbus A320neo)
For the Airbus A320neo, five different system architectures have been investigated,

- a reference case with a conventional turbofan and state-of-the-art on-board systems: *conv.*,
- a conventional turbofan with more electric on-board systems: *conv. MEA*,
- a hydrogen-burning turbofan with more electric on-board systems: *LH2 MEA*,
- a hydrogen-burning turbofan with fuel-cell-powered on-board subsystems assuming conservative technology advancements *LH2 FC cons.*,
- and a hydrogen-burning turbofan with fuel-cell-powered on-board subsystems assuming optimistic technology advancements *LH2 FC opt.*

Figure 4 shows the mission performance comparison of the five configurations based on PREE. The individual effects resulting from the use of hydrogen have already been described for the ATR 72. However, in case of the A320, the combination of these effects leads to a lower PREE for the hydrogen-powered configurations. This is mainly due to the heavy tanks carrying a light fuel, causing an increase of the empty mass fraction, which, in turn, results in a higher average mass to be carried along the mission. The previously mentioned disadvantages of the tank integration also play a role here. Additionally, in contrast to the ATR, the thrust-specific energy consumption almost remains constant for the hydrogen-burning configurations, because the turbofan is not replaced by a more efficient fuel-cell-electric system here.

The integration of a fuel cell powering the on-board subsystems, on the other hand, comes with a PREE increase compared to the *LH2 MEA* configuration, because the power supply of the subsystems is now decoupled from the task of providing thrust to the aircraft. Thus, the thermal engines are solely used for thrust supply while the fuel cell provides electric power for the on-board subsystems.

Figure 5 presents the PREE comparison for a variation of the payload based on the *conv. MEA* and the *LH2 MEA* configurations.

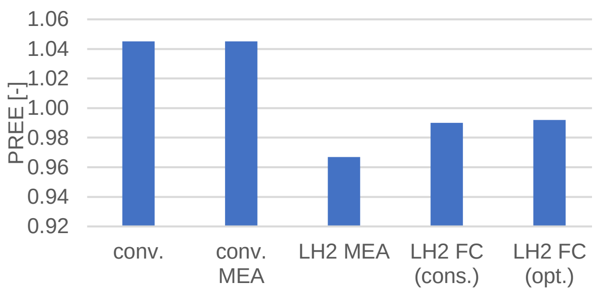


Figure 4: Mission performance comparison for the A320neo system architectures

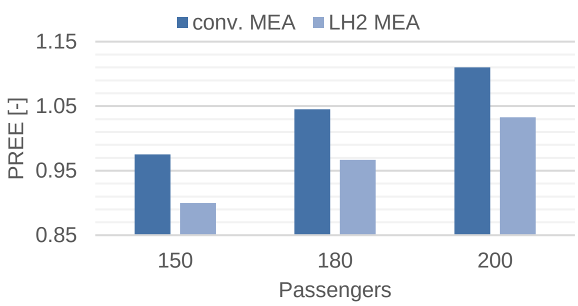


Figure 5: Comparison of PREE for a payload variation (conv. MEA vs. LH2 MEA)

While the PREE is increased with the number of passengers for both configurations, the *LH2 MEA* remains below the *conv. MEA* in terms of PREE. Nevertheless, with an increase of the payload, the PREE values of the *LH2 MEA* come closer to those of the *conv. MEA*, with a difference of 7.6% at 150 passengers compared to a difference of 6.9% at 200 passengers.

4. Summary & Conclusion
This paper presents an overview and preliminary results of the technology evaluation task within the SIENA project. Based on a combination of the aircraft design capabilities at PoliMi and the systems design and evaluation capabilities at Collins Aerospace ART, a new systems architecture evaluation

methodology is developed and utilized for vehicle-level performance studies of two commercial aircraft platforms, an ATR 72 and an Airbus A320neo. Both aircraft are equipped with different system architectures ranging from conventional turboprop/turbofan engines with conventional subsystems to fuel-cell-electric propulsion system architectures with liquid hydrogen as the main energy source on board.

For the ATR 72, the integration of hydrogen combined with fuel-cell-electric propulsion is suitable even with conservative technology assumptions. For the A320, however, the hydrogen-burning configurations have a lower mission energy efficiency than the kerosene configurations due to the added weight of the cryogenic hydrogen tanks and the required fuselage extension. While at first glance, this may seem to indicate that a transition to hydrogen is unfavorable for this aircraft category, it should be noted that the climate impact can still be significantly reduced due to the CO_2-neutrality of hydrogen.

The results presented in this paper are preliminary evaluations on given architectures, and only a fraction of the analysis in SIENA. Future steps in the project include an expansion of the design space, an exploration of a wider range of technology options, and parameter studies to investigate, e.g., the sensitivity of the results to technology parameters and assumptions.

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