JET VERSUS PROP, HYDROGEN VERSUS KEROSENE FOR A REGIONAL FREIGHTER AIRCRAFT

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Abstract
This paper describes the design and analysis of four different variants of a regional freighter aircraft on the basis of the ATR72 full freighter version. The variants differ in their type of propulsion system (jet/turboprop) as well as in the fuel they use (kerosene/hydrogen). The presented work has been performed within the scope of the joint aircraft design project “Green Freighter” (GF). The setup of the aircraft models inside the Preliminary Aircraft Design and Optimization program PrADO is shown with special respect to the propulsion systems and the integration of the hydrogen tanks. Afterwards, the resulting aircraft parameters, such as the aircraft masses and the payload-range diagrams, are presented, and the aircraft variants are compared according to their Direct Operating Costs (DOC) and their emissions. In order to integrate two large hydrogen tanks inside the aircraft fuselage it is necessary to stretch the original fuselage. This stretch plus the masses of the hydrogen tanks increase the empty masses of the hydrogen-powered aircraft compared to the kerosene variants by about 8%. From a purely economic point of view, the use of hydrogen as fuel is not favorable at today’s kerosene and an energy equivalent hydrogen price. However, its combustion produces only water vapor and about 10% of the amounts of nitrogen oxides of the kerosene variants as emission. This makes hydrogen favorable from an ecologic point of view, and in the future, these low emissions are expected to become economic benefits as well.

1. INTRODUCTION
1.1. Motivation
Freighter aircraft are becoming an increasingly interesting aircraft market segment. The worldwide air traffic of passengers and cargo has grown significantly over the last decades, and each of the major transport aircraft manufacturers (Airbus, Boeing, ATR, Bombardier and Embraer) expects this growth to continue [1] – [5]. Even today, in the light of the world economic crisis, Embraer states in its Market Outlook 2009–2028 from February 2009 that “Air Travel Demand Will Grow Despite Current Economic Crisis” [5]. The expected annual growth rates over the next two decades lie around 4.9% for passenger transport [1], [3], [5] and even 5.8% for cargo transport [1], [3]. This increasing demand for cargo transport also leads to an increased demand for freighter aircraft. In consequence, “…over the next 20 years, world air cargo traffic will triple compared to current levels, and the number of airplanes in the freighter fleet will double” [6].

“Today, freighters carry an estimated 60% of the world’s revenue cargo...” [6]; the rest is transported in the lower deck compartments of passenger aircraft. Among the freighters, most aircraft are former passenger aircraft that were converted to a freighter after they were decommissioned as passenger aircraft. The rest are new-built aircraft derivatives of passenger aircraft programs like the Airbus A330F or the Boeing B777F. Consequently, all these aircraft were not designed as dedicated freighter aircraft, and the special demands of a freighter were not fully taken into account during their design phase. The results are e.g. the unfavorable usual position of the cargo loading door at the side of the forward fuselage and the fact that cargo containers are shaped in accordance to aircraft fuselage cross sections and not vice versa.

However, it will not be enough to just ramp up production rates of the already available freighter aircraft to tackle future demands. Besides the pure need for more cargo capacity and more freighter aircraft, aviation in general faces increasing challenges of various kinds: economic, ecologic, social and political:

- Airline business and the competition between airlines are getting increasingly intense. “Over the past two decades, freight yields have declined at an average rate of 3.0% per year” [6].
- The global climate is warming, and there is “…very high confidence that the globally averaged net effect of human activities since 1750 has been one of warming…” [7]. In 1999 the Intergovernmental Panel on Climate Change (IPCC) stated in its special report “Aviation and the Global Atmosphere” [8] that “the best estimate of the radiative forcing in 1992 by aircraft is … about 3.5% of the total radiative forcing by all anthropogenic activities... Aircraft contribute to global change approximately in proportion to their contribution to radiative forcing.”
- The growing public awareness of the climate change and a growing general environmental consciousness are drastically changing the public perception of aviation. Statements like those of the bishop of London, Richard Chartres, from 2006 that “making selfish choices such as flying on holiday … [is] a symptom of sin” [9] and the German non-governmental organization (NGO) Germanwatch from 2003 that “flying is – relating to expenditure of time – the most climate-
damaging legal activity a person can perform during peacetime" [10] are indicators as well as reinforcers of an aviation-critical public attitude.

- Noise abatement procedures are being applied at an increasing number of airports [11]. Especially nighttime operational restrictions have large influence on the logistics companies as 66 % of all flights of freighter aircraft (in Germany) take place between 22:00 h and 06:00 h in order to deliver e.g. express freight during the office hours [12].

- In July 2008, the European parliament decided to include aviation into the emissions trading scheme of the European Union for CO2 from 2012 on [13].

- The world’s crude oil resources are limited. Nevertheless, in the course of the growing world economy, the worldwide energy demand is growing, and among the consequences are rising energy and fuel prices. Consequently, "... in the foreseeable future, crude oil will no longer be able to accommodate demand; therefore, in the light of the long time period needed for a conversion of the energy sector, it is already necessary today to search for alternatives for crude oil" [14).

In summary, "in the longer term, the continuing growth of civil aviation is unsustainable given current technologies and operating systems" [15].

In view of the enormous challenges posed to the aviation industry at the beginning of the 21st century, the Advisory Council for Aeronautics Research in Europe (ACARE) set up the "Vision 2020"-called "agenda for the European Aeronautics’ ambition" [16] in 2001. This agenda defines the two European top-level goals of "meeting society’s needs and winning global leadership" [16]. Examples of direct aims of the Vision 2020 are reductions of the number of accidents in air transport by 80 % and of the air transport costs by 30%. On the environmental side, among the aims are reductions of noise emissions by 50 %, CO2 of 50 % and NOx of 80 %.

Freighter aircraft could be an appropriate means to validate and introduce the required new technologies to usher in "The Age of Sustainable Growth" [17] in aviation. They could e.g. act as demonstrators for technologies like unmanned operation of transport aircraft, the use of hydrogen as fuel or for new unconventional aircraft configurations like the Blended Wing Body (BWB). The X-48B for example, a model of a BWB aircraft which is currently being flight tested by Boeing, the NASA and the US Air Force Research Laboratory (AFRL), is also intended as a step towards a BWB freighter aircraft [18].

1.2. The Green Freighter Project

The three-year joint research project "Green Freighter" was launched in December 2006 and is partly funded by the German Federal Ministry of Education and Research (BMBF). Its project partners are the Hamburg University of Applied Sciences (HAW Hamburg), the Institute of Aircraft Design and Lightweight Structures (IFL) of the Technical University of Braunschweig, the Airbus Future Projects Office (FPO) and the SME (Small and Medium Enterprises) Bishop GmbH – an engineering office. The main project objective is to investigate unconventional short- and long-range freighter aircraft with special respect to environmentally friendly and economic aircraft operation [19]. In this context, ‘unconventional’ means unconven-
1.3. Fuels

1.3.1. Hydrocarbons

Today’s aviation fuels, usually referred to by the umbrella term ‘kerosene’, are based on petroleum and therefore crude oil. Current developments towards alternative fuels most often aim at drop-in replacements, which means that they can be used as blends or purely in existing engines. The most important ones are GTL (gas-to-liquid), CTL (coal-to-liquid) and BTL (bio-to-liquid). Those fuels have in common that they are synthetically derived liquid fuels from a different feedstock than crude oil – usually by means of the so-called Fischer-Tropsch process. Thus, they are also referred to as ‘FT-fuels’. Though alternatives to conventional kerosene in the sense that they do not depend on crude oil as the sole raw material, GTL- and CTL-fuels are still fossil fuels. Only BTL fuels represent a possibility to be an alternative in the sense of being ‘climate neutral’ if environmentally friendly produced [23].

Within the scope of the Green Freighter project, FT-fuels are not investigated as separate fuel options. They are included in the fuel option ‘kerosene’ as potential environmental benefits would be caused by the production process and not by their application as fuel in an aircraft.

A typical energy content for kerosene is 42.8 MJ/kg, its density lies between 775 kg/m³ and 840 kg/m³ at 15 °C [24]. The combustion of 1 kg of kerosene uses 3.4 kg of aerial oxygen and produces 3.15 kg of carbon dioxide (CO₂), 1.25 kg of water vapor (H₂O) plus several other substances of lower – but not negligible – quantity:

- Nitrogen oxides (NOₓ): about 14 g,
- Sulfur oxides (SOₓ): about 1 g,
- Carbon monoxide (CO): about 3.7 g,
- Unburned hydrocarbons (UHC): about 1.3 g and
- Soot: about 0.04 g [25].

The exact amounts of these reaction by-products depend highly on the type and technology level of the engine and on the specific fuel used (e.g. sulfur content).

1.3.2. Hydrogen

The application of hydrogen as aviation fuel has been the subject of previous studies like e.g. the European “Cryoplane” project under Airbus leadership [26]. Hydrogen has an energy content of 122.8 MJ/kg and a density of 70.8 kg/m³ in liquid state [27]. The combustion of 1 kg of hydrogen produces 9 kg of water vapor and – dependant on the engine – about 4.3 g of NOₓ [28]. Hence, compared to the energy content of 1 kg of kerosene, the combustion of an energy-equivalent amount of hydrogen generates only 3.24 kg of water vapor and about 1.5 g of nitrogen oxides. The mass of liquid hydrogen is only about one third of the one of kerosene. On the other hand, the storage of liquid hydrogen requires an about four times greater volume, and the hydrogen has to be cooled down to -253 °C (-423 °F) to be available in liquid state (LH₂). Of course, such a low temperature poses high demands on the thermal tank insulation and requires special fuel system components that are able to operate under such thermal conditions.

When dealing with hydrogen as fuel it is important to be aware that hydrogen is not a fuel in the sense of an energy source like e.g. crude oil. In fact it is an energy carrier, rather comparable to a battery. Hydrogen does not exist in pure state in nature but has to be separated under the expense of energy first, and only parts of this energy can be retrieved during its use afterwards. “More than ninety percent of hydrogen produced today is generated by reforming natural gas […] into hydrogen and carbon dioxide. While meeting today’s industrial hydrogen demands, the overall efficiency of this process for the production of transportation fuels should be questioned as it basically converts one fuel into another and generates carbon dioxide, a greenhouse gas” [29]. Another method to produce pure hydrogen is the so-called electrolysis. Here, water is split up into hydrogen and oxygen by means of electricity. The hydrogen produced in this way offers the potential of extremely low emissions over the whole ‘well-to-wing’ chain – if the electricity is generated from renewable energy.

At first glance, having almost only water as combustion emission of an aircraft appears perfect. However, there is a difference between the climate impact of the emissions of terrestrial applications like cars and those of aircraft. The emission of water vapor may lead under certain atmospheric conditions to the formation of contrails and in their further development to cirrus clouds. The influences of contrails and cirrus clouds on the global climate change are not fully understood yet, but the general tendency is that they enforce global warming [30]. In this context, the combustion of hydrogen has, compared to kerosene, the beneficial property that no soot particles are being pro-
duced that could act as condensation nuclei. Moreover, in the special case of the here regarded regional aircraft, the water vapor emissions have a smaller climate impact than those of longer range aircraft due to the relatively low cruise altitude of less than 8 km. Contrails usually only form above this altitude [31].

“Safe handling of hydrogen is no longer a problem in the industrial and commercial area” [27]. Especially the gaseous state at ambient atmospheric conditions is advantageous: in the event of a leakage and/or fire, it evaporates and rises away quickly and does not form a (burning) carpet like kerosene. Nevertheless, many people raise safety concerns over the use of hydrogen. These concerns are e.g. caused by pictures of the disaster of the airship “Hindenburg” in 1937 in which 36 people died. This public fear or, at least, skepticism towards the use of hydrogen as fuel represents an important psychological factor that has to be taken into account when assessing an introduction of hydrogen as aviation fuel. Here, freighter aircraft may act as demonstrators to develop confidence.

2. DESCRIPTION OF THE SHORT-RANGE AIRCRAFT VARIANTS

The investigation of four different aircraft variants is being presented in this report. The baseline aircraft is the ATR 72 full freighter version. The variants differ in their type of propulsion system (jet- versus propeller-driven) and in the fuel they use (kerosene- versus hydrogen-powered). FIG 4 shows the resulting aircraft variants matrix.

2.1. Original ATR 72 Full Freighter Version

The ATR 72 is typically used as a feeder aircraft to transport cargo between regional airports and to and from hubs. It is 27.2 m long, 7.5 m high, and has a wingspan of 27 m. It is built in high wing/T-tail configuration. Its wing is unswept, has a double-trapezoid planform with rectangular center section and an aspect ratio of 12. Most of the secondary aircraft structure plus the outer wings, the fin and the tailplane structure are manufactured from composite materials, summing up to 19 % of the overall structural mass [32]. The freighter version has an operating empty mass of 11.9 t, a maximum take-off mass of 22 t and is equipped with a 2.95 m wide and 1.8 m high (116” x 71”) cargo door behind the flight deck. It has a range at maximum payload (8625 kg including seven LD3 containers of 76 kg each) of 963 km (520 NM) under typical operational conditions (see below) [33]. The aircraft is equipped with two Pratt & Whitney Canada PW127F turboprop engines driving Hamilton Sundstrand HS568F six-blade propellers.

2.2. Fuselage Models and Hydrogen Tank Integration

The geometry of the airframe is kept as close to the original ATR 72 as possible. Therefore, in case of the kerosene versions, the geometry is widely the same as the one of the original. In case of the hydrogen versions, however, a lot of cargo volume would have to be sacrificed for internal tank volume if external tanks shall be avoided. The thickness of the hydrogen tank insulation is estimated to be 12 cm; the mass of the hydrogen tank insulation and structure is estimated to be 10 kg/m² (following Böhm [34]). A more extensive investigation of the properties of different types of internal and external hydrogen tanks is currently in progress at the HAW Hamburg.

In case of the hydrogen variants, the fuselage is stretched by 3.8 m to accommodate two large cylindrical hydrogen tanks internally (see FIG 5). One tank is installed in front of the cargo compartment and one behind it. The wings are not used to store fuel. The large thickness of the hydrogen tank insulation would either cause one very flat and therefore pressure-unfavorable tank or many very small cylindrical tanks with a very large total area. Both alternatives

![FIG 4. Aircraft Variants Matrix](image-url)
would bring too little additional fuel capacity to justify the high complexity and mass of such tank installations.

FIG 5. Original Versus Stretched Fuselage
Without any further changes to the aircraft the large cargo door in its initial position in the forward fuselage would be obstructed by the forward hydrogen tank. Therefore, the door positions are switched: the large cargo door is moved to the aft and the small one is installed in the entrance area behind the flight deck. The entrance area and the cargo compartment are connected by a channel alongside the forward hydrogen tank to allow for accessibility of the cargo compartment (see FIG 6).

FIG 6. Integration of Forward Hydrogen Tank and Entrance Area

2.3. Jet Propulsion System

The PrADO engine model for the jet variants is based on the General Electric CF34 turbofan family with the CF34-3B1 as the baseline engine. In order to verify the engine model, the CF34-3B1 has been re-modeled and successively refined as a fixed engine. For this purpose, the engine’s properties like

- Mass,
- Specific fuel consumption (SFC),
- Geometry (dimensions, no. of compressor and turbine stages, etc),
- Air mass flow, etc.

have been constantly checked against the real engine’s data taken from Rolls-Royce [35]. The main characteristics of the CF34-3B1 are listed in TAB 1; FIG 7 depicts a section view of the engine.

After the verification process has been finished, the engine models are treated as so-called ‘rubber engines’. This means that the engines are adapted and sized by PrADO according to the resulting thrust requirement and operating condition of each aircraft variant.

TAB 1. CF34-3B1 Engine Data [35] – [37]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Original</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take-off thrust (ISA, SL)</td>
<td>38.8 kN</td>
<td>38.8 kN</td>
</tr>
<tr>
<td>Bypass ratio (BPR)</td>
<td>6.25</td>
<td>6.25</td>
</tr>
<tr>
<td>Overall pressure ratio (OPR)</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>Stages*</td>
<td>Fan, 14 HPC, 2 HPT, 4 LPT</td>
<td>Fan, 14 HPC, 2 HPT, 4 LPT</td>
</tr>
<tr>
<td>Mass</td>
<td>757 kg</td>
<td>751 kg</td>
</tr>
</tbody>
</table>

* Note: The numbers of compressor and turbine stages are not given as input data but are a result of the sizing process!

FIG 7. Geometry Model of the GE CF34-3B1 Turbofan Engine

2.4. Propeller Propulsion System

The baseline engine for the turboprop aircraft variants is the original engine of the ATR72, the Pratt & Whitney Canada PW127F. Its main characteristics as well as those of the original Hamilton Sundstrand propeller HS 568F are listed in TAB 2. A picture of the turboprop propulsion system is shown in FIG 8.

TAB 2. PW127F Engine and HS 568F Propeller Data [35], [38], [39]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Original</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take-off shaft power (ISA, SL)</td>
<td>2750 hp (38.5 kN)</td>
<td></td>
</tr>
<tr>
<td>Stages*</td>
<td>Prop, 1 LPC, 1 HPC, 1 HPT, 2 LPT, 2 PT</td>
<td>Prop, 1 LPC, 1 HPC, 1 HPT, 2 LPT, 2 PT</td>
</tr>
<tr>
<td>Mass: Engine Propeller</td>
<td>481 kg 169 kg</td>
<td>516 kg 169 kg**</td>
</tr>
</tbody>
</table>

* Note: The numbers of compressor and turbine stages are not given as input data but are a result of the sizing process!

** Input data
and the development of the propeller efficiency over Mach number have first to be defined and stored in a template file. During the following design process, this data is loaded into the program and is kept constant throughout all iteration steps even if the engine size is adapted to the thrust requirements of the present aircraft layout. In case of large changes to the thrust requirement and engine size, this may lead to unrealistic geometric outputs, and a new propeller would have to be chosen and added by hand.

The total thrust of a turboprop engine is not only produced by the propeller, but the core engine adds thrust in the order of about 10%. It follows:

1. \( T_{total} = T_{prop} + T_{core\_eng} \), with

2. \( T_{prop} = \eta_{prop} \frac{P_{prop}}{V_\infty} \) and

3. \( P_{prop} = \eta_{shaft} \eta_{gear} P_{LPT} \).

### 3.2. Description of the PrADO DOC Module

For the economic assessment of civil aircraft designs it is commonplace to look at the so-called Direct Operating Costs (DOC). They "... include the total operating costs of the aircraft. ... By definition, DOC methods contain only the aircraft-related costs" [41]. Throughout aviation business, there are many DOC methods of different aircraft operators, airline associations and aircraft manufacturers in use that differ slightly in the cost elements they comprise. The calculation method applied inside the DOC module of PrADO [42] has been developed at the IFL and is mostly geared to the calculation methods applied by Lufthansa, the Association of European Airlines (AEA) and the method described in Roskam VIII [43] (based on the method of the Air Transport Association of America (ATA)). It determines the so-called DOC parameter, \( C_{DOC} \), which describes the relation of all costs that are directly related to the operation of the aircraft over its total time in operation \( \sum C \) to the totally performed transport work \( \sum W_T \). It is expressed in the unit 'Euro per ton-kilometer' \( \frac{\text{€}}{\text{t km}} \):

4. \( C_{DOC} = \frac{\text{Costs}}{\text{Transport Work}} = \frac{\sum C}{\sum W_T} \left[ \frac{\text{€}}{\text{t km}} \right] \).

In this equation, the costs are made up of the six cost elements for aircraft depreciation, insurance, fuel, maintenance, crew and fees:

5. \( \sum C = C_{\text{depreciation}} + C_{\text{insurance}} + C_{\text{fuel}} + C_{\text{maintenance}} + C_{\text{crew}} + C_{\text{fees}} \left[ \text{€} \right] \).

For a freighter aircraft, the transport work is calculated as the product of the average amount of cargo per flight \( m_c \), the number of flights per year \( n_{f,a} \), the number of years of the aircraft in operation \( n_y \) and the reference flight range \( R \):
3.3. Input Data

During the design investigations all aircraft and cost parameters are kept the same for all four variants. Consequently, all later differences in aircraft properties as well as their economic and environmental performances result from the different fuels used. The standard input values for DOC calculation using PrADO are listed in TAB 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual aircraft availability</td>
<td>4198 h/a</td>
</tr>
<tr>
<td>Turnaround time</td>
<td>0.75 h</td>
</tr>
<tr>
<td>Number of years in operation</td>
<td>14 a</td>
</tr>
<tr>
<td>Specific Component costs:</td>
<td></td>
</tr>
<tr>
<td>Airframe and systems</td>
<td>757,223 €/kg</td>
</tr>
<tr>
<td>Engine</td>
<td>24,337 €/N</td>
</tr>
<tr>
<td>Spare parts costs</td>
<td>15 % of a/c price</td>
</tr>
<tr>
<td>Annual insurance costs</td>
<td>1 % of a/c price</td>
</tr>
<tr>
<td>Interest rate</td>
<td>8%</td>
</tr>
<tr>
<td>Residual value</td>
<td>15 % of a/c price</td>
</tr>
<tr>
<td>Fuel price:</td>
<td></td>
</tr>
<tr>
<td>Kerosene</td>
<td>0.5 €/kg</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>1.5 €/kg</td>
</tr>
<tr>
<td>Number of pilots per crew</td>
<td>2</td>
</tr>
<tr>
<td>Number of crews per aircraft</td>
<td>6</td>
</tr>
<tr>
<td>Crew costs (pilots)*</td>
<td>30,667 €/flight h</td>
</tr>
<tr>
<td>Maintenance costs:</td>
<td></td>
</tr>
<tr>
<td>Airframe and systems</td>
<td>255.65 €/flight hour</td>
</tr>
<tr>
<td>Engines</td>
<td>102.26 €/flight hour and engine</td>
</tr>
<tr>
<td>Landing fees</td>
<td>8.69 €/t (MTOW)</td>
</tr>
<tr>
<td>Ground handling fees</td>
<td>40,903 €/t cargo</td>
</tr>
</tbody>
</table>

* Crew costs for each pilot of all crews per flight hour

The prices for kerosene and hydrogen are chosen to be equivalent to their specific content of energy. Consequently, the price for 1 kg of hydrogen (122.8 MJ/kg) is three times the price of 1 kg of kerosene (42.8 MJ/kg). The kerosene price is taken as 0.5 €/kg, which corresponds to the average value at the end of 2008 [44].

The reference mission for the presented investigations is the mission ‘flight at maximum payload’ of the original ATR 72 full freighter version. It is defined by the following mission requirements listed in TAB 4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net payload</td>
<td>8093 kg</td>
</tr>
<tr>
<td>Range at max. payload</td>
<td>963 km (520 NM)</td>
</tr>
<tr>
<td>Cruise Mach number</td>
<td>0.4</td>
</tr>
<tr>
<td>Cruise altitude (beginning of cruise)</td>
<td>6 km (FL 200)</td>
</tr>
<tr>
<td>Distance to alternate airport</td>
<td>161 km (87 NM)</td>
</tr>
<tr>
<td>Loiter time</td>
<td>045 min</td>
</tr>
<tr>
<td>Engine size</td>
<td>not fixed, ‘rubber engine’</td>
</tr>
</tbody>
</table>

4. RESULTS

The most obvious visible result of a conversion of the reference kerosene aircraft variants to hydrogen is the 14 % longer fuselage. Moreover, the door positions have to be switched, and two large hydrogen tanks have to be integrated inside the fuselage. The installation of these large tanks decreases the available cargo volume by the bulk cargo volume of 11.7 m$^3$ from 75.5 m$^3$ to 63.8 m$^3$ [33], which is disadvantageous for cargo of less density like e.g. parcels. However, the minimum average cargo density to achieve the maximum payload of 8093 kg results as 127 kg/m$^3$, which is still well below the average cargo density of 160 kg/m$^3$ [41].

4.1. Aircraft Masses and Required Thrust

The total dimensions and mass properties of the liquid hydrogen tanks are collected in TAB 5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel volume</td>
<td>11.7 m$^3$</td>
</tr>
<tr>
<td>Fuel mass</td>
<td>833 kg</td>
</tr>
<tr>
<td>Tank surface</td>
<td>34.8 m$^2$</td>
</tr>
<tr>
<td>Tank mass</td>
<td>348 kg</td>
</tr>
</tbody>
</table>

The additional installation of hydrogen tanks in combination with the required fuselage stretch increases the operating empty mass of the hydrogen variants significantly. Both hydrogen variants are in the order of 8 % heavier, of which only about 3 % are caused by the tanks themselves. In contrast, the maximum take-off masses of the hydrogen variants are about 2 % smaller than those of the kerosene variants. The reason for that is the much lower density of...
the liquid hydrogen. For the current reference mission the required amount of hydrogen weighs only about 35% of the amount of required kerosene. TAB 6 shows the results of the various aircraft masses and the consequential aircraft thrust requirements.

TAB 6. Mass and Thrust Comparison of ATR 72 Kerosene/Hydrogen and Jet/Propeller Variants

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Kerosene Jet</th>
<th>Kerosene Prop</th>
<th>LH₂ Jet</th>
<th>LH₂ Prop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating empty mass [t]</td>
<td>12.7</td>
<td>12.1</td>
<td>13.7</td>
<td>13.1</td>
</tr>
<tr>
<td>Maximum take-off mass [t]</td>
<td>23.2</td>
<td>22.2</td>
<td>22.7</td>
<td>21.8</td>
</tr>
<tr>
<td>Engine mass [kg]</td>
<td>805</td>
<td>510</td>
<td>791</td>
<td>552</td>
</tr>
<tr>
<td>Maximum take-off thrust [kN]</td>
<td>40.9</td>
<td>(38.3)*</td>
<td>41.3</td>
<td>(38.4)*</td>
</tr>
<tr>
<td>Specific fuel consumption (cruise) [mg/(Ns)]</td>
<td>17.8</td>
<td>(13.7)*</td>
<td>6.2</td>
<td>(4.7)*</td>
</tr>
</tbody>
</table>

* See Section 3.1 for explanation

Strikingly, the engine thrust of the hydrogen variants is larger than that of the respective kerosene variants, although the hydrogen variants have a lower maximum take-off mass. The explanation for this is the higher operating empty mass, and consequently, landing mass of the hydrogen aircraft. The higher mass significantly increases the necessary thrust to fulfill the certification requirement for a minimum climb gradient after a missed approach.

Payload-Range Diagrams

FIG 9 shows the payload-range diagrams of all four aircraft variants as well as the one of the original ATR 72.

It becomes apparent that both hydrogen variants have significantly smaller ranges beyond the point ‘flight at maximum payload’. The ‘range at maximum fuel’ of the hydrogen-powered jet variant is furthermore the same as the ‘range at maximum payload’. In case of the hydrogen-powered propeller variant it is noteworthy that a very small reduction of payload leads to a considerable increase of the possible range. Moreover, both jet-driven variants reach only about 80% of the propeller variants’ ferry range.

4.2. Direct Operating Costs

TAB 7 holds the calculated DOC parameters of the different aircraft variants. It becomes obvious that the direct operating costs of the propeller variants lie significantly below those of the jet versions. The differences are in the region of about 10%. The Direct Operating Costs of the hydrogen variants are about 2% to 3% higher as those of the kerosene-powered aircraft. Thus, from a purely economic point of view, it is not favorable to use liquid hydrogen as fuel under the given circumstances – especially energy costs.

TAB 7. Comparison of Direct Operating Costs at Reference Mission (Flight at maximum Payload)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Kerosene Jet</th>
<th>Kerosene Prop</th>
<th>LH₂ Jet</th>
<th>LH₂ Prop</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDOC [€/tkm]</td>
<td>0.540</td>
<td>0.486</td>
<td>0.556</td>
<td>0.493</td>
</tr>
</tbody>
</table>

4.3. Emissions

The numbers for energy consumption and generated emissions of the four aircraft variants are given in TAB 8.

Most noticeable, the jet variants consume about 30% more energy than the propeller variants and, in consequence, generate more emissions in the same order of magnitude. Furthermore, the energy consumption of the hydrogen-powered jet variant is calculated as about 3% larger than the one of the kerosene variant. In case of the propeller variants, it is the opposite: the kerosene aircraft uses about 5% more energy.

Of course, the hydrogen variants do not produce any carbon dioxide. Moreover, their amounts of generated NOₓ account for only about 10% of those of the kerosene variants. Their amounts of emitted water vapor are about 2.5 times larger than those of the kerosene variants. However, at this cruise altitude of 6 km contrails or cirrus clouds do not form.
Tab 8. Comparison of Energy Consumptions and Emissions at Reference Mission (Flight at maximum Payload)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Kerosene</th>
<th>Jet</th>
<th>Kerosene</th>
<th>LH2</th>
<th>Jet</th>
<th>LH2</th>
<th>Prop</th>
<th>Prop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total fuel consumption [t]</td>
<td>2.43</td>
<td>1.97</td>
<td>0.88</td>
<td>0.65</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total energy consumption [GJ]</td>
<td>104</td>
<td>84</td>
<td>107</td>
<td>80</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generated CO2 [t]</td>
<td>7.7</td>
<td>6.2</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generated water vapor [t]</td>
<td>3.0</td>
<td>2.5</td>
<td>7.9</td>
<td>5.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generated NOx [kg]</td>
<td>34.0</td>
<td>27.6</td>
<td>3.8</td>
<td>2.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5. DISCUSSION

The presented results mark a solid base for the comparison of conventional and hydrogen-powered freighter aircraft. The PrADO-analyses show well the general trends of the operation of such aircraft. However, the current propeller engine models are substitutes for the real engines with radial compressors and reverse-flow combustion chambers. Furthermore, these propeller engine models are two of the very first ones to be modeled inside PrADO at all. Hence, it is still desirable to increase the model accuracy especially concerning thermodynamics and propeller efficiency estimation to increase confidence.

It becomes apparent that the jet variants are disadvantaged compared to their competitive propeller variants. Their energy consumptions are larger, and their Direct Operating Costs are higher as well. The reason for that is the comparison of the four variants under exactly the original ATR 72’s operational conditions, which are at relatively low cruise Mach number of 0.4 and low cruise altitude of 6 km. This favors the propeller variants due to the different performances of jet and propeller engines over Mach number. As a future step, it is therefore advisable to vary the mission requirements ‘Mach number’ and ‘cruise altitude’ for each aircraft variant and conduct a set of parameter variations to find the optimum solution for each variant.

FIG 10 shows the general development of the Direct Operating Costs of a jet aircraft over cruise Mach number at different altitudes. In comparison, FIG 11 shows the development of the total fuel consumption (fuel mass) of the same aircraft as in FIG 10. Both Figures have been created by means of a parameter variation of a kerosene-powered, jet-driven ATR 72 variant.

It can be seen that the minimum value of the Direct Operating Costs is reached at significantly higher cruise Mach number than 0.4. The explanation for this development is the higher utilization of the aircraft, which means that if the aircraft flies faster, more flights can be conducted and more cargo may be transported. Consequently, cost elements like depreciation and insurance are being distributed over more flights, which reduces the Direct Operating Costs per ton-kilometer.

FIG 10. Development of the Direct Operating Costs of the ATR 72 Kerosene/Jet Variant over Mach Number and Altitude

FIG 11. Development of the Fuel Consumption of the ATR 72 Kerosene/Jet Variant over Mach Number and Altitude

In contrast to the DOC, the fuel consumption — and emissions in consequence — increase with rising Mach number. These two oppositional trends in Figures 10 and 11 show clearly the basic discrepancy between the requirements for low costs and low emissions. Low emissions require a lower cruise speed and cause higher costs.

For future aircraft this means that if low emissions shall be beneficial in terms of costs as well, the economic circumstances have to change considerably. Examples to achieve such circumstances are a significant increase in the price for fuel and energy in general or to penalize large fuel consumption in a different way (e.g. by an emissions
trading scheme). However, if rising energy prices lead to higher cargo (and ticket) fares the affordability of air cargo and traffic might be limited to rich people and countries again, like decades ago. Besides the social effects, such development could harm the development of worldwide aviation.

In the case of a hydrogen-powered aircraft a trade-off between payload and range as in the case of kerosene-powered aircraft is no longer reasonable. Due to the low density of the liquid hydrogen, the line between the points ‘range at maximum payload’ and ‘range at maximum fuel’ in the payload-range diagram runs very flat. So, looking at the point ‘range at maximum fuel’ a move towards maximum payload would only bring a very small increase in payload while sacrificing much range and carrying all the necessary tank (and fuselage) structure for the integration of the large hydrogen volume. For hydrogen aircraft it is therefore more advisable to define one maximum range and one maximum payload and to design an aircraft that is able to fulfill those requirements at minimum mass and aerodynamic penalty.

6. CONCLUSIONS

Jet versus Prop

In the regarded Mach number region of around 0.4 propeller aircraft are more fuel-efficient than jet-driven aircraft. They are more environmentally friendly, and, in addition, they produce less Direct Operating Costs. Jet aircraft become more economically favorable at higher cruise Mach numbers (due to a better utilization of the aircraft) but under the expense of an increasing fuel consumption. In those regions saving costs means burning more fuel. Thus, propeller aircraft are clearly the more favorable ‘feeder’ freighters.

Hydrogen versus Kerosene

The hydrogen propeller variant consumes less energy than the kerosene aircraft in an order of 5 %, and it is more environmentally friendly due to its significantly lower emissions (no carbon dioxide, 90 % less nitrogen oxides, more water but no contrails). Of course, an overall environmental benefit is highly depending on the way the hydrogen is produced. The Direct Operating Costs of the hydrogen propeller variant are about 1 % to 2 % higher. Consequently, from a purely economic point of view, the use of hydrogen is not favorable at today’s kerosene and an energy equivalent hydrogen price and under the current circumstances, particularly at today’s kerosene and energy equivalent hydrogen prices. Future steps

In the course of the Green Freighter project it has become possible to model and analyze unconventional fuels, fuel combinations and turboprop engines using the Preliminary Aircraft Design and Optimization program PrADO. The new modules for unconventional fuels, turboprop engines analysis etc. and the other tools of the project partners (like PreSTo of the HAW Hamburg) will be further improved and extended.

The next future steps in the investigation of the short range aircraft are to improve the current models in more detail and to perform parameter variations to determine the best operational conditions for each aircraft variant. Moreover, there are unmanned versions of the regarded aircraft variants in preparation, in which the former cockpit region is used as installation region of the forward hydrogen tank. This avoids the necessity to stretch the fuselage as in case of the manned versions and is therefore expected to save empty and take-off mass as well as energy and costs.

Furthermore, a DOC method for freighter aircraft is in preparation at the HAW Hamburg that especially takes into account environmental aspects like emissions trading scheme etc. The development of this method is going along with a research of freighter specific data on their utilization like number of flights per day/night, stage lengths, handling times and charges.

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NOMENCLATURE AND ABBREVIATIONS

ACARE Advisory Council for Aeronautics Research in Europe
AEA Association of European Airlines
AFRL Air Force Research Laboratory
ATA Air Transport Association of America
ATR Avions de Transport Régional
BMBF Bundesministerium für Bildung und Forschung (German Federal Ministry of Education and Research)
BTL Bio-To-Liquid
BWB Blended Wing Body
C Costs
CO Carbon monoxide
CO₂ Carbon dioxide
DMS Data Management System
DOC Direct Operating Costs
FL Flight Level
FPO Future Projects Office
FT Fischer-Tropsch
GTL Gas-To-Liquid
HAW Hochschule für Angewandte Wissenschaften (University of Applied Sciences)
HPC High-Pressure Compressor
HPT High-Pressure Turbine
H₂ Hydrogen
IFL Institut für Flugzeugbau und Leichtbau (Institute of Aircraft Design and Lightweight Structures)
IPCC Intergovernmental Panel on Climate Change
ISA International Standard Atmosphere
LH₂ Liquid Hydrogen
LPC Low-Pressure Compressor
LPT Low-Pressure Turbine
MTOW Maximum Take-Off Weight
n_{\text{fc}} Average number of cargo mass per flight
NASA National Aeronautics and Space Administration
NM Nautical Mile(s)
NO₂ Nitrogen Oxides
n_{\text{fl}} Number of flights per year
\( n_e \) Number of years in operation

OPR Overall Pressure Ratio

P Power

pax Passenger(s)

PL Payload

PreSto (Aircraft) Preliminary Sizing Tool

PT Power Turbine

R Range

SFC Specific Fuel Consumption

SL Sea Level

SME Small and Medium Enterprises

SO\(_x\) Sulfur Oxides

T Thrust

UHC Unburned Hydrocarbons

US United States

W\(_t\) Transport work

\( \eta \) Efficiency

REFERENCES


