ASSESSMENT OF REFORMER CONCEPTS FOR THE PROPULSION SYSTEM OF AN ELECTRIC REGIONAL AIRCRAFT POWERED BY CHEMICALLY BOUND HYDROGEN

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Abstract

The aviation sector is increasingly considering hydrogen as a potential energy source to mitigate its climate impact. However, challenges such as infrastructure development as well as hydrogen handling and storage emerge both on ground and during flight. One proposed alternative concept envisages the in-flight continuous generation of hydrogen through the reforming of hydrocarbon-based fuels like methanol. These fuels are advantageous due to the possibility that existing airport infrastructure can be used. This preliminary study delves into the feasibility of integrating methanol-based autothermal reformer systems in the megawatt range into an *ATR 72*-like fuel cell-based electric regional concept aircraft with distributed propulsion slated for an entry into service in 2040. It has been found that autothermal reforming with methanol poses the highest gravimetric power density out of the considered reforming methods and thus seems to be most promising for airborne applications with respect to weight. The analysis includes assessing system and aircraft mass and installation space demand. The findings indicate a marginal increase of $+1\,\%$ in aircraft takeoff mass for the reformer-based aircraft compared to a LH2-powered aircraft variant.

Keywords

Reformer; Fuel Cell; Electric Aircraft Propulsion; Concept Study

1. INTRODUCTION

Reformer-based propulsion system concepts for commercial aircraft pose an alternative to vastly discussed liquid (LH2) propulsion concepts to achieve climate neutral aviation until 2050 [1]. Reformer systems utilize hydrocarbon-based fuels like methanol. These fuels have storage properties akin to kerosene, and they chemically bind the hydrogen. The hydrogen (H2) is extracted continuously during flight by means of a reforming process, such as steam or autothermal reforming. The generated hydrogen supplies fuel cells as part of an electric drive train. Thus, reformer concepts have the potential to overcome key challenges of LH2-based propulsion concepts, concerning, for example, sustainable hydrogen production, H2 ground and airport infrastructure, H2 ground handling, and H2 on-board storage and distribution [2]. Moreover, as the fuel for reformer-based propulsion systems can be stored in conventional wing tanks, no cryogenic LH2 tanks are required on board the aircraft. In general, the absence of cryogenic LH2 on board the aircraft leads to a less complex on-board systems architecture and possibly results in less certification effort.

In this paper, a preliminary analysis is performed regarding the integration aspects of reformer-based fuel cell concepts. The generated electric power is used for powering the all-electric drive train as well as the on-board systems of a regional concept aircraft. The considered reformer technologies are steam reforming and autothermal reforming with a propylene glycol water (PGW) mixture and methanol as fuels, respectively. The reformer-based system concept is evaluated based on the assessment criteria mass, installation space, and thermal loads and is compared to a LH2-powered concept aircraft.

The *ATR 72*-like reference aircraft, termed *ESBEF Concept Plane 1 (CP1)* and originating from the LuFo project *Development of Systems and Components for Electrified Flight (ESBEF)*, is depicted in figure 1. The top-level aircraft requirements (TLAR) are listed in Table 1. Expected to enter service in 2040, the concept aircraft's on-board systems architecture and associated mass results are detailed by Bielsky [3]. The *ESBEF-CP1* incorporates ten distinct propulsion units or so called Pods. Each Pod includes a hybrid fuel cell system (FCS), a power management and distribution unit (PMAD), the drive train components, i.e. motor controller and permanent magnet synchronous motor, and cooling systems (cf. figure 3). The hybrid FCS consists of multiple low-temperature

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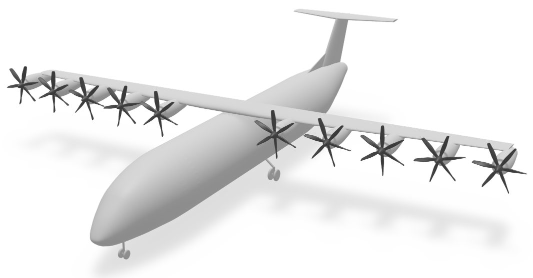

FIG 1. Electric regional concept aircraft *ESBEF-CP1*

TAB 1. *ESBEF-CP1* TLARs

Parameter	Unit	Value
Max. PAX	-	70
Max. takeoff mass	t	23
Max. altitude	ft	27000
Design range	nm	1000
Mach at cruise	-	0.55
El. power at cruise	MW	2.9
El. power at takeoff	MW	4.4

TAB 2. Considered reforming technologies and their state-of-the-art gravimetric power densities

		Reforming method	
		Steam	Autothermal
Fuel	PGW	Not promising	$\rho_g = 0.19 \frac{kW}{kg}$
	Methanol	$\rho_g = 0.25 \frac{kW}{kg}$	$\rho_g = 0.42 \frac{kW}{kg}$

+120%

+70%

Selected for aircraft integration study

proton-exchange membrane (LT-PEM) fuel cell (FC) stacks, batteries and capacitors to balance power peaks, and essential balance-of-plant (BoP) components, like recirculation pumps and air supply subsystems. The PMAD's task is to control the flows of electric power on aircraft system level, i.e. between the drive train subsystem (primary power) and the on-board systems (secondary power). The PMAD also integrates the relevant voltage transformers. As FCs are employed for electric power generation, the electric power supply network is specified to be high voltage direct current (HVDC) with a voltage level of $270\,\mathrm{VDC}$.

With respect to a first assessment of reformer-based propulsion based on the presented concept aircraft, the paper is structured as follows: the technical concepts for H2 generation using steam and autothermal reforming are introduced in section 2. Moreover, the associated aircraft integration requirements for reformers and the overall system concept at aircraft level are outlined. Section 3 proposes a preliminary sizing procedure for reformer-based H2 aircraft power systems, with the results being system mass and installation space. Subsequently, the reformer integration study on the *ESBEF-CP1* is presented in section 4.

2. AIRCRAFT INTEGRATED REFORMER SYSTEM

The fuel processor (FP) is a process plant which uses a chemical conversion process to extract the chemically bound hydrogen from alcohol, hydrocarbon fuels, or alternative renewable fuels [4]. To achieve this, the FP combines several reactors and additional BoP components, such as heat exchangers, evaporators, air compressors, mixers, and pumps into one unit [5]. The product of the reforming process is a hydrogen-rich gas called reformate [4]. The general aim of the reforming process is to maximize the purity of the reformate with regard to its H2 content [6]. However, depending on the employed reforming method, the exact setup of the FP varies and the reformate contains variable amounts of hydrogen, carbon monoxide, carbon dioxide, methane, water, and possibly nitrogen [4].

The following sections provide an overview of airborne-suitable reformer technologies and the associated requirements for aircraft integration, ultimately leading to the proposal of a system concept.

2.1. Airborne-suitable reformer technologies

This paper focuses on evaluating the well-known reforming methods of steam and autothermal reforming for the application within an airborne propulsion system. The evaluation includes the respective use of propylene glycol water mixture and methanol as a fuel, as summarized in table 2.

Steam reforming is carried out by mixing the fuel with hot water vapor. The mixture then reacts with a heterogeneous catalyst in the gas phase. It is an endothermic process which requires the continuous supply of external heat [7]. Steam reforming is considered to be a matured reforming method for ground applications and thus is applied in a large-scale industrial context with respect to H2 production from natural gas [8, 9]. However, today's research focuses on more compact reformer designs to make them available for mobile and possibly airborne applications. Thus, reformer systems may pose a solution for the challenges connected to the availability of compressed and liquefied hydrogen on board commercial aircraft. For example, Diehl Aviation in association with the Fraunhofer Institute of Microengineering and Microsystems (IMM) developed a concept for self-sufficient galleys including a propylene glycol fuel processor for a $5\,\mathrm{kW}$ fuel cell compactly integrated into a trolley in the context of the projects DIANA and GETPOWER [10–12].

As another reformer technology, autothermal reforming is considered. It combines the processes of steam reforming and partial oxidation and maintains the internal reforming process by using inherent heat [13]. Autothermal reforming is favored for its ease of operation, ability to function at lower temperatures with high control, good start-up behavior, and reduced tendency for coking [14]. Present research regarding reforming processes focuses on autothermal reforming for mobile applications, with a special emphasis on creating on-board fuel processors [14].

Steam reforming poses advantages in terms of process stability and higher efficiencies in direct comparison to autothermal reforming. However, steam reforming requires a higher amount of process steps and thus more reactor components within the FP to output reformate with the required purity, leading to higher system complexity and mass. [15]

Regarding the fuel, in general, methanol is easier to reform at lower reaction temperatures due to it's higher responsiveness compared to PGW. Latter has a higher boiling point and tends to self-decomposition. Thus, PGW requires a significant more complex reforming process including a water gas shift reactor, which is not needed for methanol reforming. However, the reforming of PGW produces higher concentrations of carbon monoxide compared to methanol. [12]

Regarding integration aspects in commercial aircraft, PGW, on the one hand, is an already certified substance widely used as a de-icing fluid for aircraft. Methanol, on the other hand, is toxic and consequently additional safety measures have to be employed concerning ground and on-board handling. With respect to the resulting system mass, the process characteristics of the considered reformer technologies lead to the power densities displayed in table 2. The presented values are considered to be state-of-the-art and are derived by Fraunhofer IMM from a $300\,\mathrm{kW}$ reformer-based fuel cell system using the ProSim® modeling software. The power density values include the fuel processor, the fuel cell, and the required peripheral systems, i.e. cooling system, pumps, and compressors.

Steam reforming for airborne applications is not considered in more detail as it has been identified to yield unreasonable high system masses when applied to high-power aircraft propulsion systems. Ultimately, autothermal reforming with methanol is selected for the aircraft integration study as it yields the most promising results with respect to system mass. The simplified reaction equation for autothermal reforming with methanol is given by Palo [7]:

$$\mathrm{CH_3OH} + \frac{1}{2}\mathrm{H_2O} + \frac{1}{4}\mathrm{O_2} \rightarrow \mathrm{CO_2} + 2.5\mathrm{H_2} \quad (1)$$

The general composition of a FP serving as a simplified schematic of the ProSim® model is depicted in figure 2. The reformer, or reforming reactor, is the first and major processing stage for the fuel. The subsequent water gas shift reactor (only needed for PGW) and the preferential oxidation reactor are conditioning the reformate with respect to unwanted gases, especially carbon monoxide (CO) [4]. To this end, the remaining CO concentration should be $c_{\mathrm{CO}} < 10\,\mathrm{ppm}$ for the feeding of LT-PEMFC to avoid severe poisoning of the anode catalyst which will accelerate fuel cell degradation [8, 16]. The water of the fuel cell anode exhaust is fed back to the reformer.

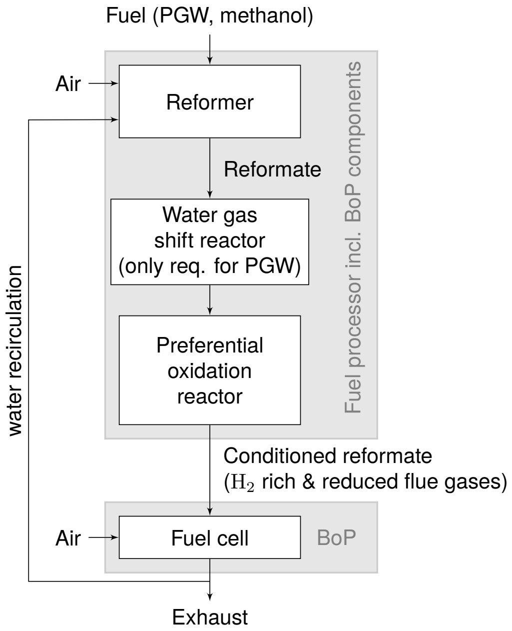

FIG 2. Process steps of a fuel processor-based fuel cell system [8]

2.2. Aircraft integration requirements

The integration of airborne reformer-based power systems into commercial aircraft necessitates the compliance of a number of technological and operational requirements. Airborne reformer system concepts are rather disruptive and imply significant changes on aircraft level with respect to today's known and well-understood aircraft propulsion and on-board systems. Besides the integration of the electric drive train and the fuel cell, as currently being discussed in literature in connection with LH2-based propulsion concepts, foremost, the physical integration of the FP into the airframe and the functional integration into the on-board systems architecture is an additional challenge.

2.2.1. Fuel processor reactant supply

For the H2 reforming process to take place, the FP requires a continuous supply of fuel, air, and water.

As for the fuel it can generally be stored in conventional wing integral tanks. However, in case methanol is used as a fuel, additional safety measures regarding the tank system must be taken due to the relatively high flammability and toxicity of methanol [15]. PGW as a fuel does not require such additional safety precautions.

The required air for the FP is drawn from the environment and needs additional compression to reach around $1.3 - 1.4\,\mathrm{bar}$ on ground and approximately $0.9\,\mathrm{bar}$ during cruise. An on-board air tank seems unfeasible as high volumes of air are required for the continuous operation of the FP throughout the flight mission.

In addition to fuel and air, steam and autothermal reforming processes require the continuous supply of water. Preferably, the water-rich anode exhaust air of the FC is recirculated and fed back to the FP. Typically, the water balance between the reformer and the FC is achieved at the majority of operating points. However, a small refillable water tank has to be integrated as a safety measure to guarantee that the FP does not run dry.

2.2.2. Fuel cell reactant supply

Analogous to the FP, the FC requires a continuous supply of oxygen as well. Although the oxygen can be stored on board in dedicated tanks, this solution entails large integration efforts and adds a mass penalty on system level as high quantities of gas are needed. Thus, the utilization of ambient air for FC supply is considered to be the preferred solution.

Flow-through operation is preferred for the FC's cathode with a stoichiometry of $\lambda_{\mathrm{O2}} = 2$ for optimum FC operation [17]. This will result in the need of a relatively large air mass flow. Hence, the integration of air ducts and blowers is required. Consequently, a significant amount of air inlets is needed for FP and FC operation, which will lead to drag penalties on aircraft level. However, the air required for the on-board FP accounts for only about $10\,\%$ of the air flow required for the FC cathode. This is because the cathode exhaust air can be used as air for the burner inside the fuel processor.

The gaseous hydrogen produced by the FP must be safely and reliably routed to the FCs. High requirements with respect to the impermeability to gas and leak detection apply to the hydrogen distribution system. Regarding the stoichiometry of the FC's anode, $\lambda_{\mathrm{H2}} = 1.2 - 1.4$ is typically applicable [17]. Hence, the FCS encompasses a H2 recirculation circuit. In the context of the studies in this paper, a hydrogen utilization, defined as the ratio of H2 consumed to H2 delivered, of $80\,\%$ is assumed.

2.2.3. Operation strategy

In general, fuel cells should be operated at a stationary operating point, as possible, independent of the flight phase. High dynamics with regards to the fuel cell's electric power demands and fluctuations in the reactants supply promote accelerated degradation or may even cause irreversible damage to the fuel cell stack [18]. Hence, power peaks must be buffered by means of appropriate energy storage systems, i.e. batteries and supercaps.

Due to the intrasystem coupling of the FP and the FC, the FP contributes significantly to the robust operation of the FC. Therefore, the operation requirements of the FC are also valid for the FP, meaning that the operation strategy should be aiming at operating the FP at a steady-state point as possible. The general operating strategy of the reformer-based fuel cell system envisages that the two subsystems are always operating in close coordination with each other. Hence, a H2 buffer tank is not necessary. Further aspects regarding the system's control strategy are not discussed in greater detail in the scope of this paper.

2.2.4. Thermal management

With respect to the FP, the exhaust gas of the afterburner contains waste heat, which can be channeled overboard. No active cooling is required as the temperature of the exhaust is about $45\,°\mathrm{C}$. However, the fuel cell produces larger amounts of waste heat as the fuel cell efficiency is typically in the range of $50 - 60\,\%$ [19]. The FC waste heat must be dissipated by means of a high-power cooling system.

2.3. Reformer system architecture concept

The previously discussed integration aspects and requirements lead to the proposed reformer-based system architecture for the considered concept plane *ESBEF-CP1* depicted in figure 3 on the left. Autothermal reforming with methanol as a fuel is selected due to the expected lowest system mass compared to other reforming methods according to table 2. For the sake of clarity only one wing side is shown, assuming system symmetry for the other wing side. For comparison, the LH2-based concept is shown on the right in figure 3.

The methanol is stored in wing integral tanks and is supplied to two fuel processor units (FPU) per wing side. For reasons of redundancy, four FPUs in total are installed in the fuselage underfloor area of the considered high wing concept aircraft. The FPU itself is a highly integrated subsystem comprising the fuel processor, water supply components, and additional peripherals, such as valves, pumps, and electric compressors for ram air supply.

The gaseous hydrogen reformate generated by the FPUs is supplied to the individual Pods by means of adequate supply lines routed inside the wing structure. The FCs transform the delivered hydrogen into electrical power to supply the drive trains and on-board systems. The FCs' anode exhaust air is fed back to the FPUs for water recovery. Hence, the installation of return pipes from the individual Pods to the fuselage, where the FPUs are located, is required.

3. METHODOLOGICAL APPROACH FOR SYSTEM KEY DESIGN PARAMETER ESTIMATION

In this section, the methodological approach regarding the preliminary estimation of the relevant reformer-based propulsion system design parameters, being mass and installation space, is presented.

3.1. Estimation of mass and installation space

In the scope of this paper, one evaluation metric is the system mass and ultimately the aircraft's takeoff mass (TOM) as stated in equation 2.

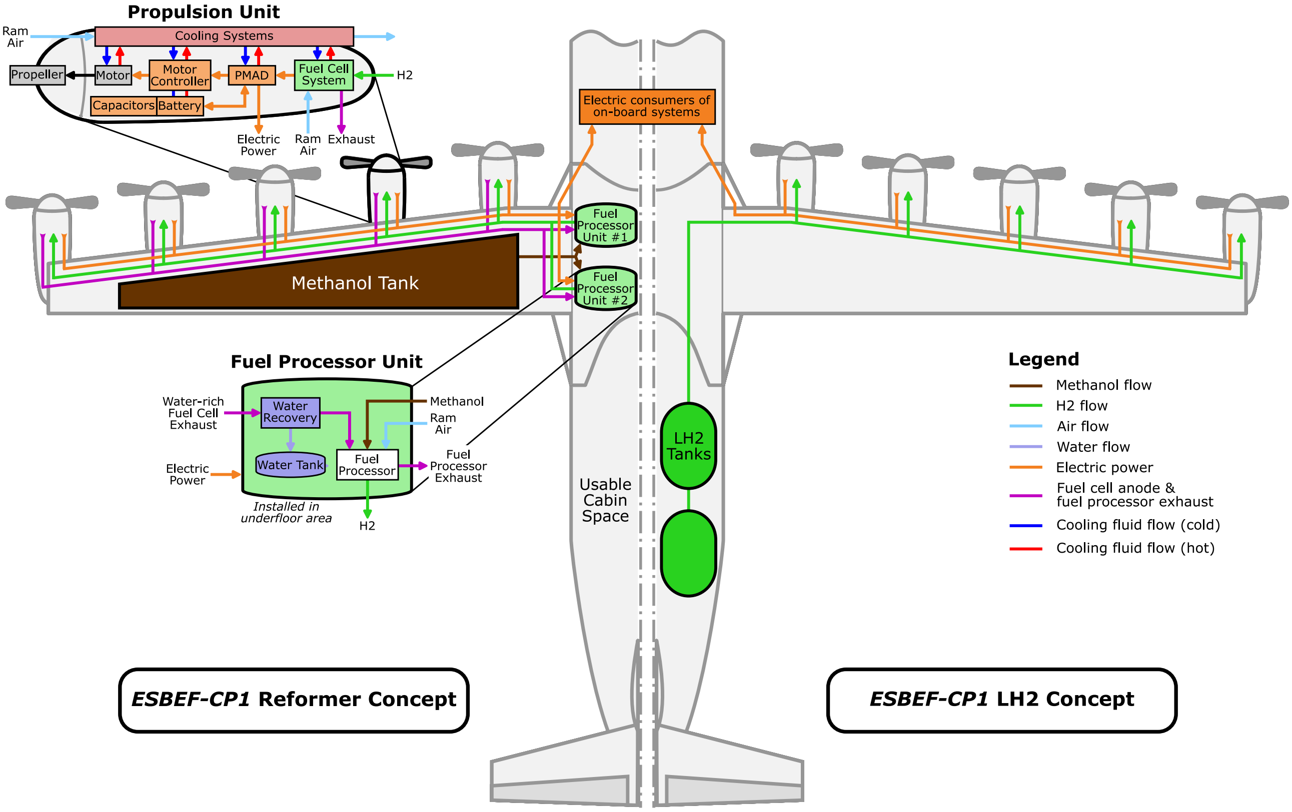

FIG 3. Reformer-based H2 power system architecture of the regional concept aircraft and the LH2-based concept for comparison

$$m_{\text{TOM}} = m_{\text{OWE}} + m_{\text{fuel}} + m_{\text{payload}} \tag{2}$$

The fuel mass required by the fuel processors throughout the flight mission is calculated by

$$m_{\text{fuel}} = \dot{m}_{\text{fuel}}(t) \cdot \Delta t_{\text{ops,FP}} \ , \tag{3}$$

with $\dot{m}_{\text{fuel}}(t)$ being the flow of fuel to the FP and $\Delta t_{\text{ops,FP}}$ being the time span the FP is operated throughout the mission. The fuel flow is determined with the FP efficiency, which describes the efficiency of the energy conversion process from the fuel to H2. It is defined as

$$\eta_{\text{FP}} = \frac{\dot{m}_{\text{H2}}}{\dot{m}_{\text{fuel}}} \ . \tag{4}$$

Knowing the required fuel mass, the fuel tank volume can be determined from

$$V_{\text{fuel}} = \frac{m_{\text{fuel}}}{\rho_{\text{fuel}}} \ . \tag{5}$$

The aircraft operating weight empty (OWE) is given by

$$m_{\text{OWE}} = m_{\text{structure}} + m_{\text{OBS}} + m_{\text{prop}} \ . \tag{6}$$

The parameter $m_{\text{structure}}$ refers to the aircraft fuselage and wings masses. The mass of the aircraft on-board systems (excluding the propulsion system) is represented by m_{OBS}. The total mass of the reformer-based propulsion system m_{prop} follows from

$$\begin{aligned} m_{\text{prop}} &= m_{\text{FPU}} + m_{\text{FC}} + m_{\text{peripherals}} \\ &\quad + m_{\text{bat}} + m_{\text{powerTrain}} \ . \end{aligned} \tag{7}$$

The subsystem masses of the FPUs, the FCs, and the peripherals are estimated based on the required maximum electric power of the fuel cell and the assumed gravimetric specific power density according to

$$m_{\text{FPU/FC/peripherals}} = \frac{P_{\text{FC}}}{\rho_{\text{g,FPU/FC/peripherals}}} \ . \tag{8}$$

The peripherals encompass the cooling systems for the FC and BoP subsystems for the FP and FC, such as FP-internal heat exchangers, pumps, and compressors. The water tank within the FPU is neglected as it is expected to be rather small. Furthermore, any component mass scaling effects are neglected.
The mass of the battery is estimated based on its capacity and the assumed specific gravimetric energy density according to

$$m_{\text{bat}} = \frac{E_{\text{bat}}}{\rho_{\text{e,g,bat}}} \ . \tag{9}$$

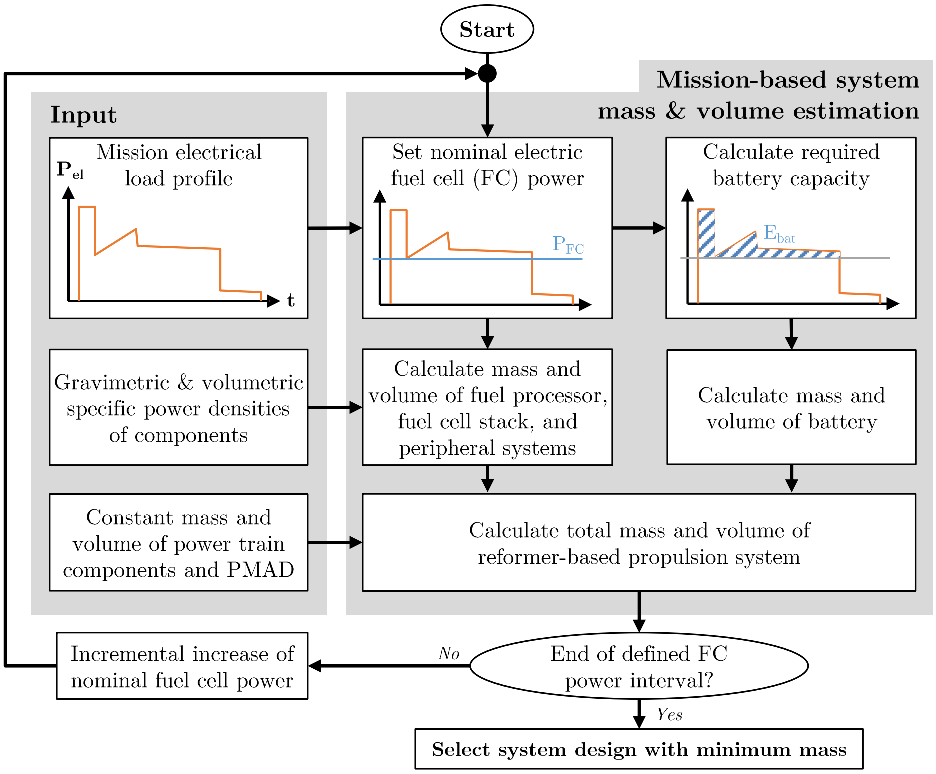

FIG 4. Procedure for the preliminary mass and volume estimation of the reformer-based propulsion system based on a given mission-level electrical load profile

The mass fraction $m_{\text{powerTrain}}$ in equation 7 comprises the mass of the propeller, the motor, the motor controller, and the PMAD. The value itself is driven by the maximum electric power demand of the aircraft's electric drive train.

In analogy to the mass estimation, the total installation space demand of the reformer-based propulsion system is given by

$$V_{\text{prop}} = V_{\text{FPU}} + V_{\text{FC}} + V_{\text{peripherals}} + V_{\text{bat}} + V_{\text{powerTrain}} \ . \tag{10}$$

The total volume of the individual subsystems is estimated with equations 8 to 9 using the components' specific volumetric power or energy densities instead of the gravimetric ones.

3.2. Mission power demand analysis for the selection of a suitable system design

For the preliminary design of the reformer-based power system in terms of mass and installation space demand, the design space is explored. To this end, the system is dimensioned across a range of nominal electric power values for the reformer-based fuel cell system, set within a specified power value interval. Given the anticipated mass sensitivity of integrating a reformer-based power system on board an aircraft, the system design yielding the least total mass is chosen in the scope of the integration study. The employed mission-based procedure for system mass and volume estimation is shown in figure 4.

As an input, the total electrical load profile of the aircraft, including propulsion and on-board systems electric power demands throughout a given flight mission is required. Initially, the nominal electric FC power P_{FC} is set to the lower bound of the design space power interval. It is assumed that the FC operates on a constant power level throughout the mission to minimize effects associated with the accelerated degradation of the stack. Mass and volume are calculated with the equations given in section 3.1.

Power on aircraft level exceeding the nominal FC power is provided by a lithium-based battery. It is assumed that the battery is not charged in flight. Moreover, the battery's state of charge (SOC) is assumed to be $20 - 80\,\%$ at all times to minimize degradation. Supercaps are neglected as they are expected to have no significant mass impact. The required battery capacity results from the total aircraft's mission energy demand for the mission duration t_{mis}:

$$E_{\text{mis}} = \int_{t=0}^{t_{\text{mis}}} \left(P_{\text{FC}}(t) + P_{\text{bat}}(t)\right)\,\mathrm{d}t \tag{11}$$

Battery mass and volume is calculated with equation 9. Ultimately, the total mass and volume of the reformer-based power system is given by equations 7 and 10. The nominal electric FC power is incrementally increased and the sizing loop is repeated until the upper bound of the design space has been reached. Finally, the system design with the lowest overall mass is selected.

TAB 3. Assumed power and energy densities for the components of the reformer-based power system

	State-of-the-art		2040	
Component	**Gravimetric**	**Volumetric**	**Gravimetric**	**Volumetric**
Fuel Processor	1^a kW/kg	1400^a kW/m^3	2^b kW/kg	2800^b kW/m^3
Fuel Cell	1.5^a kW/kg	6000 kW/m^3 [20]	3^b kW/kg	12000^b kW/m^3
Peripherals FP & FC	1.5^a kW/kg	2100^a kW/m^3	3^b kW/kg	4200^b kW/m^3
Battery	0.15 kWh/kg [21]	500 kWh/m^3 [22]	0.7 kWh/kg [23]	1000 kWh/m^3 [21]

^{a} Based on ProSim® simulation results.

^{b} Based on state-of-the-art including a future technology factor of 2 for EIS 2040.

4. REFORMER-BASED PROPULSION SYSTEM INTEGRATION STUDY ON AIRCRAFT LEVEL

In the following, the results of the preliminary integration study on the reformer-based propulsion system for the electric regional concept aircraft *ESBEF-CP1* (cf. figure 1) are presented. First, the assumed power densities of the system components are introduced. Second, the mass and installation space results are shown, first at system level and then at aircraft level. Regarding aircraft mass, the results are compared with the LH2-powered aircraft variant presented by Bielsky [3]. Finally, relevant thermal aspects are addressed.

4.1. Subsystem technology parameters

Mass and installation space estimation for the reformer-based propulsion system is carried out based on assumed technology parameters for the individual subsystems, being the gravimetric and volumetric power and energy densities. According to table 3 the parameters are either a result from the system simulation performed by Fraunhofer IMM and associated with the power density for the complete autothermal reformer-based fuel cell system supplied with methanol stated in table 2 or based on data available in literature. The state-of-the-art parameters are projected to an entry into service in 2040 to be applicable for the *ESBEF-CP1* by assuming a factor of 2 for future technology improvement.

4.2. Aircraft electric power requirements

In the scope of the present integration study, the *ESBEF-CP1* reference flight mission depicted in figure 5 is used [3]. The flight range is 1000 nm (cf. table 1). The stated electric power demand includes primary power required for the electric propulsion units and secondary power for supplying the on-board systems.

As a result of the preliminary sizing procedure presented in subsection 3.2, the reformer-based fuel cell systems powering the drive train are mass-optimal when sized to the required total electric aircraft power during cruise. Thus, the reformer system is operated at maximum design power prior to takeoff until the end of cruise. After cruise, the reformer system power is adjusted to the power demand during the descent.

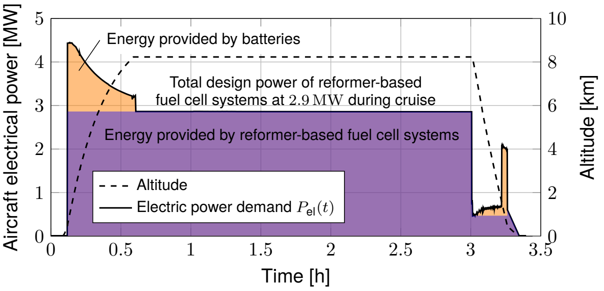

FIG 5. Reference design mission and electric power demand of the *ESBEF-CP1*

The energy demand that the reformer cannot meet is provided by the batteries, e.g. at takeoff and before landing. In the scope of the presented study, this basic operational strategy of reformer-based fuel cell systems overlooks the option to charge the batteries in low-power flight phases.

4.3. Mass and installation space evaluation of the reformer-based propulsion system

In the following, the mass and installation space demand of the aircraft-integrated reformer-based propulsion system are evaluated for the reformer-based *ESBEF-CP1*. Figure 6 shows the mass and volume of the reformer-based propulsion system and its subsystems on aircraft level depending on the overall system's electric design power of the fuel cells. The mass and volume shares of the fuel cells, the batteries, and the drive train components are divided among the aircraft's ten Pods. The mass and volume share of the fuel processor is divided among a total amount of four fuel processor units integrated in the fuselage (cf. figure 3). The peripherals include the FC cooling systems and the BoP subsystems required to operate the FP and FC. Masses of the water buffer tank and the hydrogen supply and fuel cell exhaust pipes between the FP and the FC are neglected. Moreover, the stated fuel cell electric power values refer to the usable net electric output power. An assumed BoP electric power demand of $10\,\%$ has already been deducted from the fuel cell total power output.

Mass and volume of the FP, the FC, and the peripherals increase linearly with increasing FC electric power. The FP has the highest impact on total system mass

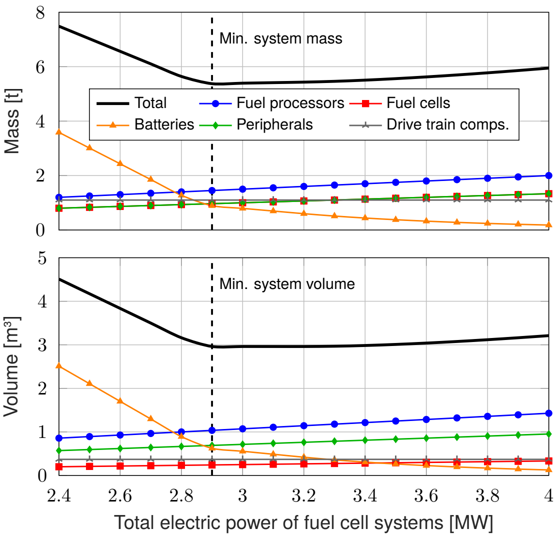

FIG 6. **Mass and volume share of the reformer concept's subsystem components depending on the electric design power of the fuel cells**

and volume due to its relatively low gravimetric and volumetric power densities. The batteries' mass and volume linearity show a discontinuity at a total electric power output of the fuel cell systems of $2.9\,\mathrm{MW}$, which marks the aircraft's required continuous electric power during cruise. For FC electric power values $< 2.9\,\mathrm{MW}$, the batteries partly need to provide power for cruise. This significantly increases the mass of the batteries due to their relatively low gravimetric energy density adverse solely sizing the batteries to provide power during the takeoff and landing power peaks. Mass and volume of the drive train components are independent from varying the FC electric power. Here, a constant mass of $110\,\mathrm{kg}$ per Pod is assumed, including the propeller, an electric motor and motor controller, oil and fluids, and the PMAD [3]. For the motor, a volume of $10\,\mathrm{l}$ is assumed [24]. The volume of the PMAD and the motor controller is estimated to be $27\,\mathrm{l}$ in total.

A mass and volume-optimized system is obtained for a FC nominal power rating of $2.9\,\mathrm{MW}$, meaning that the reformer-based propulsion system should be sized for the cruise electric power demand for a mass-optimized design. The total mass of the reformer-based propulsion system is $5375\,\mathrm{kg}$. The associated total installation space required is $3\,\mathrm{m}^3$. Thus, this design point is selected for further considerations.

4.4. Evaluation against the LH2-powered aircraft

In the following, the previously determined mass and installation space results for the reformer-based propulsion system are assessed on aircraft level using the takeoff mass as an evaluation metric and the existing *ESBEF-CP1* geometry. The results regarding mass for the reformer-based *ESBEF-CP1* are set in relation to the LH2-powered *ESBEF-CP1*.

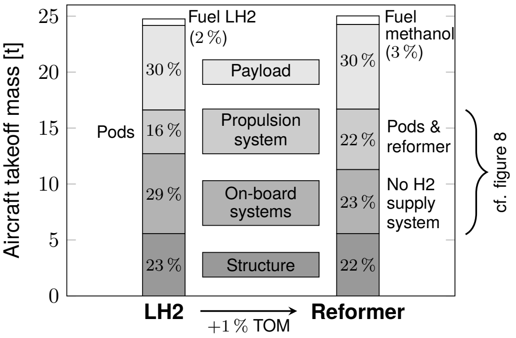

FIG 7. **TOM composition for the LH2-powered and reformer-based *ESBEF-CP1* aircraft**

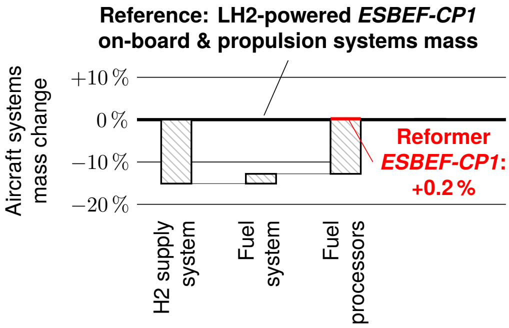

FIG 8. **Aircraft systems mass impact of reformer integration in relation to LH2 variant**

4.4.1. Aircraft mass

The takeoff mass breakdown for both the LH2-powered *ESBEF-CP1* according to Bielsky [3] and the reformer-based *ESBEF-CP1* subject of this paper is depicted in figure 7. With a TOM of $25\,\mathrm{t}$, the reformer-based aircraft yields a $+1\,\%$ higher TOM compared to the LH2-variant in the scope of the considered reference flight mission.

For the structure, a mass of $5570\,\mathrm{kg}$ is assumed for both aircraft [25]. For the payload mass, $105\,\mathrm{kg}$ per passenger are assumed for both aircraft [26]. The total aircraft system mass for the reformer *ESBEF-CP1* is derived based on the LH2 concept aircraft systems architecture, including the Pod-based propulsion system, environmental control system, electric power supply, cabin equipment and furnishing, flight controls, hydraulic power supply, ice protection system, landing gear, lights, and hydrogen supply [3].

In this regard, a more detailed breakdown is provided in figure 8. The absolute mass of aircraft systems is about $+0.2\,\%$ higher for the reformer concept compared to the LH2 variant and thus the systems mass change is negligible. Based on the LH2-powered aircraft as the reference, the hydrogen supply system is not required for the reformer aircraft. However, a wing-integrated fuel system for methanol storage and distribution needs to be considered. Here, a fuel system mass of $250\,\mathrm{kg}$ is assumed [3]. Additionally, for the reformer-based *ESBEF-CP1*, the mass of fuel processors is considered. The internal structure of the Pods, including fuel cell, PMAD, and drive train components, remains unchanged for both aircraft. Consequently, no mass deviation is considered. However, for the sake of comparability, masses of the FC, cooling system, and batteries of the LH2-powered *ESBEF-CP1* are linearly scaled from $400\,\mathrm{kW}$, stated as the design electric power per Pod by Bielsky [3], to $290\,\mathrm{kW}$ per Pod, using the power densities listed in table 3.

From figure 8 it becomes clear that the mass added due to the integration of the reformer-based propulsion system just corresponds to the mass savings achieved by the elimination of the hydrogen supply system under the assumptions made.

The required fuel mass in terms of the considered reference mission is estimated based on the H2 reformate mass flow $\dot{m}_{\mathrm{H2}} = 200\,\mathrm{kg/h}$ from the fuel processors to the fuel cells on aircraft level as a result from the reformer system simulation. Assuming the same H2 mass flow rate also being valid for the LH2-powered aircraft and assuming the same fuel cell operating strategy for both aircraft, the reformer-based *ESBEF-CP1* yields with $m_{\mathrm{fuel}} \approx 770\,\mathrm{kg}$ a $+34\,\%$ higher methanol fuel mass compared to the LH2 fuel mass of the LH2 aircraft variant. To this end, a simulated fuel processor efficiency of $\eta_{\mathrm{FP}} = 0.76$ is considered. The methanol takes up a volume of $V_{\mathrm{fuel}} \approx 1000\,\mathrm{l}$.

Assuming a similar tank system between the *ESBEF-CP1* and the *ATR 72* with a maximum fuel mass of $5000\,\mathrm{kg}$ and a tank capacity of approximately $6000\,\mathrm{l}$, no restrictions are expected with regard to the fuel mass to be carried [27]. This leads to the conclusion that there is ample reserve for extended flight missions beyond the one currently being evaluated. The differences between the reformer-based aircraft and the conventional *ATR 72* in terms of mass flow (*ATR 72*: $650\,\mathrm{kg/h}$ in cruise [27]), fuel mass, and volume result from the higher energy density of hydrogen.

Both the considered LH2-powered and the reformer-based aircraft variants exceed the TOM ($23\,\mathrm{t}$, cf. table 1) of the initially provided overall aircraft design of the *ESBEF-CP1*. For the LH2-powered aircraft, the initial TOM is exceeded by $+7.7\,\%$ and for the reformer aircraft by $+8.6\,\%$. The same statement is valid when comparing the TOM of the reformer-based *ESBEF-CP1* and the conventional kerosene-powered *ATR 72* aircraft, since the *ATR 72* also states a TOM of $23\,\mathrm{t}$ [27]. Thus, an iteration loop with overall aircraft design is required to heuristically integrate reformer-based propulsion technology.

4.4.2. Installation space

According to figure 6, the components installed in a single Pod require the installation space of $V_{\mathrm{pod,sys}} \approx 160\,\mathrm{l}$, assuming a portion of $50\,\%$ for the peripherals associated with the fuel cells. This volume can be accounted for by assuming $d_{\mathrm{pod,nacelle}} = 0.45\,\mathrm{m}$ for the nacelle diameter and $l_{\mathrm{pod,nacelle}} = 1\,\mathrm{m}$ for the nacelle length, which is considered to be rather conservative assumptions. Consequently, it is expected that the components to be integrated into the Pod fit into the nacelle.

The integration of the fuel processors in the underfloor area at wing level is more challenging, since the required installation space poses $V_{\mathrm{FP}} \approx 1380\,\mathrm{l}$ including peripherals. To fit the FPs, a section of $0.75\,\mathrm{m}$ in length is required in the underfloor area [25]. This represents a non-negligible space requirement, especially since other on-board system components, such as the hydraulic power package, are housed in the area near the main landing gear.

Generally, the *ESBEF-CP1* aircraft design is derived from the *ATR 72* with the difference of a wider fuselage cross section to make space for the installation of LH2 tanks at constant passenger capacity. As for reformer-based aircraft, no LH2 tanks are needed, but rather conventional tank systems, the original *ATR 72* airframe may be considered for future reformer integration studies. However, the space available for integrating the fuel processors within the *ATR 72* airframe is significantly less compared to the *ESBEF-CP1*, increasing the challenge for the system integration.

4.4.3. Thermal aspects

Using the reformer simulation model in ProSim®, the total efficiency of the system comprising the FPs and the FCs is estimated to be around $41.5\,\%$. This translates to the waste heat of the FPs at aircraft level during cruise being at around $1.8\,\mathrm{MW}$ for methanol autothermal reforming. The FP waste heat is discharged with the exhaust gas. However, the FCs must be actively cooled, with a total waste heat of $2.4\,\mathrm{MW}$ to be dissipated. Active cooling of the FCs applies to both aircraft, the reformer and LH2-powered variant. Other components within the Pod, such as the motor, motor controller, and battery, need additional cooling, which is not further considered. To this end, ram air presents a potential heat sink. Hence, with respect to system integration aspects, additional mass and drag penalties on aircraft level are expected.

5. CONCLUSION AND OUTLOOK

Reformer-based power supply systems offer a compelling alternative to LH2-powered aircraft concepts, currently being highly discussed in both industry and academia. Generating H2 continuously on board the aircraft from hydrocarbon-based fuels negates the need for H2 handling both on board and on the ground. This permits the use of conventional wing tanks for fuel storage and reduces the complexities associated with integrating a cryogenic LH2 tank in the fuselage. Additionally, on-board reformer technology eliminates the need for H2 ground infrastructure.

In this paper, a preliminary study was conducted to assess the integration potential of an autothermal reformer, using methanol as fuel, into the propulsion system of an electric regional concept aircraft. Using the *ESBEF-CP1* concept aircraft model, which is derived from an *ATR 72*-like aircraft model, with an entry into service in 2040 as integration platform, a comparative analysis was performed against a LH2-powered variant, focusing on mass and installation space demand as evaluation metrics. The proposed reformer-based propulsion system contains ten individual fuel cell systems, integrated in each of the aircraft's ten propulsion units, and four fuel processor units, each comprising the reformer, fuel cell anode exhaust water recovery, and peripheral systems.

In terms of mass impact at aircraft level, the reformer-based configuration leads to a marginal increase of $+1\,\%$ in takeoff mass compared to the LH2-powered aircraft variant. The combined mass of the fuel processors and the conventional tank system of the reformer-based aircraft closely matches that of the hydrogen storage and distribution system of the LH2-powered aircraft. Moreover, analysis indicates that the reformer-based propulsion system is mass and volume-optimal when sized to the cruise electric power demand which is $2.9, \mathrm{MW}$ for the *ESBEF-CP1*. For the design mission of the *ESBEF-CP1*, the necessary methanol can be stored in terms of both mass and volume, assuming a conventional wing integral tank system comparable to the one of the *ATR 72*. Nonetheless, dissipating the substantial waste heat, quantified at $2.4\,\mathrm{MW}$ for the fuel cells for both the reformer and the LH2 aircraft, remains a technical challenge to be addressed. The waste heat from the fuel processors is channeled overboard with the exhaust gas.

Despite additional challenges like a residual share of CO2 emissions, the need for technological advancements in terms of mass reduction, and safe methanol storage on board, reformer-based aircraft could significantly contribute to aviation decarbonization, particularly in regions with limited H2 infrastructure.

Subsequent studies should be performed using higher-fidelity methods for the sizing and simulation of fuel processors and fuel cells, ensuring a more detailed assessment of the technology's gravimetric, volumetric, and thermal integration potential on the aircraft. In this context, the assessment should encompass additional criteria, such as reliability, maintainability, and cost, ultimately aiming at validating reformer technologies with regard to aviation suitability. Furthermore, given that the reformer-based aircraft's takeoff mass surpasses that of the original design, an iterative process with the overall aircraft design is necessary.

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