PROJECTION OF KEY POWERTRAIN COMPONENT FIGURES OF MERIT FOR OVERALL ASSESSMENT OF ELECTRIC FLIGHT SCENARIOS

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Abstract

One potential pathway for the future of aviation is the electrification of the propulsion system. This study connects projections for component technology development with powertrain range predictions for electric aircraft. The investigation involves summarising electrified propulsion topologies, identifying key components, and projecting the advancements of individual technologies with respect to relevant key metrics such as specific power and efficiency. These component projections are then applied to an overall assessment of all-/hybrid-electric powertrains for various aircraft classes. The paper highlights the increasing potential of electrified propulsion from 2025 to 2070 under different development scenarios – a conservative and a progressive scenario. Both emphasise the impact of the thermal management system (TMS) on powertrain development. In particular, the pertinence of considering the TMS in the preliminary design of electrified aircraft with a high degree of accuracy is derived. The assessment identifies key contributors, such as fuel cells and TMS. An improvement of their respective specific power and specific heat rejection significantly impact the predicted aircraft ranges – particularly in current and near-term technology levels. Negligence with regards to TMS effects in preliminary design may lead to an overly optimistic prediction of achievable aircraft range.

Keywords: electric flight, electric powertrain, key component metrics, technology projection, range prediction

1. Introduction

In the project DEPA2070, the German Aerospace Center (DLR) derives a vision for pathways of aviation up to the year 2070 [1]. One area of interest in the project are comprehensive trend analyses for the aviation market, aviation and propulsion system technologies as well as sustainable aviation fuels. Two different development scenarios are derived which cover a conservative-evolutionary as well as a progressive-revolutionary development. Next to external socio-economic developments, these technology trend analyses are used to define scenario-specific and aircraft vehicle-specific technology road maps. Based on the road maps, subsequent impact assessments address e.g. the technology impact on noise, emissions and mobility gains.

With the target of climate-neutral aviation, electric propulsion systems within aviation are explored as a means to reduce CO_2 effects next to sustainable aviation fuels [2]. Within current investigations, both the use of hydrogen Fuel Cell (FC) [3]–[6] as well as batteries [7]–[10] is assessed. Key to these assessments, are the assumed technology developments and achieved component specific powers and efficiencies. Comparability of different assessments to derive a consistent time line for developments is limited, as the assessments consider different levels of detail with regard to the aircraft sizing process, the powertrain architecture with its components and time frames considered.

Within the scope of DEPA2070, the trend analyses for electrified propulsion systems reported in this paper focuses on establishing a link between component development and overall powertrain range predictions and to illustrate the developments throughout the time frame from 2025 to 2070. The required assessment methodology is outlined in section 2 and illustrates the process steps for the assessment from system definition to system evaluation. Section 3 reports on the three main points of the investigation. Firstly, the electrified propulsion topologies are summarised and key components for the subsequent detailed investigation are identified. Secondly, for each component, an individual technology projection is carried out for parameters such as the specific power as well as efficiency. Lastly, the technology projection of the individual components is transferred to an overall all-/hybrid-electric powertrain assessment for regional aircraft using a simplified, performance-based preliminary design process. Hereby, the increasing potential of electrified propulsion is illustrated for the years 2025-2070 for two different development scenarios. Especially, the effects of the TMS on the development of electrified powertrains are addressed in detail. The paper concludes in section 4 with a summary and recommendations for further work.

2. Methodology

The increasing potential of electrified propulsion systems can be evaluated by comparing range estimates for different propulsion system technology scenarios. To achieve such an investigation, the steps illustrated in Figure 1 are required.

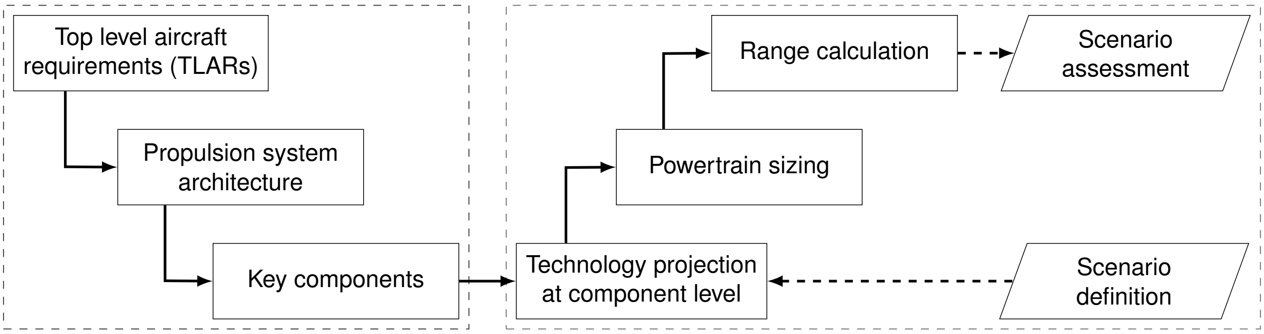


Figure 1 – System definition and evaluation workflow

Initially, the top level aircraft requirements (TLARs) are captured to define the relevant aircraft application. Subsequently, a generic electric propulsion system topology with its components is defined for a fully electric aircraft. A technology projection at component level is carried out for the identified powertrain components based on a literature review. In addition to currently ongoing short to mid-term developments up to 2035, available existing technology projections that typically range up to the year 2050 are also summarised. Combining those two inputs, an extrapolation of technology developments up to the year 2070 is carried out. Two technology development scenarios are generated to cover both a conservative as well as a progressive development scenario up to the year 2070.
The sizing of the powertrain is carried out based on the derived component data for the two development scenarios. A simple mission calculation as introduced by Finger *et al.* [11] is used to determine the predicted range of the aircraft. This approach enables consideration of a broad range of hybrid-electric as well as battery or Fuel Cell (FC) only applications via a time step based mission calculation. The predictions cover the years 2025 to 2070 and are carried out in 5 year intervals. The results of the scenario assessment are illustrated by evaluating the calculated mission range as well as the component and propulsion system masses. This enables identifying the key components within the powertrain to increase the potential of electric aircraft.
Figure 2 illustrates the workflow for the range prediction calculation of the presented study. Key inputs are the aircraft data such as the target MTOM, payload mass and basic aerodynamic parameters as well as the projection data for the electric powertrain components. Within one iteration, the powertrain is sized across different range assumptions until the MTOM difference ΔMTOM between the predicted and the target MTOM is less than the threshold $\varepsilon \leq 10^{-3}$. Within the powertrain sizing, the components are sized individually to their power demand according to their derived specific powers and efficiencies. As hybridisation strategy a power split between Fuel Cell System (FCS) and battery is defined at take-off which is used to size the FCS. At other conditions during the mission the FC is used as primary energy source and battery power is only used if supplementary power is required.

The battery is then sized according to the total mission power demand. The TMS for both the EDT and the FCS are sized according to the predicted heat loads. While the mass penalty impact of the TMS is considered, any oversizing of the electric powertrain related to the additional power demand penalty of the TMS has not been considered within the assessment.

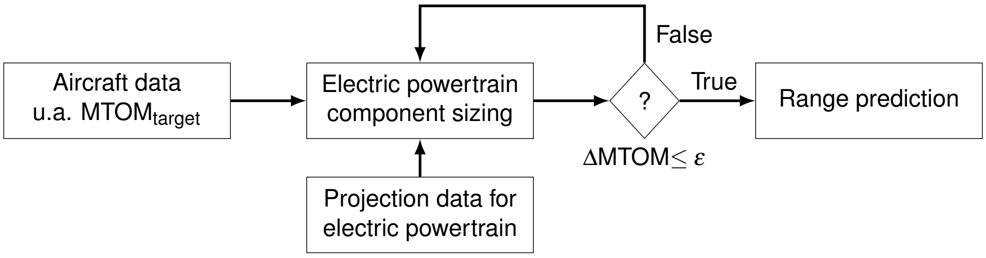


Figure 2 – Assessment workflow for range calculation

3. Results

3.1 Aircraft Requirements and Propulsion System Architecture

The scope of DEPA 2070 addresses the complete aviation market from small air transport, regional and mainliner air transport as well as business jets and potential supersonic applications. The presented study focuses on fully electric concepts based on FCs and batteries. This type of electric powertrain has high potential for small and regional air transport applications. Typical conventional aircraft for these categories range from a Dornier Do228 to an ATR72 and provide passenger capacities between 19 to 72 passengers. For these aircraft applications, input data for aircraft performance parameters such as wingloading and lift-to-drag ratios, mission details such as cruise altitude and take-off duration as well as aircraft mass contributors have been collected.
The aircraft Maximum Take-Off Mass (MTOM) m_{MTOM} is

$$m_{MTOM} = m_{OE} + m_{PL} + m_{Prop} + m_{Fuel} \ , \quad (1)$$

where m_{OE} is the operating empty mass of the aircraft excluding its propulsion system, m_{PL} is the assumed payload mass, m_{Prop} is the propulsion system mass and m_{Fuel} is the fuel mass. In this study, both the aircraft MTOM as well as the considered payload mass are prescribed assumptions. The operating empty mass for a given aircraft MTOM, is derived by using correlation data based on existing commuter and regional aircraft. The remaining mass is available for the electric powertrain and its energy storage.
In consideration of electric propulsion concepts with both hydrogen usage and/or batteries, m_{Fuel} is calculated as

$$m_{Fuel} = m_{H_2System} + m_{bat} \quad (2)$$

where $m_{H_2System}$ is the mass of the hydrogen system including both the hydrogen itself as well as its storage system and m_{bat} is the battery mass. Herein, the hydrogen storage system mass is explicitly considered to be dependent on the total hydrogen mass and with that the mission. The reason is that the mass of the tank system is significantly higher compared to that of a kerosene tank storing the same amount of energy. Therefore, its mass cannot be considered as already included in the operating empty mass of a conventional aircraft.
A number of different propulsion system architectures can be used to enable electrified aircraft propulsion systems. Key criteria for distinction are the use of: one or more energy sources (i.e. batteries, hydrogen or kerosene), different energy converters (i.e. batteries, FCs or gas turbines) and different component arrangements (i.e. serial or parallel). Within this context, the use of at least two different energy sources is referred to as a hybrid architecture. For the presented assessment of commuter and regional aircraft with the scope of fully electric applications, the energy for the propulsion system is supplied either by batteries or by hydrogen with subsequent conversion in FCs. The propulsion systems can use one of the energy supplies or follow a hybridisation strategy.

Figure 3 illustrates a generic electric propulsion system with its key components: electric motor, power electronics such as inverter and converter, battery, FCS, hydrogen system as well as the TMSs. Due to the different requirements of the electric components, the TMS of the Electric Drive Train (EDT) and the FC are treated independently from one another. This is a simplified representation of an electrified powertrain where some components, such as the gearbox, cables and circuit breakers, are not included. At the same time, the assessment will focus on the mass of the electrified powertrain and its individual components. Therefore, volumetric consideration and integration aspects are neglected.

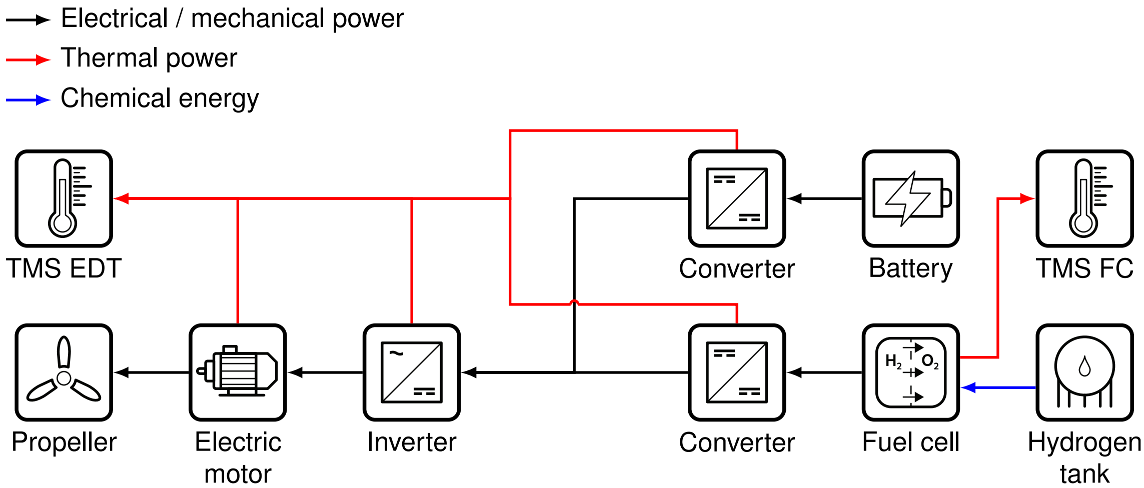


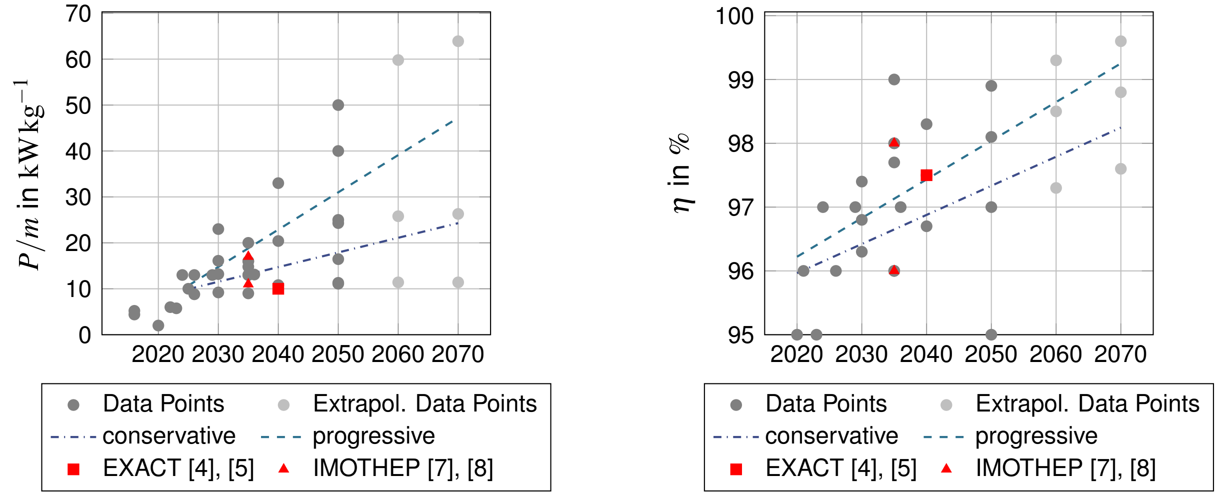
Figure 3 – Hybrid-electric powertrain architecture with battery and fuel cell usage

3.2 Key Powertrain Component Technology Projections

Based on the derived architecture with its individual components, two technology projection scenarios are considered within DEPA2070: a conservative-evolutionary and a progressive-revolutionary development scenario. All components are evaluated to derive a projection for both their mass as well as their efficiencies. Herein, the mass is derived by the specific power or specific energy referring to the power or energy per unit mass respectively [12]. While for all individual components projections and improvements are assumed until the year 2070 for the purpose of this study. However, in reality there will be physical limitation beyond which improvements can only be incremental and may not be considered economically viable. This strongly depends on the figures of merit set for a specific use case.

3.2.1 Electric motor

Within aviation applications, there are a number of different electric motor types currently evaluated for their feasibility and advantages as well as disadvantages [13]. Compactness, scalability as well as efficiency are key design criteria for aviation applications with an inherent conflict between achievable specific power and efficiency. Lighter machines with an increased specific power usually require higher current levels which in turn are linked to higher losses and therefore lower efficiency.
Initial developments have been accelerated within the last couple of years, with first small aircraft already flying based on electric propulsion with motors such as the Siemens SP260D [14]. Currently there is work ongoing funded by NASA looking into the potential of three different electric motor types [15] with a target specific power of $13\,\mathrm{kW\,kg^{-1}}$ to $16\,\mathrm{kW\,kg^{-1}}$ for an EIS of 2035. Further references [9], [14]–[22] are included in the data set illustrated in Figure 4. The specific power P/m and efficiency η technology projections are shown in Figure 4a and 4b respectively. The derived technology projections cover a large range from $10\,\mathrm{kW\,kg^{-1}}$ to above $60\,\mathrm{kW\,kg^{-1}}$ highlighting a significant uncertainty in the expected developments. For specific powers of $20\,\mathrm{kW\,kg^{-1}}$ and above, a radical technology change such as superconducting motors will be required. From an efficiency perspective, target values reach up to $99\,\%$ which also relate to the selected technologies.



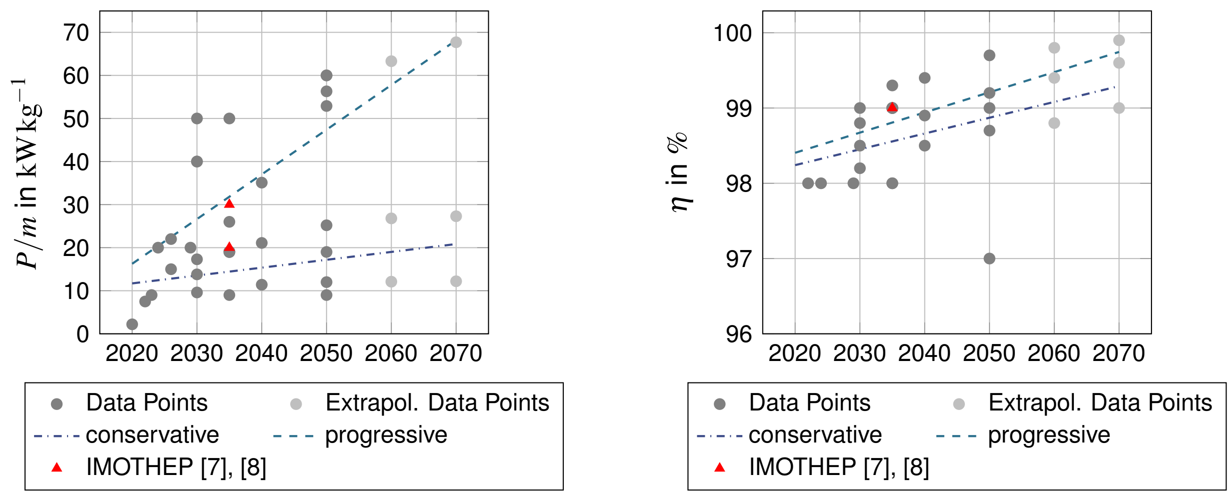
(a) Specific power (b) Efficiency

Figure 4 – Technology projection for electric motor specific power and efficiency with data from [9], [14]–[22]

3.2.2 Power Electronics

Inverters and converters enable the control of voltage and current levels within the powertrain and are therefore required to achieve a sensible electrical architecture. Inverters enable switching between direct and alternating current while converters enable switching between different voltage levels. The design of inverters and converters for aeronautic applications, especially within the MW-range is currently one key enabler for electrified propulsion technologies.

With the focus on aircraft specific inverter and converter technology, a development of rapidly increasing specific power within the near term future is expected while maintaining and potentially increasing their efficiencies to $98\,\%$ and above [19]–[21], [23], [24]. Ongoing developments include works by General Electric, the University of Illinois and Boeing targeting specific power goals of $19\,\mathrm{kW\,kg^{-1}}$ to $26\,\mathrm{kW\,kg^{-1}}$ and efficiencies above $99\,\%$ [15] within the near term future. The data is illustrated in Figure 5a for the specific power P/m and Figure 5b for the efficiency η. For the long term future, technology projections for the specific power cover a large range from $10\,\mathrm{kW\,kg^{-1}}$ to $60\,\mathrm{kW\,kg^{-1}}$ highlighting uncertainty in the expected developments. The difference between the scenarios for the efficiency is less pronounced as the efficiency of inverters and converters is already quite high.



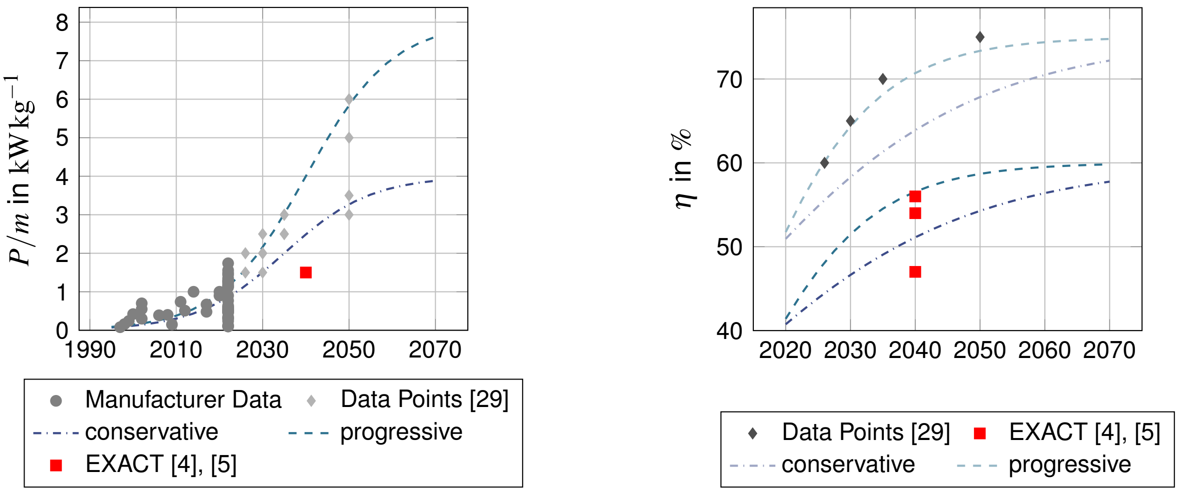
(a) Specific power (b) Efficiency

Figure 5 – Technology projection for inverter/converter specific power and efficiency with data from [19]–[21], [23], [24]

The achievable specific power also correlates with the component power level. Hence, ideally this would be considered in a more detailed technology projection. As that is not the case here, the range of the projections is rather wide. Some of the key challenges for aeronautics applications are the operating temperatures of the inverters and converters within the aircraft environment as well as switching frequency related losses.

3.2.3 Fuel Cell System

Out of the different FC types, Polymer Electrolyte Membrane Fuel Cells (PEMFCs) and Solid Oxide Fuel Cells (SOFCs) have been identified as the most promising types [25]. From a maturity perspective, both low temperature PEMFC and high temperature PEMFC are expected to power aviation applications in the mid-term future. First demonstration in flight has been performed for low temperature PEMFC-based propulsion systems already by H2FLY [26], Zero Avia [27] and Universal Hydrogen [28], for instance.
While a wide range of technology projections for electric components were available, the data for FCs is very limited. One of the few available projections was performed by Bhatti *et al.* [29]. Therefore, a data set based on past low temperature PEMFC specific power values has been collected as well using manufacturer data sheets by General motors, Toyota, Ballard, Horizon Fuel Cell and Powercell. When evaluating the specific power P/m of a FCS, it is important to distinguish between the FC stack alone and the FCS including the Balance Of Plant (BOP) components. For the data illustrated in Figure 6a, any FC stack specific data has been converted to a BOP data point by accounting for a conversion factor of $50\,\%$ between stack and BOP based on technology screenings and previous investigations on fuel cell systems. Large potential scatter within the data set is visible in the current state of the art data. The two derived scenarios align with the different projections for both low temperature and high temperature PEMFC by Bhatti *et al.* [29].



(a) Specific power

(b) Efficiency

Figure 6 – Technology projection PEM fuel cells

Within the design, the FCS might also be oversized compared to the required maximum power demand throughout the mission. This leads to heavier FCS, as the specific power is related to the maximum possible power of the FCS. An advantage of oversizing the FCS is that the operation under partial load during most of the mission increases the FC efficiency. The efficiency assumptions have direct impact on the subsequent sizing of the TMS as well as on the hydrogen storage system. While peak projected efficiencies η range from $60\,\%$ to $75\,\%$ as illustrated in Figure 6b, these values refer to rated power conditions at part power of $10\,\%$ to $30\,\%$ [29]. Within the presented investigation, an operation at part power conditions of $50\,\%$ and above is more likely for the selected powertrain and hybridisation strategy. Therefore, knockdown factor of $80\,\%$ has been assumed onto these peak efficiency values to account for operation outside of the point of peak efficiency.

3.2.4 Hydrogen System

When changing from kerosene to hydrogen as an energy carrier, new tank installations are required to allow proper storage of the hydrogen. The type of storage, either pressurised as gas or cryogenic as liquid hydrogen, has a significant impact on the required size and the losses associated with the storage system.

Within the DEPA2070 projections, the hydrogen storage system is accounted for as an additional mass contributor in addition to the hydrogen mass based on the tank gravimetric efficiency η_{H_2Tank} which is defined as the ratio between hydrogen mass m_{H_2} to the sum of both hydrogen and the associated hydrogen tank m_{H_2Tank}:

$$\eta_{H_2Tank} = \frac{m_{H_2}}{m_{H_2} + m_{H_2Tank}} \tag{3}$$

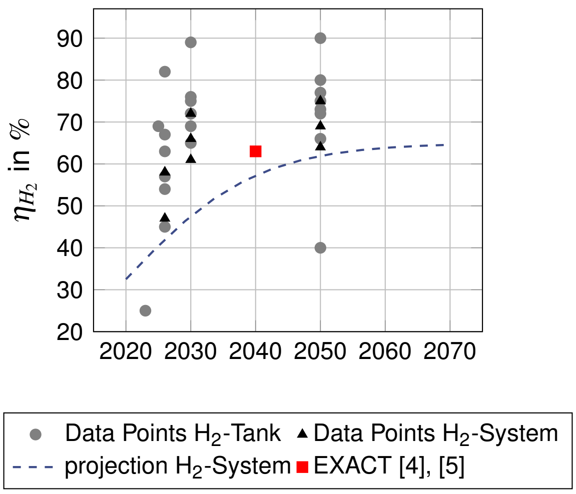
Further penalties onto the hydrogen system are incurred by additional system components such as pipes and pumps and their mass $m_{H_2System}$. These penalties are included in the hydrogen system gravimetric efficiency $\eta_{H_2System}$

$$\eta_{H_2System} = \frac{m_{H_2}}{m_{H_2} + m_{H_2Tank} + m_{H_2System}} \ . \tag{4}$$

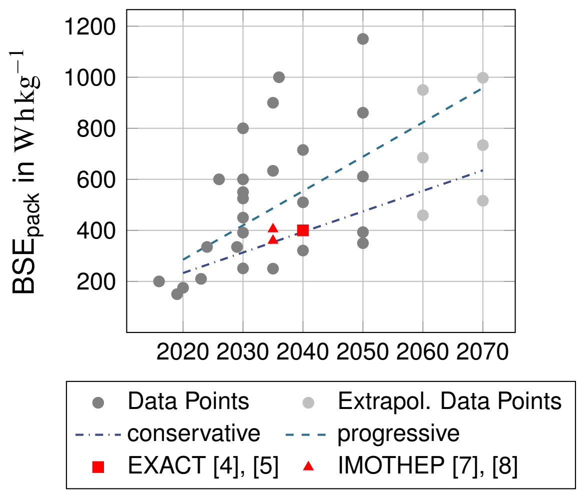
This gravimetric storage efficiency is used to couple the calculated hydrogen mass to the total mass of the hydrogen system.

What is not considered here is, that for liquid hydrogen, in practice, a minimum amount of hydrogen ought to remain in the tank at all time – even after a full mission has been flown – in order to maintain the storage conditions. If this can not be achieved, the tank is exposed to severe thermal cycling affecting the lifetime and reliability of the tank system.

The data has been grouped by data for the liquid hydrogen tank [22], [30], [31] as well as by data for the complete liquid hydrogen system [31] and is illustrated in Figure 7a. The achievable gravimetric storage efficiency is also related to the amount of stored hydrogen. Compared to the other components, only one projection has been derived for the hydrogen storage system and no distinction between conservative and progressive development scenarios has been considered. The projection implicitly reflects a rapid development occurring within the next 10 to 15 years with a significantly slower development for later years.



(a) H_2-System storage efficiency



(b) Battery pack specific energy

Figure 7 – Technology projection for hydrogen storage solution with data from [22], [30], [31] and batteries with data from [9], [18], [20]–[22], [32]–[35]

3.2.5 Batteries

For batteries, the key technology assumptions are related to their Battery Specific Energy (BSE). The term BSE can be defined at theoretical, cell and pack level. Each of those definitions considers a different level of detail w.r.t. contributing components. Effects for allowable battery state of charges, such as a discharge only up to $20\,\%$ are usually considered separately within the mission calculation and are not included in the technology projections.
The C-Rate of a battery is a measure for how fast a battery can be discharged or charged. The required C-Rate will vary throughout the mission and is especially important if batteries are used for peak power support. While this is in reality a limiting factor, within the projections this effect is not considered. Herein it is assumed, that the batteries with the projected BSE are able to supply the according C-rate in support of the battery usage.
Battery road maps mostly consider detailed estimates for developments up to the years 2030 to 2035 with only a couple of projections reaching to 2050. The current assumptions within literature assumed in aviation studies consider a wide range of BSE at pack level [9], [18], [20]–[22], [32]–[35] which are illustrated in Figure 7b.
Batteries Europe [34] describe further topics for imminent research next to target values for different transport applications including battery and hybrid electric flight. While lithium-ion batteries still have some room for performance improvement, long term developments require new battery concepts and chemistries to increase the specific energy and energy density of the battery system. It is important to highlight that these performance improvements also need to include considerations of battery thermal management as well as thermal runaway propagation mitigation. The additional mass required for both of these aspects heavily depends on the chemistry type.

3.2.6 Thermal Management System

The TMS sizing is considered for both the waste heat of the EDT as well as for the FCS. Within the sizing of the TMS, the waste heat of the components is correlated to the TMS mass via the Specific Heat Rejection (SHR) [36]. Similar to FCS, limited data is available to support the development of two different technology projections for TMSs. Data from Chapman *et al.* [37] indicates predicted specific heat rejection values for different electric drive train components anywhere from $1\,\mathrm{kW\,kg^{-1}}$ to $5\,\mathrm{kW\,kg^{-1}}$ across from both baseline and advanced TMS architectures. The data is illustrated in Figure 8 and notably shows that with improved electric system efficiency, i.e. lower heat loads for the advanced TMS architectures, the achievable specific heat rejection value tends to decrease as well.

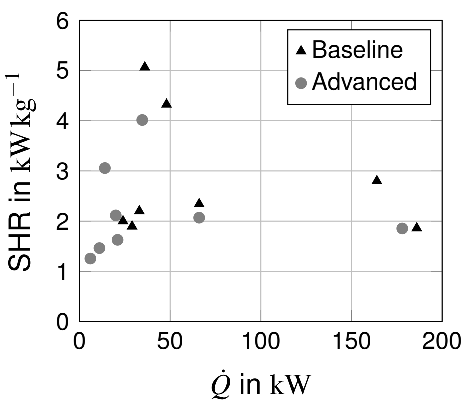
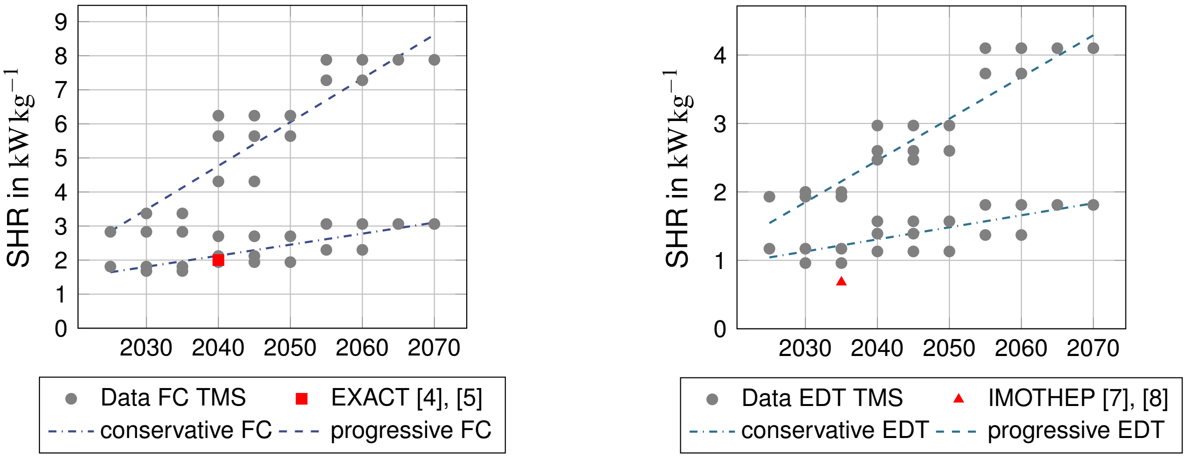


Figure 8 – Derived TMS SHR data for electric components based on Chapman *et al.* [37]

Due to the different operating conditions of the different electric components, two separate projections have been derived for the TMS of the FCS and the EDT which are illustrated in Figure 9. The data points have been derived by considering TMS sizing calculations for a liquid cooled systems based on Link *et al.* [36]. The main differences between EDT and FCS TMS projections are related to the assessed heat load and operating conditions of the systems. The difference between the conservative and progressive scenario within the projections is driven by: the assumed degree of integration, i.e. the selected assumptions for pipe lengths and diameters, and improved component performance with regard to allowed temperature gradients which enables a reduction in coolant mass flow rate and thus coolant mass. Across both projections, further data points have been added which consider improved component design for fans and pumps as well as improved coolant medium thermal properties that yield a reduction in TMS mass. With those assumptions, the projections values cover a similar range as the data by Chapman *et al.* [37] while also providing a timescale for the developments.



(a) TMS for the FCS

(b) TMS for the EDT

Figure 9 – Thermal Management System (TMS) technology projections

3.3 Scenario Assessment

Based on the derived input scenarios and assumptions, two main studies have been carried out:

- Identification of key drivers for powertrain mass across different aircraft classes for FC-battery hybrid electric powertrains
- Assessment of the impact on appropriate consideration of the TMS onto predicted aircraft ranges

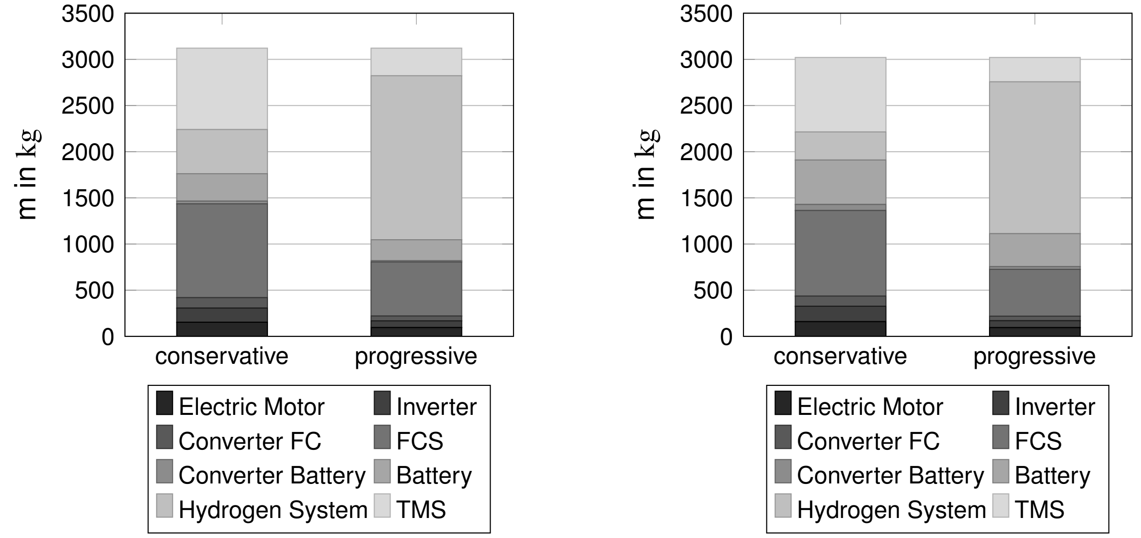
Hereby, the studies focus on the mass contributions of the propulsion system components. Volumetric constraints, such as for the hydrogen storage, FCS or batteries, are not addressed within these studies.

3.3.1 Key levers for range improvement of FC-battery hybrid aircraft

The assessment has been carried out for both an ATR42 and ATR72 aircraft applications. The applied hybridisation strategy considers the definition of a hybridisation factor HF at take-off to size the FC. With the assumption that the battery only needs to supply additional power during take-off and climb phases, the hybridisation factor is derived by the ratio of cruise power to take-off power requirement for the different aircraft. This leads to hybridisation factors of $HF = 0.73$ for the ATR42 and $HF = 0.65$ for the ATR72.

For both aircraft, a comparison of the conservative-evolutionary and progressive scenario predictions has been carried out. When considering no payload reduction, design mission ranges from $1000\,\mathrm{km}$ to $1500\,\mathrm{km}$ are not reached until the years 2045 to 2050 within the conservative-evolutionary scenario. Within the progressive scenario, similar ranges are already achieved by the year 2035. Alternatively, this requires an approximate $20\,\%$ payload mass reduction.

Considering the conservative-evolutionary scenario as reference, the predicted powertrain component mass contributions are illustrated in Figures 10a and 10b for the ATR42 and ATR72 respectively. For the ATR42, FCS and TMS masses account for $32.5\,\%$ and $28.2\,\%$ respectively in the conservative scenario resulting in a total contribution of $60.8\,\%$ to the propulsion system mass. This contribution is reduced to $18.7\,\%$ and $9.6\,\%$ for the TMS and the FCS respectively for the progressive scenario for a total contribution of $28.3\,\%$. Between those two scenarios, the hydrogen system mass fraction

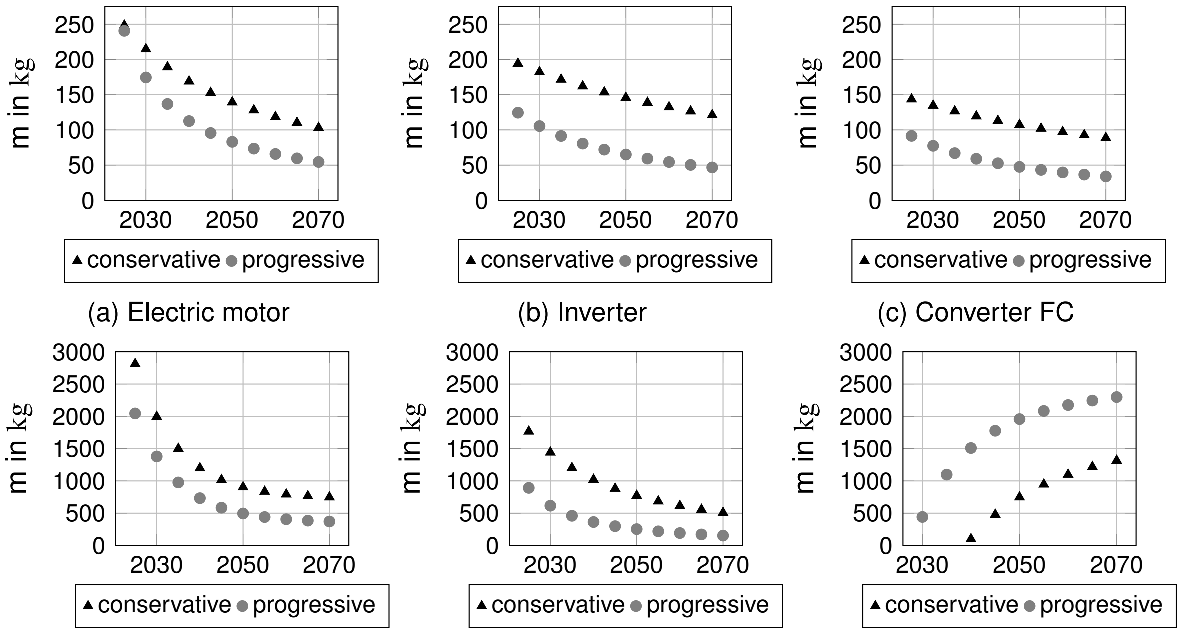


(a) ATR42 in 2045 with payload = 5250 kg (b) ATR72 in 2050 with payload = 7200 kg

Figure 10 – Powertrain mass break down for conservative and progressive scenario for different aircraft applications

increases by 41.6 % of which 32.5 % can be attributed to the improvements of the FCS and its TMS. These general trends are supported by the predictions of the ATR72. This illustrates, that of all the powertrain components, improvements to the FCS and TMS will yield the biggest potential to increase the available mass fraction for the hydrogen system and thus enable larger ranges for electrified aircraft.

While Figure 10 focuses on the powertrain mass breakdown to identify its key contributors, the assessment also enables an evaluation of the estimated component mass development across the investigated time scales. For selected individual components, the impact of the technology projection on the component weight is illustrated in Figure 11 for the ATR42 aircraft application.



(a) Electric motor (b) Inverter (c) Converter FC

(d) FC (e) TMS (f) H_2-System

Figure 11 – Component mass developments for the conservative and progressive scenario

While significant mass reductions are projected for the electric motor, inverter and converters as shown in Figures 11a to 11c, their overall contribution to the powertrain total mass is comparably

small in relation to the FCS, TMS and hydrogen system as shown in Figures 11d and 11e. Due to their initially higher mass contribution, the FCS and TMS provide a larger opportunity for the reduction of the powertrain mass and thus are key enablers for electrified propulsion.
Relating these results back to the technology projections, this can be used to define the following target requirements for the FCS specific power and TMS SHR specifically for FC-battery electric regional aircraft provided in Table 1:

Component	**Target Specific Power**
FCS	$3\,\mathrm{kW\,kg^{-1}}$
Component	**Target SHR**
TMS FCS	$2.5\,\mathrm{kW\,kg^{-1}}$ to $3\,\mathrm{kW\,kg^{-1}}$
TMS EDT	$1.5\,\mathrm{kW\,kg^{-1}}$ to $2\,\mathrm{kW\,kg^{-1}}$

Table 1 – Feasibility targets for FCS and TMS developments for FC-battery hybrid aircraft

While those targets provide a reference for future development, two considerations have to be kept in mind:

1. The electric powertrain component sizing is highly interlinked and therefore trade-offs in component sizing can be used to achieve the overall powertrain design, i.e. considering a heavier FCS with a lighter TMS than defined by the targets above or vice versa

2. These predictions are only applicable for the investigated aircraft size and might not be applicable for other aircraft sizes.

3.3.2 Influence of TMS upon predicted ranges

While the TMS might influence mass, power demand and drag of the aircraft, this dedicated assessment focuses purely on the mass contribution of the TMS. As highlighted previously, the TMS adds a significant mass contribution to the overall powertrain mass and limits the available hydrogen onboard the aircraft. It therefore has a significant influence onto the achievable mission ranges within the preliminary design calculations.
To quantify the impact of the TMS on the range predictions, the difference between the mission ranges ΔR_{TMS} is calculated as

$$\Delta R_{TMS} = R_{TMS} - R_{noTMS} \tag{5}$$

where R_{noTMS} is the range without TMS considerations and R_{TMS} is the range with TMS considerations. The range reduction ΔR_{TMS} for the case study of the ATR42 aircraft application is illustrated in Figure 12. For the years 2030 and 2035 no results for the conservative scenario are provided as the range prediction with TMS effects considered did not converge and thus no comparison has been made.

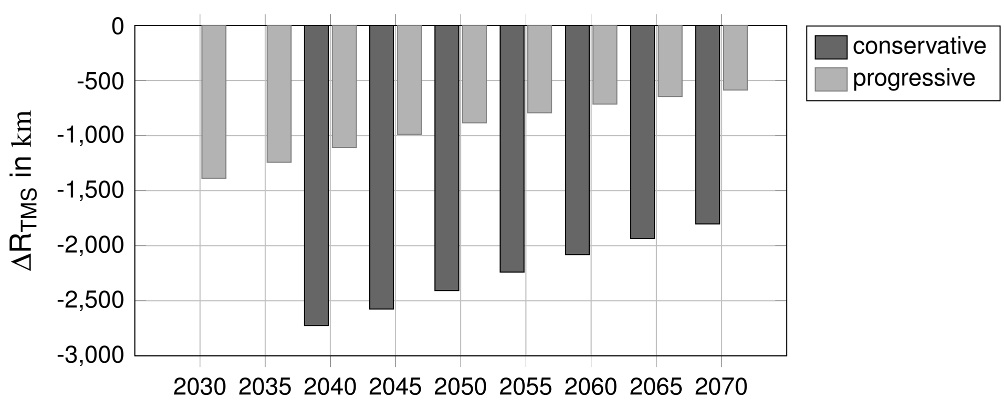


Figure 12 – Range reduction with TMS considerations for conservative and progressive scenarios

The predicted range reduction is significantly larger for the conservative scenario than for the progressive scenario. When the TMS effects are neglected, the design mission ranges might be over predicted by $1800\,\mathrm{km}$ to $2800\,\mathrm{km}$ and $500\,\mathrm{km}$ to $1400\,\mathrm{km}$ for the conservative and progressive scenarios respectively. Across the assessed time period, the predicted range reduction decreases for both scenarios. Especially with targeted mission ranges for electrified regional aircraft of $1000\,\mathrm{km}$ to $2000\,\mathrm{km}$, this reveals a significant source of error.
The difference between the two scenarios is caused by two effects which lead to different TMS mass contributions: increasing efficiency of the electric components and therefore reduced heat loads to be managed by the TMS, as well as the increasing TMS SHR. Figure 13 illustrates the relative mass reduction Δm_{TMS} for both the conservative and the progressive scenario related to the initial values predicted for the year 2025. While both factors contribute to the mass reduction, the increased component efficiency and thus heat load reduction is responsible for a larger fraction of the mass reduction than the SHR improvement.

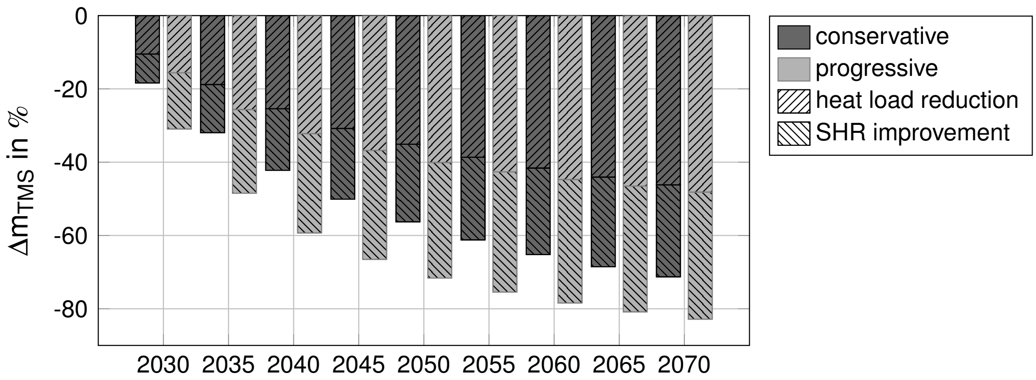


Figure 13 – Contributors to TMS mass reductions for conservative and progressive scenario

Within the current status of technology developments, neglecting the TMS within the electrified aircraft design process, leads to a significant over prediction of achievable ranges. At the same time, appropriate quantification and projection of the TMS are required to judge its effects accurately.

4. Conclusion

Within this paper, technology projections have been carried out on individual component level of the electric components of an electrified aircraft powertrain including its TMS. The projections cover both a conservative-evolutionary as well as a progressive-revolutionary scenario.
The projections have been combined for an assessment at powertrain level through an aircraft mission to allow identification of the key levers for overall improvements. The FC and TMS are two contributors that, when improved on specific power and SHR level, will yield a significant increase in achievable aircraft range. In addition to increases in TMS SHR, the TMS mass also reduces with increasing fuel cell efficiencies and thus reduced heat loads managed by the TMS.
Especially within the current and near term future technology levels, it is required to consider TMS effects within the preliminary design of electrified aircraft powertrains as the achievable ranges will be over predicted otherwise.

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6. Copyright Statement

7. Acknowledgements

The authors wish to acknowledge the fruitful discussions with their colleagues Matthias Lang, Jeff Kugener, Ankit Pal, Victor Bahrs, Jonas Ludowicy, Caio Dias Fernandes and Dimitrios Dimos on future component technology developments.

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