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Modelling of a battery supported fuel cell electric power train topology for a regional aircraft

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Abstract. Electrification of aircraft propulsion may offer a way towards carbon dioxide (CO_2) neutral air travel. Here, the electric aircraft demonstrators already flying mostly rely on the use of batteries as energy source. While battery electric concepts may be suitable solutions for short range applications, such as urban air vehicles, the energy density of state of the art batteries is not yet sufficient to power regional aircraft with a typical range of 1000 nautical miles and 70 passengers. One possible topology option of a propulsion concept suitable for a regional aircraft is a hybrid composed of a fuel cell system (FCS) and a battery. On the one hand, this concept uses hydrogen (H_2) as the primary energy carrier, resulting in a significant reduction of the required battery stack mass in comparison to a battery only aircraft. On the other hand, a battery support of flight phases with high power demand, such as take-off or climb, allows a smaller dimensioning of the fuel cell system and the corresponding thermal management system (TMS) and therefore additional overall system mass benefits in comparison to a fuel cell only aircraft. The present paper analyses the weight reduction potential of a battery stack supported fuel cell system electric power train architecture for a typical regional aircraft with regard to the hybridization factor (HF) and battery specific energy (BSE). The modelling includes the sizing of the fuel cell system and the battery stack, other mechanical and electric components, such as gearboxes, electric motors and power electronics and the corresponding TMS. The according electrified aircraft is resized, keeping wing loading and power-to-weight ratio constant. The best combination of HF and BSE yielding the lowest MTOM with 27 100 kg is still about 19.9 % heavier than the conventionally powered reference aircraft with 22 800 kg. The study shows that future aircraft of similar weight and hence size require very advanced battery technology with regard to the BSE compared to available state of the art solutions.

1. Introduction

Ambitious goals to limit climate change have been defined by the international community in the Paris Agreement. In Europe, these are set by the Advisory Council for Aeronautics Research (ACARE) within the strategy paper Flightpath 2050. The objectives include a 75% reduction in CO_2 emissions, a 90% reduction in nitrogen oxide (NOx) emissions, and a 65% reduction in noise emissions compared to a year 2000 reference aircraft [1].

Electrification of aircraft propulsion offers a way to lower aircraft emissions. In recent studies several electrified power train architectures are discussed. Here, the design space extends from purely electric concepts, using batteries or fuel cells, to serial or parallel hybrids combining electric components with a conventional gas turbine [2]. However, due to the energy density of state of the art batteries, purely battery electric power trains are limited to smaller and low range applications, such as two-seater airplanes, unmanned aerial vehicles or urban air vehicles and no near-time option for larger passenger capacity or long range flight [3]. Parallel hybrids of gas turbines and batteries have been identified as a potentially suitable alternative for the regional segment, enabling decreased fuel consumption and therefore a reduction of CO_2 emissions [4]. If this gas turbine is operated with sustainable aviation fuel (SAF), global CO_2 emissions can be theoretically reduced to zero. However, a disadvantage compared to the direct use of hydrogen are additional conversion steps in the SAF synthesis, which reduce the overall well-to-wheel efficiency significantly.

Besides the direct combustion of hydrogen, fuel cells offer an attractive option of utilizing hydrogen in an electric power train for aviation due to their high efficiencies. This concept also takes advantage of the increased gravimetric energy density of hydrogen compared to hydrocarbons by a factor of roughly three [3]. The use of hydrogen also completely eliminates any carbon from the reaction equations, leaving only water vapour and possibly contrails as relevant emissions [5]. Unfortunately, solely fuel cell-powered propulsion systems are expected to be relatively heavy in comparison to modern gas turbines. A typical fuel cell efficiency of about 40 % to 60 % also implies the need for a TMS that can remove the same amount of waste heat as useful electrical energy is produced by the FCS. By supporting flight phases of high power demand, such as take-off and climb by battery power, the FCS can be downsized as batteries are added. Hence, such a hybrid architecture could be a suitable option [6].

The goal of this work is to analyze the trade-off between the FCS and its TMS weight vs. the battery stack weight for a regional aircraft and different degrees of hybridization and battery technology levels. Therefore, in the next section the top level aircraft requirements (TLAR) for a typical regional aircraft and the detailed power train architecture are presented and the used analytical component models are briefly discussed. Following, the sizing methodology, utilizing a time step and energy based mission analysis, is introduced. Finally, a parametric study varying the hybridization factor between fuel cell system and battery power and the assumed energy density for the battery pack is performed and discussed.

2. Mission, TLAR definition and power train component modelling

2.1. Mission and top level aircraft requirements

A simplified flight mission comprising cruise speed and altitude, range and payload for a typical regional aircraft, such as the ATR 72-600 shown in Fig. 1, is considered. The assumed flight mission consists of a take-off, climb, cruise, an initial descent, a loiter and a final descent segment. The loiter segment represents a reserve and is therefore not included in the range calculation as are climb and descent. The basic TLARs, used for the aircraft sized in this paper, are listed in Tab. 1.

2.2. Power train modelling

Figure 2 illustrates the implemented battery and fuel cell-based hybrid. Two propulsor units, one at each wing, are assumed. While the temperature of the FCS, gearbox, motor, inverter and converter is actively managed by a TMS, the battery pack is assumed to operate passively cooled.

In addition DC/DC- and DC/AC-power converters adjust the voltage level beteween energy sources and consumer and alter direct current (DC) to alternating current (AC) for the propulsor units. The propulsor units consist of a propeller, an electric motor combined with a gearbox and a motor controller, an FCS, their corresponding TMS and a battery. The installation of a gearbox allows a decoupling of the propeller and electric motor sizing. While a configuration with two propulsor units results in relatively large propellers with moderate rotational speed to achieve a high aerodynamic efficiency, light weight and volumetric compact electric motors

Figure 1: Illustration of the ATR 72-600. Source: Laurent ERRERA from L'Union, France, derivative work Lämpel, CC BY-SA 2.0

Table 1: Top level aircraft requirements.

Parameter	Value
Cruise Mach number	0.45
Cruise altitude	5100 m
Range	1850 km
Payload	6650 kg

usually demand for significantly higher rotational speeds. Due to the different temperature levels and magnitudes of waste heat to handle, the TMS of the power electronics, electric motors and gearboxes of the propulsor units are modelled separately from the TMS of the FCS. All electric components are interconnected by wiring that accounts for ohmic losses. Even though shafts for mechanical power and pipes for transporting heat are assumed, they are not modeled in this study.

Hydrogen is stored in a liquid hydrogen (LH_2) tank. The tank model accounts for an insulation to keep evaporation losses beneath $1\,\%\,\mathrm{h}^{-1}$. The integration of the tank into the aircraft, reducing useful space or enlarging the hull is not taken into account in these studies.

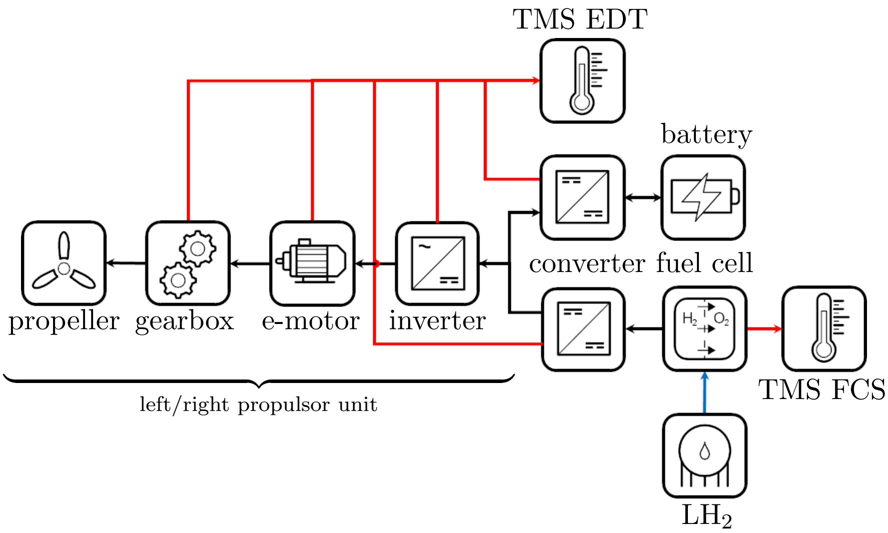

Figure 2: Modelled power train architecture for the left/right propulsor unit. Arrows indicate the direction of electric/mechanical power (black) and heat (red) flow.

Fuel cell and battery stack modelling: The fuel cell system constitutes of high temperature proton exchange membrane (HTPEM) fuel cell stacks and a compressor [7]. For simplicity the compressor is modelled via a constant isentropic efficiency. Note that the power to drive the compressor has to be provided by the FCS itself. The objective of this air conditioning is to enable a reliable operation of the FCS by providing it with pressurized cathode air at 1013 hPa independently of the current flight altitude. This necessary parasitic compressor power depends on the ambient conditions. A typical polarization and power curve for the assumed FCS is qualitatively shown in Fig. 3. The fuel cell efficiency is correlated to its voltage, which increases with decreasing power output. Thus, an over-sizing of the FCS is desirable for optimal operation. The over-sizing factor, minimizing the combined TMS and FCS mass, used for this work is 1.75. The operating characteristic of the assumed Li-ion battery is exemplary illustrated in Fig. 4. In the present study discharge up to a level of 20% battery pack capacity is allowed to avoid a harmful deep discharge of the batteries.

Note that both electric energy sources are operated together in a peak power shaving strategy as shown in Fig. 5. The idea is that only during peak power loads the FCS is supported by the battery stack [8], enabling a downsizing of the FCS, as it does not have to be sized for maximum peak power and adding only limited battery capacity. As fuel cells are slow in changing power output, the batteries can also act as a buffer in transient conditions. The strategy also allows to use a surplus of FCS power during less power demanding flight phases to recharge the battery for later power demanding manoeuvres, such as a go-around.

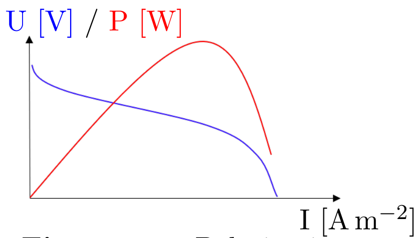

Figure 3: Polarization (bl.) & power (red) curve.

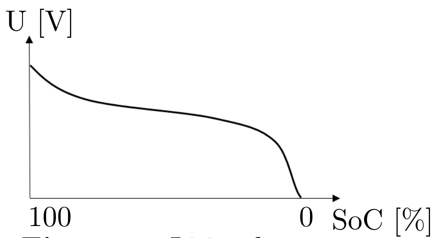

Figure 4: Li-ion battery characteristic curve.

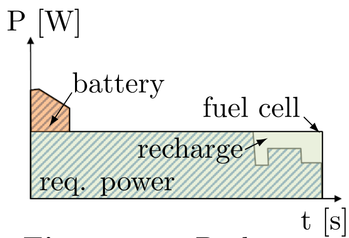

Figure 5: Peak power shaving strategy.

TMS modelling: The modelling of both thermal management systems, for the FCS and the other power train components, includes a heat exchanger, the coolant and corresponding piping, the coolant pump and an air fan. The latter is again modelled based on a constant isentropic efficiency. The heat exchanger sizing utilizes the ε-NTU method. The modelling accounts for the additional parasitic power that is needed to operate the coolant pump and the air fan, which also has to be provided by the FCS. A detailed description of the TMS components modelling, although not for the same use case and slightly deviating assumptions, can be found in [9].

Electric component modelling: The electrical wiring, DC/DC-converter, DC/AC-inverter and electric motors are modelled individually. The analytical motor model is described in detail in [10]. The modelling of the DC/AC-inverter is based on a three level neutral point clamped (3L-NPC) architecture. Note that the models for the electric motors and power electronics account for power dissipation into waste heat that needs to be removed by a TMS, which is also part of the power train unit, as depicted in Fig. 2.

3. Sizing methodology

The sizing methodology is illustrated in Fig. 6. Based on an initial maximum take-off mass (MTOM) estimation, the above described mission is simulated by a time step approach, that takes the hybridization into consideration and accounts for the potential and kinetic energy changes of the aircraft in every single time step. The chosen approach is similar to the one presented in [11]. For the power train sizing a required power to weight ratio of $160\,\mathrm{W\,kg^{-1}}$ related to the aircraft mass is assumed based on the ATR72-600's PW127M engines and a MTOM of 22 800 kg. The power train components are sized with the current MTOM, power to weight ratio and hybridization factor. This way, their weight is determined. To compute the aerodynamic parameters during the mission, a reference wing area is calculated based on a wing loading of $3666\,\mathrm{N\,m^{-2}}$ deduced from the ATR72-600 original wing area and MTOM.

After completing the mission simulation, the required amount of hydrogen for the fuel cell system as well as the amount of electric battery energy is determined depending on the selected hybridization strategy. With the amount of hydrogen and additional electric energy known the LH_2 tank and battery stack can be sized. The weight of the aircraft structure without the propulsion system is estimated via a correlation for existing aircraft of the commuter to regional class. The payload is kept constant at 6650 kg. The feasibility of volumetric integration of the payload is not considered. Finally, a new MTOM is calculated and checked for convergence with the previously found result. The iteration process terminates when the change of MTOM becomes less the tolerance ε.

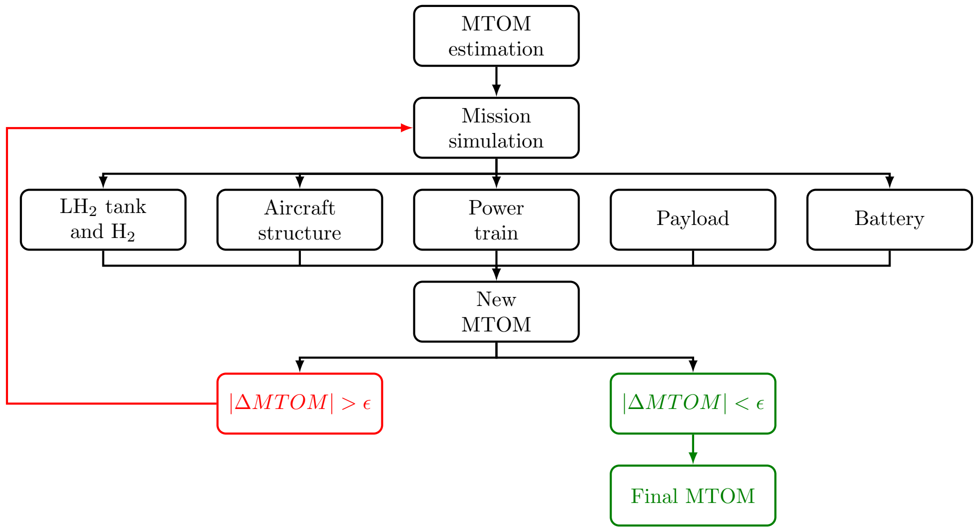

Figure 6: Illustration of developed sizing methodology.

4. Parametric studies and results

For the present study the hybridization factor (HF) and the assumed battery pack specific energy (BSE) are varied from 20 % to 80 % and from 300 W h kg^{-1} to 1000 W h kg^{-1}. In the present paper the hybridization factor is defined as the fraction of the FCS net provided power to the total installed shaft power based on the assumed power to weight ratio of 160 W kg^{-1}. Thus a small HF implies a small FCS, always running at high power and hence not ideal efficiency, which would additionally need a lot of battery power and capacity to support it. A higher HF yields a larger FCS, smaller batteries and lower power settings and therefore higher efficiencies for the FCS and may even allow to use excess power in flight phases with low power demand to recharge the battery. Note that the MTOM iterations, as described in section 3, did not converge for parameter combinations in the white area at the bottom left of Figs. 7 to 10.

An increase in BSE can be interpreted as progress of the available battery technology. It should be noted that the battery model used for the present study reproduces the characteristics of Li-ion batteries. The theoretical upper limit on cell level for this type of battery is 390 W h kg^{-1} [12]. Higher BSE could be achieved e.g. with Li-air batteries [13]. Thus the simplifying assumption is made that the charge and discharge characteristics of Li-ion batteries also apply to batteries with BSE above 390 W h kg^{-1}.

The figures 7 and 8 show results for the FCS and battery stack masses. As expected, an increase of BSE yields a decrease of battery stack mass for a fixed HF or allows a constant battery stack weight for a lower HF. As the overall aircraft weight is reduced with a higher BSE at a fixed HF, the required FCS in conjunction with its TMS is also reduced in size yielding a lower overall system weight, as can be seen in Fig. 10.

The FCS mass shows a minimum for HF values around 0.5 and high BSE values. Around this HF value a critical change in the cruise power split happens. For higher HF values the FCS is able to solely power the cruise phase without assistance from the battery. This is beneficial as the LH_2 has a higher gravimetric energy density than batteries. For lower values the net power of the FCS is not sufficient and power from the battery is required over the whole duration of the cruise flight. This leads to a strong increase in battery mass, which is also very prominent in Fig. 8.

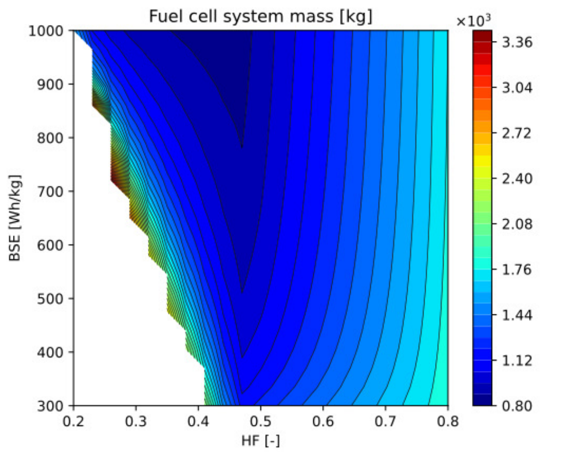

Figure 7: Results for the FCS mass.

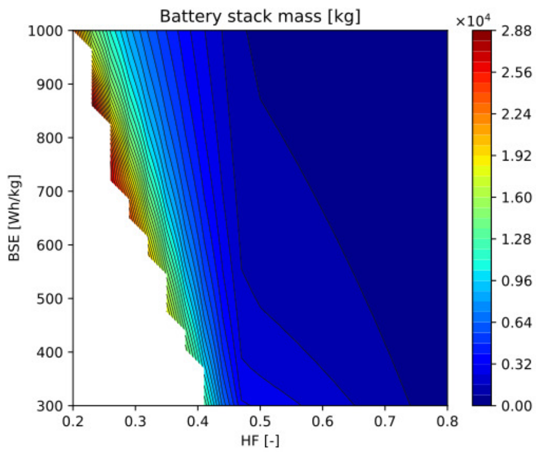

Figure 8: Results for the battery mass.

A higher HF is resulting in an increase in FCS and TMS mass. Here the FCS has to provide a higher share of the total power demand resulting in a larger and heavier FCS and corresponding TMS. The FCS TMS mass is proportional to the installed FCS power and mass, as can bee seen from Fig. 9. It is worth noting that the gradient of the FCS mass and MTOM is significantly less steep in the direction of higher HF values due to the significantly lower battery stack mass.

It shall be noted that the mass of the remaining components, i.e. gearboxes, electric motors, power electronics and electrical wiring is proportional to the trend for the MTOM shown in Fig. 10. This results from the scaling of these component masses with the required propulsion power, which scales directly with MTOM via the power to weight ratio.

Figure 10 shows that the optimization of the hybridization factor is required to find the most weight advantageous fuel cell battery hybrid configuration. In the present study, Fig. 10 indicates a global minimum at a HF of roughly 0.5 and the highest BSE investigated of $1000\,\mathrm{W\,h\,kg^{-1}}$. The resulting MTOM of approximately 24 000 kg is close to the ATR72-600's MTOM of 22 800 kg. This implies that for the present study an advanced battery technology, exceeding the BSE achievable with state of the art Li-ion batteries, is required to achieve a similar MTOM as the reference aircraft.

Finally, Fig. 11 shows the power split between the FCS and battery stack for three different BSE and three different HF values. Note that these HF/BSE combinations are also highlighted in Fig. 10 by red dots. The before discussed flight phases (take-off, climb, cruise, descent and loiter) are clearly visible by the total power demands given by the solid lines in the three illustrations of the figure.

An increase of BSE from $405\,\mathrm{W\,h\,kg^{-1}}$ to $825\,\mathrm{W\,h\,kg^{-1}}$ for a HF value of 0.38 roughly reduces the MTOM by a factor of 2, as can be seen in Fig. 10. With the decrease in MTOM the overall power demand of the electric drive train is also reduced by a factor of roughly two. However, for all BSE values investigated, a HF value of 0.38 is not sufficient to avoid the usage of battery

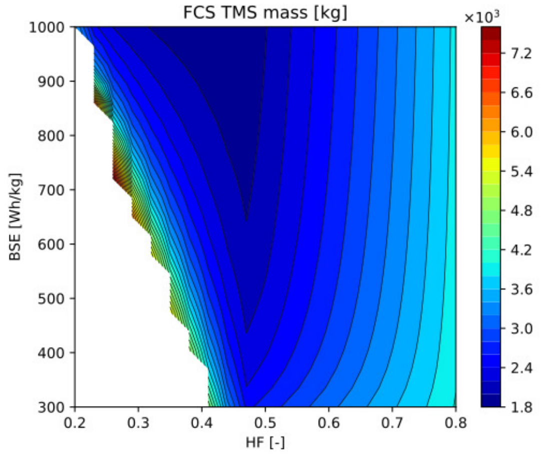

Figure 9: Results for the total TMS weight.

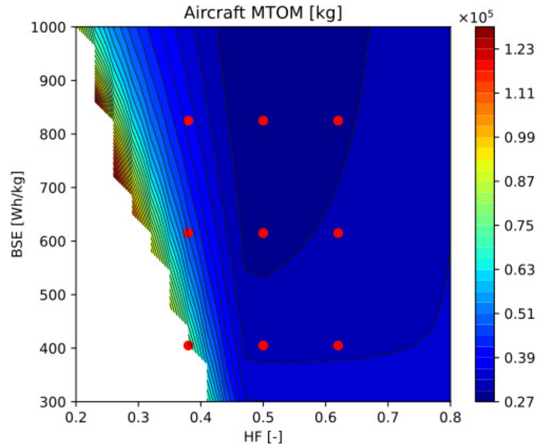

Figure 10: Results for the maximum take-off weight.

power during cruise. This is disadvantageous because in this case the necessary support of the fuel cell requires a large and heavy battery, yielding a relatively high MTOM.

An increase of the HF value to 0.5 eliminates the usage of battery power for the cruise segment of the mission. Battery power is now only used to support the high power demanding take-off and climb segments. In the mission simulation no propulsive power is required during the descent since the conversion of potential energy into kinetic energy is sufficient to overcome the aircrafts drag. Thus, a small surplus of FCS power is used to recharge the battery during descent as shown by the negative battery stack power, which equals the power provided by the FCS, during the time segment from roughly 1.4×10^4 s to 1.45×10^4 s and at the very end of the mission.

An additional increase of HF values from 0.50 to 0.62 does not yield any benefits in sense of a reduced power demand. Contrary, the MTOM and with it the power demand slightly increases again. The reasons are the aforementioned and discussed rise of FCS and TMS weight for more powerful fuel cell systems.

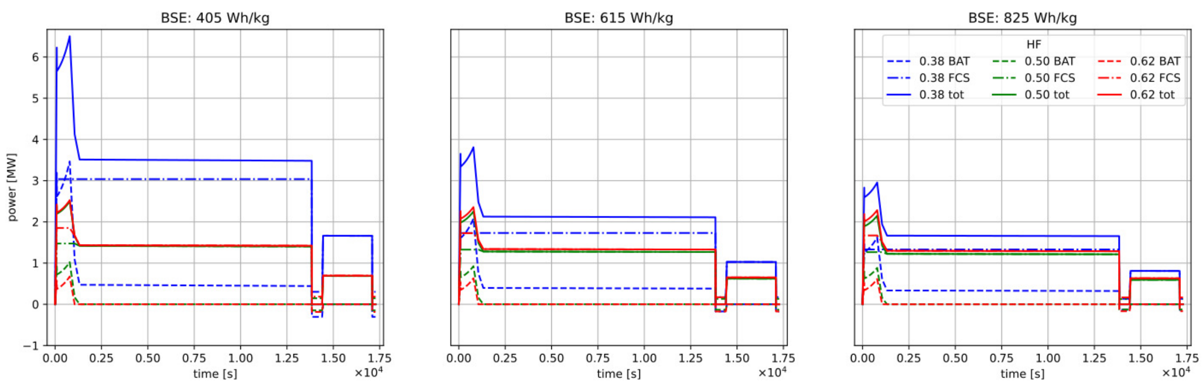

Figure 11: Power split between FCS and battery stack for dedicated HF and BSE values.

5. Conclusion

Decarbonization of air travel may be achieved by the use of hydrogen and electrified power train architectures. This paper presents a possible hybrid propulsion topology for a regional aircraft consisting of a HTPEM fuel cell system in combination with a battery. The operating strategy is aiming on supporting short but power demanding flight phases, such as take-off and climb, by battery power. This avoids a significant oversizing of the heavy fuel cell system to provide peak power for such flight phases. As a consequence a lighter FCS and corresponding TMS can be used and the overall aircraft mass is reduced. For a fixed BSE an optimal HF was found determining the optimal power split between the two energy sources for this specific case. For the investigated aircraft a HF value of roughly 0.5 yielded the best results with respect to the MTOM. For the BSE, the expected result is that this should be as large as possible. The study was based on an aircraft similar to the ATR72-600. The best combination of HF and BSE yielding the lowest MTOM with 24 000 kg is still about 5 % heavier than the conventionally powered reference aircraft with 22 800 kg. Finally, this study shows that future aircraft of similar weight and hence size require very advanced battery technology with regard to the BSE compared to available state of the art solutions.

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