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DEVELOPMENT OF A HYDROGEN-POWERED FUSELAGE-MOUNTED BLI PROPULSOR ADD-ON FOR PASSENGER AIRCRAFT

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Abstract

The concept of an "Auxiliary Power and Propulsion Unit" (APPU) is introduced, which consists of a Boundary-layer-ingesting (BLI) propulsor with an engine mounted at the rear of an passenger aircraft fuselage, replacing the Auxiliary Power Unit (APU) and contributing around 10% of total cruise thrust, as well as auxiliary power. This APPU unit is using hydrogen provided by an additional tank installed in the tailcone of the aircraft. The concept is aimed at lowering the threshold to installing both hydrogen-driven propulsion and BLI propulsors on aircraft in the short term, while minimizing resulting operational risk. The concept has been investigated using a preliminary aircraft synthesis tool and further component-level mass estimates. Operational aspects, sensitivities and limits to the design have been investigated. Estimates of mission fuel burn find that CO_2 emissions emissions reduce roughly proportionally to the APPU thrust share, with additional savings due to improved overall efficiency. Further improvements are deemed feasible and are the topic of ongoing research.

Keywords: Boundary Layer Ingestion, hydrogen aircraft, conceptual aircraft design

Nomenclature

Abbreviations

APPU	Auxiliary Power and Propulsion Unit
BLI	Boundary Layer Ingestion
CG	Centre of Gravity
CROR	Counter-Rotating Open Rotor
HTP	Horizontal Tailplane
LCI	Layered Composite Insulation
MLI	Multilayer Insulation
OR	(single) Open Rotor
RMSE	Root of Mean Squared Error (std. error)
SLS	Sea Level Static
ToC	Top of Climb
VTP	Vertical Tailplane

Symbols

E	Energy
F	Thrust force
F_N	Net thrust
m	mass
ΔE	Change of energy use rel. to reference
Δm	Mass difference rel. to reference case
η	Efficiency
Φ_{APPU}	APPU thrust share

Suffixes

$appu$	APPU engine and propulsor
F	Fuel
TF	Turbofan
GTF	Geared Turbofan
H_2	Hydrogen
k	kerosene
mis	design mission (w/o diversion)
OE	Operational empty
PM	maximum payload
TO	Take-off
TOM	Take-off, maximum
SLS	Sea Level Static
tot	sum of all components
ToC	Top of Climb
tp	tailplane
ZF	Zero Fuel
ZFM	maximum zero fuel

1. Introduction

Both BLI and the use of hydrogen (H_2) as a fuel for aeroplanes are widely regarded as tools to significantly reduce the impact of aviation on the Earth's climate. Conceptual designs which exclusively rely on these principles, however, represent a large departure from the conventional design of transport aircraft, and thus require a large step change in the design, manufacture, operation and maintenance, including new certification criteria. The conceptual aircraft design being developed in the APPU (Auxiliary Power and Propulsion Unit) programme tries to address this hurdle, by augmenting an existing, conventional aircraft design with a hydrogen-driven fuselage-mounted BLI propulsor which provides around 10% of total thrust, as well as all electricity and other auxiliary power. Because the contribution of the additional unit is limited, the changes to the existing design are manageable: The unit replaces the conventional APU (Auxiliary Power Unit), the hydrogen tank is small enough to be included in a redesigned tailcone structure with only a minor change to total fuselage length and a reconfiguration of the empennage to a cruciform tail, without the need to change other parts of the aircraft, such as wing, passenger cabin or even the main engines. The fact that the APPU unit is treated as an "add-on" permits safe operation even in the event that no hydrogen is available on some routes or in case reliability of the new technology in day-to-day operations should be less than achieved by the mature conventional engine designs in use today.

The aim of this study is to develop the overall concept and demonstrate that producing even a small part of thrust in this way is technically and economically feasible. The new concept should therefore present a way for manufacturers and operators to gain experience with the new technologies and maturing them while minimizing technological risk, particularly during a transitional phase when worldwide production of sustainably-generated H_2 and respective refuelling infrastructure are not yet sufficient for completely H_2-powered aircraft.

2. The APPU concept

As the baseline reference, the Airbus A321neo was chosen. This aircraft has a payload of 25t and a range with full payload of 4630km, which leads to a high enough fuel fraction that savings in fuel mass can offset the added mass of the APPU unit, but not such a long distance that the low density of H_2 requires a very large tank volume, unless the APPU thrust contribution becomes insignificant. Another advantage of this baseline over bigger aircraft of similar range is that the comparably low thrust requirement makes it easier to develop and manufacture a propulsion system based on new technology.

2.1 Thrust and power contribution

The total power share was chosen such that it can be satisfied with a tank size that can conceivably fit into the tailcone of the baseline aircraft without a major fuselage extension, and in order to utilize the BLI effect well.

Thrust depends on the momentum added to the flow passing through a propulsor, independent of its initial velocity. This means that for a given mass-flow and thrust, the required exhaust velocity reduces with the velocity of the incoming flow. The kinetic energy of the exhaust flow relative to the ambient air, however, is left behind. This makes it desirable to achieve the required thrust with the lowest possible exhaust velocity, maximizing propulsive efficiency. For engines operating in free-stream conditions, this means increasing the mass-flow and decreasing specific thrust. The benefit of BLI propulsion is that the low-speed flow in a vehicle's own boundary layer can be used to achieve a given amount of thrust with a lower exhaust velocity, even with the same engine mass-flow as a comparable conventional engine. The application of BLI propulsors is advantageous in cases where this benefit outweighs the penalty of the non-uniform intake flow and the design changes needed to avoid separation of the incoming boundary layer.

Like conventional aero-engines, the propulsive efficiency of BLI propulsors also benefits if the mass-flow is increased to further reduce the required exhaust velocity. However, there is only a certain mass-flow within the boundary layer, and ingesting more than this amount leads to taking higher-velocity air in, thus reducing the relative BLI benefit compared to a conventional free-stream intake. It follows that the relative BLI benefit decreases with increasing thrust, until it no longer compensates

for the adverse effects created by the ingested boundary layer. In order to take this into account, it was decided to aim for a thrust of the BLI propulsor to around 10% of total aircraft thrust, which is expected to be a suitable magnitude for BLI, with respect to the momentum deficit in the fuselage boundary layer. In this study, variations of the thrust share from 5% to 15% were investigated.
In addition to thrust, it was decided that the APPU unit should also take over the provision of onboard electricity and hydraulic power and bleed air from the main engines. This requires a larger engine core, which in turn allows for a more efficient engine cycle and greater utilisation of the hydrogen-powered component.
The core engine is designed to be capable of burning both H_2 and kerosene, in order to allow operation on kerosene on routes where it is not possible to refuel before flight, if the LH_2 should be depleted due other operational issues or if there is a failure in the hydrogen fuel system.

2.2 Hydrogen tank

The hydrogen is stored in liquid state (LH_2). This requires liquefaction and the associated expenditure of energy on the ground but currently provides the best ratio of tank mass to H_2 mass, at simultaneously high volumetric density [1] [2]. The length of the passenger cabin and the location of the rear bulkhead are not changed when integrating the tank, although the fuselage cross-sections in the tailcone area are changed to increase the available volume.

2.3 Propulsor

There are currently several concepts for ducted rear fuselage BLI[3], but there are currently no established design rules to ensure that drag and losses incurred by integrating such a propulsor don't neutralize a large part of the BLI benefits. At the same time, open rotors may be a way to keep increasing propulsive efficiency without the need to design ever larger turbofan nacelles and deal with the consequences of the associated low fan pressure ratios[4]. There are recent examples of open rotor designs which can operate well within the transonic region [5]. The cruise Mach number of the A321neo, is comparably low, at 0.78. The pressure increase around the fuselage tail cone further reduces local velocities at the propulsor location. This may allow the use of an open rotor as a simple and efficient method of sidestepping the need to design a nacelle with acceptable characteristics at all relevant conditions.
It was thus decided to evaluate the use of an open rotor as the APPU propulsor.

2.4 Other changes

Other changes are kept at a minimum in order to keep as much commonality with the baseline aircraft. This strategy allows easier comparison of performance and efficiency, but also further lowers the threshold to actually design and build an APPU system in the future. The remaining changes to the aircraft are:

- The horizontal tailplane (HTP) is moved onto the vertical tailplane (VTP) to create a cross-tail. This is required in order to remove the HTP trimming mechanism from the tailcone to make space for the LH_2 tank, and to provide additional freedom for reshaping the tailcone. Since the mass distribution and empennage configuration are changing, the tailplane surfaces need to be redesigned as well, in order to fulfil stability and control requirements.

- The wing and all attached components (e.g. main landing gear, engines) is moved backwards to account for the mass of APPU and the LH_2 tank added to the downstream end of the fuselage. This is done by adding a number of fuselage frames in front of the wing and removing the same number behind the wing, keeping the distance between frames constant. This way, there are only minor changes required to the manufacturing process.

- The main engines are *not* changed compared to the baseline. This is due to the fact that the engines on the A321neo are up-rated versions of the engines used on the A320neo. This means that the engine mass, and accordingly pylons, fuel systems etc. do not need to change at all, leading to more commonalities between the new version and the baseline, and simplifying comparisons between them. Moreover, the thrust range of e.g. the CFM LEAP-1A is 107kN to

143kN [6], with the A320neo using versions rated 107kN to 130kN, and the A321neo only using versions rated 143kN [7]. It seems likely that the engine is operating at its highest efficiency near the centre of its thrust range, which would even provide a minor gain in engine efficiency when operating the main engines at a lower thrust setting but maintaining a rating which allows normal operations in case the APPU unit cannot provide thrust.

2.5 Certification and Reliability

It may not necessarily to fully certify the APPU unit as a third engine in the context of ETOPS ratings and for climb-out during critical engine failure. While this option would prevent downsizing the main engines according to the additional thrust provided by the APPU unit, the requirements to reliability for a dual-fuel engine and cryogenic LH_2 tank may require a protracted engineering effort, which can be helped by the experience gained from routine operations of such a unit introduced earlier with less strict requirements. In a scenario where an entire aircraft with APPU unit is designed from the ground up, certification as a third engine allows choosing smaller main engines and reduces engine mass, as well as the provisions that need to be made for incidents of critical engine failure, either of the main engines or the APPU unit. In combination with the ability to run on either kerosene or hydrogen, the new configuration is expected to help keep the risk of implementing both hydrogen and BLI propulsion on an aircraft low.
For this study, it was assumed that the APPU unit is used for the diversion part of the design mission, and that both kerosene and hydrogen can be used as reserve fuel. This means that in case of unavailability of sufficient amounts of H_2, the maximum range may be reduced, unless the permitted maximum take-off mass is increased in order to allow taking more kerosene on board.

3. Methods

The configuration is regarded mainly on a system level, using preliminary the design methods implemented in the in-house tool *Initiator* [8] [9] [10]. This can generate a preliminary aircraft design starting with empirical component mass estimates, wing and thrust loading, and progresses to increasingly accurate methods including a vortex-lattice method solver to regard longitudinal stability and tailplane sizing, and fuselage and wing structural mass estimates based on mechanical load distribution. Initiator was used for all whole-aircraft design tasks in this study. In the component-level detailed analysis, some of Initiator's built-in methods were used separately to estimate component masses and CG locations for a more detailed analysis of the minimal modifications necessary to implement an APPU unit. This investigation was also aided by CAD geometries of the reference aircraft, to investigate the maximum volume which could be used for an LH_2 tank in the aircraft tailcone.

3.1 Pilot Study: Full Redesign

The pilot study regarded a scenario in which the entire aircraft is redesigned following the addition of an APPU unit to the configuration. This represents a best-case scenario, as all components are adapted to the new configuration, as opposed to a retrofit. This was done to inform the work with higher-level methods for the main task of creating a retrofit design. For this study, additional methods for the sizing of LH_2 tanks [11], heat flux for cryogenic tanks were implemented, as well as the ability to use conical tanks with spherical end caps, and to regard two independent drive trains. The hydrogen tank was regarded as a non-integral aluminium pressure vessel located rear of the aft pressure bulkhead (APB). A pressure tank made of carbon fibre composites with a thin aluminium layer to counter diffusion or the use of an integral tank are expected to allow lower overall mass [12] [13] but have not yet been proven for passenger aircraft applications. Similarly, the insulation material was assumed to have a thermal conductivity of $0.01\frac{W}{Km}$. This is well below the performance of conventional insulation foam (0.015 to $0.02\frac{W}{Km}$ at temperatures between 150 and 200K [14]), but over an order of magnitude higher than achievable by high-performance vacuum Multi-Layer Insulation (MLI)[15]. This, too, was done in order to ensure that the resulting solution was feasible also in a scenario where insulation materials which rely on low pressure or vacuum could not be used. The mass of the BLI propulsor was estimated using the built-in method in Initiator for turboprop engines, which is uses a database of known turboprop engines to predict bare engine mass. The APPU engine cycle efficiency was predicted using a statistical model from Raymer[16], based on known turboshaft

engines. The benefit of BLI to propulsive efficiency was calculated based on an actuator disk analogy in potential flow. The method calculates pressure and velocity differentials caused by the propulsor, and computes the resulting changes to friction losses and axial force on a generic fuselage body [17][18].
The study used Initiator to generate am A321-like baseline aircraft using on the A321neo main specifications for payload, cruise condition and mission profile[19], as well as several variations which include APPU unit of varying contribution to overall engine power. The fuel burn analysis for each design uses the method in Initiator [10], which regards a Mach-number-dependent aircraft drag polar and regards climb, cruise, descent as well as diversion flight, to find the required fuel mass at take-off.

3.2 Retrofit scenario

For the retrofit scenario, additional effort was applied to establish the baseline reference aircraft and its individual component masses, to match the available information on the Airbus A321neo more accurately. This was done by using Initiator to approximate the particular version of the A321neo (WV053) in greater detail, manually adjusting some of the component masses, and scaling the resulting dataset to match the known data. This results in a fuel burn estimate for the design mission and the diversion, as well as the Center of Gravity (CG) locations of all aircraft components, including the fuel and payload.
Since Initiator does not allow for manual component-level modifications or additions, the analysis of the modified configurations was conducted using a separate tool which estimates the required changes to aircraft components as well as the expected effects to mission fuel burn, relative to the baseline aircraft.

3.2.1 Baseline Reference

The variant chosen for the study is the WV053 [19, 7], with a maximum take-off mass (m_{TOM}) of 93.5t, 25t maximum payload, 4630km design mission range (with maximum payload and m_{TOM}), and a single-class cabin layout for 220 passengers. The operational empty mass (m_{OE}) of the A321neo WV053 is 50.7t, based on the published masses and payload/range diagrams [19, 7]. The seat pitch, power-specific engine mass and engine cycle efficiency were adjusted in order to better match published data on cabin and fuselage length, main engine mass and design mission fuel mass, respectively. Component and partial masses of the resulting design are shown in table 1. While the dry engine mass, fuel mass for the harmonic mission and fuselage length were directly adapted to replicate the known data, resulting operational mass is within 1% of the known value, indicating that the prediction of the combined mass of other components matches the original aircraft to a good degree. One of the known deviations between the Initiator model and the actual A321neo is the mass

		A321neo, WV053	Initiator result	adjusted baseline
	m_{PM}	25.0	25.0	25.0
	m_{OE}	50.7	50.24	50.7
	m_{TOM}	93.5	93.1	93.5
	m_{ZFM}	75.6	75.24	75.6
component masses (t)	installed engine	?	4.86	4.89
	APU (installed)	0.28 – 0.42	0.33	0.33
	HTP	?	1.08	1.19
	VTP	?	0.38	0.41
	fuselage length (m)	44.51	44.7	44.51
design mission	$m_{F,TO}$(t)	17.83	17.88	17.83
	$m_{F,mis}$(t)	?	16.23	16.19

Table 1 – Known A321neo data compared to the output of the aircraft synthesis process in Initiator, and the adjusted and scaled data used as baseline for this study

of the tailplane, since it was designed for stability and control on the A319 aircraft, which has shorter fuselage and thus requires larger tailplane surfaces than the A321neo. To account for this, the mass of Horizontal Tailplane (HTP) and Vertical Tailplane (VTP) was increased by 10% over the Initiator projection, before scaling all component masses to match the operational empty mass of the original aircraft. Similarly, the fuel fractions for mission and reserve fuel were scaled in order to match the known fuel mass at take-off of the A321neo at maximum payload. This provides the adjusted baseline data shown in table 1, which was used for comparison to the modified versions.

3.2.2 Tank Mass Estimation

One outcome from the pilot study is the dependency of hydrogen tank mass on the required LH_2 capacity. The gravimetric tank efficiency of a tank is defined as the ratio of usable fuel mass to the combined mass of fuel and tank (eq. 1) and is shown for the APPU configuration in Figure 1.

$$\eta_{grav,H_2} = \frac{m_{H_2}}{m_{H_2} + m_{tank}} \tag{1}$$

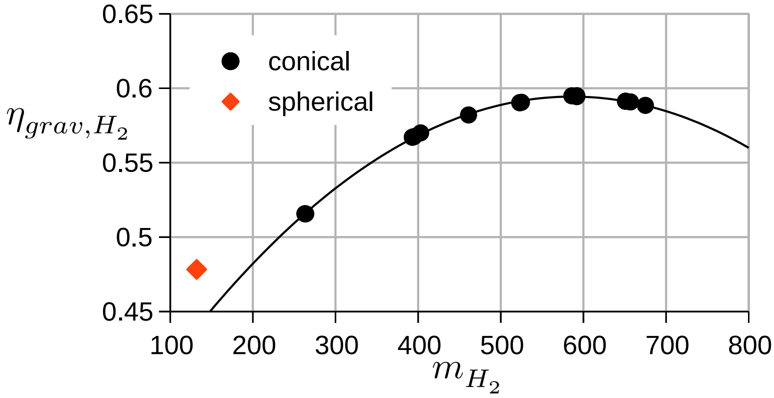

Figure 1 – gravimetric tank efficiency over usable hydrogen mass, for a range of different tank sizes, with tank shape adapted to the fuselage tailcone. For very low capacities, the tank sizing routine switches to spherical shapes, which were ignored for the curve-fit.

The tank loses efficiency when switching from a spherical shape to a truncated cone but then becomes more efficient with increasing size, since the ratio of volume to surface increases, and thus the ratio of insulation material to contents reduces. This trend reverses as the tank size approaches the limit of available volume, and the tank becomes more elongated and fills the narrower parts of the tailcone, which decreases the ratio of volume to surface. The quadratic curve-fit (eq. 2) shown in figure 1 matches the input data for conical tanks with a 1% relative RMSE (Root of Mean Squared Error) and was used to predict the mass of conical tanks in the retrofit study. It should be noted that this equation is specific to the fuselage radius and tailcone shape used for the study.

$$\eta_{grav,H_2} = 0.3353 + 8.862 \cdot 10^{-4} kg^{-1}\ m_{H_2} - 7.574 \cdot 10^{-7} kg^{-2} m_{H_2}^2 \tag{2}$$

3.2.3 APPU Engine Mass Estimate

The mass estimation method for the APPU engine itself was updated after the pilot study, as the integration and operation of this engine corresponds more to an open rotor engine than to a conventional turboprop. Since there are so far only prototypes of open rotor engines in operation, there are no sufficient statistical data on available on these engines for an empirical mass estimate, so several comparative design studies of open rotor engines [20, 21, 22, 23] compared to turbofan engines were used to derive an estimate for a pusher-type open rotor that operates at low transonic Mach numbers. Given the design condition for passenger aircraft like the A320, the sizing thrust requirement for an open rotor is usually at Top of Climb (ToC), due to the significant thrust lapse. Therefore, the equivalency between turbofan and open rotor engines also needs to be established at ToC. Based on the comparative study results, it was concluded that a *Counter-Rotating* Open Rotor (CROR) engine in a pusher configuration can be expected to have a roughly 40% increased mass over an equivalent turbofan engine with equal top-of-climb (ToC) thrust. This mass disadvantage is expected to be reduced for a *single-rotor* engine. Using the mass component breakdown given by Larsson et al. [21], and assuming that a single-rotor setup would require roughly half the gearbox mass (which is still slightly heavier than the equivalent turbofan gearbox), and about two thirds of the propeller mass, since the single remaining propeller would need to be larger and produce more thrust than a single stage of the counter-rotating open rotor. This would give a single pusher open rotor (OR) a mass advantage of about 23.5% over a counter-rotating setup, making it 7% heavier than an equivalent geared turbofan with equal ToC thrust (eq. 3).

$$m_{OR}|_{F_{ToC}} = 0.765\, m_{CROR}|_{F_{ToC}} = 0.765 \cdot 1.40\, m_{GTF}|_{F_{ToC}} \approx 1.07\, m_{GTF}|_{F_{ToC}} \tag{3}$$

The turbofan sizing method in Initiator uses a database relating sea-level static (SLS) thrust to dry engine mass, coupled with equations from Torenbeek [24] for the masses of auxiliary units, fuel system, nacelle, relative to the dry engine mass. For the main engines on the reference aircraft, the total installed engine mass is found to be around 1.7 times the dry engine mass, which matches the mass breakdown by Larsson et al. [21]. In order to generate a simple function to estimate the mass of the APPU unit, the turbofan engine mass estimation in Initiator was replicated using a curve fit of the engine dry mass database, as shown in equation 4. The curve fit for dry engine mass is shown in figure 2.

$$m_{TF,dry} = 26.223kg \left(\frac{F_{N,SLS}}{kN}\right)^{0.936} \tag{4}$$

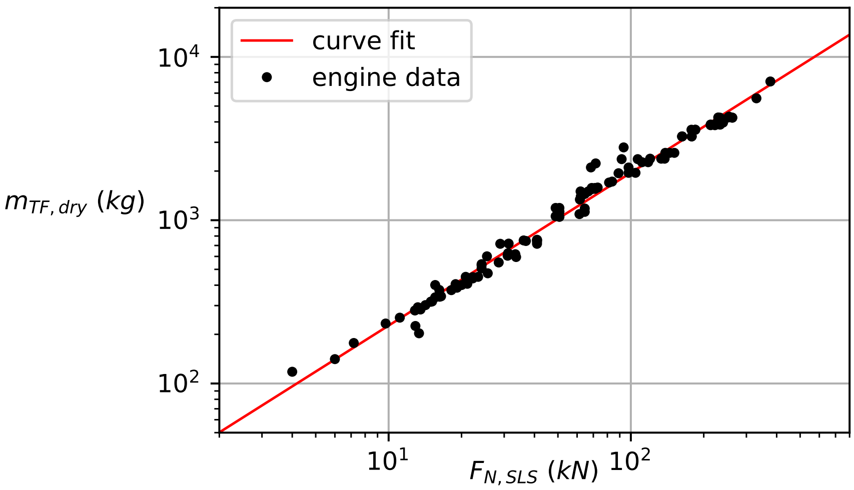

Figure 2 – Known turbofan mass over SLS thrust, and derived power law (RMS of relative fitting error is 11.2%)

Since the SLS thrust of the main engines of the reference aircraft is known (143kN per engine [6]), the mass of an open rotor engine with a given thrust share (Φ_{APPU}) at ToC condition can be derived from the mass of a turbofan engine which provides the same thrust share at take-off. Thrust share is defined as the ratio of APPU thrust contribution to total aircraft thrust, see equation 5.

$$\Phi_{APPU} = \frac{F_{N,APPU}}{F_{N,tot}} \tag{5}$$

However, equation 3 relates to the mass of an equivalent *geared* turbofan but the database does not contain geared turbofans, which are usually heavier than non-geared equivalent turbofans. Based on the data provided by Hendricks [23], a mass penalty of 8.5% for a geared turbofan was assumed, which leads to equation 6, which was used to estimate the mass of the APPU propulsor.

$$m_{TF} = 1.7 \left(26.223kg \left(\frac{F_{N,SLS}}{kN}\right)^{0.936}\right) \cdot 1.085 \cdot 1.07 \tag{6}$$

3.2.4 Tailplane mass estimate

During the modification process, the tailplane needs to be reconfigured to a cruciform, which was found in the pilot study to lead to a mass increase of the VTP of 9.6%, and a mass decrease of 7.9% of the HTP, compared to a fuselage-mounted tailplane designed for the unmodified version. Taking into account that the baseline used in the retrofit study assumes a 10% mass penalty to both HTP and VTP to account for the fact that they are oversized for the A321neo (see section 3.2.1), and assuming that the redesigned tailplane may be specific to the A321appu aircraft, the overall mass reduction over the baseline is estimated to be 5kg for the VTP and 185kg for the HTP. These masses were kept constant for the fuel burn analysis.

3.2.5 Fuel burn analysis

Since early analyses showed that the change to mission fuel burn of the APPU configuration over the reference aircraft was significantly more sensitive to component masses than to APPU engine efficiency, it was elected to regard a simple cruise-only scenario for fuel burn analysis, which assumes a constant $tsfc$ and constant lift-to-drag ratio (L/D). While this is a strong simplification, it the dependency of mission fuel burn on both overall engine efficiency and aircraft mass is almost unchanged compared to a more detailed approach, and allowed focussing work on improved component mass predictions.
The value of (L/D) was based on the average L/D during the design mission, as found for the reference aircraft by Initiator, and is taken as the approximate mean conversion factor from aircraft mass to propulsive work per distance travelled. The $tsfc$ value determines the fuel flow as a function of required thrust, and was adjusted iteratively so that a flight for the design mission range results in the same fuel burn as expected from the A321neo. A second "diversion" segment was added, whose range was adjusted such that all reserve fuel was burned. This process creates a simplified setup which has same same mass and mission fuel burn characteristics for the main mission and the diversion as the reference aircraft derived from the A321neo data and Initiator results.
Starting from this reference scenario, a parametric process was used (see Figure 3), which sizes an APPU engine and tank for a given thrust share, calculates the resulting change to aircraft mass, simulates fuel burn of both kerosene and hydrogen for the reference "cruise" and "diversion" segments, and then iteratively adjusts the amount of kerosene and hydrogen at the start of the mission, as well as LH_2 tank mass, so that all fuel is burned at the end of the "diversion" segment. This process is applied to a range of different thrust share values, and for various other variations of e.g. APPU engine efficiency or mass, in order to test the sensitivity to various design decisions and assumptions.

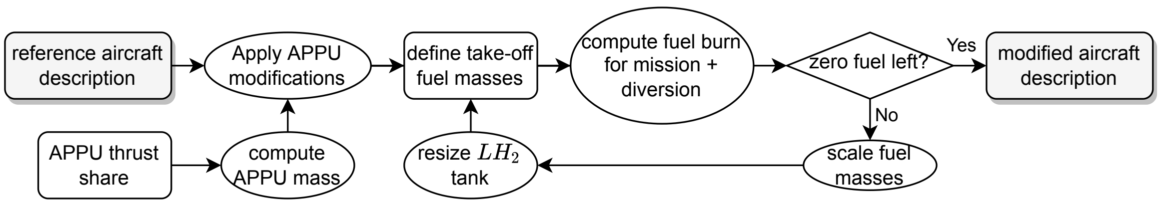

Figure 3 – Flow chart showing the generation of the different APPU aircraft versions

3.2.6 Wing Movement, Geometry Analysis

In order to investigate the possible tail geometries, feasible tank volumes and rotor sizes, a 3D geometry model was created based on published data and sketches [19]. This was used to visualize the changes to the aircraft geometry and to test for viability of the modifications needed to install an APPU unit.
Since the addition of the APPU propulsor and hydrogen tank to the rear of the fuselage affect the aircraft CG, the wing needs to be shifted by some amount in order to ensure that stability and control requirements can be met by the new configuration. This was done by amending data from loading diagrams generated by Initiator for different wing positions on the reference aircraft, and updating the CG according to the added and removed masses and component locations of an APPU configuration

with 10% thrust share, to find a wing location which provides a similar range of Aircraft CG relative to the wing as for the reference aircraft.
The landing gear is positioned relative to the wing, shifting the wing also moves the landing gear closer to the rear of the aircraft. The landing gear position was then used in combination with the maximum permissible take-off rotation angle to define a geometrical constraint for the redesign of the aft fuselage shape and the APPU propulsor location. The take-off rotation angle of the A321neo was estimated to be 12° with uncompressed landing gear [19].
The disk area for the rotor was set to 4.5m^2 for this study, based on conservative estimates of achievable disk area loading at 10% thrust share. A new tailcone geometry was then constructed, using circular cross-sections, such that the volume behind the aft pressure bulkhead (APB) was maximized, while taking into account the constraint for take-off rotation and providing sufficient space to accommodate the rotor, without breaking curvature continuity or creating an exceedingly large a boat-tail angle (20° was chosen as the limit). The resulting geometry was then used to determine the largest tank volume that can be accommodated, and the resulting upper limit to hydrogen storage capacity.

4. Results

4.1 Redesign Pilot Study

The results of the redesign study were mainly used to inform the models used in the main study, but may be used as an indicator for a "best case" scenario, since all components of the APPU-equipped versions are redesigned to take advantage of the presence of the APPU unit. However, since the baseline aircraft was also assumed to be an optimal design, not a modified version of another aircraft, the resulting numbers are under-representing the potential gains, since they ignore e.g. the mass reduction achievable by downsizing the tailplane to match the longer fuselage of the A321neo rather than the A3219 for which it was originally designed.
At the nominal 10% shaft power share, a modest 0.8% (or 400kg) increase in operational empty mass (m_{OE}) is offset by 7.4% (or 1.4t) savings in total fuel mass, due to the 2.8 times higher energy density of hydrogen, leading to a little over 1% reduction on take-off mass (m_{TO}). While the main effect of including the APPU unit on carbon emissions consists of displacing kerosene with hydrogen, the overall energy use is also reduced by about 1.3%, due to the higher efficiency of the APPU unit and the reduction in m_{TO}, leading to a 10.9% reduction of kerosene use, with a 10% shaft power share being provided with hydrogen as fuel.

4.2 Retrofit

The procedure explained in section 3.2.5 was used to estimate the performance of a modified A321neo with an APPU unit This was done for a variable APPU thrust share, as well as for modified assumption, in order to test the sensitivity to uncertainties of the mass and efficiency estimates, and thus to gain some measure of confidence in the benefits of modifying an A321neo with a hydrogen-driven APPU unit. Unless otherwise stated, all fuel burn analyses concern the design mission with full (25t) payload and a range of 4630km, and assume a constant APPU thrust share for the entire flight, including the diversion used to calculate reserve fuel.

4.2.1 Influence of Thrust Share on System Performance

Figure 4 shows the changes to some of the component and fuel masses due to installation of the APPU unit, obtained from the process laid out in section 3.2.5 and figure 3 with a varying thrust share. As thrust share increases, the rate at which kerosene is displaced by hydrogen slightly above the ratio of energy contents of the two fuels (2.8), with $m_{k,tot}$ reducing by 2.9kg for each kg increase of $m_{H_2,tot}$. In contrast to the full redesign scenario, however, the empty mass of the aircraft does increase, by about 1t at a thrust share of 0.1. Although the empty mass is increases almost linearly with APPU thrust share, it is not directly proportional since the tailplane reconfiguration (m_{tp}) and the removal of the APU provide a mass reduction to all APPU configurations, independent of the thrust share. It is also visible that the H_2 tank mass is not proportional to the hydrogen amount that needs to be accommodated, since the gravimetric efficiency is not constant.
At a 10% thrust share, the combined mass of APPU engine and (empty) H_2 tank is 1.6t, but due to the aforementioned beneficial effects, operation empty mass only increases by 1.05t, and the lower

mass of H_2 reduces overall fuel mass, leading to an almost unchanged take-off mass. If thrust share is increased further, the take-off mass does increase over the baseline, by about 240kg at 15% thrust share.

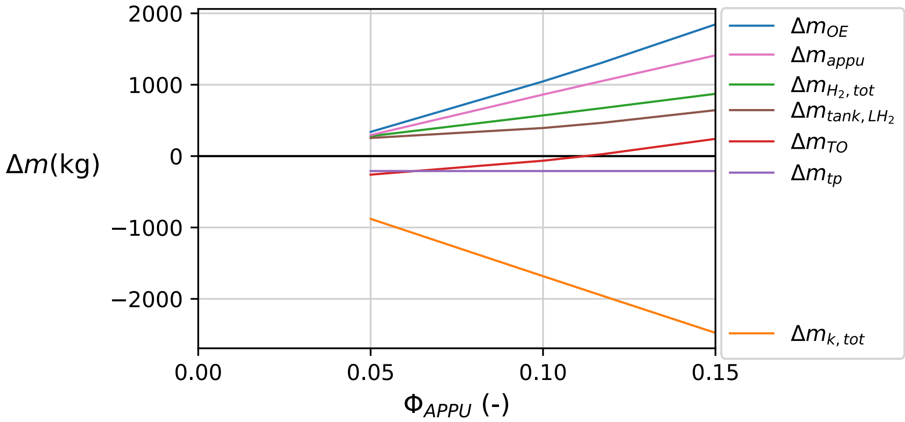

Figure 4 – Estimated change to masses of individual components and fuel at take-off, as a function of APPU thrust share, relative to the masses of the A321neo reference. Δm_{APPU} includes the benefit of removing the APU (327kg) from the reference aircraft

Calculating the energy content of the fuel being used, it is found that with a thrust share between 5% and 10%, the total fuel energy use is reduced by 0.59%. Since m_{OE} is increased for all versions, this is due to the fact that the APPU propulsor can convert fuel to thrust more efficiently than the main engines. This benefit reduces to 0.36% at a thrust share of 15%, due to the increased mass of the aircraft, the reduced gravimetric tank efficiency, and an expected reduction of 3% of the APPU propulsor efficiency.
An additional analysis regarded the the version with 10% thrust share, for a scenario where either hydrogen is not available or the hydrogen fuel system may be damaged, and the aircraft needs to operate on kerosene alone. It was assumed that the LH_2 tank still contains 10% usable hydrogen, in order to prevent complete boil-off during the flight, and that the amount of kerosene on board at take-off is increased accordingly, over the amount needed for regular operations. The outcome showed that the efficiency gain of the APPU unit allows the aircraft to complete such a kerosene-only mission with fuel savings of about 0.3% compared to the unmodified aircraft, but requires an increase of m_{TOM} by about 1t, to 94.5t. Since versions of up to 97.4t m_{TOM} exist [19], this is not expected to require further modifications to the airframe.

4.2.2 Sensitivity Analysis

The results obtained so far rely on several assumptions and simplifications, in particular regarding the achievable efficiency benefit from using a BLI open rotor at a cruise Mach number of 0.78, and the masses of the APPU engine, and the LH_2 tank mass. The absence of established and validated methods for these quantities puts some risk on the derived predictions. It is therefore useful to test the robustness of the outcomes to deviations in efficiency and mass of the APPU system. For this reason, the analysis from shown in section 4.2.1 was repeated with some modifications to the efficiency and mass models.
In the first scenario (figure 5a), it is assumed that the efficiency of the APPU engine is reduced by 14%, at equal engine mass and thrust. This is roughly equivalent to losing the benefit of both BLI and the open rotor propulsive efficiency, giving the APPU engine a disadvantage over the main engines since its cycle efficiency is expected to be about 5% lower than that of the bigger main engines. This is considered to be an unrealistically pessimistic scenario. The main primary effect is that 16% more hydrogen fuel is needed (84kg extra at a 10% thrust share), which requires a bigger LH_2 tank. The increased aircraft mass leads to an increased overall energy requirement and results in 21kg more kerosene being burned and a modest take-off mass increase of 117kg in the case of 10% thrust share. While this is not desirable, the main objective of reducing kerosene burn would be barely affected by this loss of efficiency, despite the very pessimistic assumptions. A more important

consequence of this scenario would be that the APPU thrust share, which is the main determinant of kerosene savings, may be limited if the LH_2 tank capacity cannot be increased to accommodate the larger amounts of hydrogen.

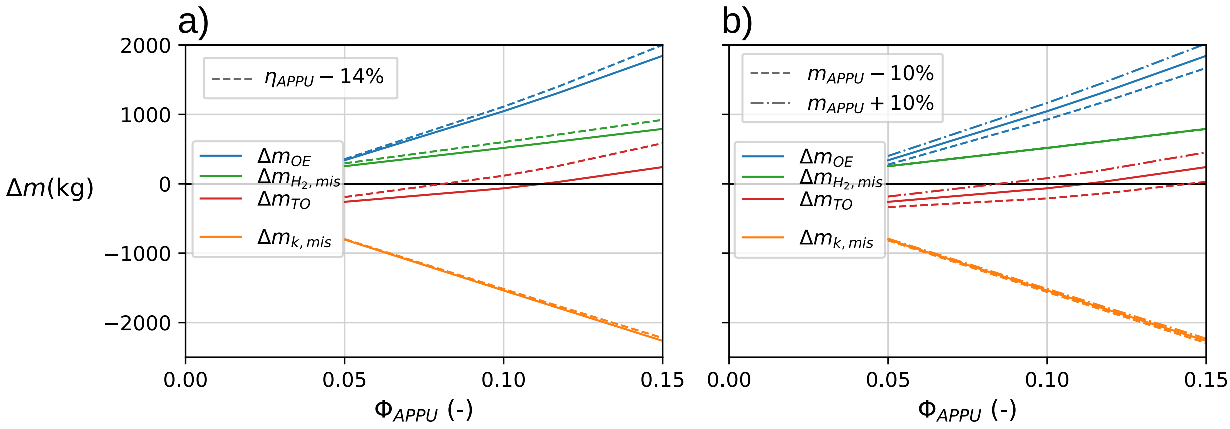

Figure 5 – Sensitivity of the overall aircraft masses and mission fuel burn to APPU efficiency (left), assuming that the engine delivers equal thrust but has increased fuel consumption), and APPU engine mass (right).

In another set of scenarios (figure 5b), a variation of aircraft mass by 10% of the APPU engine mass is shown. Since the mass estimation of the APPU engine is currently based on a small number of theoretical studies of significantly larger engines, and the design of the LH_2 tank and surrounding tail structure is still ongoing, a change to component masses of this magnitude is considered to be plausible. At a thrust share of 10%, the change directly adds or removes 119kg of mass, with fuel masses increasing proportionally, causing 25kg more or less of kerosene to be consumed, a change of 0.15% to the total kerosene burn, but 1.5% of the savings made by introducing the APPU propulsor. The fact that a modest change to component masses has a similar effect on take-off mass and kerosene savings as an exceedingly pessimistic change to APPU efficiency, demonstrates that the mass of the retrofitted system is of significantly higher importance than the efficiency, in terms of determining how well the system is able to reduce CO_2 emissions. The significance of efficiency lies in determining the amount of LH_2 required for operations with a given thrust contribution, which determines fuel costs, and may impose a limit on the thrust share if the required amount of L_2 cannot be accommodated in the tailcone.

4.2.3 Geometry and Maximum Tank Size

Using the component masses for a modified aircraft with a 10% APPU thrust share, a wing movement of two frames (1.22m) was found to be appropriate balance the aircraft CG movement, based on the loading diagrams of the baseline aircraft.

Figure 6 shows the resulting modified geometry for $\Phi_{APPU} = 0.1$, compared to the baseline, including a line indicating the location of the ground at 12° rotation angle during take-off ("tail scrape line"). The boattail angle on the modified version was increased to 20°, in order to provide as much space between the tail scrape line and boattail to accommodate the rotor disk with 4.5m^2 through-flow area. In order to find the maximum feasible tank size, several measures were applied:

- The Aft Pressure Bulkhead (APB) was inverted in place. This does not change the cabin length but aligns its shape better with the curvature of the LH_2 tank. This will likely cause a minor mass increase to the bulkhead.
- The rotor was placed downstream of any HTP and VTP structural elements, in order to avoid structural damage to the tailplane in case of a blade-off event or a rotor disk burst.
- The two spherical caps of the tank are not tangentially continuous to the conical section. This allows filling a larger part of the available volume.

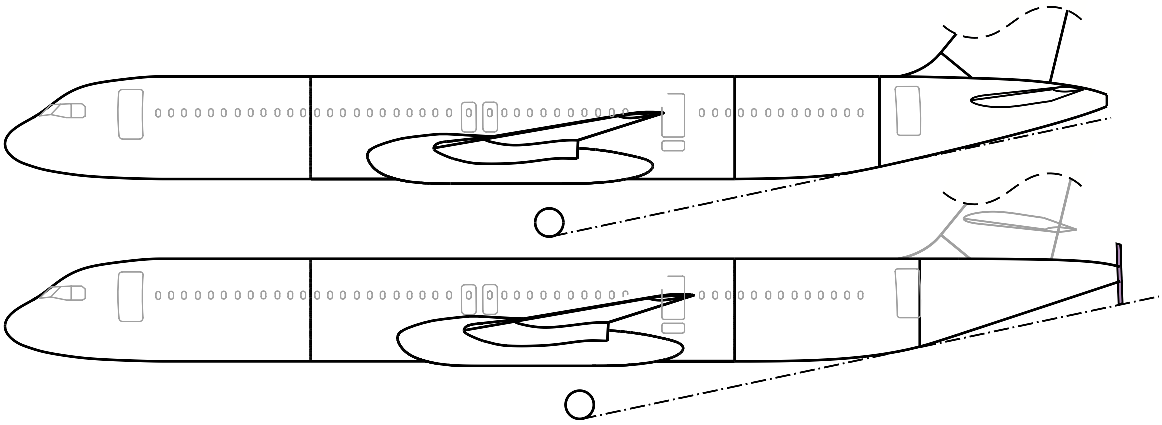

Figure 6 – Sie view of the baseline A321neo (top) and the modified "APPU" version with shifted wing, remodelled tailcone and open rotor (bottom).

- Instead of a separate tank, it was assumed that an integral tank is used, whose conical section also bears the structural loads otherwise carried by the tailcone structure. While this is expected to allow an overall mass reduction [14][11], it also allows for an increased tank volume. The volume of integral tank is therefore more suitable to provide an estimate for the maximum feasible amount of usable H_2 that can be carried.
- The insulation makes use of MLI and LCI materials [15]. Using sufficiently high vacuum, these would permit insulation thicknesses well below 5cm. It is however assumed that additional conventional, non-vacuum layers of insulation are added to insure against loss of vacuum and allow safe and certifiable operations, bringing the total thickness of tank structure, insulation and outer shell to 15cm.

The resulting tail geometry is shown in detail in figure 7, in comparison to the baseline aircraft, and extends the fuselage by about 1m, or 2% of baseline fuselage length. The largest possible internal tank volume was found to be 14.6m^3. It is assumed that 90% of this volume is usable LH_2, the remaining volume being needed for a gas bubble to accommodate pressure changes due to heat ingress of the filled tank, and for residual liquid fuel in the empty state. This results in 13.1m^3 of usable volume, enough for up 930kg of usable LH_2 This is more than needed to support a constant 15% APPU thrust share, which was found to require 870kg of usable hydrogen at take-off, according to figure 4.

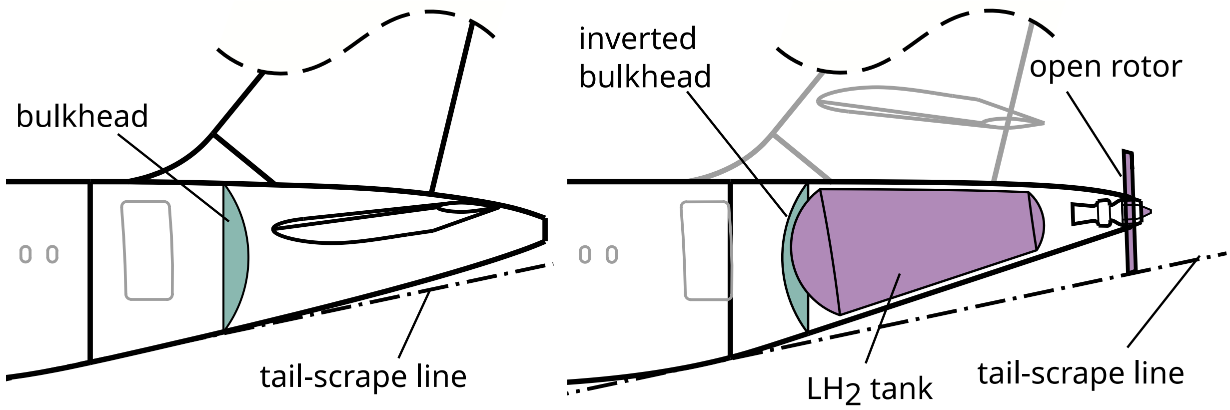

Figure 7 – close-up of the tailcone geometries of the A321neo (left) and the modified version with a 14.6m^3 LH_2 tank (right)

5. Conclusions and Outlook

This study investigates the effect of replacing the APU in an A321neo with an APPU, a hydrogen-driven engine driving a BLI propulsor. The analysis has attempted to make pessimistic assumptions in order to avoid over-estimates of system performance. Remaining uncertainties on the efficiency of an open BLI rotor in transonic flight, cycle efficiency of an APPU engine with a BLI intake and potential mass gains from fuselage reinforcement may lead to a reduction of the currently predicted performance. There are, whoever, several beneficial effects which were not regarded in the current study, such as the mass benefits of using an integral composite tank instead of the non-integral aluminium tank regarded in the study, or using the heat sinking capacity of the liquid hydrogen to improve the APPU engine cycle efficiency. The assumption that the main engines of the baseline aircraft are unchanged is also pessimistic, since updated engines could be downsized to take advantage of the additional thrust provided by the APPU engine.

It is therefore plausible that the potential benefits of the APPU concept predicted in this study are achievable and can likely be exceeded: Even with only the minimal changes to the aircraft necessary to accommodate a hydrogen-driven BLI engine at the tail of the aircraft, the reduction of CO_2 emissions corresponds to about 95% of the thrust share of the new propulsor. This is due to the fact that substitution of kerosene with hydrogen for thrust generation is the main effect observed in the new configuration, and all secondary effects are significantly weaker. As the geometry analysis shows, the amount of kerosene that can be displaced by hydrogen is more likely to be limited by the thrust capability of the open rotor than by the amount of hydrogen which can be accommodated onboard.

Consequently, the efficiency of the APPU engine only has a minor direct influence on CO_2 reduction, despite its significance for operational costs for LH_2 and the range during kerosene-only operations. The latter scenario shows that the APPU efficiency gains (a tsfc reduction of about 11.7% over the main engines) allow it to compensate for the mass added by the modification to the baseline aircraft and achieve the design range without fuel burn increase, even in kerosene-only operations. An outcome of the sensitivity analysis is that a change in mass of the aircraft has a much more significant influence on overall fuel economy than APPU efficiency, and therefore minimisation of component masses and more accurate mass estimates should have high priority during the further development of the APPU concept.

Further work is planned to improve mass estimates, including of the engine and rotor themselves and the structural configuration of the modified aircraft tail, including the potential for implementing an integral LH_2 tank, as well as the effect of the wing shift on fuselage mass, and aerodynamic design and more accurate mass estimate of a cruciform tailplane. It is also planned to investigate how much more kerosene can be displaced by hydrogen if the thrust produced by APPU is maximized at all times during a mission, by conducting a more detailed mission analysis including sfc and thrust lapse maps as well as realistic aircraft drag model. Lastly, a CFD analysis is necessary to more accurately assess the potential benefits of BLI propulsion for the APPU configuration.

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