

AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

SONDERVORTRAG zum 50. Geburtstag der DGLR Bezirksgruppe Hamburg:

Design of Hydrogen Passenger Aircraft – How much "Zero-Emission" is Possible?

with backup slides

Dieter Scholz

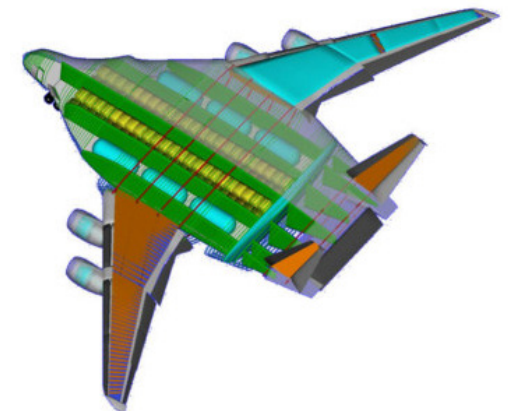
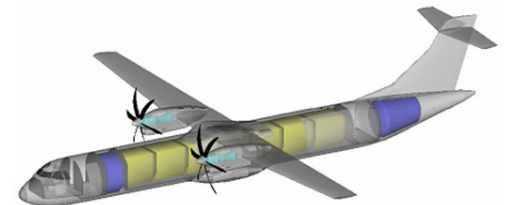
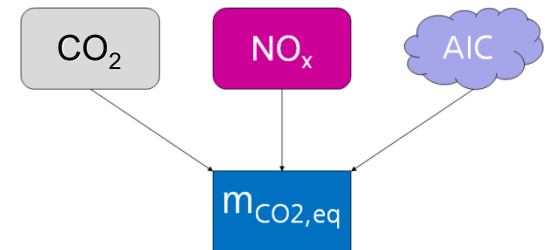
Hamburg University of Applied Sciences

Hamburg Aerospace Lecture Series (AeroLectures)

DGLR, RAeS, VDI, ZAL, HAW Hamburg

Online, 19 November 2020

<https://doi.org/10.5281/zenodo.4301103>



Design of Hydrogen Passenger Aircraft – How much 'Zero-Emission' is Possible?

Abstract

Purpose – 1.) Presentation and evaluation of selected past and present design projects for passenger aircraft with liquid hydrogen (LH2) propulsion. LH2 aircraft are also referred to as cryoplanes. 2.) Research question: Can cryoplanes be "zero emission"? 3.) Information for everyone interested.

Methodology – Revisiting of HAW Hamburg past research projects. Literature review. Combination of given knowledge to new insight.

Findings – An A319 cabin fits almost into a LH2 cryoplane based on an A321 fuselage. Such a design limits investment into new aircraft. It needs 40% more energy, 20% more DOC and shows about 27% less environmental burden (considering emissions and energy based on a LCA) if(!) hydrogen is from electrolysis and electricity from renewable sources. However, since electricity has to be taken from the grid with given energy mix, a cryoplane is as polluting as a kerosene plane, but has the advantage that it burdens future generations less due to its predominantly short term non-CO2 emission effects. Renewable energy will by far not be sufficient to maintain flying at the level we know today (2019). It is therefore paramount to reduce flying as it happened already during the Corona pandemic. Nevertheless, the aviation industry maintains the physically implausible "zero emission" goal based on advanced technology, because otherwise the credo "aviation needs growth" will not convince politics and society and could result in restrictions. This is why industry cannot enter a technical debate about: "How much 'zero emission' is possible?". Maintaining the extreme position of "zero emission" by means of a hydrogen powered aircraft contributed further to truth decays in the aviation industry. Notwithstanding these problems, we need to find a sincere way to communicate while we abide in ethical standards like "do not lie".

Practical implications – Results are presented in a pragmatic way.

Social implications – A discussion based on facts is facilitated beyond scientific circles and can build up political pressure to initiate change in aviation into a direction which is really ecological.

Originality/value – A presentation spanning from in depth aircraft design to social implications is otherwise missing, but most probably needed if we want to avoid a knowledge monopoly with the aviation industry that dictates the rest of society what has to be done.



Hamburg Aerospace
Lecture Series

DGLR
HAW Hamburg RAeS
VDI ZAL



Hamburg Aerospace Lecture Series
Hamburger Luft- und Raumfahrtvorträge

 <http://www.AeroLectures.de>

DGLR in cooperation with the RAeS, HAW Hamburg, ZAL and VDI invites to a lecture



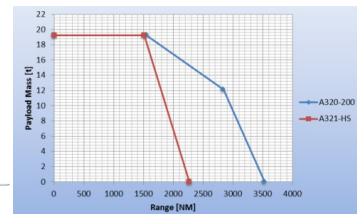
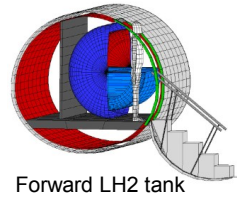
SONDERVORTRAG zum 50. Geburtstag der DGLR Bezirksgruppe Hamburg:

Design of Hydrogen Passenger Aircraft – How much 'Zero-Emission' is Possible?

Prof. Dr.-Ing. **Dieter Scholz**, MSME, HAW Hamburg

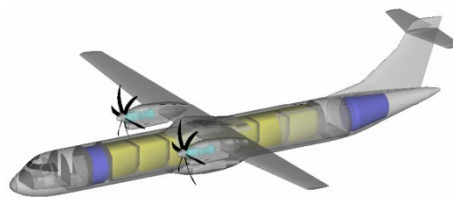
Date: Thursday, 19 November 2020, 18:00

Online: <http://purl.org/ProfScholz/zoom/2020-11-19>

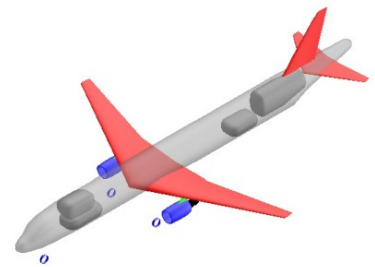


"Zero-emission" is not possible! Hydrogen combustion emits 2.6 times more water per energy than kerosene. This leads to contrails forming already at lower altitudes and hence more often. Hydrogen is an energy carrier that is responsible for as much CO₂ as its production has emitted. It is not only about emissions, it is also about depletion of resources and primary energy consumption. A Life Cycle Analysis (LCA) sums it up. Nevertheless, **hydrogen has a potential in aviation!**

Hydrogen aircraft design research from HAW Hamburg since 2006 is presented



ATR 72 LH2 freighter



A321 stretch with LH2 tanks

Hamburg Aerospace Lecture Series

Free lectures in Hamburg on aerospace topics that are jointly organized by DGLR, RAeS, VDI, ZAL and HAW Hamburg (PSL). The aim is the exchange of information between specialists and the training and further education of students and young engineers. The topics range from historical reviews to the description of current trends. A non-commercial, voluntary activity by committed individuals and invited speakers.



History – Local Branch Hamburg, German Aerospace Society (DGLR)



The "AeroLectures" have a **history** that goes back to the year **1970**. In this year, the Hamburg local branch of the German Society for Aeronautics and Astronautics (DGLR) was founded. Local branch head was Dr.-Ing. H.H. Menke. So-called "DGLR-Sprechabende" were held beforehand. Aerospace lectures have therefore been organized in Hamburg regularly and verifiably for more than 50 years.

The first major joint lecture event by DGLR and VDI in Hamburg took place on November 13th **1974**. The speaker was Ludwig Bölkow (picture), topic: "The Integration of the German Aerospace Industry Into the European Community".

Since **2000** lectures from [Praxis-Seminar Luftfahrt](#) of Hamburg University of Applied Sciences (at that time still Fachhochschule Hamburg) under the direction of Prof. Dr. Scholz were integrated into the program.



In **2002** it was started to announce the lectures with the logo "Luftfahrtstandort Hamburg", because the lecture series was part of the strategy of the Authority for Economy and Labor. The [Hamburg Branch of the Royal Aeronautical Society \(RAeS\)](#) was founded on [October 19,](#)

[2005](#). Since **2006** the aviation lectures of DGLR, VDI, RAeS and HAW Hamburg are offered together in a series of events.

Since **2015** one can refer to the series of lectures by a name: "*Hamburg Aerospace Lecture Series*" is the international name that does justice to the fact that many lectures are held in English. The corresponding designation is in German "*Hamburger Luft- und Raumfahrtvorträge*". We often speak briefly of "*AeroLectures*". In 2015, the series of lectures continued to be the "specialist working group" of Hamburg Aviation and had (on neutral ground) a homepage there (www.hav-connect.aero/Group/Lectures). In the year **2016** the [Center for Applied Aviation Research \(ZAL\)](#) was accepted as a new partner.

2019 the "AeroLectures" received their own full-fledged homepage (this one) and thus detached themselves from the homepage of the DGLR. The entire "hav-connect" network was terminated by Hamburg Aviation in **2020**. The homepage www.hav-connect.aero/Group/Lectures and the specialist working group at Hamburg Aviation disappeared. Contents of the homepage www.hav-connect.aero/Group/Lectures have been integrated into www.AeroLectures.de.

The **Homepage** can be reached via <http://www.AeroLectures.de>. "AeroLectures" is also the name used in social networks (Facebook, Twitter, Instagram, ...). Various subdomains facilitate direct access to the depth of the homepage. The homepage is stored on a server of Hamburg University of Applied Sciences: <https://www.fzt.haw-hamburg.de/pers> in the account of Prof. Dr. Scholz.

Design of Hydrogen Passenger Aircraft – How much 'Zero-Emission' is Possible?

Contents

- Introduction
- **Airbus ZEROe** and Remarks
- **Airbus A321 for LH2** (HAW Hamburg)
- **Life Cycle Analysis (LCA) in Aviation**
- **Airbus A320 with LH2 LCA Evaluation**
- **Equivalent CO2 Mass**
- Summary

Design of Hydrogen Passenger Aircraft – How much 'Zero-Emission' is Possible?

Acknowledgments (People, Projects, Funder)

Kolaj Seeckt (HAW Hamburg)

Dr. Wolfgang Heinze (TU Braunschweig)

Green Freighter (BMBF), <http://GF.ProfScholz.de>, 2006 – 2010

Leon Dib (HAW Hamburg, Master Thesis)

Dr. Andreas Johanning (HAW Hamburg / TUM, Dissertation)

Airport2030 (BMBF), <http://Airport2030.ProfScholz.de>, 2008 – 2014

Deutsche Bundesstiftung Umwelt, 2014 – 2016

Brecht Caers (HAW Hamburg, Master Thesis)

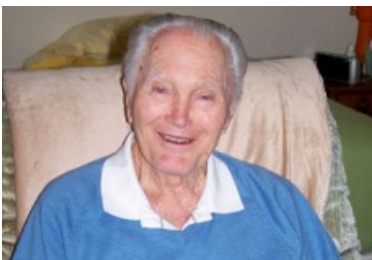
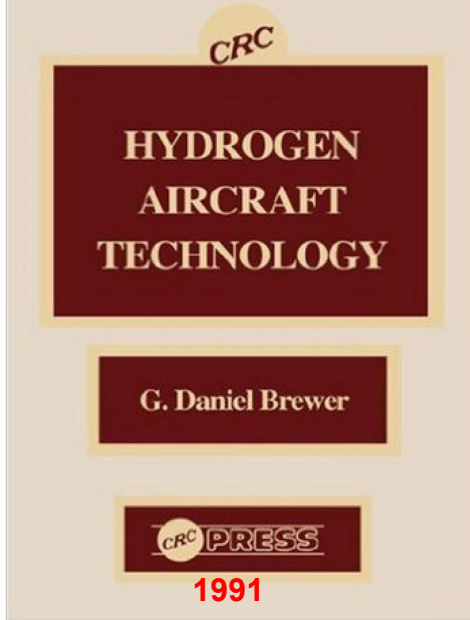
Funding from HAW Hamburg, up to 2020

... and many others.

Introduction

Literature / Previous Projects

<https://www.amazon.com/dp/0849358388>



In 2012: Dan BREWER at 93.

FINAL TECHNICAL REPORT (PUBLISHABLE VERSION)

CONTRACT N°: G4RD-CT-2000-00192

PROJECT N°: GRD1-1999-10014

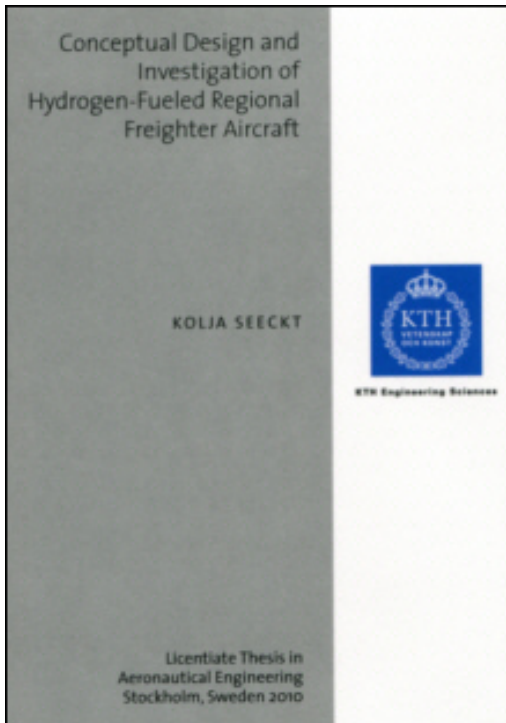
ACRONYM: CRYOPLANE

TITLE: Liquid Hydrogen Fuelled Aircraft – System Analysis

PROJECT CO-ORDINATOR : Airbus Deutschland GmbH

WESTENBERGER, Andreas, 2003: *Liquid Hydrogen Fuelled Aircraft – System Analysis, CRYOPLANE*. Final Technical Report.
Available from: <http://purl.org/AeroLectures/2004-02-26> (PDF)

Literature / Previous Projects



Green Freighter
HAW Hamburg (lead)
 TU Braunschweig (IFL)
 Airbus, Hamburg
 Bishop GmbH
 09/2006 to 04/2010



Airport 2030 – Possible A320 Successor
HAW Hamburg
 Airbus, Hamburg
 12/2008 to 01/2014

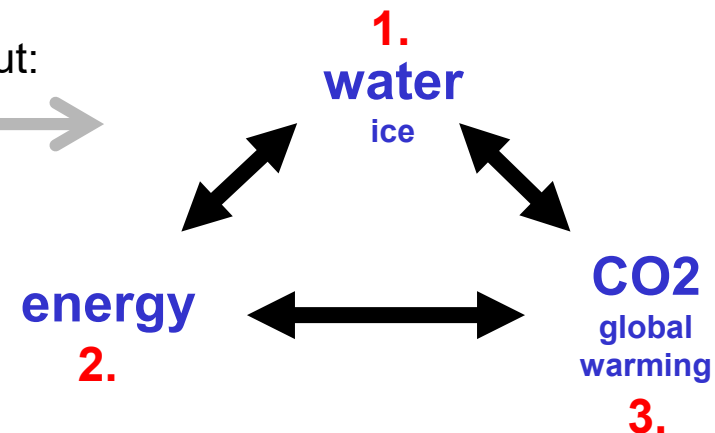


SEECKT, Kolja, 2010. *Conceptual Design and Investigation of Hydrogen-Fueled Regional Freighter Aircraft*. Stockholm, KTH, Licentiate Thesis in Cooperation with HAW Hamburg. Download: <http://GF.ProfScholz.de>

Availability of Energy Important! Consider Global Warming!

- Depletion of fossil fuels => **aviation energy carrier** instead of **aviation fuel**
- Renewable energy is **electrical energy**. How to carry on board?
 - biofuel, synthetic fuel, drop-in fuel *advantage:* aircraft stay the same
 - batteries *advantage:* direct use of electricity
 - **hydrogen** *advantage:* **highest overall efficiency**
- Current focus: CO₂, Global Warming, Climate Change, but:
- There are **more issues than CO₂** & global warming →
- **Needed:** Balanced look with **Life Cycle Assessment**

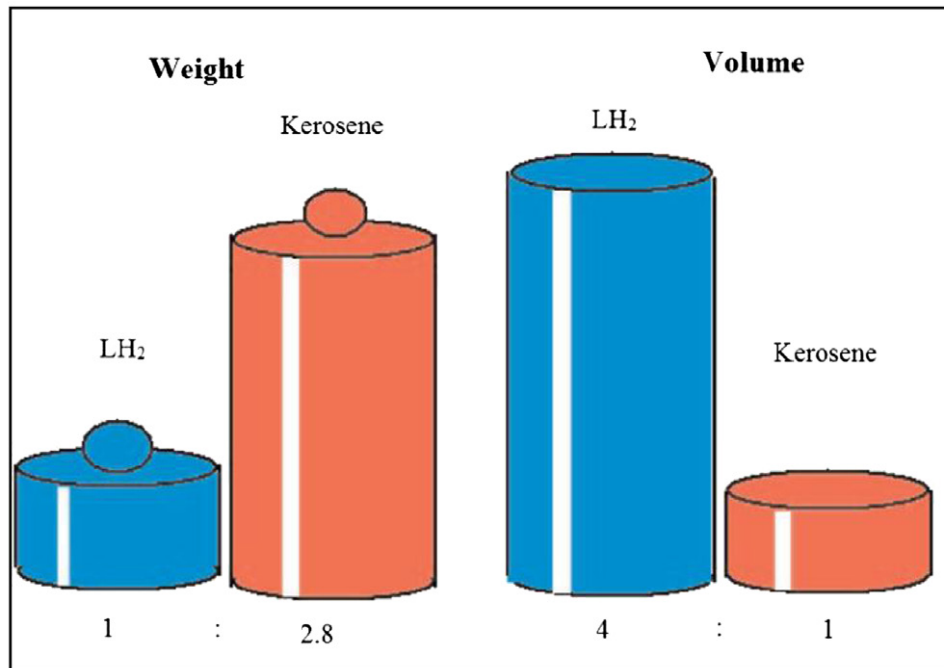
Ensure with **2. priority** (after water):
Future availability of energy (in aviation) !
 (or tell your kids the party is over)
3. priority: Consider global warming



SCHOLZ, Dieter, 2012. *Eco-Efficiency in Aviation – Flying Off Course?* German Aerospace Congress 2012 (DLRK2012), Berlin, Germany, 10.-12.09.2012.
 Available from: <https://doi.org/10.5281/zenodo.4067014>

Characteristics of Hydrogen – Important for Aircraft Design

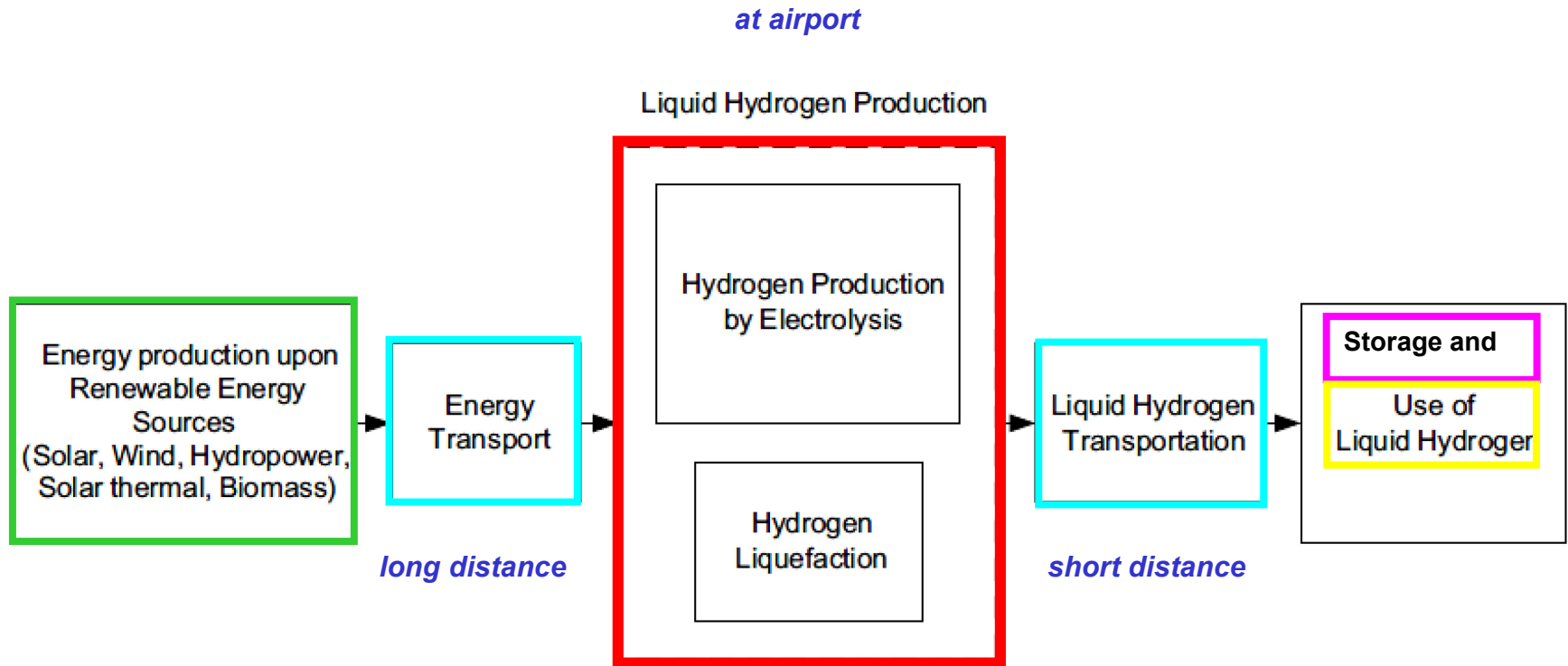
- LH2 comparison at equal energy (20 K = -253 °C):



KHANDELWAL, 2013, <http://doi.org/10.1016/j.paerosci.2012.12.002>

- **Boil-off**
- **Hydrogen embrittlement (Wasserstoffversprödung) of materials**

Handling of LH2 From "Well to Tank"



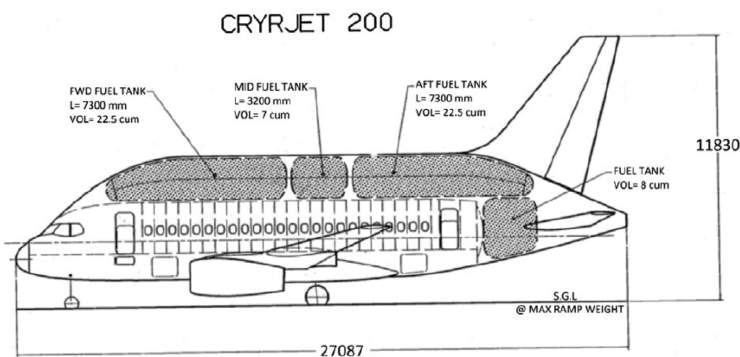


Liquefaction should be at the airport. To avoid unnecessary boil-off, distances to the aircraft are kept short. Refueling has to be done directly before take-off.

EU, 2020. Hydrogen-Powered Aviation. Available from: <https://doi.org/10.2843/471510>

Hydrogen Aircraft Configurations

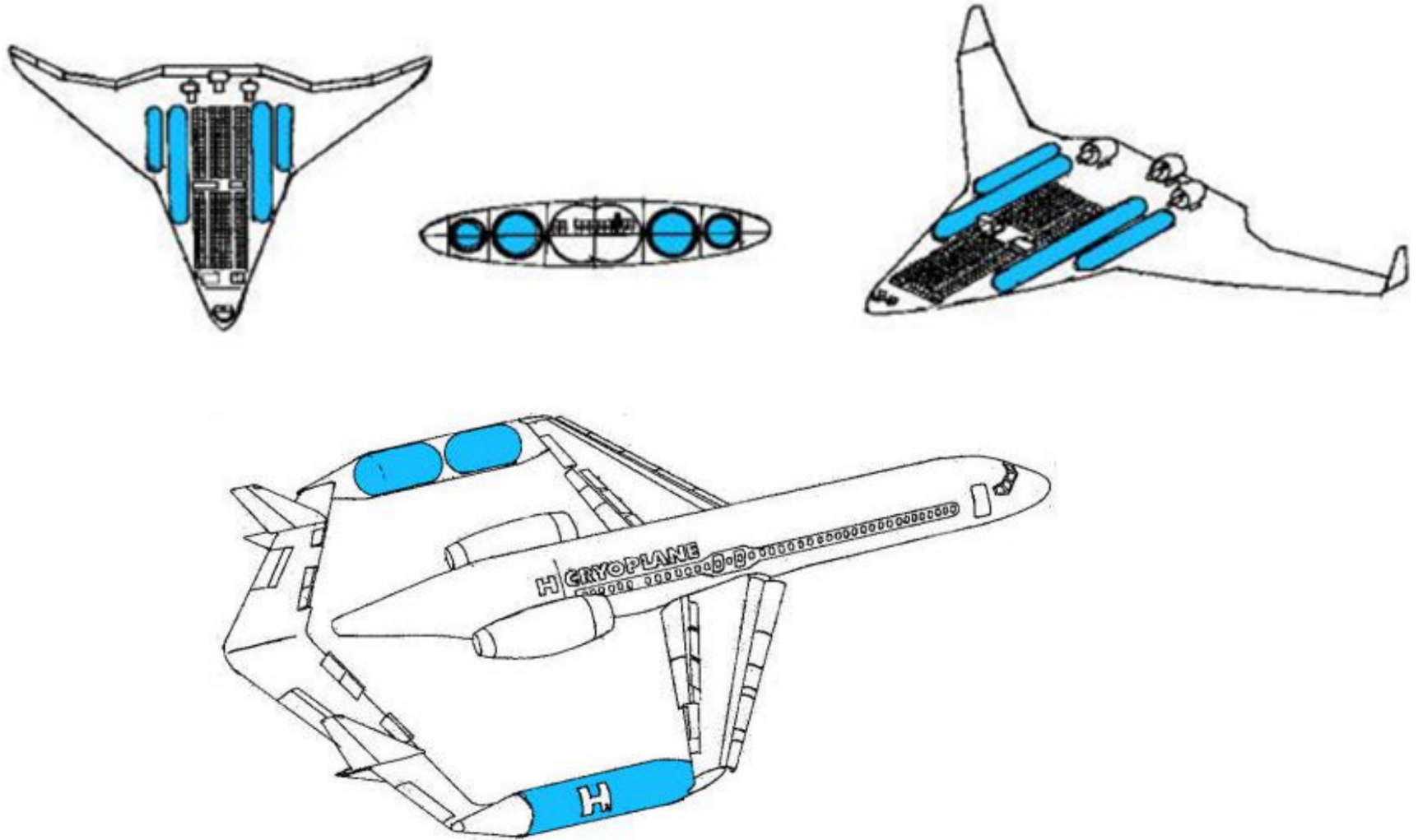
The selection of a type of **aviation energy carrier** needs to be seen **together with** the resultant **aircraft configuration**!



WESTENBERGER, 2003



WESTENBERGER, 2003



WESTENBERGER, 2003

Findings from CRYOPLANE (1999 – 2003)

Various tank layouts appeared to be optimal depending on aircraft category. Crucial element is balancing of the aircraft's center of gravity. Due to the large and heavy tanks, aircraft empty weight will go up by some 25% compared to kerosene aircraft. However, due to the light LH2 maximum take-off weights will go down, especially with increasing fuel fraction. As a consequence of the bulky tanks the energy consumption increases as well, resulting in a 25 % increase in DOC as of today for a 1000 nm mission. When LH2 production cost drops to levels below that of kerosene, DOC's for LH2 and kerosene fuelled aircraft may reach a crossover point as far away as 2040. This is in line however with the motivation behind LH2 technology: a long-term alternative for kerosene when crude oil production comes to an end.

Flying remains possible after the end of fossil fuels with LH2.

Large Very Long Range Passenger LH2 Aircraft

DESIGN GROSS WT - 266,429 KG

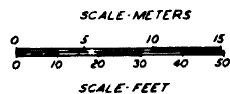
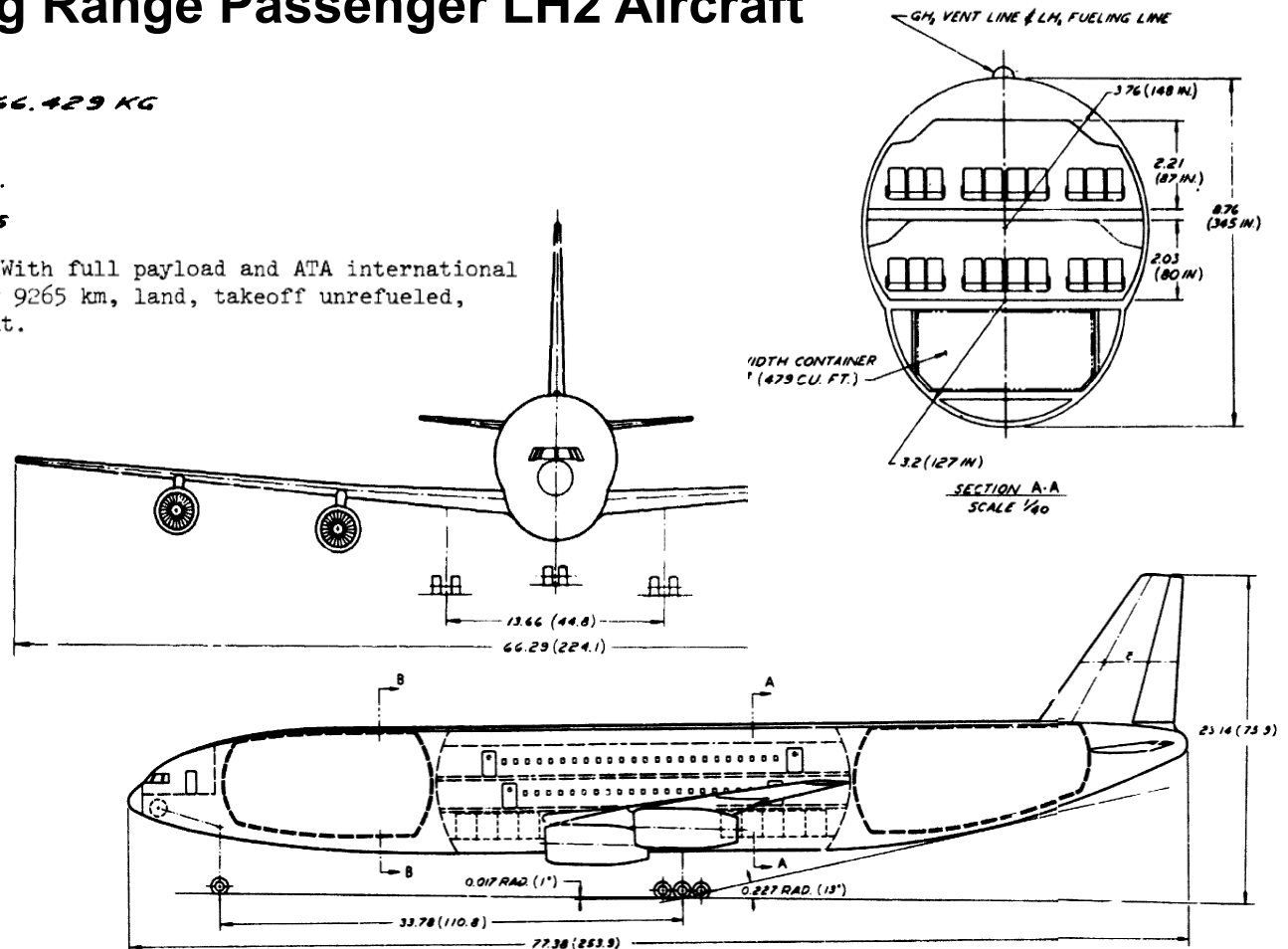
PASSENGERS - 400

FUEL (LH₂) - 68,424 KG.

RANGE - 9,265 KM RADIUS

9265 km (5000 n.mi.) radius. With full payload and ATA international reserves for each segment, fly 9265 km, land, takeoff unrefueled, and fly another 9265 km segment.

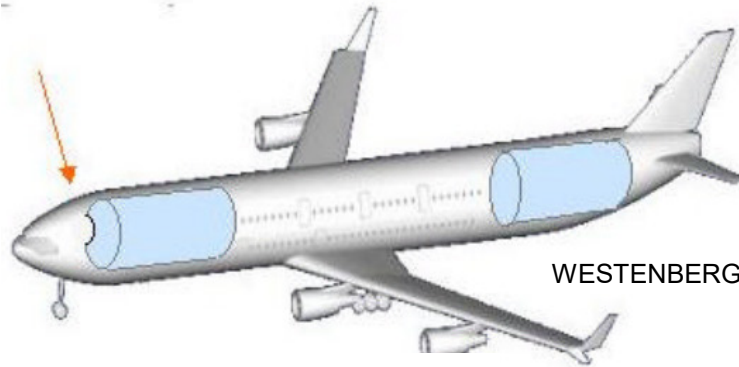
Range: 18530 km = 10000 NM



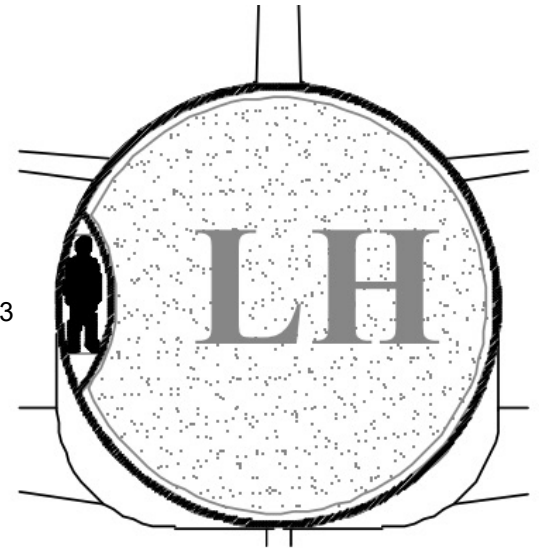
BREWER, G.D., MORRIS, R.E., 1976. *Study of LH₂ Fueled Subsonic Passenger Transport Aircraft*. Lockheed, NASA CR-144935. Available from: <https://ntrs.nasa.gov/citations/19760012056>

Cockpit Integration – Passageway to Cabin?

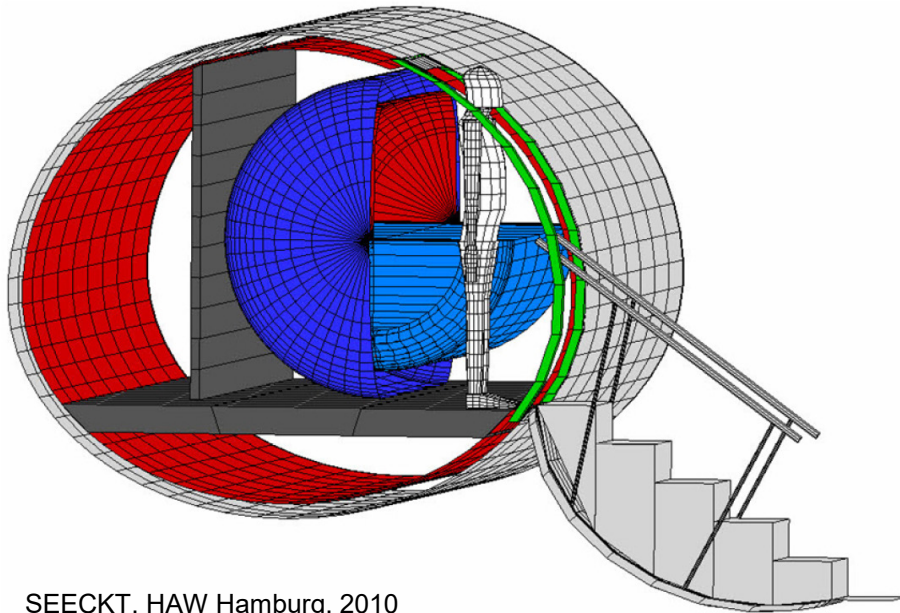
Yes:



WESTENBERGER, 2003

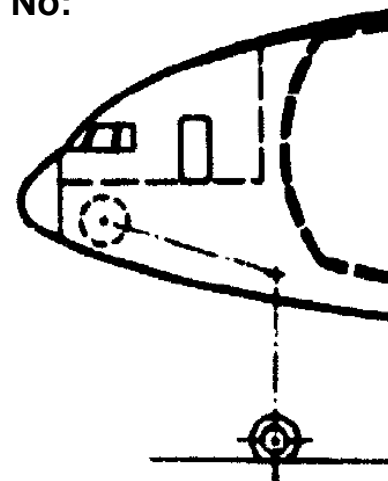


Yes:



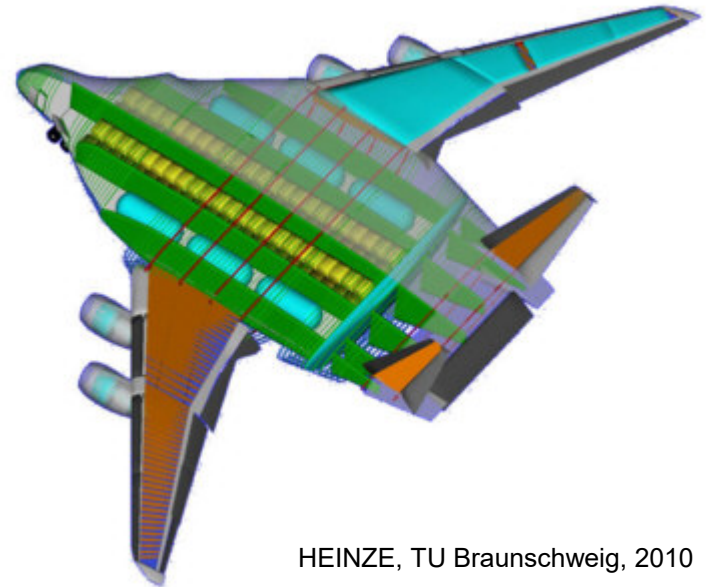
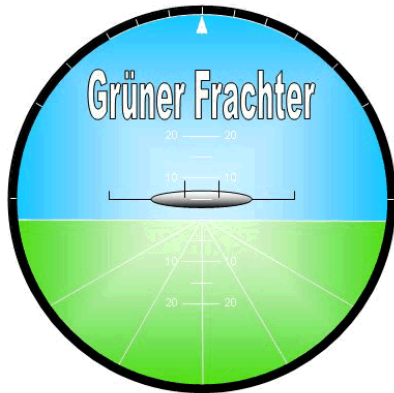
SEECKT, HAW Hamburg, 2010

No:

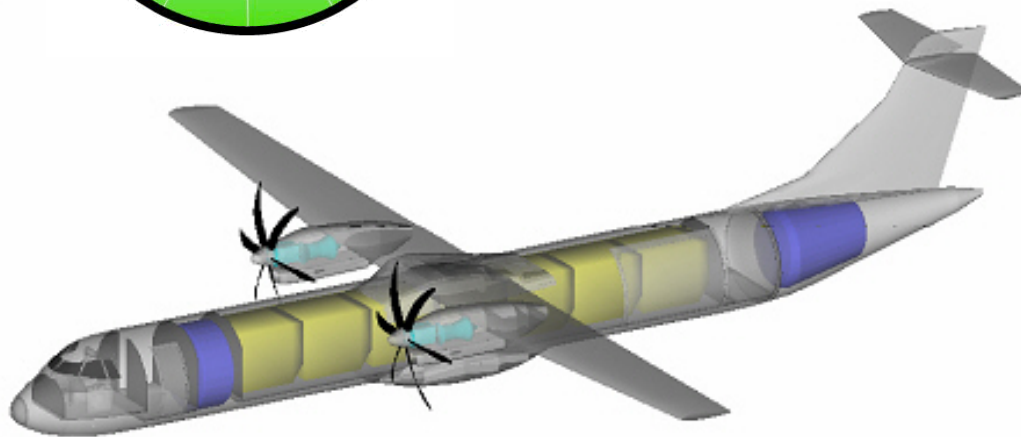


BREWER 1976

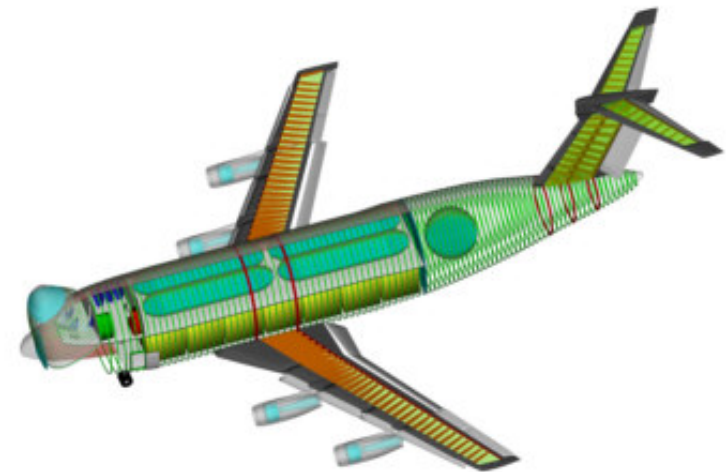
Configurations From the "Green Freighter" Project



HEINZE, TU Braunschweig, 2010



SEECKT, HAW Hamburg, 2010



Findings From the "Green Freighter" Project

Advantages of LH2:

- Flying remains possible even after the end of fossil fuels!
- LH2 technology is already known and can be used in aircraft today.
- Burning hydrogen is more environmentally friendly than burning kerosene.
- Hydrogen is lighter than kerosene - but tanks are heavy. MTOW drops slightly. Induced drag decreases.



Disadvantages of LH2:

- Conventional aircraft cannot be used, but may be modified.
- New infrastructure is required at the airport: hydrogen production, hydrogen liquefaction
- To transport the same payload over the same range
 - Larger accommodation spaces have to be found for the (almost) cylindrical LH2 tanks.
 - LH2 aircraft are larger due to the large tanks and therefore show higher zero lift drag.
- All LH2 aircraft configurations have higher operating costs: short range: + 5%, long range: + 15%.
- Despite the insulation of the tanks, the hydrogen heats up and sometimes becomes gaseous again.
 - This hydrogen can be used in flight.
 - On the ground, the pressure in the tank would rise and hydrogen would have to be blown off.
- A refueled aircraft cannot simply be left standing on the apron.
 - Refueling only makes sense shortly before the start.
 - Flight operation must take this into account and are therefore a little less flexible.

Please see Bibliography for "Green Freighter" References and <http://gf.ProfScholz.de>

Airbus ZEROe and Remarks

Airbus: "Zero-Emission" Hybrid-Hydrogen Passenger Aircraft



<https://www.airbus.com/innovation/zero-emission/hydrogen/zeroe.html>

Archived at: <https://perma.cc/HJ6L-3HUB>

"At Airbus, we have the **ambition** to develop the world's **first zero-emission commercial aircraft** by **2035**."
(2020-09-21)

Airbus Hydrogen Turbofan Concept Plane



<https://www.airbus.com/innovation/zero-emission/hydrogen/zeroe.html>

Archived at: <https://perma.cc/HJ6L-3HUB>

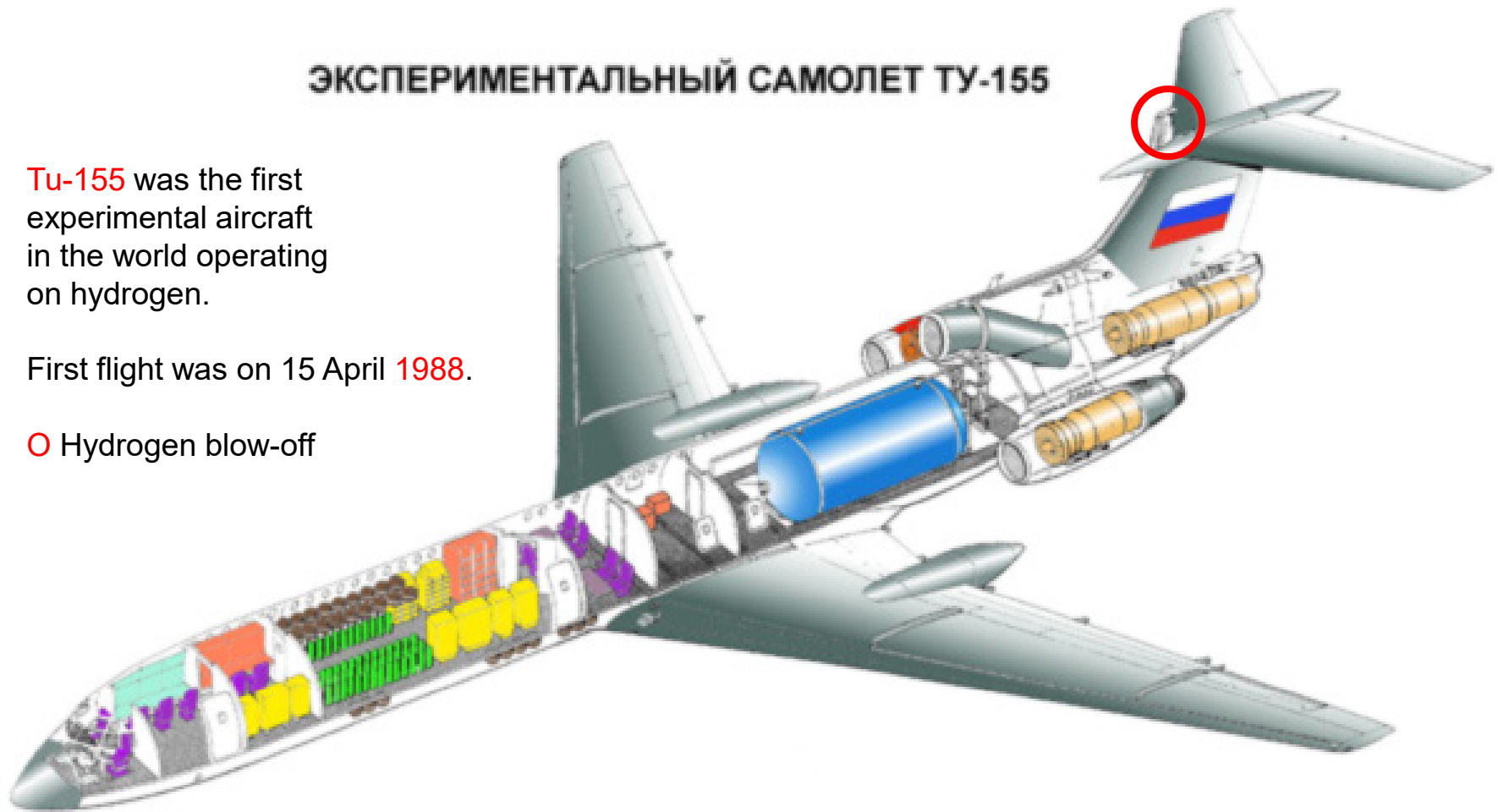
Airbus First? Tu-155 First Experimental Hydrogen Aircraft

ЭКСПЕРИМЕНТАЛЬНЫЙ САМОЛЕТ ТУ-155

Tu-155 was the first experimental aircraft in the world operating on hydrogen.

First flight was on 15 April 1988.

○ Hydrogen blow-off



<https://web.archive.org/web/20120213180146/http://www.tupolev.ru/English/Picture.asp?PubID=1788>

Airbus First? Tu-155 First Experimental Hydrogen Aircraft



For safety purpose the experimental **cryogenic fuel complex** was in a **special compartment** isolated from adjacent fuselage compartments by buffer areas provided with a **ventilation** system.

Picture and text from:

<https://web.archive.org/web/20130218231656/http://www.tupolev.ru/English/Show.asp?SectionID=82>

The **experimental** hydrogen-powered NK-88 **engine is located in the right side nacelle**. The cryogenic fuel is kept in a fuel tank of 17.5 m³ capacity. It is installed in a special compartment in the rear portion of the passenger cabin.

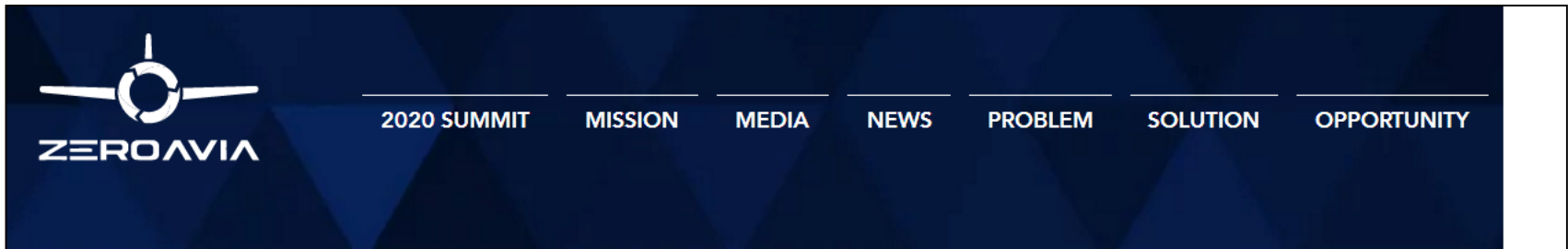
A large flight testing program was fulfilled (about 100 flights). Several **international flight demonstrations** were made including those to Bratislava (Czechoslovakia), Nice (France), Berlin and Hannover (Germany).


To use cryogenic fuel, the **airframe and some standard systems were modified**, cryogenic fuel charging, storage and feeding systems were installed that ensured fire/explosion safety, and data acquisition and recording system.



Schiffmann, CC BY-SA, <https://bit.ly/3o4Sjbm>

Airbus First? First Passenger Hydrogen Fuel Cell Aircraft




2020 SUMMIT
MISSION
MEDIA
NEWS
PROBLEM
SOLUTION
OPPORTUNITY

ZeroAvia Completes World First Hydrogen-Electric Passenger Plane Flight

25 September, 2020, 08:00 BST

- Leading innovator in the decarbonisation of aviation makes major breakthrough with first hydrogen fuel cell flight of a commercial-size aircraft.
- ZeroAvia’s retrofitted Piper M-class is now the largest hydrogen powered aircraft in the world.

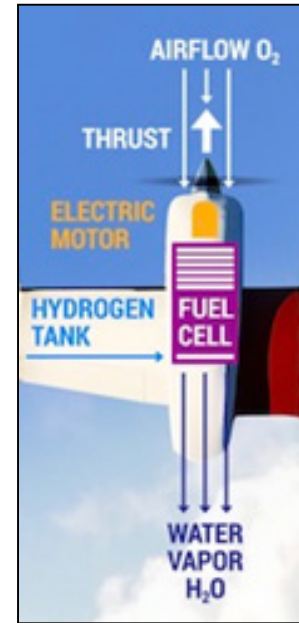
<https://www.zeroavia.com/press-release-25-09-2020>

Archived at: <https://perma.cc/K2G4-XEJP>

ZeroAvia Hydrogen Fuel Cell Flight



ZeroAvia's hydrogen powered Piper



<https://www.zeroavia.com/press-release-25-09-2020>

<http://sustainableskies.org/zeroavia-first-out-gate-h2>

Interior of a Piper M350 (<https://www.piper.com>)

Airbus: The Schedule Towards 2035



<https://youtu.be/LJGMLoSctZY>

Airbus: A **full-scale aircraft prototype** is **estimated** to arrive by the **late 2020s**.

<https://www.airbus.com/newsroom/stories/these-new-Airbus-concept-aircraft-have-one-thing-in-common.html>
 Archived at: <https://perma.cc/33W7-BBY6>

Airbus Zero Emission?



<https://www.airbus.com/innovation/zero-emission.html>

Archived at: <https://perma.cc/A2F9-6J5C>

The image shows the Airbus concept plane from 2011.

The engines seem to have only a relatively small by-pass-ratio.

Efficient cabin design is usually asking for the first door aft of the cockpit in order to have sufficient cabin width in first row.

Fundamentals of Environmental Aviation Goals

Goals can be distinguished by:

- **Level:**
 - Technology (e.g. ACARE)
 - Aircraft
 - Global Fleet (e.g. IATA)
- **Entity** (CO₂, NO_x, H₂O, Noise, ...)
- **Amount of Reduction** (50%, 75%, 100%)
- **Year of Announcement**
- **Year of Achievement**
- **Governing Body** (ACARE, ...)

For more on aviation goals see:

SCHOLZ, Dieter, 2020. *Review of CO₂ Reduction Promises and Visions for 2020 in Aviation.*

German Aerospace Congress 2020 (DLRK 2020), Online, 01 - 03.09.2020.

Available from: <https://doi.org/10.5281/zenodo.4066959>

History of "Zero Emissions":

IATA 2007: First in Proclaiming "Zero Emissions" (Goals Not Active Anymore)

[Home](#) » [Pressroom](#) » [Press Releases](#) » [IATA Calls for a Zero Emissions Future](#)

No.: 21

Date: 4 June 2007



IATA Calls for a Zero Emissions Future

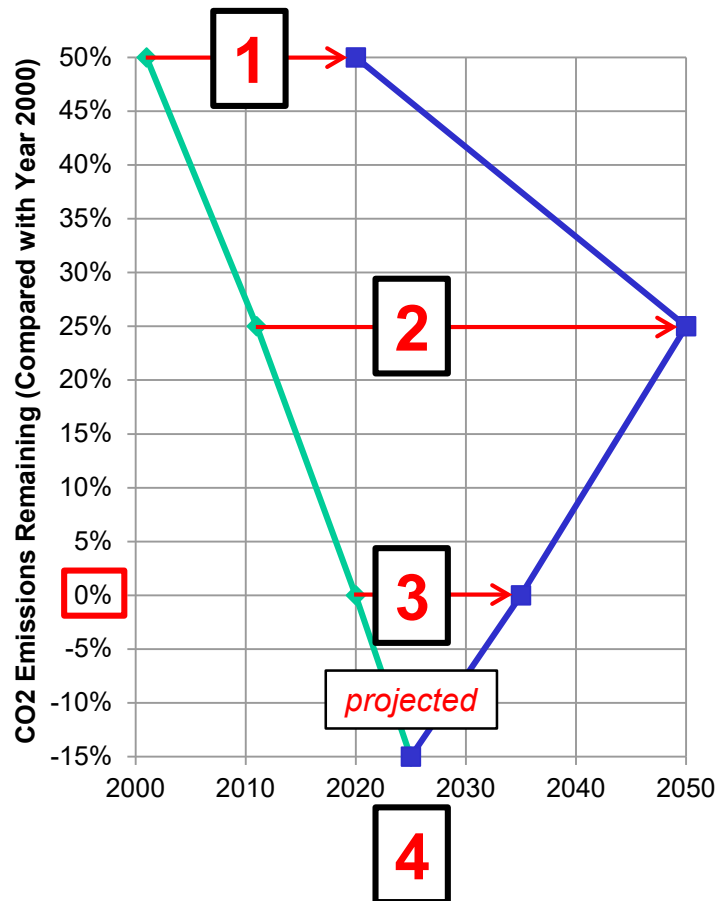
VANCOUVER - The International Air Transport Association (IATA) issued four challenges to drive the air transport industry towards its vision of zero emissions.

“The environmental track record of the industry is good: over the last four decades we have reduced noise by 75%, eliminated soot and improved fuel efficiency by 70%. And the billions being invested in new aircraft will make our fleet 25% more fuel efficient by 2020. This will limit the growth of our carbon footprint from today’s 2% to 3% in 2050” said Giovanni Bisignani, IATA Director General and CEO.

“But a growing carbon footprint is no longer politically acceptable—for any industry. Climate change will limit our future unless we change our approach from technical to strategic. Air transport must aim to become an industry that does not pollute—zero emissions” said Bisignani.

Archived at: <https://perma.cc/JSR2-JC79>

History of "Zero Emission" – The Logic of Political Goal Setting



- 1: ACARE: Vision 2020
- 2: ACARE: Flightpath 2050
- 3: Airbus, DLR*, ...: Zero Emission
- 4: Hypothetical, if political trend continues

* DLR, BDLI, 2020-11-14: Zero Emission Aviation.
 Archived at: <https://perma.cc/M5VN-HG3Z>

—●— Announced
 —■— Achieved



Goal setting is linked to asking for public money:

- If money came for goal #n, a goal #n+1 has to be proclaimed as the base for a new requests for more money.
- Goal #n+1 needs to surpass goal #n in terms of reduction percentage and in an ever shorter time frame for its achievement.
- Goal #n+1 is proclaimed before goal#n has been reached.

Airbus: "Zero-Emission"?



Beware! **"Zero-emission" is never possible**; not for aircraft, not for animals/humans (CO₂, CH₄).

Airbus: *By 2035, the world's first zero-emission commercial aircraft could [or could not] take to the skies. To bring this vision to reality, Airbus is exploring [not: developing and building] game-changing concept aircraft – known as ZEROe – powered by hydrogen, a disruptive zero-emission technology [note: the technology is zero-emission not the aircraft] with the potential [but not necessarily the capability] to reduce aircraft emissions by up to 50%. [1]*

What is meant? "zero-emission aircraft" or only "reduce aircraft emission by up to 50%"?

What is meant? "zero-emission aircraft" or only "zero-emission technology"?

[1] <https://www.airbus.com/newsroom/stories/these-new-Airbus-concept-aircraft-have-one-thing-in-common.html>
Archive at: <https://perma.cc/33W7-BBY6>

Airbus: "Zero-Emission" – Corporate Statements

"At Airbus, we are convinced that carbon-neutral aviation is ... achievable." [1]

When?/What? What is "carbon-neutral aviation"? Is it "**carbon-neutral growth (CNG)**"? This is due in 2020, but is not achieved (or only due to the Corona pandemic). So it must be "**no carbon**" or "**a closed carbon cycle**" making carbon (CO₂) emissions "neutral".

"... it is estimated that hydrogen has the potential to reduce aviation's CO₂ emissions by up to 50%." [2]

"50%" is not "carbon-neutral aviation". How to achieve "**carbon-neutral aviation**", if **50% CO₂ is still emitted**?

Please compare with the statement on previous page: "reduce aircraft emissions by up to 50%" versus "reduce aviation's CO₂ emissions by up to 50%". "**aircraft emissions**" or "**aviation's emissions**"? "**emissions; 50%**" or "**CO₂ emissions; 50%**"?

"This is why we have the ambition to develop the world's first zero-emission commercial aircraft by 2035." [1]

"**Zero-emission**" by **only reducing CO₂** by 50%? Aviation's emissions are more than only CO₂.

We do not have a CO₂ problem. We have a water problem!

"All three ZEROe [**zero-emission**] concepts are ... powered by **hydrogen combustion**." [3]

"Zero-emission" is linked to an aircraft's "**hydrogen combustion**". **This is far from true!**

[1] <https://www.airbus.com/company/sustainability/environment/decarbonisation.html>

Archived at: <https://perma.cc/58TL-YKCC>

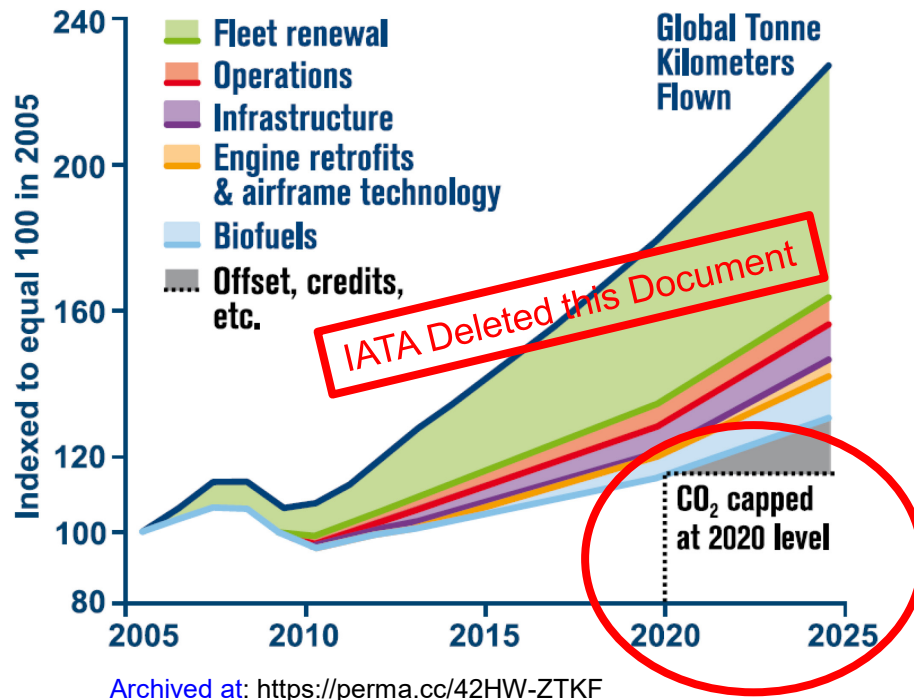
[2] <https://www.airbus.com/innovation/zero-emission/hydrogen.html>

Archived at: <https://perma.cc/AM2K-4C9Q>

[3] <https://www.airbus.com/innovation/zero-emission/hydrogen/zeroe.html>

Archived at: <https://perma.cc/HJ6L-3HUB>

Insert: Carbon-Neutral Growth Starting 2020?



2020 is **arbitrary** to start with CO₂ compensation.

Compensation could have started earlier.

Why not postpone longer?

Did we notice any change with the 2020 CO₂ cap?

- IATA (and ATAG) wanted to achieve "Carbon-Neutral Growth" (CNG) from 2020 onwards.
- This is only possible with CO₂ compensation (carbon **offset schemes**).
- **In 2020 the goal of "Carbon-Neutral Growth" (CNG) was swept under the carpet.**
- Some may point to CORSIA, but CORSIA does not deliver CNG.
- The industry does not argue with Corona for CNG, because the Corona pandemic resulted in decline instead of the industry propagated continuous growth.

Airbus: "Zero-Emission" – Interesting Personal Statements

Glenn Llewelyn (Vice President Head of Zero Emission Aircraft, Airbus):

We make sure that there are no non-CO2-effects when we use hydrogen onboard the aircraft. It's not all resolved in terms of the solution and the details. We have a road map ... to secure our ambition to zero emission. Very clearly we see that hydrogen has the potential ... has some work to do but [hydrogen] is really the most promising vector to deliver ultimately zero emission flight. [1]

Dr. Sandra Bour-Schaeffer (Head of Airbus Group Demonstrators, CEO of Airbus UpNext):

We will be producing more vapor and probably more contrails ... Yes there remain open questions we have to look on and contrails are one of them. [2]

Glenn Llewelyn:

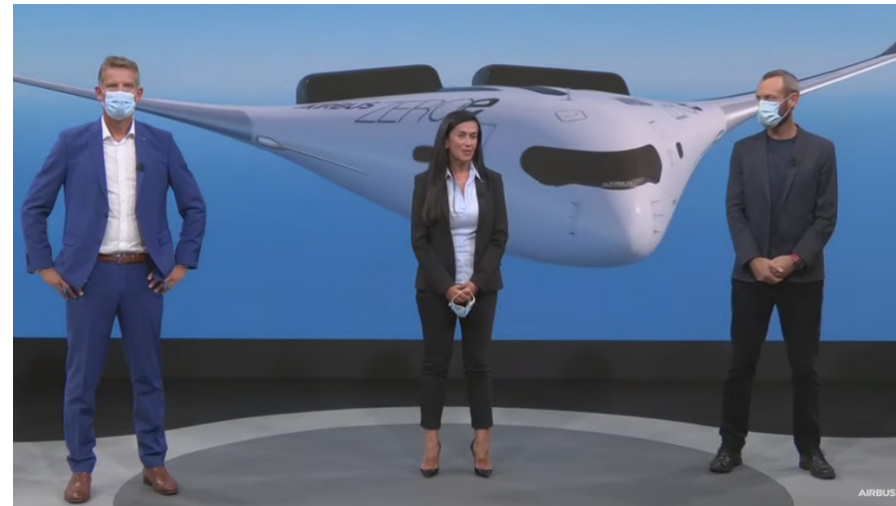
As recently as five years ago, hydrogen propulsion wasn't even on our radar as a viable emission-reduction technology pathway. Today, we're excited by the incredible potential hydrogen offers aviation in terms of disruptive emissions reduction. [3]

[1] Introducing #ZEROe, 2020-09-21,
https://youtu.be/525YtyRi_Vc (22:22)

[2] Decarbonising Aviation. Royal Aeronautical Society Corporate Partner Briefing, 2020-11-05, <https://youtu.be/LJGMLoSctZY> (24:30)


[3] <https://www.airbus.com/newsroom/stories/these-new-Airbus-concept-aircraft-have-one-thing-in-common.html>,

Archived at: <https://perma.cc/33W7-BBY6>



Introducing #ZEROe, https://youtu.be/525YtyRi_Vc. Left to right: Jean-Brice Dumont (Executive Vice President Engineering, Airbus), Grazia Vittadini (Chief Technology Officer, Airbus), Glenn Llewelyn (Vice President Head of Zero Emission Aircraft, Airbus).

AIRBUS

Commercial Aircraft Helicopters Defence Space Innovation Company Media [Airbus Home](#) > [Company](#) > [Sustainability](#) > [Environment](#) > [Decarbonisation](#)

Decarbonisation

Towards more sustainable air travel for future generations

<https://www.airbus.com/company/sustainability/environment/decarbonisation.html>

Archived at: <https://perma.cc/58TL-YKCC>

**Decarbonisation means reducing CO₂, but
aviation emissions is more than CO₂!**

Life Cycle Analysis (LCA): Combined View on Emissions and Resources

Emissions:

- **Hydrogen** combustion emits **2.6 times more water** per energy than kerosene.
- This leads to **contrails** forming already at lower altitudes and hence **more often**.
- **Hydrogen** is an energy carrier that is responsible for as much **CO2** as its **production** has emitted.
- If **hydrogen** is produced **from electricity**, the **energy mix** has to be accounted for.
- As long as electricity is taken from the grid:

No one should claim only the "clean portion" of the electricity and leave the "dirty portion" of the electricity to others!

- Aviation's emissions contributing to global warming are much more than CO2! They include also **NOx**.
- A large contribution to global warming is from **Aircraft-Induced Cloudiness (AIC)**.

Resources / Energy:

- It is not only about emissions, it is also about depletion of resources and **primary energy consumption**.
- The **primary energy factor** of **electricity** is about **2.2**, for fuel 1.1 (see next page)
=> **ratio** electricity/fuel: **2.0**

Combined View:

- A **Life Cycle Analysis (LCA)** sums it all up.

From Energy to Approximate Emission Comparison

Type of Comparison	Kerosene	Electricity / Battery
Energy (wrong)	$E = m_F H_L$	$E = E_{bat} / \eta_{charge}$
Max. Exergy (not good)	$B_{max} = \eta_C H_L m_F$	$B_{max} = E$
Exergy (ok)	$B = \eta_{GT} H_L m_F$	$B = \eta_{EM} E$
Primary Energy (better)	$E_{prim} = 1.1 H_L m_F$	$E_{prim} = k_{PEF} E$
CO2 (without altitude effect)	$m_{CO2} = 3.15 \cdot 1.1 m_F$	$m_{CO2} = 3.15 x_{ff} E_{prim} / H_L$
Equivalent CO2 (good, simple)	$m_{CO2,eq} = m_{CO2} (k_{RFI} + 0.1)$	$m_{CO2,eq} = m_{CO2}$

$$H_L = 43 \text{ MJ/kg} \quad \eta_{charge} = 0.9$$

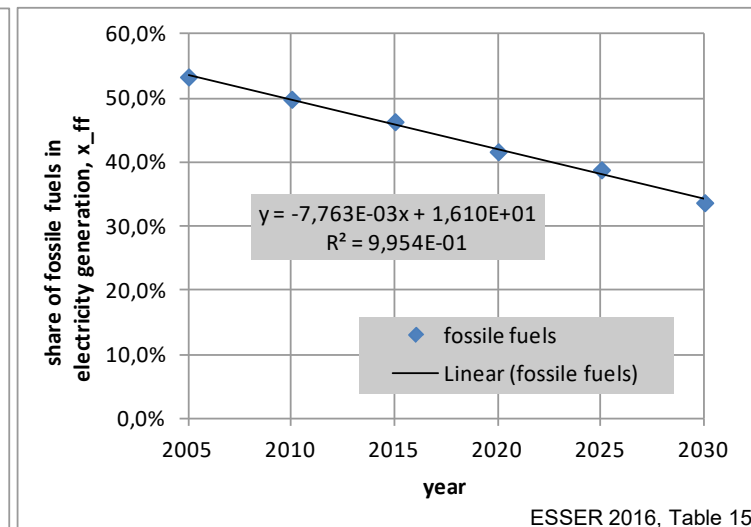
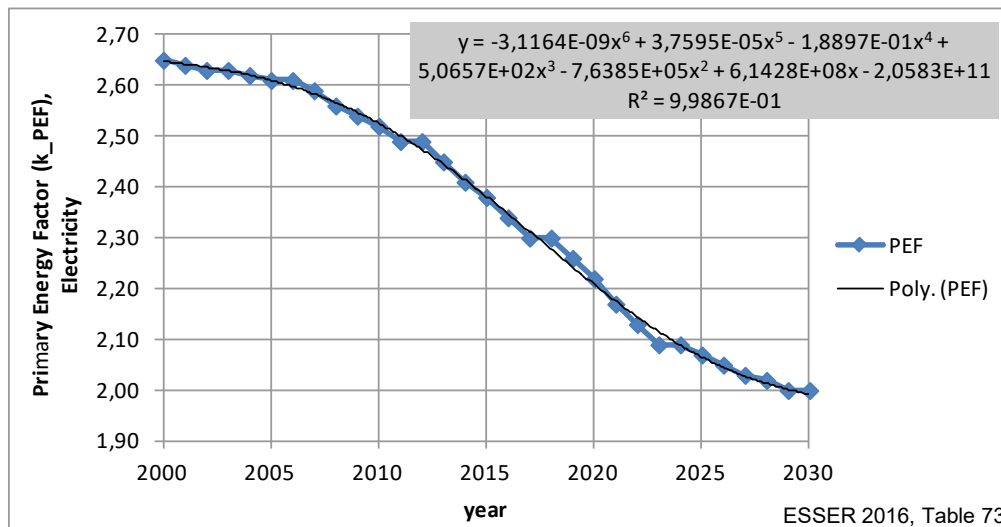
Carnot Efficiency:

$$\eta_C = 1 - T/(h) / T_{TET} = 1 - 216.65 / 1440 = 0.85$$

$$\eta_{GT} = 0.35 \quad \eta_{EM} = 0.9$$

Radiative Forcing Index:

$$k_{RFI} = 2.7 \quad (1.9 \dots 4.7)$$



ESSER, Anke, SENSFUSS, Frank, 2016. *Evaluation of Primary Energy Factor Calculation Options for Electricity*. Karlsruhe: Fraunhofer-Institut für System- und Innovationsforschung (ISI). Available from: https://ec.europa.eu/energy/sites/ener/files/documents/final_report_pef_eed.pdf
 Archived at: <https://perma.cc/WMY7-QER4>

EU-Study, May 2020



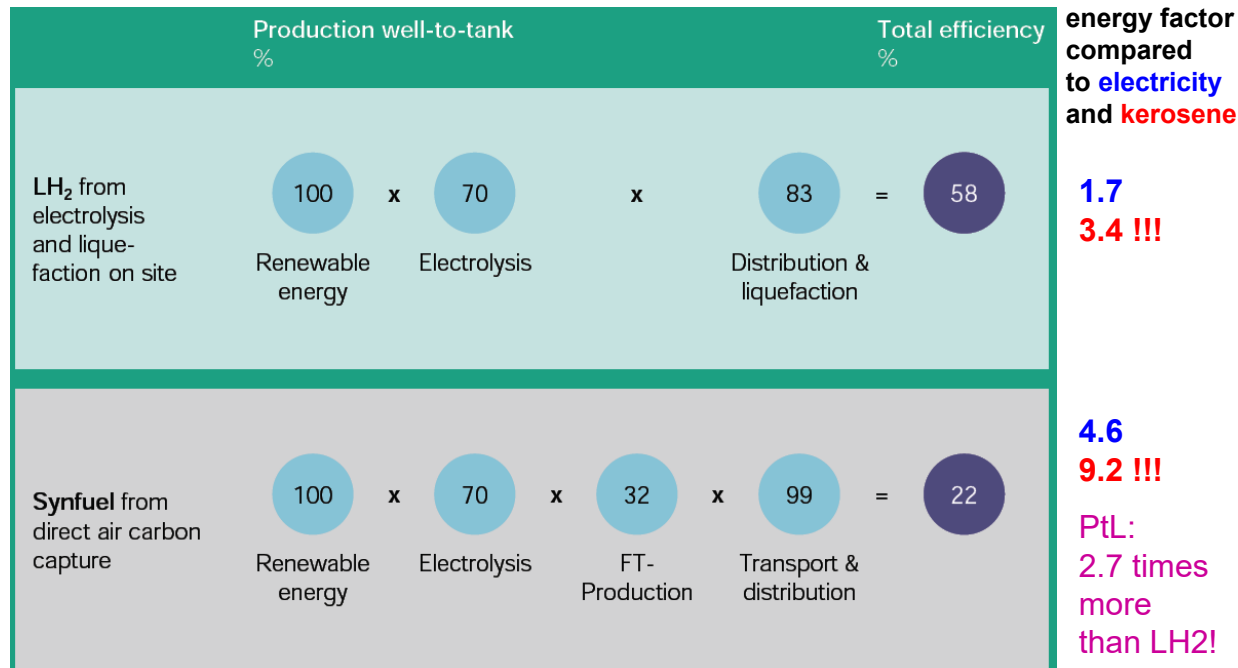
<https://doi.org/10.2843/471510>
 Archived at: <https://perma.cc/BJJ6-5L74>

AIRBUS and many others

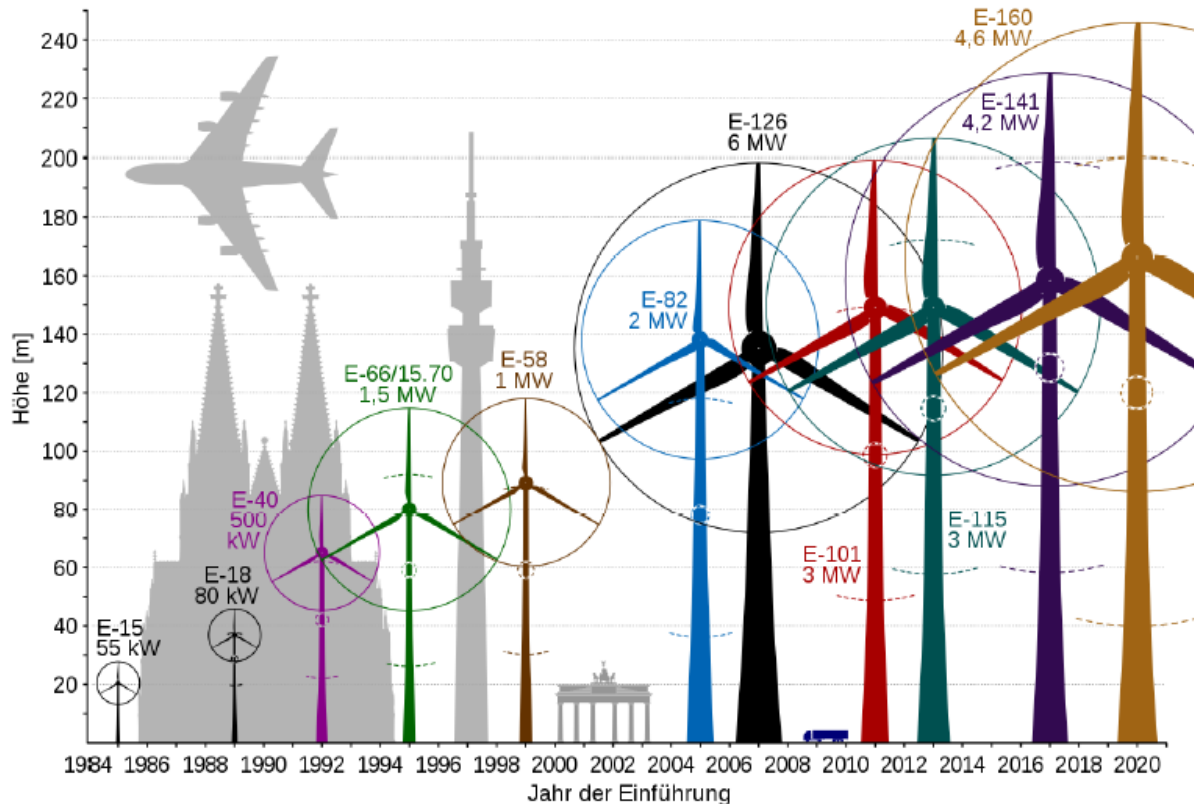
Emissions

Average values	CO ₂	NO _x	Water vapor	Contrails	Total
Kerosene	100%	100%	10%	100%	310%
Synfuel	0%	100%	10%	75%	185%
H₂ turbine	0%	35%	25%	60%	120% ≠ 0%
H ₂ fuel cell	0%	0%	25%	30%	55%

Energy / Primary Energy



Refueling an A350 Once per Day Can Be Done with 52 Big Wind Power Plants (4.6 MW Each)



Airbus A350-900:
 Kraftstoffkapazität: 138.000 L
1x Volltanken pro Tag
 entspricht
52x E-160 4,6 MW
 (Annahmen: CF=50%, $\eta_{PIL} = 0.45\%$)

EU-Study, May 2020: Aviation's Energy Demand – Too Much

The full global demand for LH₂ in aviation would require as much as 500 or 1,500 gigawatts of renewable energy capacity, depending on the scenario assumed, or about 20 or 60 percent of the total capacity of renewable energy available today.³⁸ Scaling up to this capacity would obviously raise significant planning challenges. That being said, if an energy-equivalent amount of synfuel from direct air capture were produced, it would require about three times the amount of renewable energy and one and a half times the amount of electrolysis. This is a significant drawback for synfuel, as the global energy system will already be challenged to scale up enough renewable energy to make the overall energy transition a success (as illustrated in the box on the next page.)

Footnote 38: Total generation capacity of renewable energy: 2351 GW (2018)

Globally, total renewable energy generation capacity reached 2,351 GW at the end of last year – about a third of total installed electricity capacity. Hydropower accounts for the largest share with an installed capacity of 1,172 GW – about half of the total. Wind and solar energy account for most of the remainder, with capacities of 564 GW and 480 GW, respectively. Other renewables included 121 GW of bioenergy, 13 GW of geothermal energy and 500 MW of marine energy (tide, wave and ocean energy).

<https://www.hydroreview.com/2019/04/03/irena-reports-renewable-energy-now-accounts-for-a-third-of-global-power-capacity>
Archived at: <https://perma.cc/YLY4-CG2R>

Aviation's energy demand today is too high: Minimum all wind or solar energy available today!

First we need to reduce the amount of air travel.

Then we may have a chance to power aviation with renewable energy.

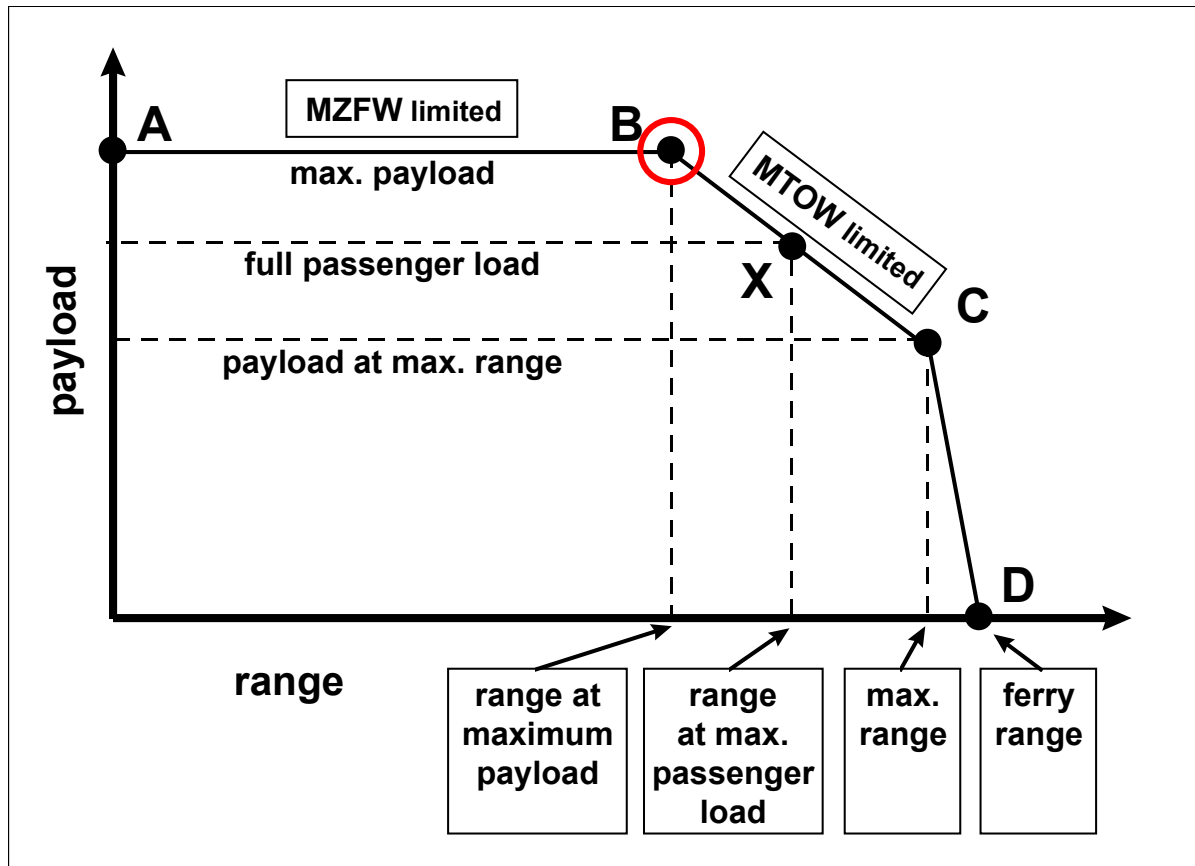
Airbus Hydrogen Concept Planes: Payload and Range

Introducing Airbus ZEROe

<p>Turboprop</p> 	 <100 Passengers  Hydrogen Hybrid Turboprop Engines (x 2)	 1,000+nm Range  Liquid Hydrogen Storage & Distribution System
<p>Blended-Wing Body</p> 	 <200 Passengers  Hydrogen Hybrid Turbofan Engines (x 2)	 2,000+nm Range  Liquid Hydrogen Storage & Distribution System
<p>Turbofan</p> 	 <200 Passengers  Hydrogen Hybrid Turbofan Engines (x 2)	 2,000+nm Range  Liquid Hydrogen Storage & Distribution System

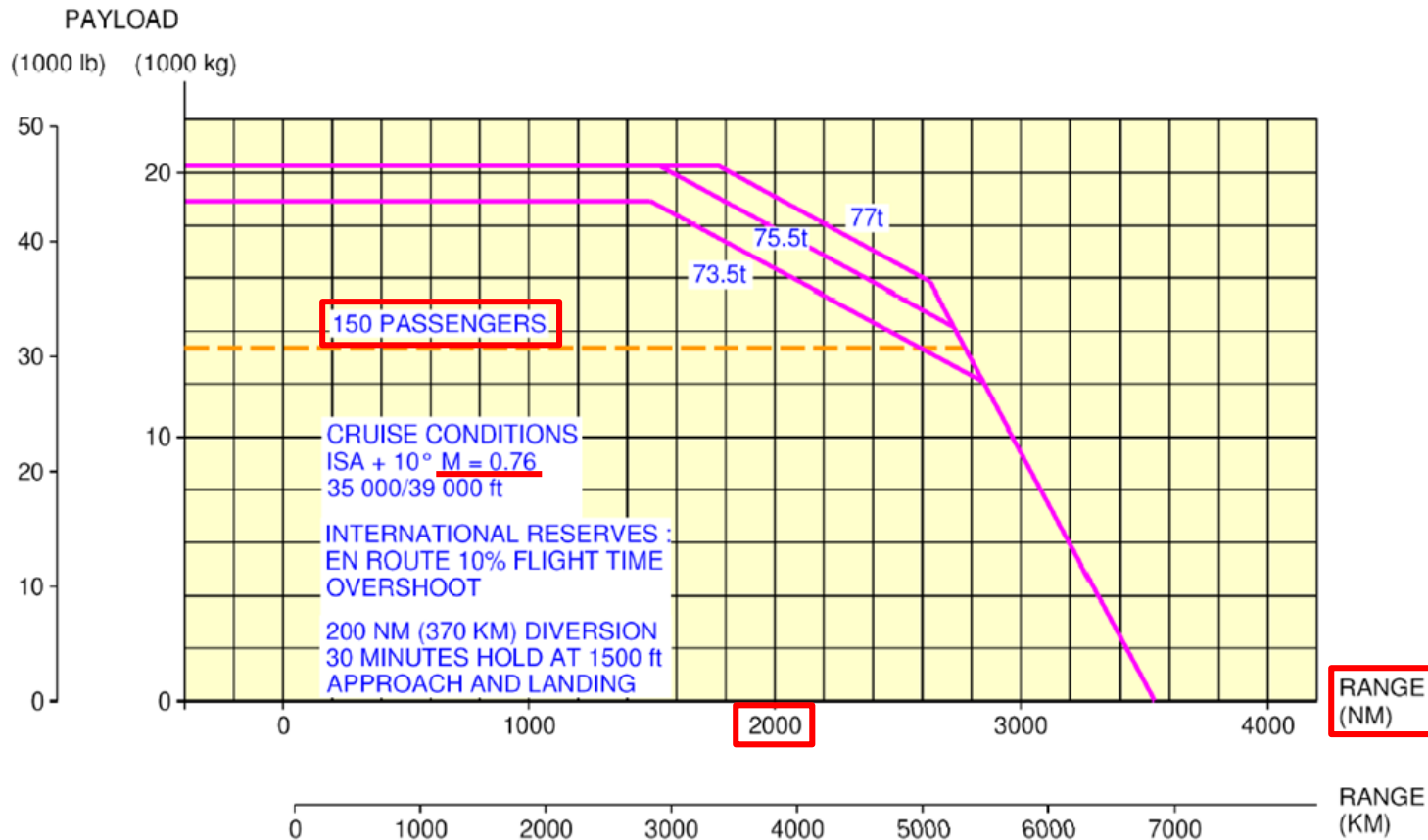


Payload-Range Diagram – Fundamentals



 usual design point

Payload-Range Diagram – Airbus A320



A320-200, Payload range diagram for CFM 56 5A series engine (Airbus 2011, p. 113)

ZEROe concept aircraft



Turbofan

Two hybrid-hydrogen turbofan engines provide thrust. The liquid hydrogen storage and distribution system is located behind the rear pressure bulkhead.

Here "hybrid" means: generator/motor embedded in the engine



Turboprop

Two hybrid-hydrogen turboprop engines, which drive eight-bladed propellers, provide thrust. The liquid hydrogen storage and distribution system is located behind the rear pressure bulkhead.



Blended-Wing Body (BWB)

The exceptionally wide interior opens up multiple options for hydrogen storage and distribution. Here, the liquid hydrogen storage tanks are stored underneath the wings.
Two hybrid-hydrogen turbofan engines provide thrust.

<https://www.airbus.com/innovation/zero-emission/hydrogen/zeroe.html>

Archived at: <https://perma.cc/HJ6L-3HUB>

Some Comments



Turbofan



Turboprop



Blended-Wing Body (BWB)

<https://www.airbus.com/innovation/zero-emission/hydrogen/zeroe.html>, Archived at: <https://perma.cc/HJ6L-3HUB>

- **Turbofan and turboprop** have the **LH2 tank only in the back**. This produces an unbalanced aircraft with a considerable CG shift during flight. The project "Green Freighter" (<http://GF.ProfScholz.de>) shows a turboprop with tanks fore and aft to balance the aircraft. (See Chapter "Introduction".)
- The project "Airport2030" (Possible A320 Successor, <http://Airport2030.ProfScholz.de>) was looking at a **200-passenger turboprop**. The turboprop needs less fuel than a turbofan, is lighter, the smaller wing area in 36 m span has a larger aspect ratio. Snowball effects help further. Together with other adapted parameter, **fuel consumption can be reduced by 30%** compared to a turbofan.
- The **BWB** above seems to be out of proportions. The aircraft has **only one door** (each side), which is not sufficient to evacuate 200 passengers. A design without vertical tail(s) is not advisable. BWB make sense (if at all) only for aircraft larger than the A380 (square-cube-law). With an efficient aerodynamic layout, a flying wing is **longitudinally statically unstable** and **cannot be certified** (today) to CS-25. Other show stoppers exist. See: Scholz 2006, <https://bit.ly/3leyyMr>

Related to "Hybrid": E-Fan X Hybrid-Electric Demonstrator based on Avro RJ100 / BAe 146



- Project announced on 2017-11-28.
- Project ended on 2020-04-24.

"The partners are committed to meeting the EU technical environmental goals of the European Commission's Flightpath 2050 Vision for Aviation (**reduction of CO₂ by 75%**, reduction of NO_x by 90% and noise reduction by 65%)." (<https://bit.ly/2UB4D6v>)

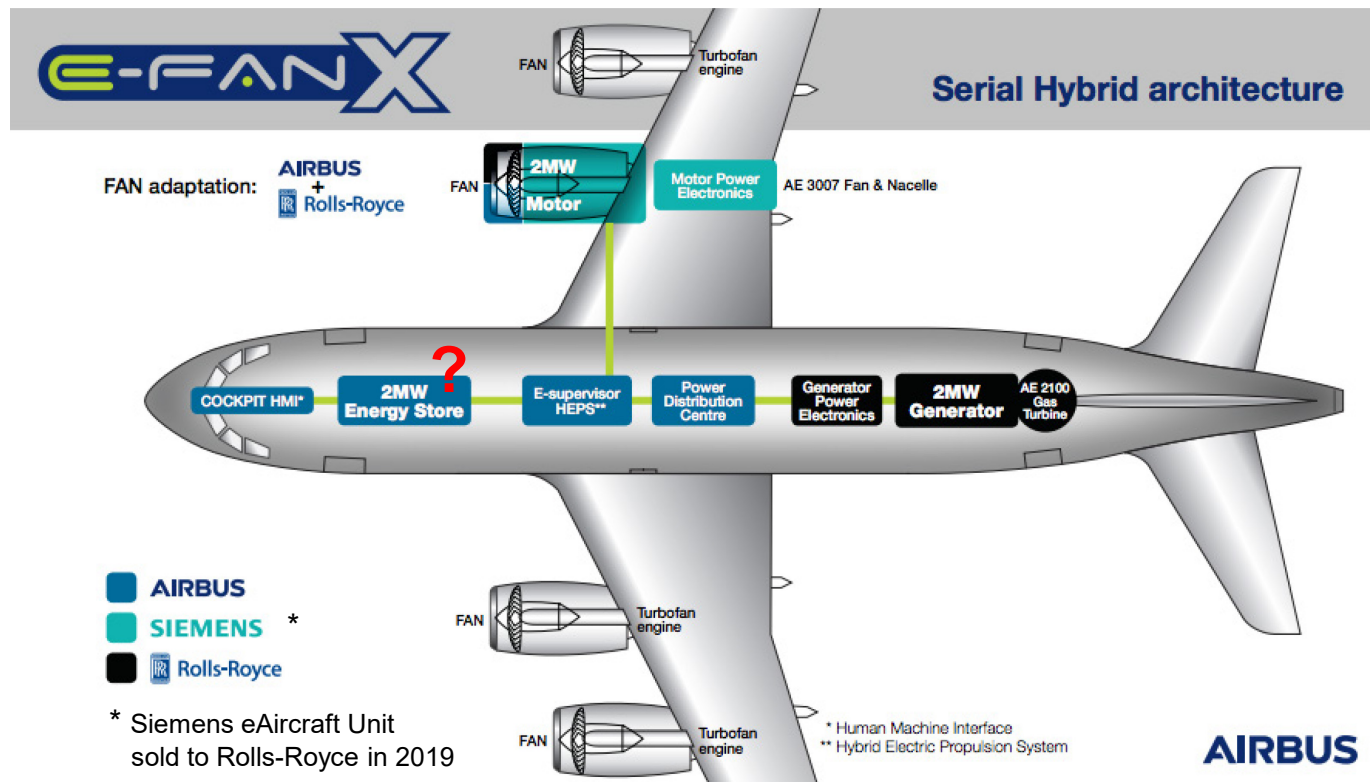


E-Fan X project lead Olivier Maillard



AIRBUS, 2018. *The Future is Electric*. Press Release, 2018-07-17. Available from: <https://www.airbus.com/newsroom/news/en/2018/07/the-future-is-electric.html>, Archived at: <https://perma.cc/V36S-7UVR>

Airbus / Rolls-Royce: E-Fan X Hybrid-Electric Propulsion



- Electric engines have at best the same mass as an aviation gas turbine.
- The new propulsion system (gas turbine, generator, electric motor) has **at least 3 times the mass of the original propulsion system**, which could do with only the gas turbine.

ROLLCE-ROYCE, 2017. We've Teamed up with Airbus and Siemens to Fly a Hybrid-Electric Aircraft by 2020. Twitter, 2017-11-28. Available from: <https://twitter.com/RollsRoyce/status/9354443638137622528>
 Archived at: <https://perma.cc/C26X-PLCR>

Airbus / Rolls-Royce: E-Fan X Hybrid-Electric Demonstrator

Evaluation Results at HAW Hamburg (Master Thesis, Benegas 2019):

- Given aircraft => Wing area, maximum loads, mass (MTOW, MZFW) relevant for certification is fixed!
- E-Fan X: Three Lycoming ALF 502 engines (old), one AE2100A turboshaft (new)
- New AE2100A gas turbine is slightly more efficient
- Take-off requires less than 2.5 MW (for one engine)
 - => **no batteries required** (therefore **eliminated here** to improve design)
- Operating empty weight (**OEW**) **increases**
 - => payload (MPL) decreases
 - => **number of passengers decreases** to 73 (from 82) by 11%
 - => **fuel burn** and **emission** per passenger **increase**
- Direct Operating Costs (**DOC**) per passenger seat mile **increase by about 10%**.

Airbus / Rolls-Royce: E-Fan X Hybrid-Electric Demonstrator

Greenwashing



E-Fan X
A giant leap towards zero-emission flight



<https://www.airbus.com/innovation/zero-emission/electric-flight.html>

Archived at: <https://perma.cc/9ZPP-ULRS>

For more on hybrid-electric flight see Bibliography:

Scholz 2017, <https://doi.org/10.5281/zenodo.3265212>

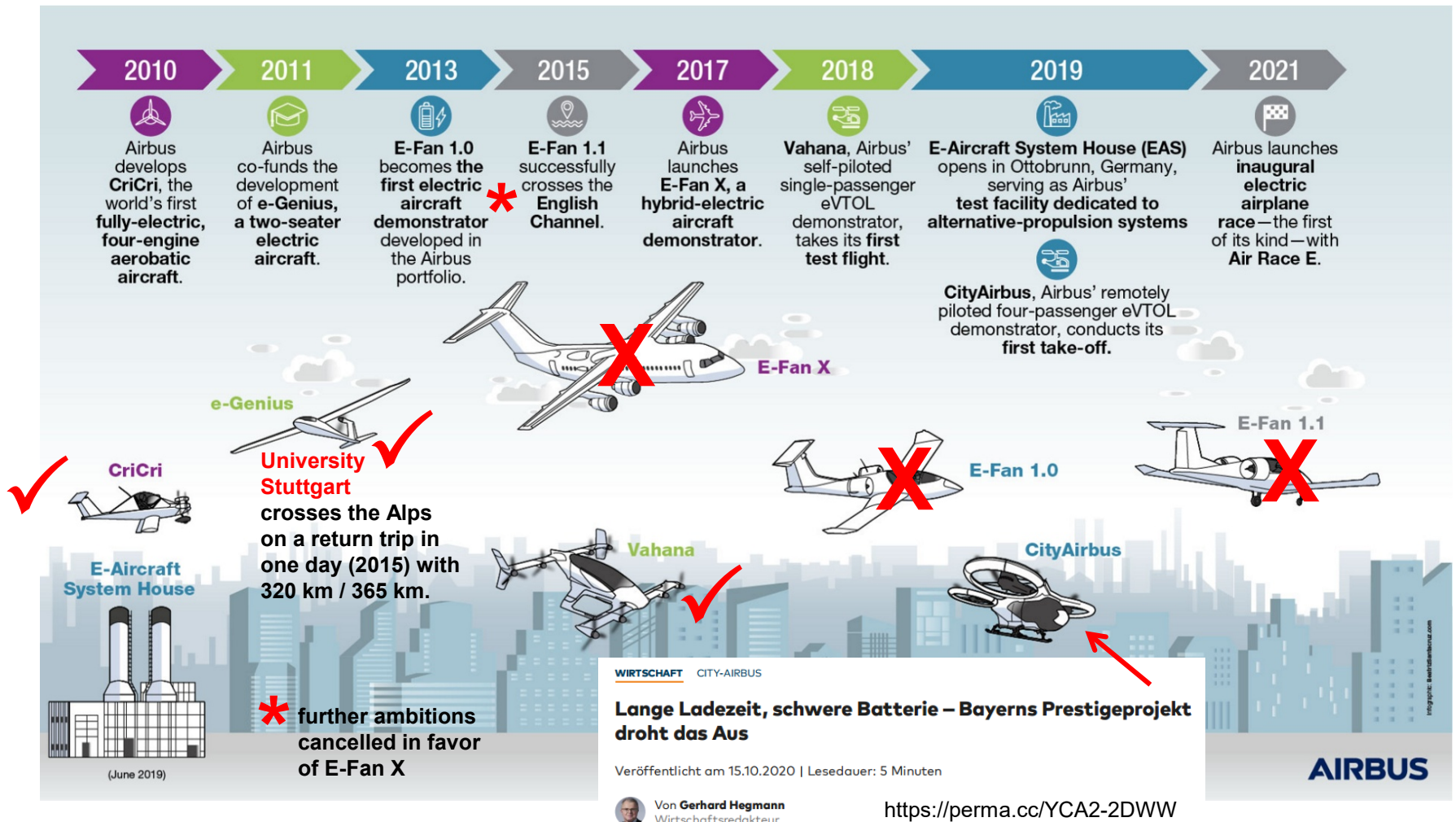
Scholz 2018, <https://doi.org/10.15488/3986>

Scholz 2019, <https://doi.org/10.5281/zenodo.4072283>

Modern Aviation Vocabulary

- a giant leap (for mankind; Neil Armstrong when setting foot on the moon)
- to rise to the challenge
- seismic shift
- game-changing
- (bold) vision
- revolutionary design
- disruptive technology (braking with the traditional way e.g. of technology)
- (there is no) silver bullet (simple solution to a complicated problem)
- crystal ball (forecasting the future)
- the entire aviation ecosystem
- ...

Electric Propulsion at Airbus – Limited Success



Airbus Concept Planes



<https://www.airbus.com/company/sustainability/environment/future-aircraft.html>

Archived at: <https://perma.cc/7EQH-88DY>

"The aviation industry has committed to **carbon-neutral growth** starting from **2020**.

But this ambitious target **cannot be achieved using existing aircraft...**"

This is an Airbus statement still on the Internet on 2020-11-19.

Question: **When does Airbus want to offer the new aircraft to manage carbon-neutral growth in 2020?**



The Airbus Concept Plane

Airbus experts in aircraft materials, aerodynamics and engines came up with a Concept Plane design that is an 'engineer's dream'.

More than a flight of pure fantasy, The Airbus Concept Plane embodies what air transport could look like in 2050 – even 2030 if advancements in existing technologies continue apace. Ultra long and slim wings, semi-embedded engines, a U-shaped tail and lightweight intelligent body all feature to further improve environmental performance or 'eco-efficiency'. The result is lower fuel burn, a significant cut in emissions, decreased noise pollution and greater comfort.

The Airbus Concept Plane brings together a package of technologies, which although feasible, are unlikely ever to coexist in this manner. So it is not a plane that will fly, but it stretches the imagination of engineers, it highlights some of the challenges and decisions that lie ahead for air travel, and it illustrates the main technologies being explored in anticipation of the future needs of passengers and their planet.

Airbus, 2011-06-25:
The Future by Airbus.
Archived at:
<https://perma.cc/NNS6-EB6M>

Airbus Concept Plane: MAVERIC (11 February 2020)



<https://perma.cc/92XW-266S>

Airbus Concept Plane: Bird of Prey (19 July 2019)



<https://perma.cc/QF4J-QF3A>

Airbus Concept Plane: E-Thrust (9 January 2014)



<https://perma.cc/3VTP-HM47>

Airbus Concept Plane: No Name (4 February 2011)



<https://perma.cc/K2N4-2ZCS>

Many pretty pictures, but **it was never intended that anything would come out of it.**
 Will it be **different** this time **with** the latest concept plane, **ZEROe**? Or is ZEROe **only buying time**?

Corona, Politics, and Lots of Money Behind ZEROe

9-Jun-2020 12:07 PM

CORAC to receive EUR1.5bn over three years to research carbon neutral aircraft

<https://centreforaviation.com/news/corac-to-receive-eur15bn-over-three-years-to-research-carbon-neutral-aircraft-1003496>

Archived at: <https://perma.cc/9WEM-TGAV>

The French government has earmarked 1.5 billion euros for the development of carbon-free aircraft as part of a support plan for the aviation sector, which has been brought to its knees by the fallout from the coronavirus pandemic. Overall, France is planning to invest 7 billion euros in the development of hydrogen solutions, with neighboring Germany setting aside 9 billion.

<https://www.dailysabah.com/business/transportation/airbus-aims-for-zero-emission-planes-by-2035>

Archived at: <https://perma.cc/8MV9-4HMN>

In a sharp increase in funding for the [Council for Civil Aviation Research] CORAC research body, France said it would invest 1.5 billion euros over three years to support research into environmentally friendly technology. The main goal of the investment would be a carbon-neutral successor to the A320, Europe's best-selling jet, with hydrogen as an energy source instead of today's oil-based gas turbines. "Our target is to have a carbon-neutral airplane in 2035 instead of 2050, thanks especially to an (ultra-efficient) engine using hydrogen," Le Maire [french finance minister] said.

<https://www.reuters.com/article/us-health-coronavirus-france-aerospace-idUSKBN23G0TB>

Archived at: <https://perma.cc/3HL5-ARRF>

Corona, Politics, and Lots of Money Behind ZEROe

The Conseil Stratégique pour la Recherche Aéronautique Civile Française (CORAC)

English: Council for Civil Aviation Research

*The decision to **create** a Council for Civil Aviation Research (**CORAC**) was taken at the French environment round table and included in the agreement of January 28, **2008** which outlined the resulting commitments of the air transport industry. The council, which takes as **its model the EU's Advisory Council for Aeronautical Research in Europe (ACARE)**, was set up on July 23, 2008. Bringing together the [Direction Générale de l'Aviation Civile] DGAC with all the other industry bodies (companies, airlines, airports, air navigation institutions, research centres), it is **charged with drawing up and implementing the research projects and technological innovations** needed to attain the environmental targets set by the ACARE.*

https://www.ecologie.gouv.fr/sites/default/files/DGAC_Environmental_Report_ENG_for_2008.pdf

Archived at: <https://perma.cc/M2QF-NJ9W>



Aeronautics: "The ecological transition requires a profound transformation of our industry"

*Google translation
of French webpage.*

Technical progress will not be enough to reduce greenhouse gas emissions from airplanes, essential against global warming, say more than 700 students from the aeronautics sector in a forum at the "World", who plead in favor of industrial conversions and a reduction in air traffic.

Posted May 29, 2020 at 7:30 a.m. - Updated June 25, 2020 at 2:56 p.m. | ⌚ 5 min read

https://www.lemonde.fr/idees/article/2020/05/29/aeronautique-la-transition-ecologique-impose-une-profonde-transformation-de-notre-industrie_6041127_3232.html

Archived at: <https://perma.cc/5L84-G4QN>

Biggest Emission Reduction in Aviation History Thanks to the Corona Pandemic



Ikreis, CC BY-SA, <https://bit.ly/2Jn11T0>



Traffic reduction is
more efficient than
technology



<https://stay-grounded.org>

It's about more than just CO2

Aviation must reduce its total impact on climate

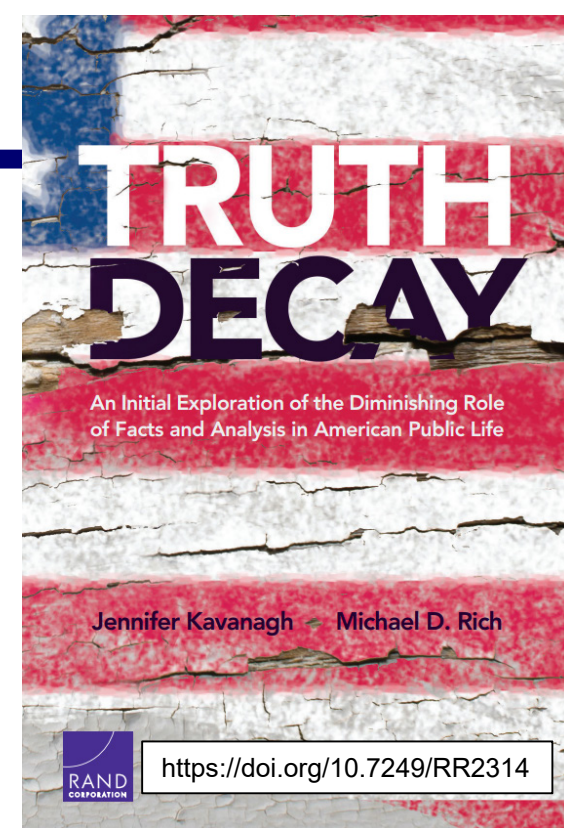
Summing Up the Airbus ZEROe Case

- Environmental arguments are inconsistent.
- Effect of emitted water (AIC: contrails & cirrus clouds) not mentioned.
- Statement "Zero Emission" is wrong.
- Primary energy consumption not considered.
- Global energy demand of aviation under LH2 scenario not considered.
- Concept plane is wrong medium to communicate serious research and development.
- Requirements from concept planes are incomplete (only number of passengers and range).
- Concept plane are just ideas and nice pictures, but no commitment.
- Absolutely no results or more detailed ideas communicated with concept planes.
- Design errors on concept planes.
- No track record of successful alternative energy aircraft projects.
- Probably motivated by 1.5 billion euro bailout money.
- 1.5 billion euros to be spent in 3 years. Compared with: 10% of this time (9.6.-21.9.2020) elapsed at day of presentation of concept planes (without meaningful results)!
- Not willing to see apparent solution for the environment: Fly less! (As we do now.)
- Disinformation of the public ("Zero Emission").
- Intentional disinformation and as such: "Fake News" disseminated via Social Media.

Truth Decay: Right or Wrong Does Not Matter Anymore

Definitions from the book:

<u>Disinformation</u>	<u>False or misleading information spread intentionally, usually to achieve some political or economic objective, influence public attitudes, or hide the truth.</u> This is a synonym for propaganda.
<u>"Fake news"</u>	Newspaper articles, televisions news shows, or other <u>information disseminated</u> through broadcast or social media that are <u>intentionally</u> based on falsehoods or that <u>intentionally use misleading framing to offer a distorted narrative</u>



Airbus spreads misleading information ("zero emission") intentionally, which makes it "Fake News":

- Airbus knows better, because Airbus partnered the EU report "Hydrogen-Powered Aviation". (<https://doi.org/10.2843/471510>)
- Dr. Bour-Schaeffer (Airbus) knows better and has publically declared as such (RAeS Corporate Partner Briefing, 2020-11-05), only when asked, however this has not changed Airbus' official narrative or written statements.
- This is not a single event. **Airbus has distributed similarly wrong statements e.g. related to cabin air ventilation:** SCHOLZ, Dieter, 2020. *Airbus' Cabin Air Explanations during the Corona Pandemic – Presented, Analyzed, and Criticized*. Available from: <http://purl.org/corona/M2020-06-19> (PDF)

For more related information see:

SCHOLZ, Dieter, 2020. *Aviation Ethics – Growth, Gain, Greed, and Guilt*. German Aerospace Congress 2020 (DLRK 2020), Online, 01.-03.09.2020. Available from: <https://doi.org/10.5281/zenodo.4068009>

What Is the Hidden Strategy?

- When a strategy is hidden, **only assumptions** about it can be made. Here an attempt.
- **Airbus** has no new aircraft under development. Aircraft deliveries are down. Little work for many employees. The know-how of the workforce needs to be maintained. Salaries need to be paid. **Government** can **help** and pay (see previous pages).
- **After the Corona pandemic** the aviation world may look different. Business travel will be less, because web meeting tools are in frequent use. Private travel may not reach the growth rates as seen before.
- **With a "zero emission" aircraft an argument is prepared...**
 - **against** possible political **ideas to keep flying at low numbers** close to those during the Corona pandemic for environmental reasons,
 - **against** any other **political limitations or financial measures** for environmental reasons,
 - **to convince passengers** that flying is not that bad after all (against a bad conscience, against flight shame or flygskam),
 - **to buy time** and to continue as long as possible without further political disturbance.
- **The aircraft needs to be "zero emission"** not because it is "zero emission", but **because anything less than that will neither convince politics nor passengers.**
- **This is why a technical debate about: "How much 'zero emission' is possible?" is impossible!**

Airbus A321 for LH2 (HAW Hamburg)

SCHOLZ, Dieter, DIB, Leon, 2015. *Hydrogen as Future Fuel Used in Minimum Change Derivatives of the Airbus A321*. German Aerospace Congress 2015 (DLRK 2015), Rostock, Germany, 22. - 24. September 2015. Available from: <https://doi.org/10.5281/zenodo.4073172>

Hydrogen's **Show Stopper** in Aviation (up to 2020)

Hydrogen's show stopper in aviation is the necessary **big investments**

- 1.) in new aircraft
- 2.) in new airport infrastructure
 - * liquid hydrogen production
 - * new refueling equipment at airports


In contrast:

Drop-in fuel (biofuel, synthetic fuel) needs **no investment in the aviation system**

- 1.) same aircraft
- 2.) same airport infrastructure
 - * no extra production facility at airport
 - * same refueling equipment

Hydrogen's **Show Stopper** in Aviation (up to 2020)

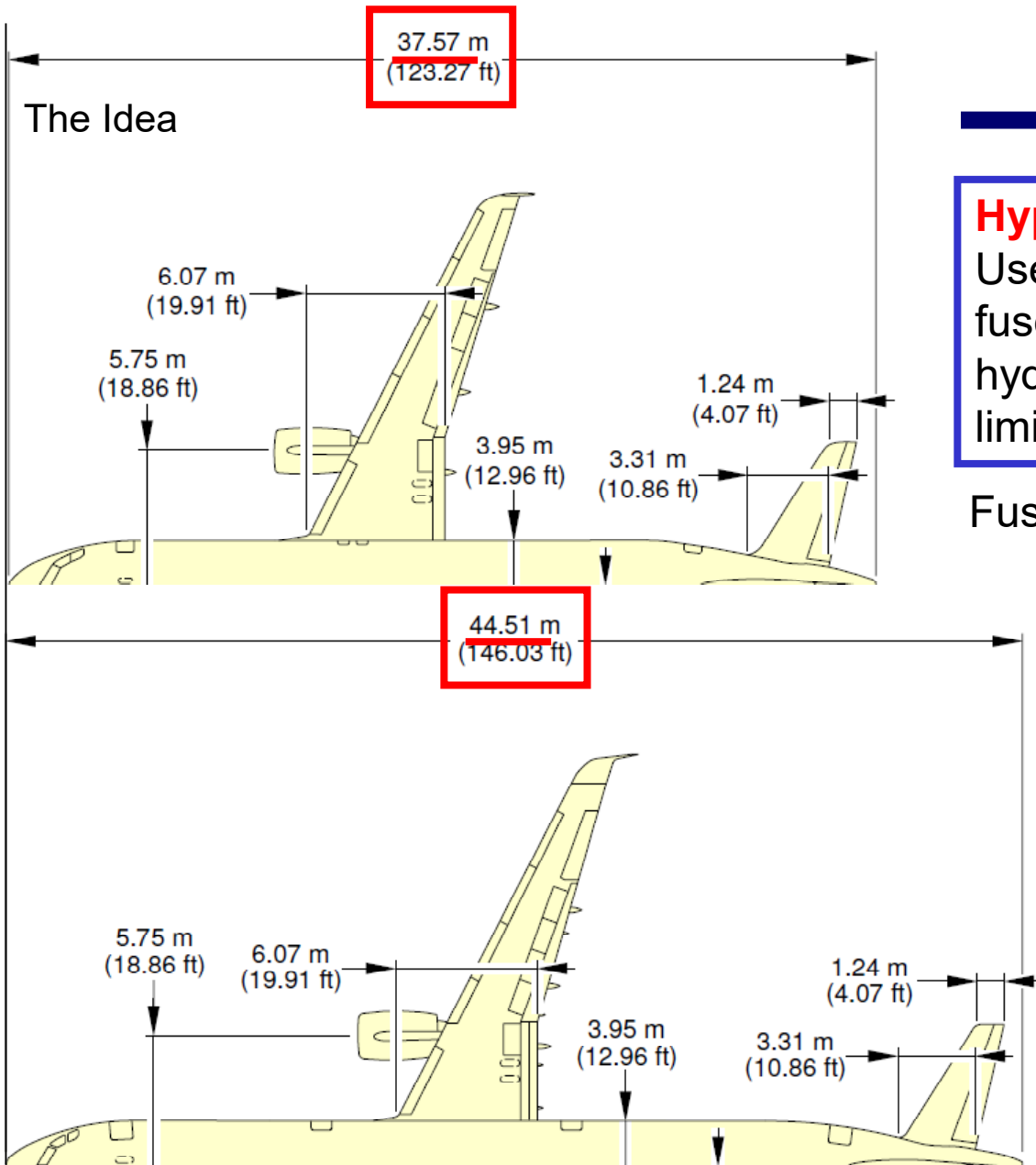
Hydrogen's show stopper in aviation is the necessary **big investments**

- 1.) in new aircraft 
- 2.) in new airport infrastructure
 - * liquid hydrogen production
 - * new refueling equipment

*Can we reduce the investment
by using modified existing
aircraft for the new energy carrier
hydrogen?*

SCHOLZ, Dieter, DIB, Leon, 2015. *Hydrogen as Future Fuel Used in Minimum Change Derivatives of the Airbus A321*. German Aerospace Congress 2015 (DLRK 2015), Rostock, Germany, 22. - 24. September 2015. Available from: <https://doi.org/10.5281/zenodo.4073172>

The Idea

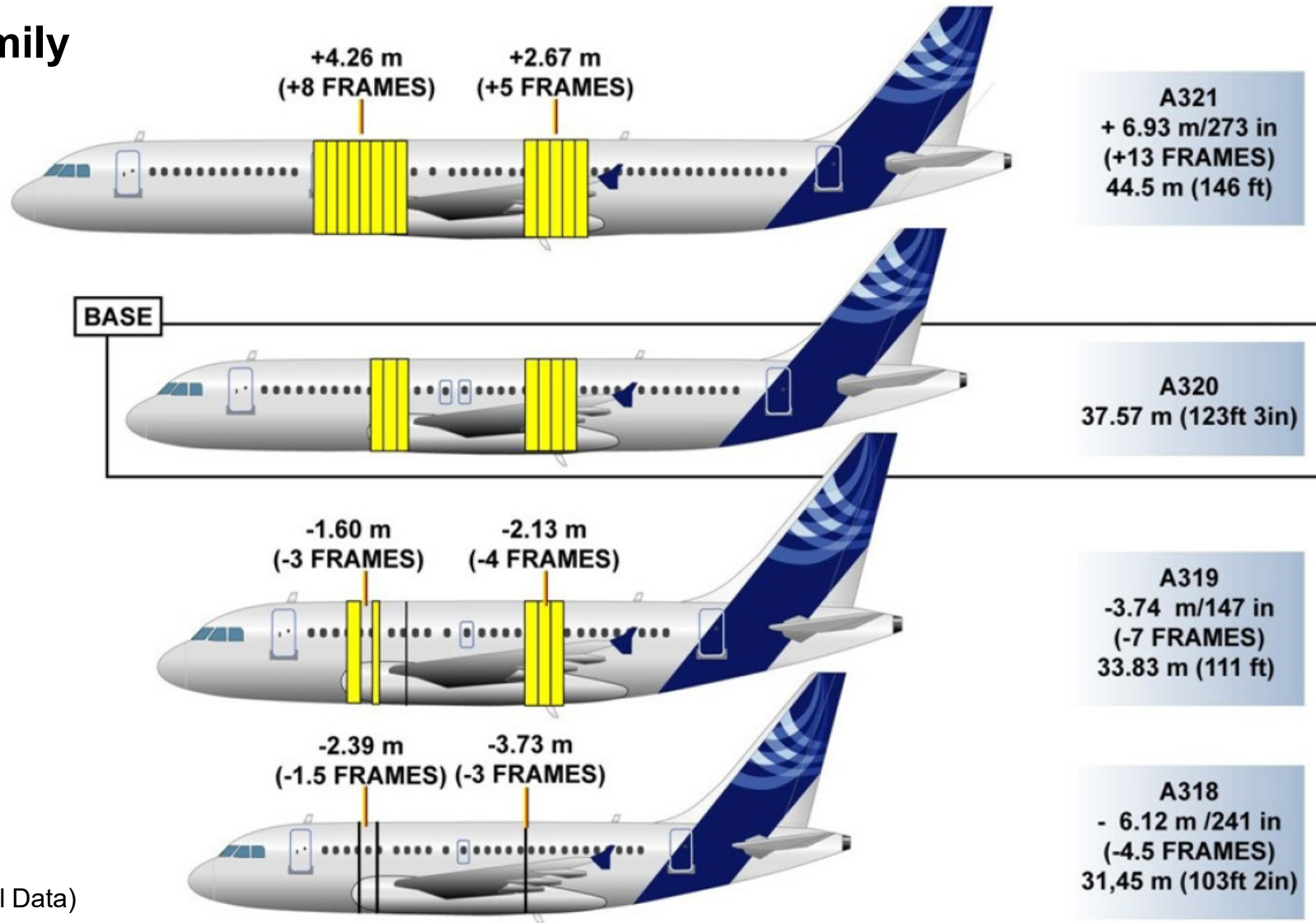


Hypothesis:
Use an existing (longer) fuselage to integrate the hydrogen tanks to limit investment!

Fuselage Length Compared:
A320

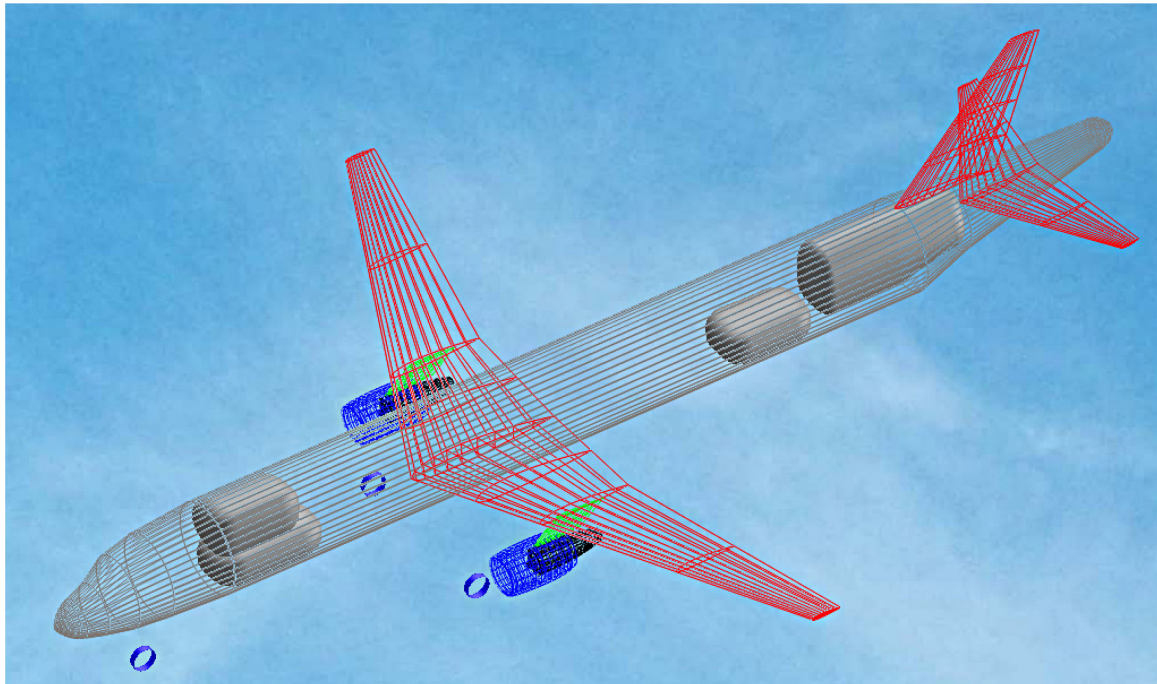
A321

A320 Family



Dimensions of the A320 family (Airbus Technical Data)

Hydrogen Storage **in** the Fuselage (Front and Rear)

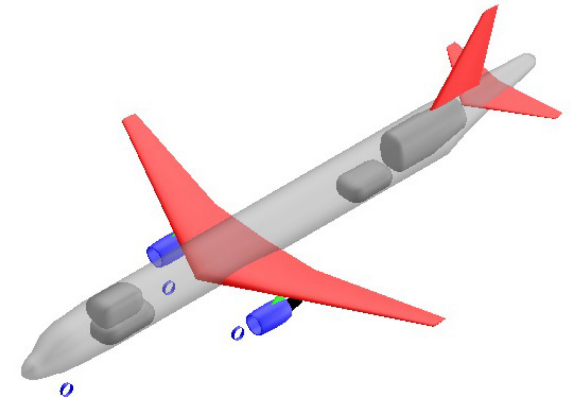


Distribution of the tank in the front and in the back to **balance CG**.

Two tanks forward and two tanks aft. Assume no double **tank failure** or aircraft robust against CG shift.

Use of some portion of the front and aft **cabin**.

Use of an even bigger portion of front and aft **cargo compartment**.



Trade-Off for Tank Location in Fuselage

Not compatible with simple fuselage stretch.

FEATURE	CONFIGURATION	
	Over the fuselage	Front and Rear
Access for crew and passengers	3 [†]	1
Surface to volume considerations	1	3
Control of C.G.	2	3
Security in case of damage	3	2
Drag Increase	1	3
Weight increase	2	2
Manufacturing process consideration	1	3
TOTAL	13	17

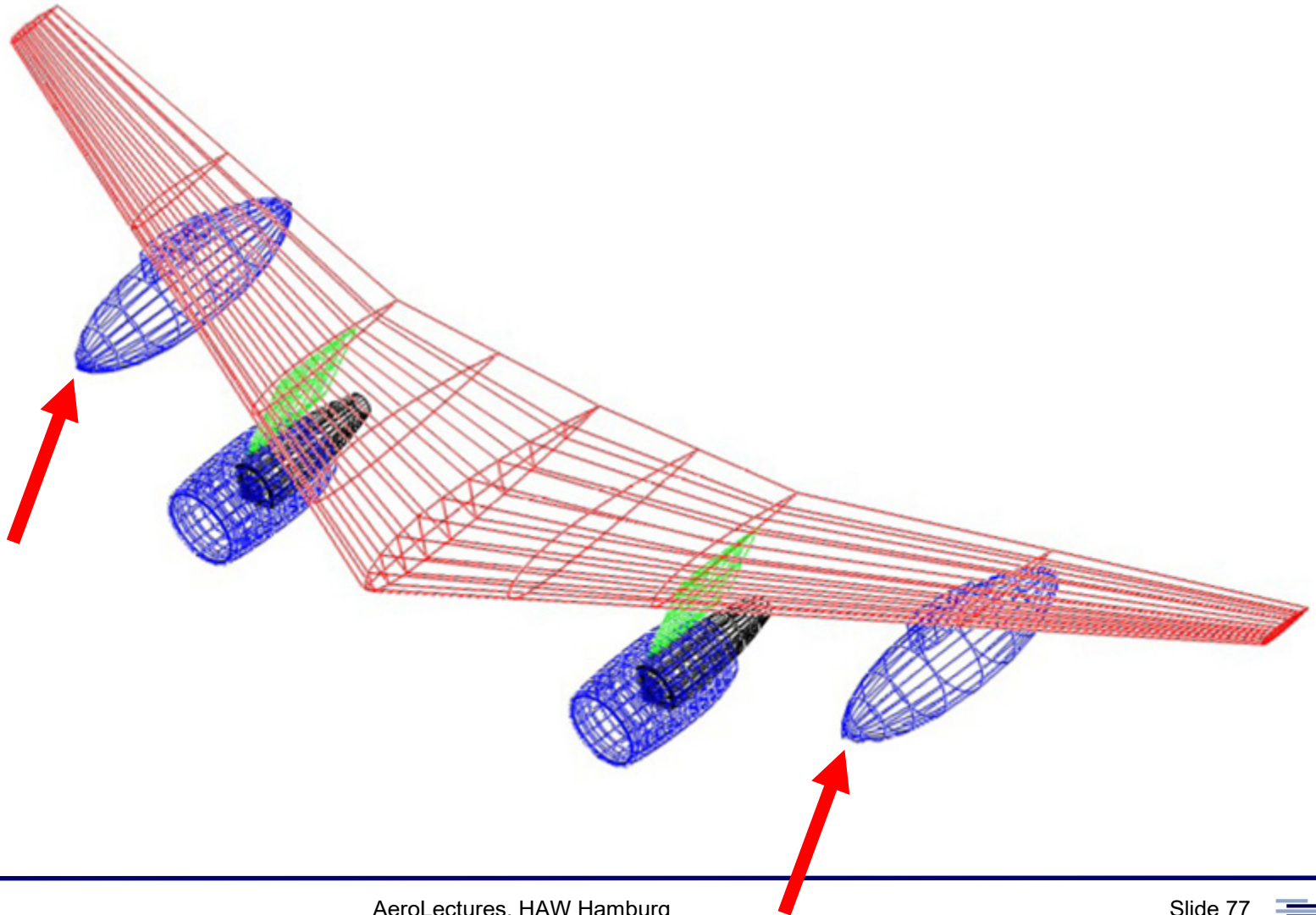
Scoring Model

[†] 3 is High; 2 is Medium; 1 is Low

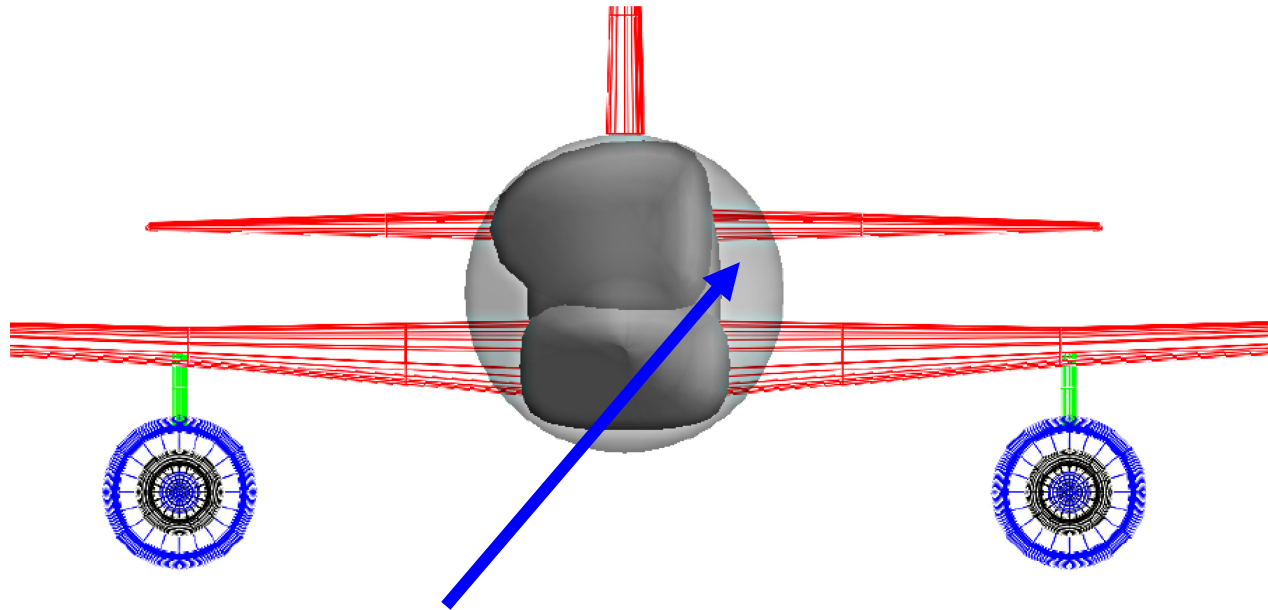
The winner!



Additional (!) Hydrogen Storage in Underwing Pods

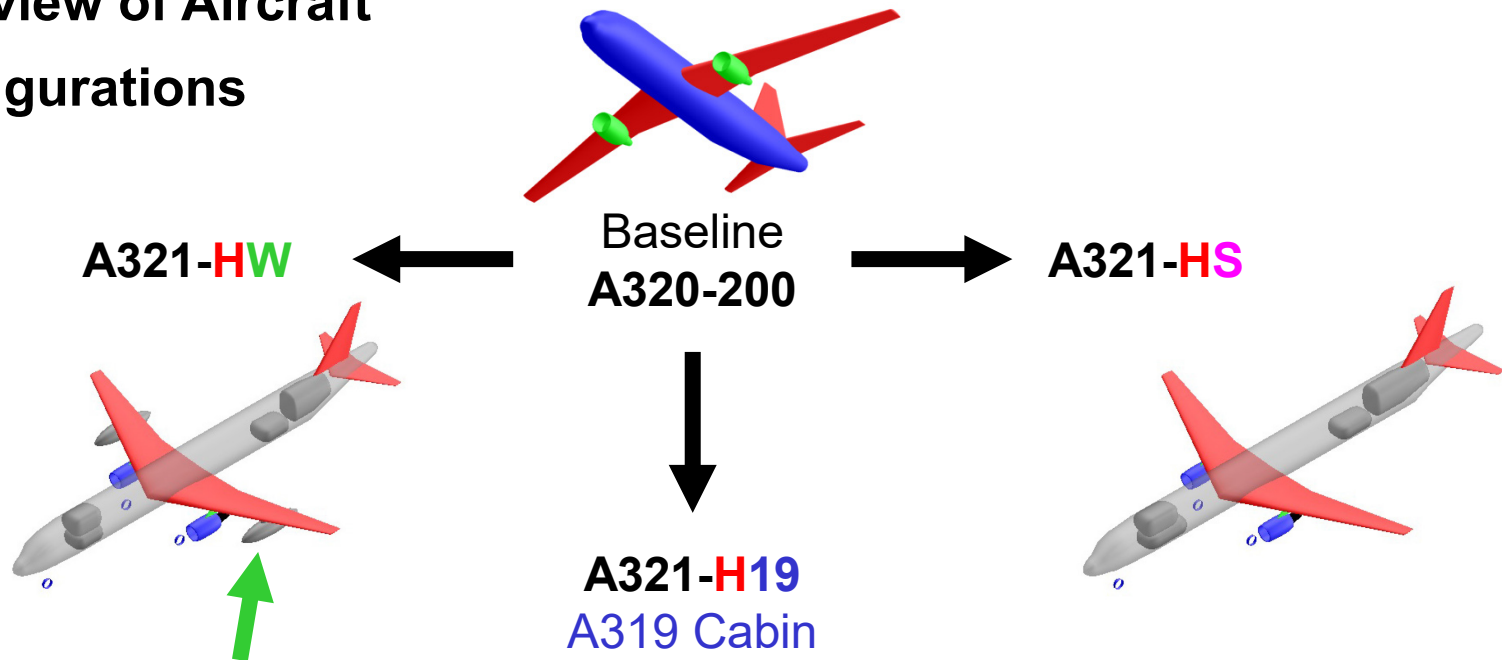


Passage Way for Cockpit Crew to Reach the Cabin



- For certification: No need for **passage** way from cockpit to cabin (according to Roskam)
- Passage way selected here for convenience.
But: Reduces tank volume in the front tank leads to longer fuselage.

Overview of Aircraft Configurations



- H:** LH2 Aircraft
- W:** A321 with additional hydrogen tanks under wing
- S:** A321 with additional stretch (to give more volume for LH2 tanks)
- 19:** A321 filled only with 156 (instead of 180) one-class passengers (more room left for LH2 tanks). Same payload & range kept

Baseline Aircraft: A320

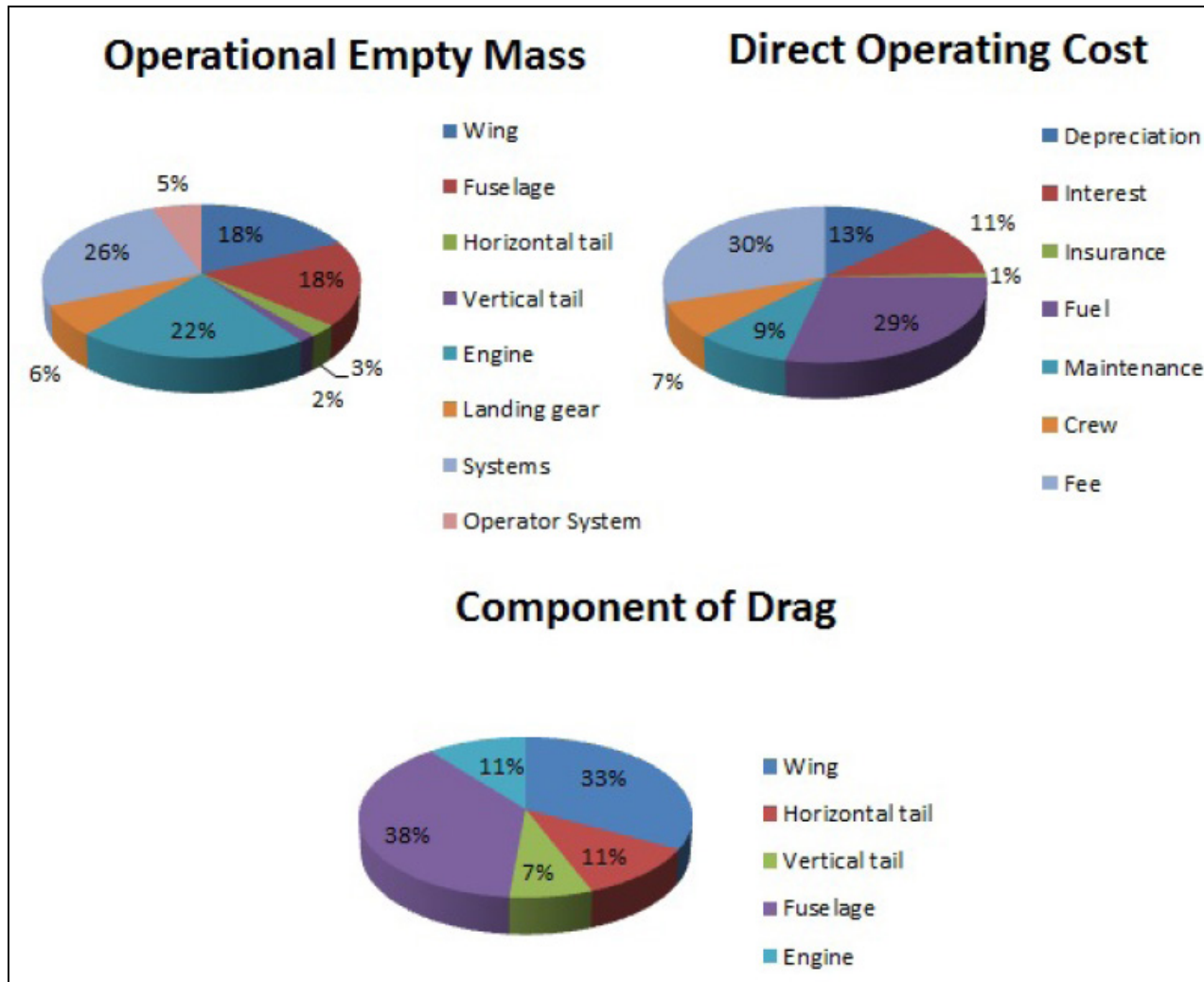
List of fundamental aircraft and cabin variables with the values of the reference aircraft

Parameter	Value
m_{MPL} [kg]	19256
R_{MPL} [NM]	1510
M_{CR}	0.76
s_{TOFL} [m]	1767.8
s_{LFL} [m]	1447.8
n_{PAX}	180
m_{PAX} [kg]	93
SP [in]	29

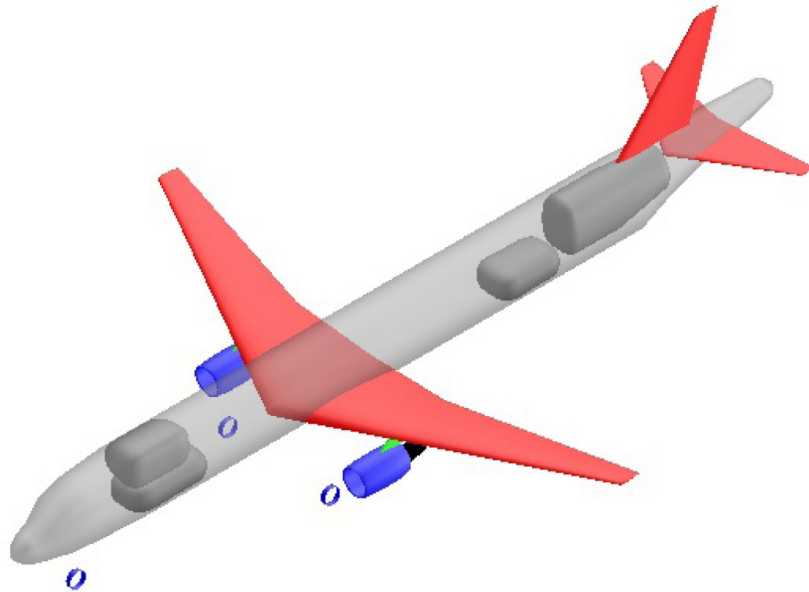
Calculation tool adapted and used:
OPerA – Optimization in Preliminary Aircraft

Parameter	Name	Value A320-200
Landing field length [m]	s_{LFL}	1448
Take-off field length [m]	s_{TOFL}	1768
Max. lift coefficient, landing	$C_{L,max,L}$	3.14
Max. lift coefficient, take-off	$C_{L,max,TO}$	2.82
Mass ratio, max landing to max take-off	m_{ML}/m_{MTO}	0.88
Aspect ratio	A	9.5
Number of engines	n_E	2
Number of passengers	n_{PAX}	180
Number of seats abreast	n_{SA}	6
Wing sweep at 25 % chord [°]	φ_{25}	25
Taper ratio	λ	0.213
Position of the vertical tail in case of cruciform config.	z_H/b_V	0.56
Minimum distance from engine to wing over nacelle diam.	$z_{P,min}/D_N$	0.15
By-Pass ratio	BPR	6
Mach number, cruise	M_{CR}	0.76
Seat pitch [m]	SP	0.74
Aisle width [m]	w_{aisle}	0.51
Seat width [m]	w_{seat}	0.51
Armrest width [m]	$w_{armrest}$	0.051
Sidewall Clearance (at armrest) [m]	$s_{clearance}$	0.015

Breakdown of the OEW, DOC and Drag Component, A320-200



Comparison of A321-HS with A320-200



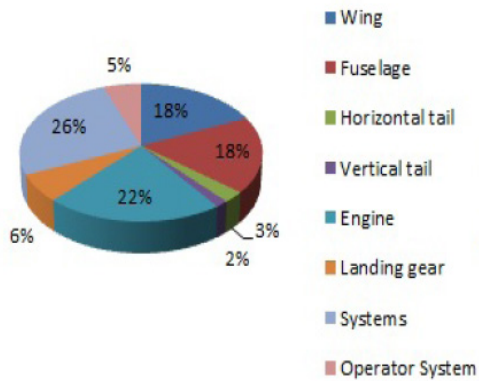
Parameter	A321-HS	Variation (A320)	
m_{MTO} [kg]	73578	+1.8	
m_{OE} [kg]	47658	+18.6	
m_F [kg]	6664	-48.0	energy up 46 %
DOC (AEA) [€/NM/t]	1.68	+26.7	
DOC (TUB) [€/NM/t]	1.49	+29.3	
l_F [m]	49.4	+28.8	A321: $l_F = 44.5$ m Delta: 4.9 m
S_W [m ²]	131.1	+9.0	
$b_{W,geo}$ [m]	35.3	+4.4	
$A_{W,eff}$	9.5	0	
ϕ_{25} [°]	25	0	
λ	0.21	0	
E_{max}	17.6	+0.4	
T_{TO} [kN]	103.9	-5.0	
BPR	6	0	
SFC [kg/N/s]	5.79E-06	-65.0	
h_{CR} [ft]	37706	-3.0	
m_{MTO}/S_W [kg/m ²]	560.7	-6.6	

Details of the tanks for the A321-HS

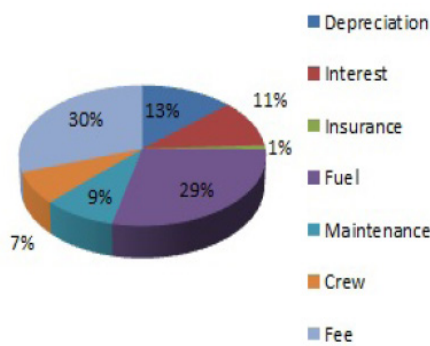
	Length [m]	Mass of tank [kg]	Mass of fuel [kg]
Rear upper tank	4.14	581.6	1600
Rear lower tank	5.24	315.4	1225
Back upper tank	6.92	1385	2874.4
Back lower tank	4.16	249.3	967.8
Total [kg]		2531.3	6667.2

Aircraft Design for Hydrogen

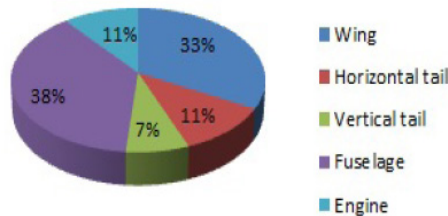
Operational Empty Mass



Direct Operating Cost

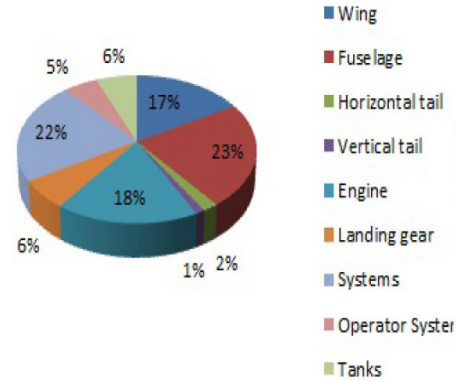


Component of Drag

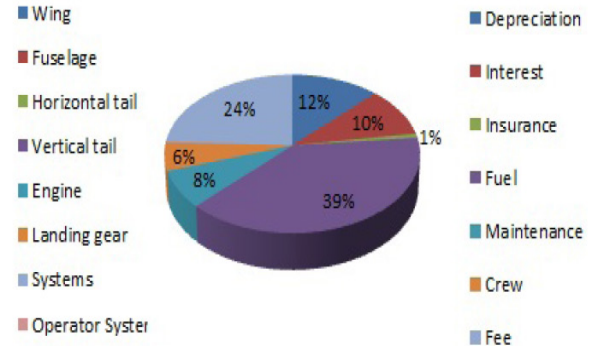


A320-200

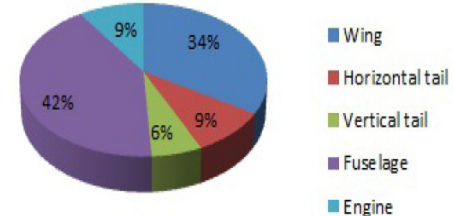
Operational Empty Mass



Direct Operating Cost

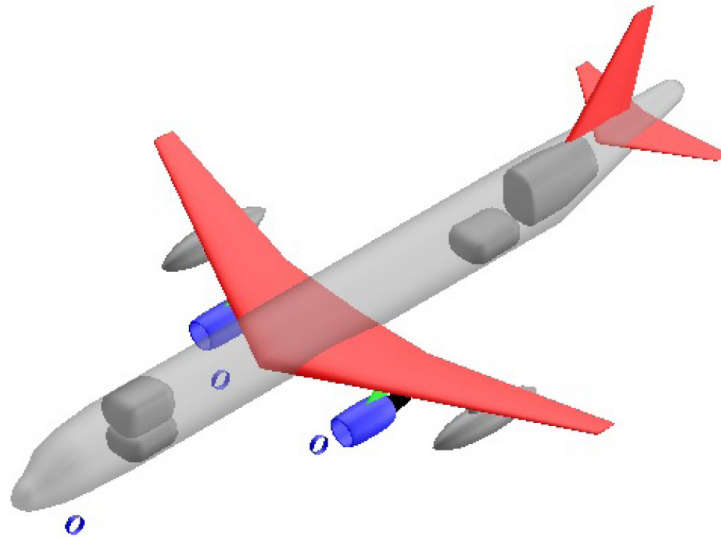


Component of Drag



A321-HS

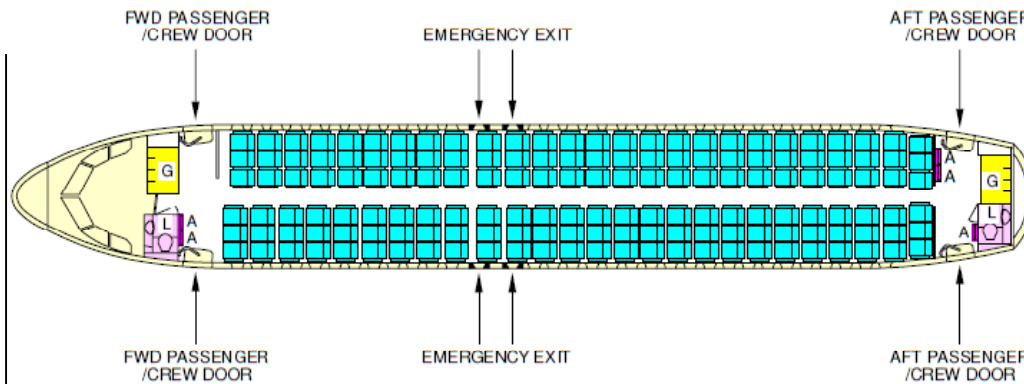
Comparison of A321-HW with A320-200



Parameter	A321-HW	Variation (A320)
m_{MTO} [kg]	70716	-2.2
m_{OE} [kg]	44871	+11.6
m_F [kg]	6588	-48.6 energy up 44 %
DOC (AEA) [€/NM/t]	1.63	+23.3
DOC (TUB) [€/NM/t]	1.45	+25.9
l_F [m]	45.2	+18.0 A321: $l_F = 44.5$ m Delta: 0.7 m
S_W [m ²]	126.1	+4.8
$b_{W,geo}$ [m]	34.6	+2.4
$A_{W,eff}$	9.5	0
φ_{25} [°]	25	0
λ	0.21	0
E_{max}	16.9	-3.9
T_{TO} [kN]	99.8	-8.8
BPR	6	0
SFC [kg/N/s]	5.82E-06	-64.8
h_{CR} [ft]	36720	-5.6
m_{MTO}/S_W [kg/m ²]	560.7	-6.6

Details of the tanks for the A321-HW

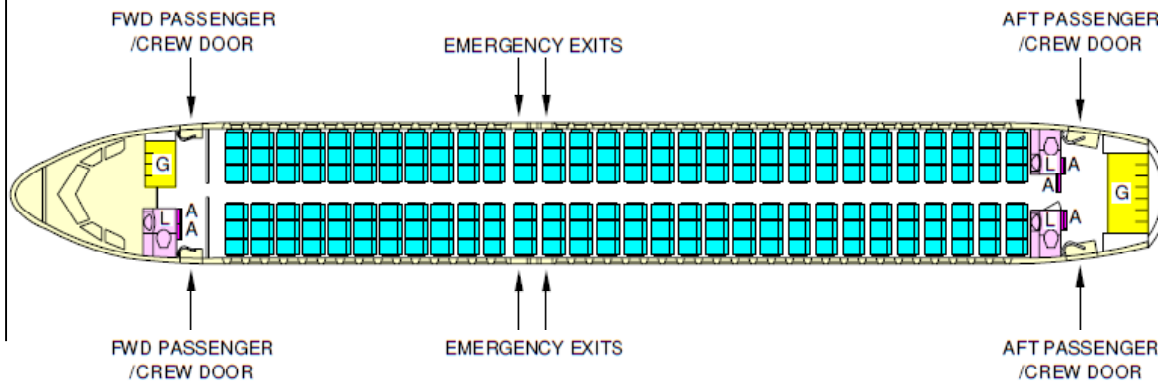
	Length [m]	Mass of tank [kg]	Mass of fuel [kg]
Rear upper tank	3.5	484.7	1333.5
Rear lower tank	3.5	207.7	805.3
Back upper tank	3.5	692.4	1300
Back lower tank	3.5	207.7	805.3
Wing tanks	6	880	2345
Total [kg]		2472.5	6589.1



A319, 156 pax

ITEM	DESIGNATION
G	GALLEY (2)
L	LAVATORY (2)
A	ATTENDANT SEAT (5)

156 SEATS ALL TOURIST CLASS
28/30 in PITCH. 6 ABREAST. 3.3

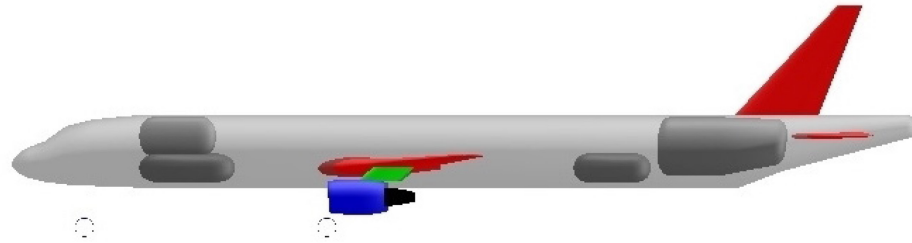


A320, 180 pax

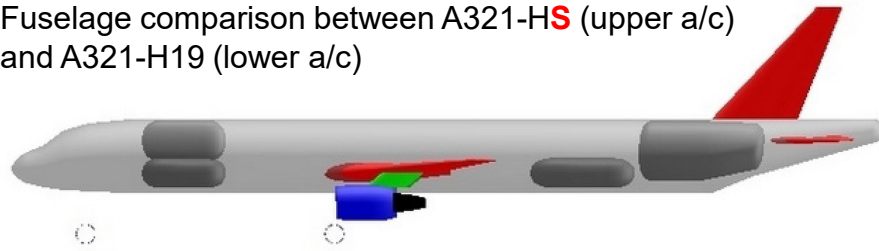
ITEM	DESIGNATION
G	GALLEY (2)
L	LAVATORY (3)
A	ATTENDANT SEAT (5)

180 SEATS ALL TOURIST CLASS
28/29 in PITCH. 6 ABREAST. 3.3

Comparison of A321-H19 with A320-200



Fuselage comparison between A321-HS (upper a/c) and A321-H19 (lower a/c)



Details of the tanks for the A321-H19

	Length [m]	Mass of tank [kg]	Mass of fuel [kg]
Rear upper tank	4.36	612.5	1685.2
Rear lower tank	4.36	262.5	1017.7
Back upper tank	6.54	1312.5	2462.9
Back lower tank	5.47	329.5	1277
Total [kg]		2517	6442.8

Parameter	A321-H19	Variation (A320)
m_{MTO} [kg]	70916	-1.9
m_{OE} [kg]	45208	+12.5
m_F [kg]	6443	-49.7
DOC (AEA) [€/NM/t]	1.78	+34.9
DOC (TUB) [€/NM/t]	1.61	+39.8
l_F [m]	46.2	+20.5
S_W [m ²]	126.5	+5.1
$b_{W,geo}$ [m]	34.7	+2.5
$A_{W,eff}$	9.5	0
φ_{25} [°]	25	0
λ	0.21	0
E_{max}	17.6	+0.3
T_{TO} [kN]	100.2	-8.4
BPR	6	0
SFC [kg/N/s]	5.82E-06	-64.8
h_{CR} [ft]	37676	-3.1
m_{MTO}/S_W [kg/m ²]	560.7	-6.6

energy up 41 %

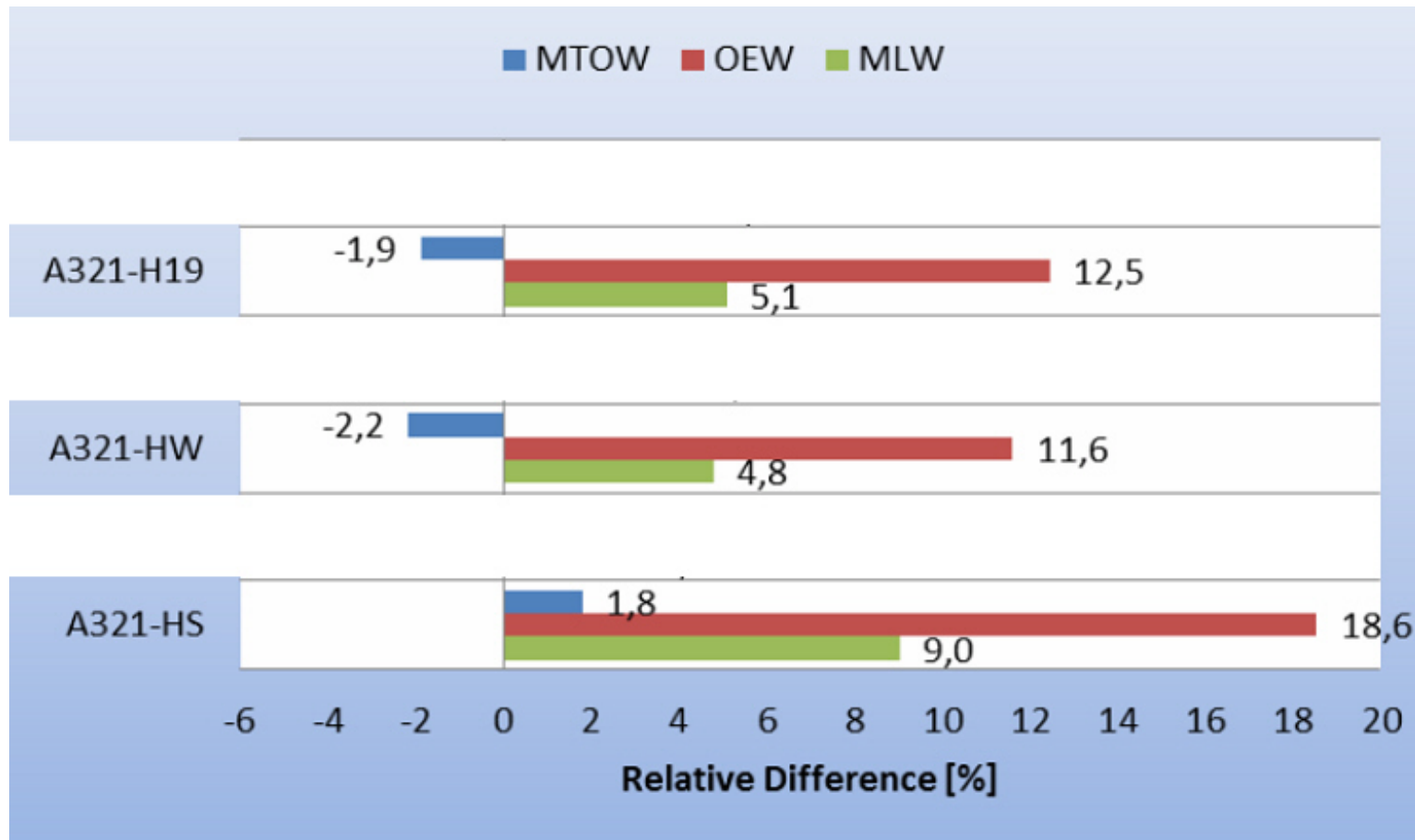
A321: $l_F = 44.5$ m
Delta: 1.7 m

If DOC are based on A319:
DOC (AEA) +17%
DOC (TUB) +21%

Overall Comparison

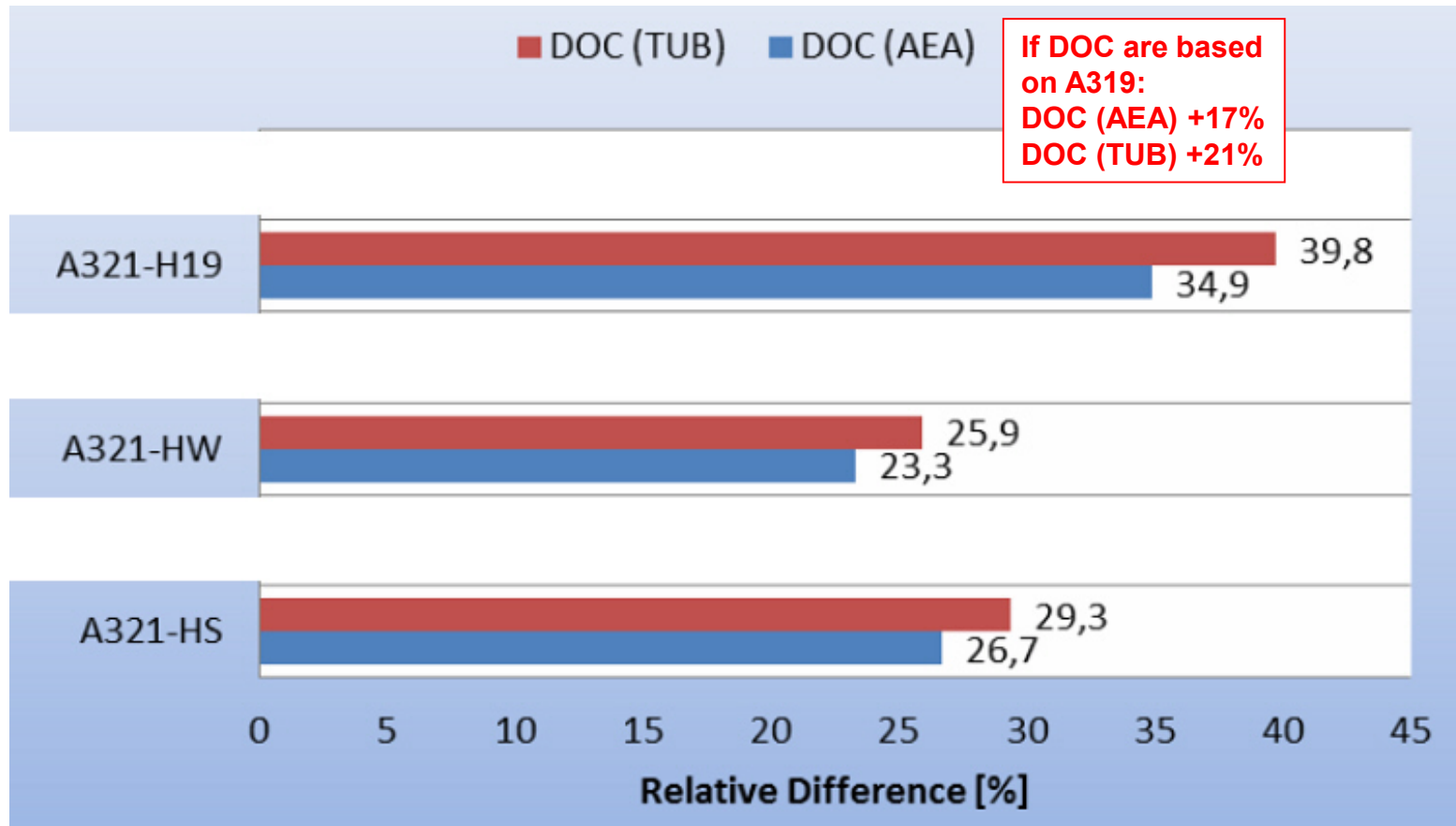
	A320-200	A321-HS	A321-HW	A321-H19	
l_F [m]	38.4	49.4	45.2	46.2	A321: $l_F = 44.5$ m
m_{MTO} [kg]	72274	73578	70716	70916	
m_{OE} [kg]	40199	47658	44871	45208	
m_{ML} [kg]	63457	69164	66473	66661	
m_F [kg]	12819	6664	6588	6443	
E_{max}	17.5	17.6	16.9	17.6	
T_{TO} [kN]	109.4	103.9	99.8	100.2	
BPR	6	6	6	6	
SFC [kg/N/s]	1.65E-05	5.79E-06	5.82E-06	5.82E-06	
m_T [kg]	-	2531	2473	2517	
n_{PAX}	180	180	180	156	
DOC [€/NM/t]	1.32	1.68	1.63	1.78	
DOC [€/NM/t]	1.15	1.49	1.45	1.61	

Overall Comparison



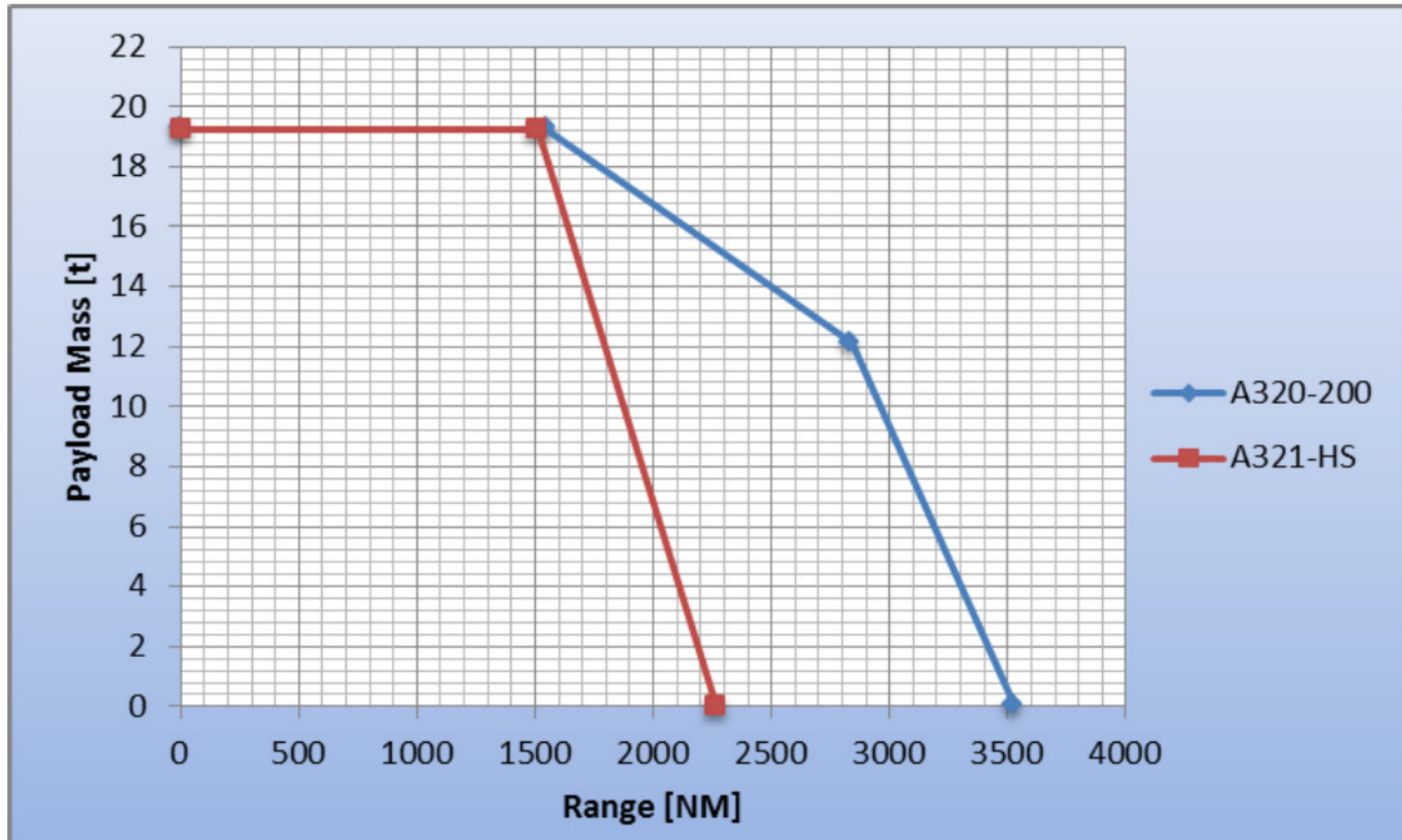
Comparison of MTOW, OEW, MLW related to the original A320-200

Overall Comparison



Comparison of DOC related to the original A320-200

Overall Comparison



Payload-Range diagram comparison between a kerosene and a hydrogen-fueled aircraft

Life Cycle Analysis (LCA) in Aviation

JOHANNING, Andreas, SCHOLZ, Dieter, 2013. *A First Step Towards the Integration of Life Cycle Assessment into Conceptual Aircraft Design*. German Aerospace Congress 2013 (DLRK 2013), Stuttgart, 10.-12.09.2013.

Available from: <https://nbn-resolving.org/urn:nbn:de:101:1-201407183813>. Download: <http://Airport2030.ProfScholz.de>

Definition: Life Cycle Assessment (LCA)

"Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system during its life cycle"

Standardized according to:

- ISO 14040
- ISO 14044

INTERNATIONAL STANDARD ORGANISATION, 2006. ISO 14040: *Environmental management — Life cycle assessment — Principles and framework*. Second edition, July 2006. Available from: <https://www.iso.org/standard/37456.html>

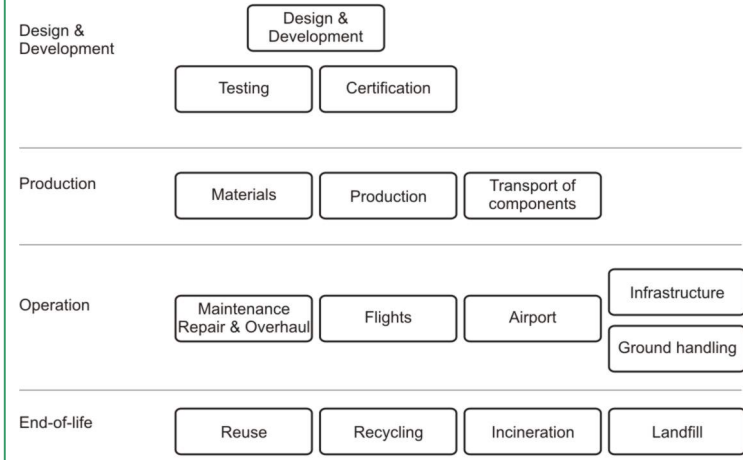
Life Cycle Assessment (LCA)

4 Phases

1) Goal and scope definition

- Goal
- System boundaries

Life-cycle phases:



- Functional unit
- Method for impact assessment
- Impact categories
- ...

Life Cycle Assessment (LCA)

4 Phases

1) Goal and scope definition

2) Inventory analysis

"Compilation and quantification of inputs and outputs for a product throughout its life cycle"

Inputs			Outputs		
Fluss	Menge	Einheit	Fluss	Menge	Einheit
Aggregate, natural	0.07139	kg	1,4-Butanediol	4.88175E-13	kg
Air	23.58890	kg	1,4-Butanediol	1.95257E-13	kg
Antimony	6.68042E-13	kg	2,4-D	3.65852E-11	kg
Barite	0.00556	kg	4-Methyl-2-pentanone	1.20567E-14	kg
Basalt, in ground	0.00369	kg	Acenaphthene	2.86861E-9	kg
Bauxite	1.67932	kg	Acenaphthene	7.19709E-11	kg
biomass; 14.7 MJ/kg	1.98174	MJ	Acenaphthene	6.97969E-13	kg
Borax, in ground	0.00062	kg	Acenaphthene	8.14351E-12	kg
brown coal; 11.9 MJ/...	6.07284	MJ	Acenaphthylene	2.82654E-11	kg
Cadmium	5.47330E-9	kg	Acenaphthylene	1.08460E-9	kg
Calcium carbonate, i...	0.63251	kg	Acenaphthylene	5.08915E-13	kg
Calcium chloride	1.34285E-11	kg	Acetaldehyde	1.54072E-6	kg
Carbon	1.61338E-7	kg	Acetaldehyde	2.75074E-10	kg
Carbon dioxide, in air	0.10779	kg	Acetic acid	6.87065E-5	kg
Cerium, in ground	3.15583E-18	kg	Acetic acid	6.59615E-9	kg
Chromium	3.01517E-5	kg	Acetic acid	1.62343E-7	kg
Chrysotile, in ground	1.75039E-7	kg	Acetic acid	4.41277E-9	kg
Clay, bentonite, in gr...	0.00262	kg	Acetone	7.30996E-6	kg
Clay, unspecified, in ...	0.00218	kg	Acetone	1.65080E-6	kg
Cobalt, in ground	3.22670E-10	kg	Acetonitrile	1.08866E-10	kg
Colemanite, in ground	0.10098	kg	Acidity, unspecified	5.83350E-9	kg
Copper	6.24400E-5	kg	Acidity, unspecified	0.00034	kg
crude oil; 42.3 MJ/kg	18.68835	MJ	Acidity, unspecified	2.95993E-14	kg
Diatomite, in ground	8.97114E-12	kg	Acidity, unspecified	1.04297E-6	kg
Dolomite, in ground	0.18529	kg	Aclonifen	1.22893E-11	kg

Life Cycle Assessment (LCA)

4 Phases

1) Goal and scope definition

2) Inventory analysis

3) Impact assessment

„Understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product“ [1]

LCI	IMPACT CATEGORIES	FACTORS	LCIA
Emissions to air			
CO ₂ 1.3 kg	GWP	1.3 kg CO ₂ * 1	160.3 kg CO ₂ Eq.
CO 3 kg		3 kg CO * 3	
CH ₄ 6 kg		6 kg CH ₄ * 25	
SO ₂ 0.001 kg	AP	0.001 kg SO ₂ * 1	0.849 kg SO ₂ Eq.
NO _x 0.08 kg		0.08 kg NO _x * 0.7	
HCl 0.9 kg		0.9 kg HCl * 0.88	
Emissions to water			
PO ₄ 2 kg	EP	0.08 kg NO _x * 0.13	2.043 kg PO ₄ Eq.
NH ₃ 0.1 kg		2kg PO ₄ * 1 0.1 kg NH ₃ * 0.33	
	CLASSIFICATION	CHARACTERISATION	

Life Cycle Assessment (LCA)

4 Phases

1) Goal and scope definition

2) Inventory analysis

3) Impact assessment

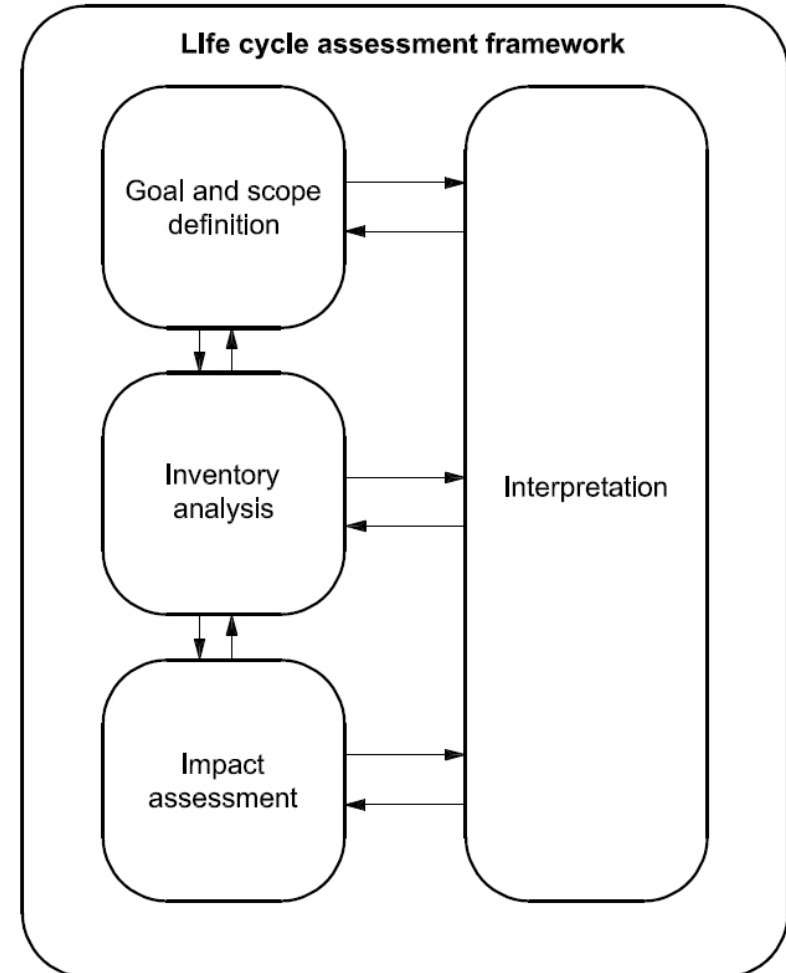
4) Interpretation

- Result presentation
- Conclusions
- Provision of recommendations
- Explanation of limitations
- ...

Life Cycle Assessment (LCA)

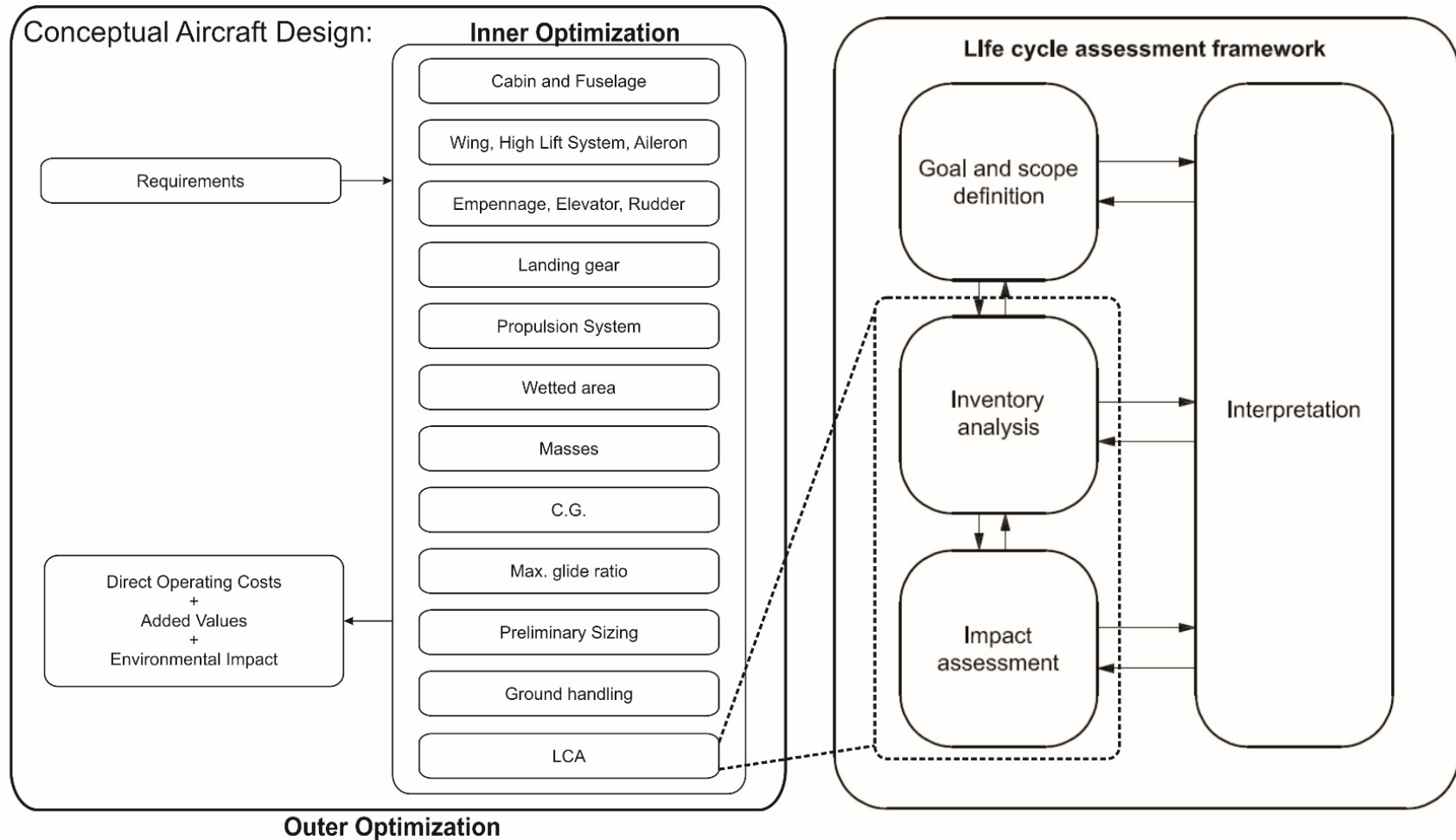
4 Phases

- 1) Goal and scope definition
- 2) Inventory analysis
- 3) Impact assessment
- 4) Interpretation

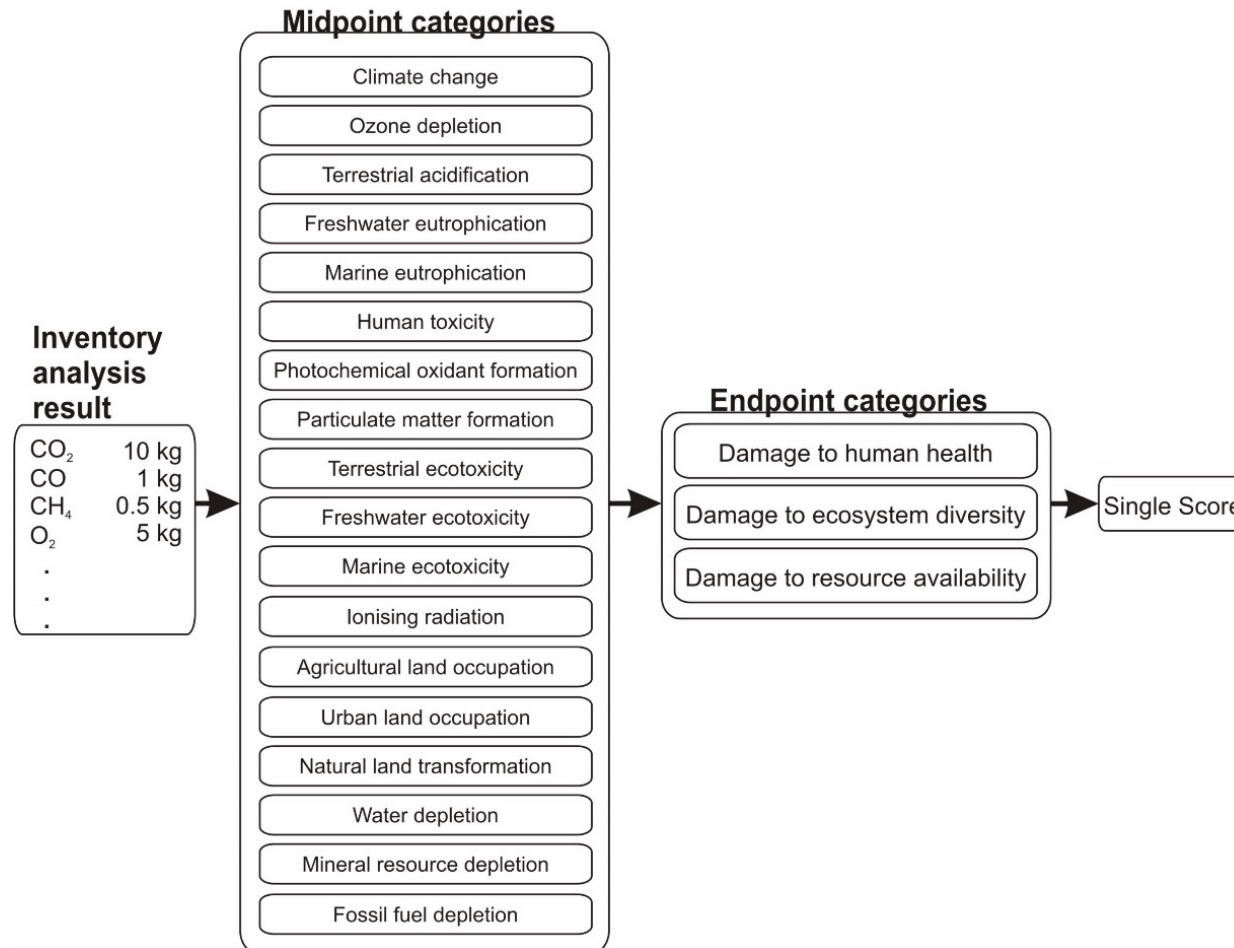


INTERNATIONAL STANDARD ORGANISATION, 2006. ISO 14040: *Environmental management — Life cycle assessment — Principles and framework*. Second edition, July 2006. Available from: <https://www.iso.org/standard/37456.html>

Integration into the Conceptual Aircraft Design Software "PrOPerA"



Impact Assessment Using the ReCiPe Method



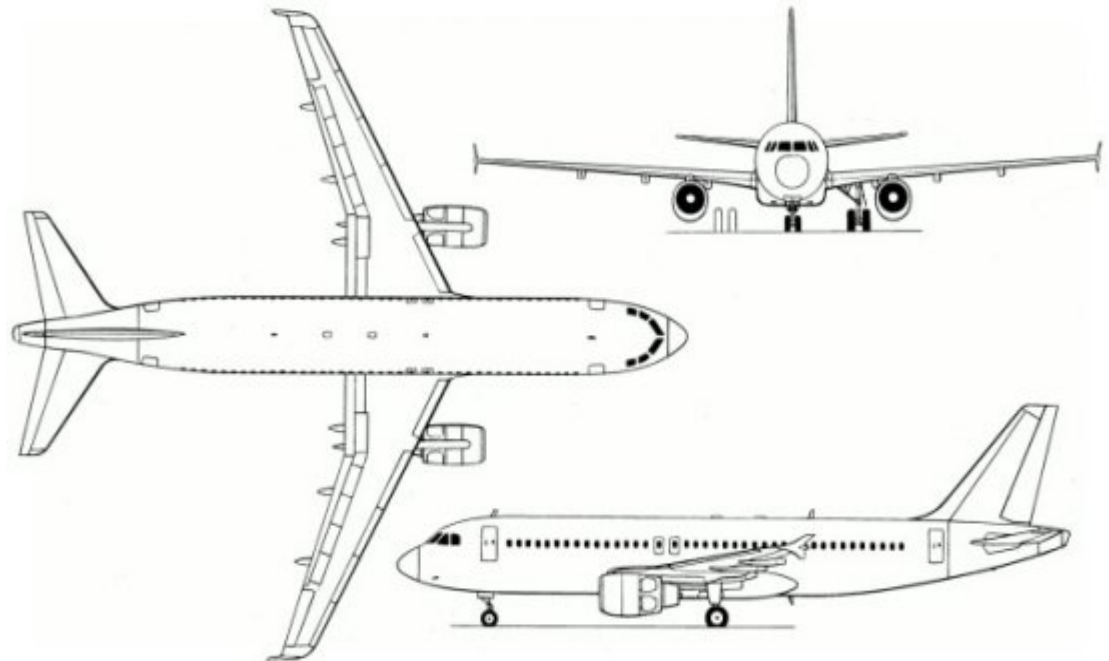
ReCiPe Method – Available from: https://www.leidenuniv.nl/cml/ssp/publications/recipe_characterisation.pdf

Airbus A320 with LH2 LCA Evaluation

JOHANNING, Andreas, SCHOLZ, Dieter, 2015. Comparison of the Potential Environmental Impact Improvements of Future Aircraft Concepts Using Life Cycle Assessment. In: CEAS: *5th CEAS Air&Space Conference: Proceedings* (CEAS2015, Delft, 07.-11.09.2015). DocumentID: 80. Download: <http://Airport2030.ProfScholz.de>

Reference Aircraft, Requirements

- **Airbus A320-200**, weight variant WV000
- Design range: 1510 NM with a payload of 19256 kg
- 180 PAX in a one-class layout
- Cruise Mach number 0.76



<http://www.aerospaceweb.org>

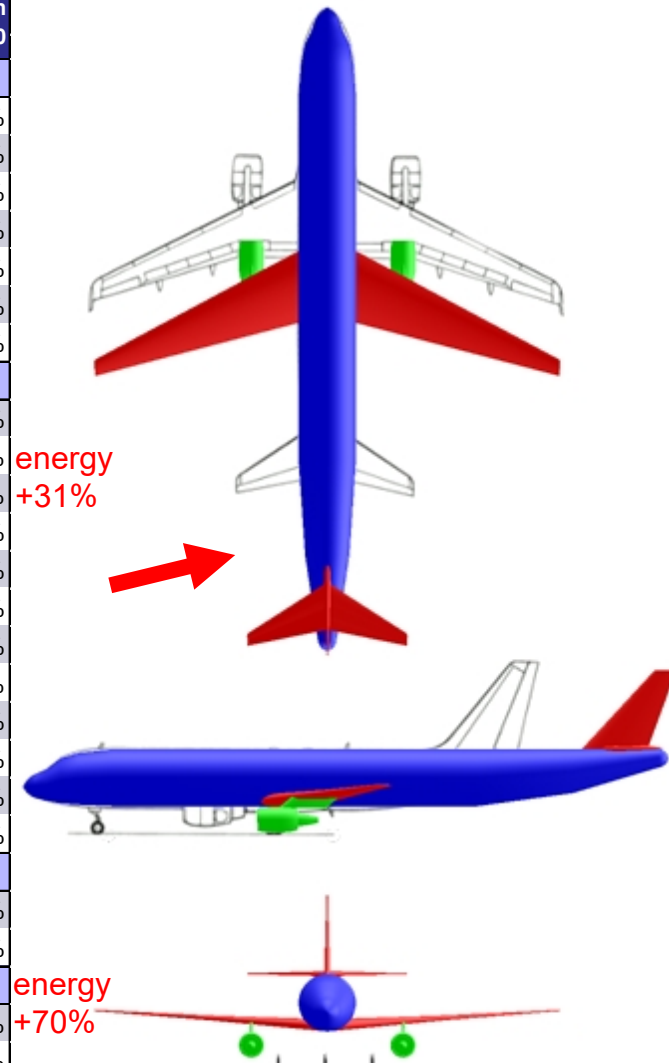
Details of the LCA for the Hydrogen Powered A320

- Hydrogen is produced:
 1. using natural gas **steam reforming** and **electricity mix**
 2. using **electrolysis** and electricity from **renewable sources**
- Liquefaction of hydrogen is considered
- Transport of the liquid hydrogen from the production site to the airport is not considered
- It is considered that **hydrogen produces 2.6 times the amount of water** compared to kerosene
- **Tanks** between cockpit and cabin, behind the cabin, and in the cargo compartment
- **Stretch** of the aircraft by **11 m**

Hydrogen Powered A320

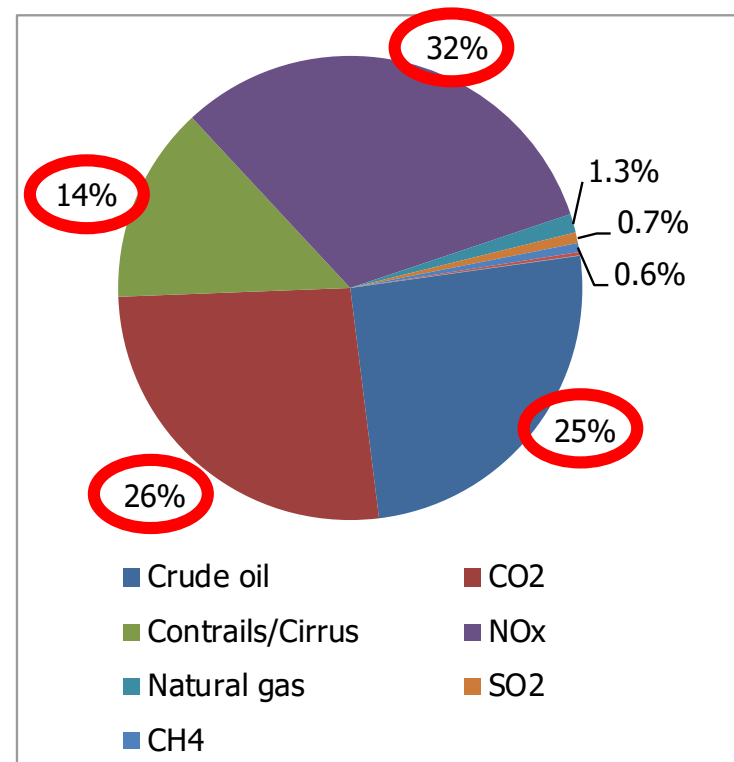
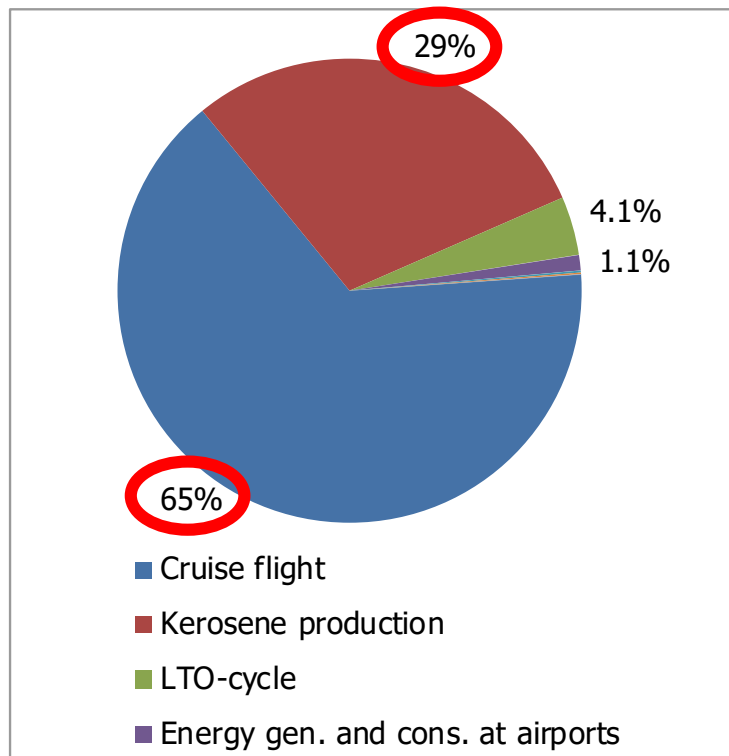
- Reduced hydrogen mass due to high mass energy density
- Stretched fuselage for additional tanks due to low volumetric energy density: 11 m
- In total: No improvement of the Maximum Take-Off Mass (MTOM)
- Steam reforming and electricity mix: SS = +300%
- Electrolysis and electricity from renewable sources: SS = -27%

Parameter	Value	Deviation from A320
Requirements		
m_{MPL}	19256 kg	0%
R_{MPL}	1510 NM	0%
M_{CR}	0.76	0%
$\max(s_{TOFL}, s_{LFL})$	1770 m	0%
n_{PAX} (1-cl HD)	180	0%
m_{PAX}	93 kg	0%
SP	29 in	0%
Main aircraft parameters		
m_{MTO}	74200 kg	1%
m_{OE}	48800 kg	18%
m_F	6200 kg	-53%
S_W	124 m ²	1%
$b_{W,geo}$	34.3 m	0%
$A_{W,eff}$	9.50	0%
E_{max}	17.00	≈ -3%
T_{TO}	100 kN	12%
BPR	6.0	0%
h_{ICA}	40000 ft	2%
s_{TOFL}	1770 m	0%
s_{LFL}	1450 m	0%
Mission requirements		
R_{Mi}	589 NM	0%
$m_{PL,Mi}$	13057 kg	0%
Results		
$m_{F,trip}$	2800 kg	-39%
SS	0.0692	300%



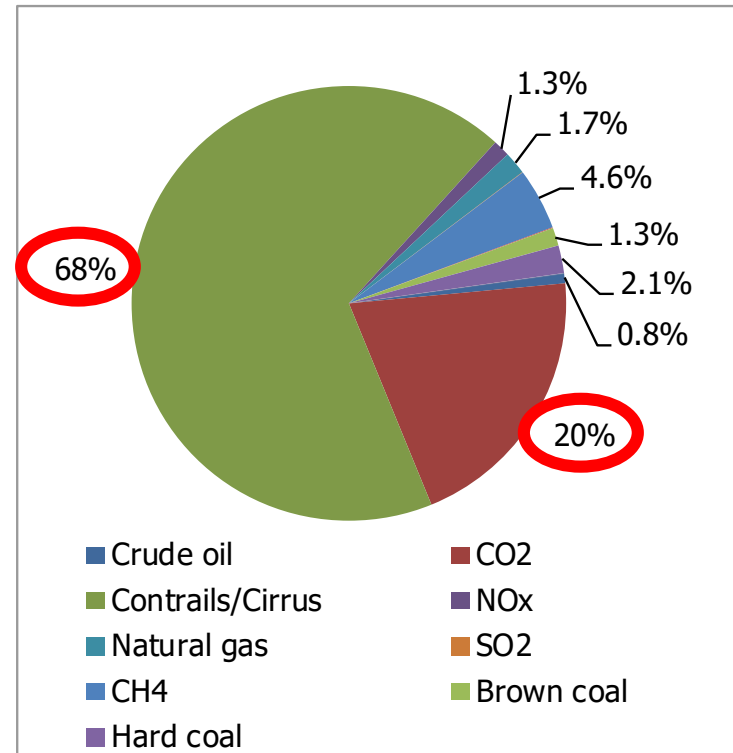
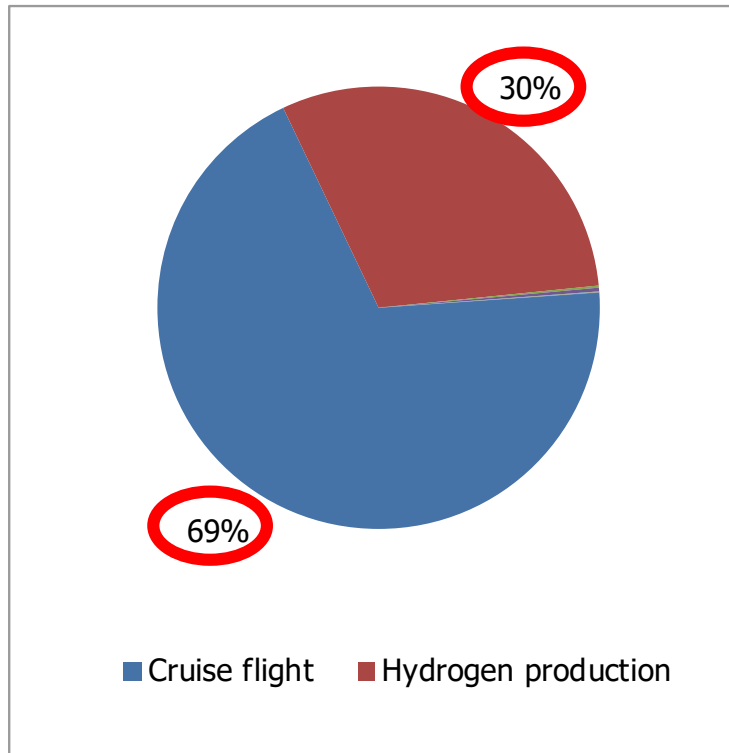
Reference Aircraft: A320

- Cruise flight and kerosene production dominate environmental impact
- CO₂, NO_x, crude oil and contrails/cirrus clouds have highest influence



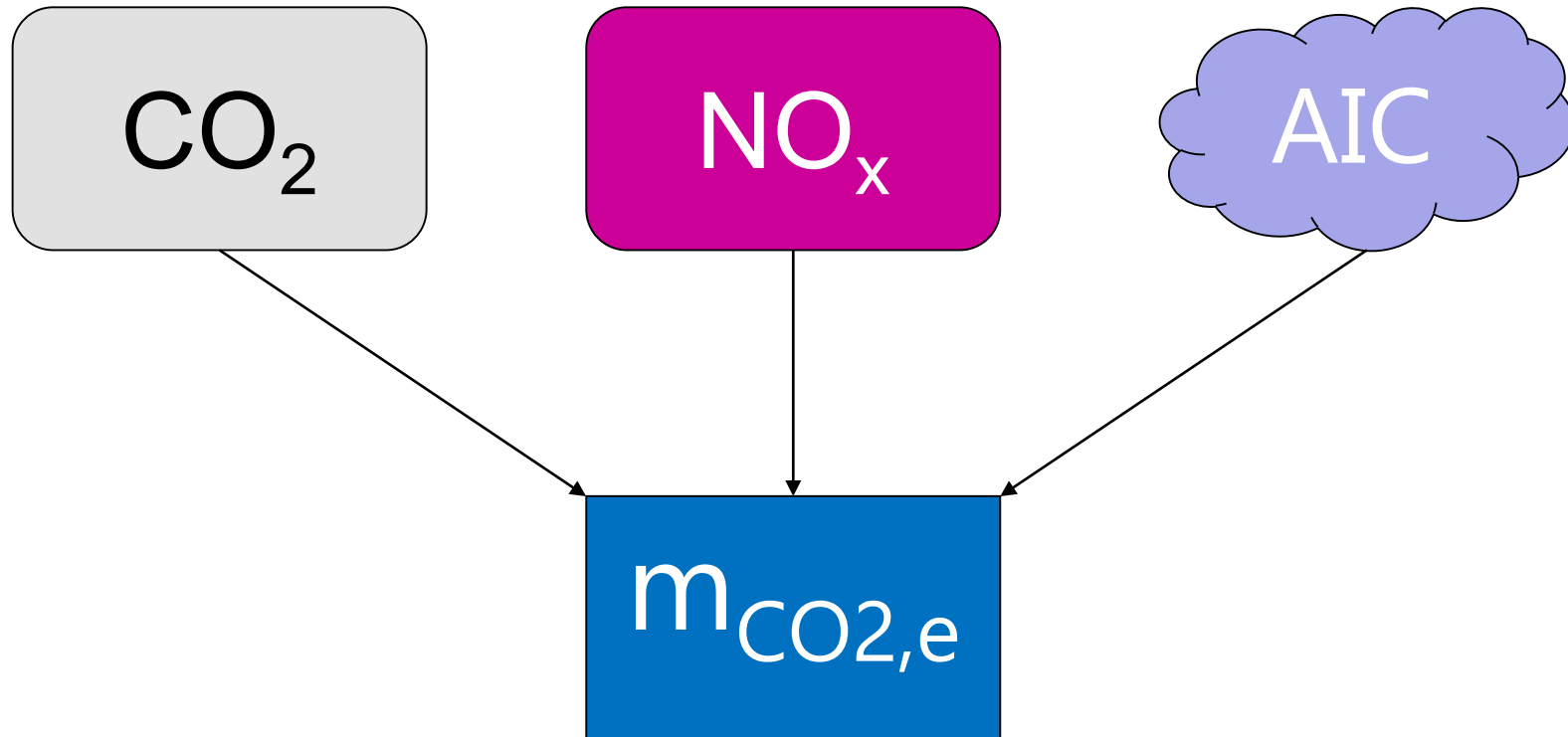
Hydrogen Powered A320 – Steam Reforming

- Cruise flight and hydrogen production from steam reforming dominate environmental impact
- Contrails/cirrus clouds from the flight (2.6 times the amount of water compared with kerosene) and CO₂ from the production have highest influence



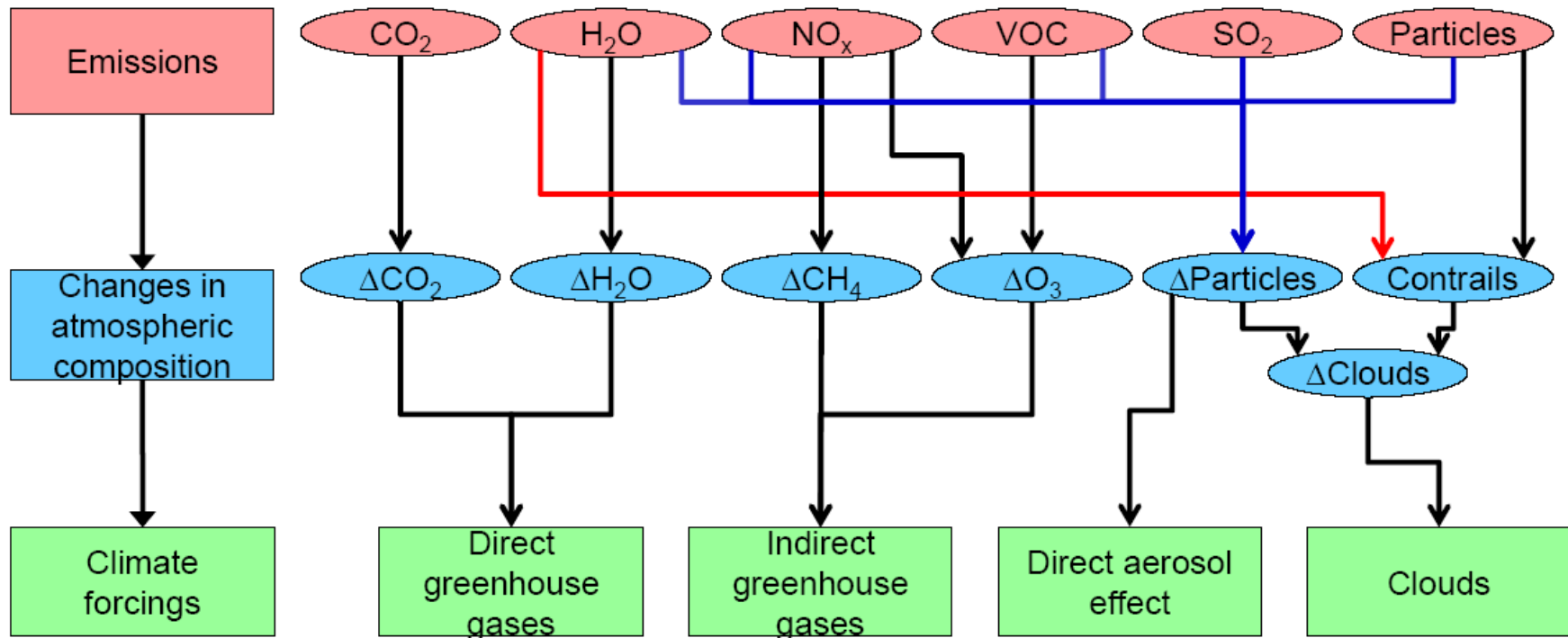
Equivalent CO₂ Mass

Equivalent CO₂ Mass



CAERS, Brecht, SCHOLZ, Dieter, 2020. *Conditions for Passenger Aircraft Minimum Fuel Consumption, Direct Operating Costs and Environmental Impact*. German Aerospace Congress 2020 (DLRK 2020), Online, 01.-03.09.2020.
 Available from: <https://doi.org/10.5281/zenodo.4068135>

Aviation Emissions and Climate Impact

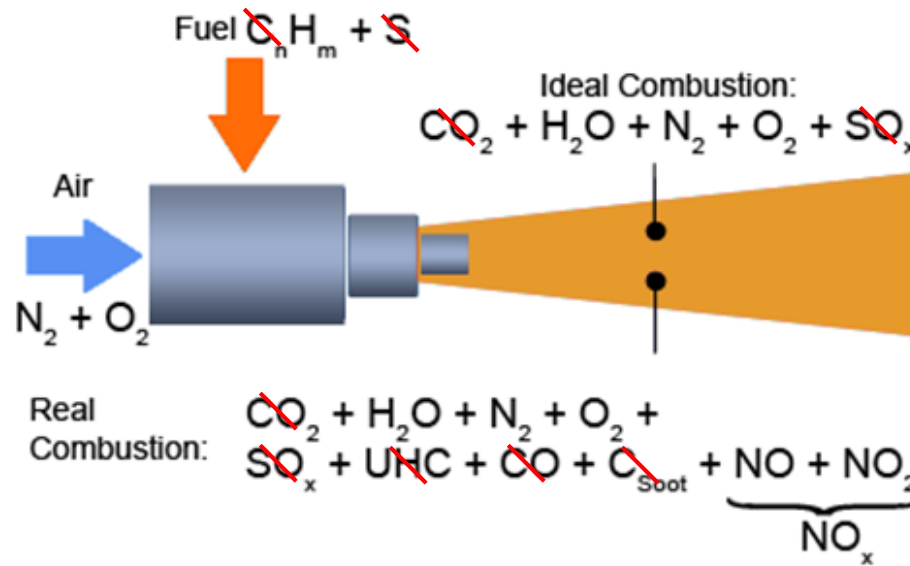



CO₂: Long term influence

Non-CO₂: Short term influence (immediate mitigation is possible)

RAPP, Markus, 2019. Perspektive: Wasserstoff & Hybride. Meeting: "Emissionsfreies Fliegen-wie weit ist der Weg?", Berlin, 13.11.2019

Kerosene and LH2 Combustion



 not included in LH2 combustion

EI_{NOx}

EMEP/EEA Guidebook
<https://www.eea.europa.eu>

m_F

Own Fuel Calculation

Altitude-Dependent Equivalent CO2 Mass

$$m_{CO_2,eq} = \frac{EI_{CO_2} \cdot f_{NM}}{n_{seat}} \cdot 1 + \frac{EI_{NO_x} \cdot f_{NM}}{n_{seat}} \cdot CF_{midpoint,NO_x} + \frac{R_{NM}}{R_{NM} \cdot n_{seat}} \cdot CF_{midpoint,AIC}$$

Sustained Global Temperature Potential, SGTP (similar to GWP):

$$CF_{midpoint,NO_x}(h) = \frac{SGTP_{O_{3s},100}}{SGTP_{CO_2,100}} \cdot s_{O_3,S}(h) + \frac{SGTP_{O_{3L},100}}{SGTP_{CO_2,100}} \cdot s_{O_3,L}(h) + \frac{SGTP_{CH_4,100}}{SGTP_{CO_2,100}} \cdot s_{CH_4}(h)$$

$$CF_{midpoint,cloudiness}(h) = \frac{SGTP_{contrails,100}}{SGTP_{CO_2,100}} \cdot s_{contrails}(h) + \frac{SGTP_{cirrus,100}}{SGTP_{CO_2,100}} \cdot s_{cirrus}(h)$$

Species	Emission Index, EI (kg/kg fuel)
CO ₂	3,15
H ₂ O	1,23
SO ₂	2,00 · 10 ⁻⁴
Soot	4,00 · 10 ⁻⁵

Species	SGTP _{1,100}
CO ₂ (K/kg CO ₂)	3,58 · 10 ⁻¹⁴
Short O ₃ (K/kg NO _x)	7,97 · 10 ⁻¹²
Long O ₃ (K/NO _x)	-9,14 · 10 ⁻¹³
CH ₄ (K/kg NO _x)	-3,90 · 10 ⁻¹²
Contrails (K/NM)	2,54 · 10 ⁻¹³
Contrails (K/km)	1,37 · 10 ⁻¹³
Cirrus (K/NM)	7,63 · 10 ⁻¹³
Cirrus (K/km)	4,12 · 10 ⁻¹³

EI emission index
f_{NM} fuel consumption per NM or km
R_{NM} range in NM or km
CF characterization factor

Cirrus/Contrails = 3.0

water vapor not considered

AIC aviation-induced cloudiness

$$s_{O_{3,L}}(h) = s_{CH_4}(h)$$

$$s_{contrails}(h) = s_{cirrus}(h) = s_{AIC}(h)$$

Altitude-Dependent Equivalent CO2 Mass

$$m_{CO_2,eq} = \frac{EI_{CO_2} \cdot f_{NM}}{n_{seat}} \cdot 1 + \frac{EI_{NOx} \cdot f_{NM}}{n_{seat}} \cdot CF_{midpoint,NOx} + \frac{R_{NM}}{R_{NM} \cdot n_{seat}} \cdot CF_{midpoint,AIC}$$

↓ units only

$$\frac{kg\ CO_2}{NM \cdot n_{seat}} =$$

$$\frac{kg\ CO_2/kg\ fuel \cdot kg\ fuel/NM}{n_{seat}} \cdot 1 + \frac{kg\ NOx/kg\ fuel \cdot kg\ fuel/NM}{n_{seat}} \cdot \frac{kg\ CO_2}{kg\ NOx} + \frac{NM}{NM \cdot n_{seat}} \cdot \frac{kg\ CO_2}{NM}$$

SCHWARTZ, Emily, KROO, Ilan M., 2009. *Aircraft Design: Trading Cost and Climate Impact*. 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition, 05.01.-08.01.2009, Orlando, Florida, AIAA 2009, No.1261. Available from: <https://doi.org/10.2514/6.2009-1261>

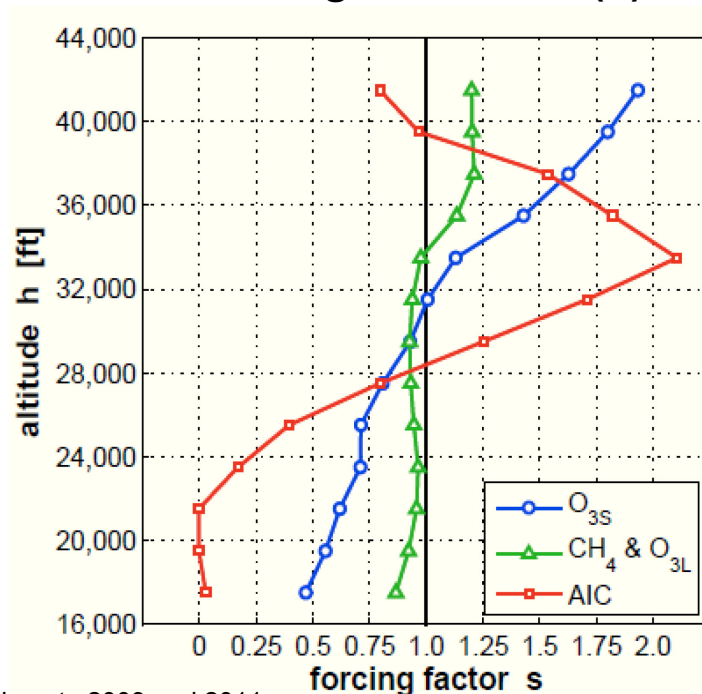
JOHANNING, Andreas, SCHOLZ, Dieter, 2014. *Adapting Life Cycle Impact Assessment Methods for Application in Aircraft Design*. German Aerospace Congress 2014 (DLRK 2014), Augsburg, 16.-18.09.2014. Available from: <https://nbn-resolving.org/urn:nbn:de:101:1-201507202456>. Download: <http://Airport2030.ProfScholz.de>

Altitude-Dependent Equivalent CO2 Mass

E.g.:
$$CF_{midpoint, cloudiness}(h) = \frac{SGTP_{contrails, 100}}{SGTP_{CO_2, 100}} \cdot s_{contrails}(h) + \frac{SGTP_{cirrus, 100}}{SGTP_{CO_2, 100}} \cdot s_{cirrus}(h)$$

$$s_{contrails}(h) = s_{cirrus}(h) = s_{AIC}(h)$$

Forcing Factor $s = f(h)$



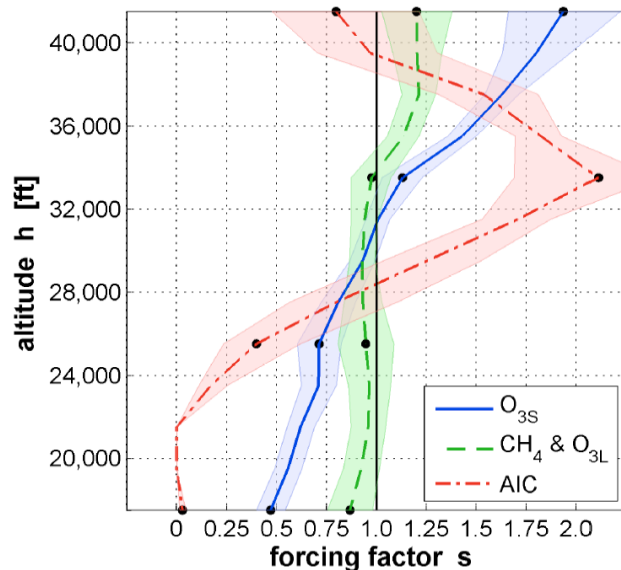
Schwartz 2009 and 2011

- The curves go along with the ICAO Standard Atmosphere (ISA) applicable for average latitudes. With a first approximation, the curves could be adapted to other latitudes by stretching and shrinking them proportionally to the altitude of the tropopause.
- The curves from SVENSSON 2004 (Fig. 1) show similar shapes. However, the importance of AIC is not yet as distinct.

SVENSSON, Fredrik, HASSELROT, Anders, MOLDANOVA, Jana, 2004. Reduced Environmental Impact by Lowered Cruise Altitude for Liquid Hydrogen-Fuelled Aircraft. In: *Aerospace Science and Technology*, Vol. 8 (2004), Nr. 4, pp. 307–320. Available from: <https://doi.org/10.1016/j.ast.2004.02.004>

Altitude-Dependent Equivalent CO₂ Mass

Forcing Factor $s = f(h)$



Forcing factors (lines) with **66% likelihood ranges** (shaded areas). Altitudes with forcing factors based on radiative forcing data with independent probability distributions. (SCHWARTZ 2011)

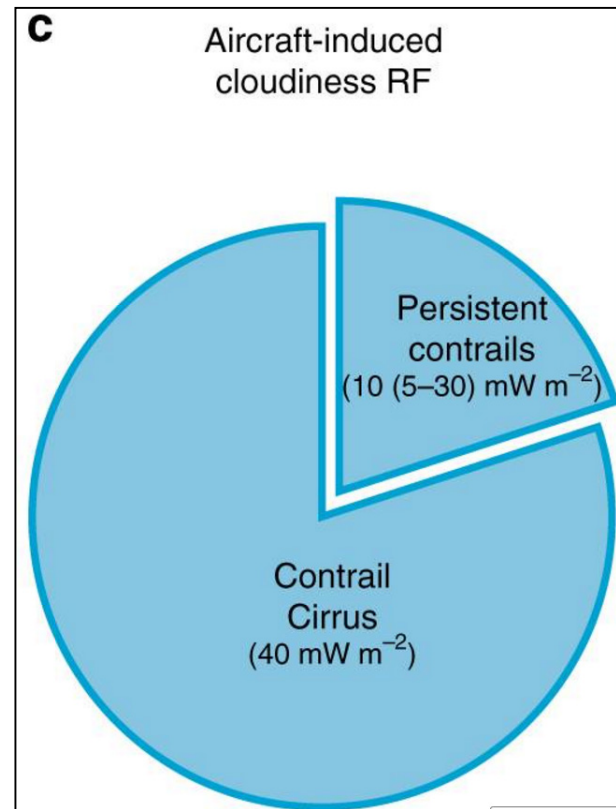
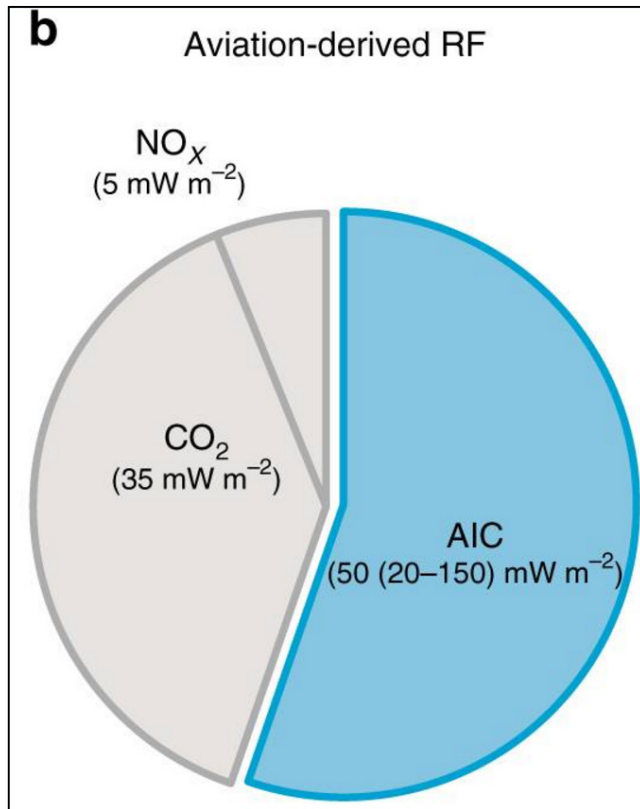
Based on KÖHLER 2008 and RÄDEL 2008.

SCHWARTZ DALLARA, Emily, 2011. *Aircraft Design for Reduced Climate Impact*. Dissertation. Stanford University. Available from: <http://purl.stanford.edu/yf499mg3300>

KÖHLER, Marcus O., RÄDEL, Gaby, DESSENS, Olivier, SHINE, Keith P., ROGERS, Helen L., WILD, Oliver, PYLE, John A., 2008. Impact of Perturbations to Nitrogen Oxide Emissions From Global Aviation. In: *Journal of Geophysical Research*, 113. Available from: <https://doi.org/10.1029/2007JD009140>

RÄDEL, Gaby, SHINE, Keith P., 2008. Radiative Forcing by Persistent Contrails and Its Dependence on Cruise Altitudes. In: *Journal of Geophysical Research*, 113. Available from: <https://doi.org/10.1029/2007JD009117>

Aviation-Induced Cloudiness: Contrail Cirrus & Persistent Contrails



Cirrus/Contrails = 4.0

- (b) Aviation forcing components, of which aviation-induced cloudiness (AIC) account for more than half.
- (c) Breakdown of AIC radiative forcing into contrail cirrus and persistent contrails.

KÄRCHER, Bernd, 2018. Formation and Radiative Forcing of Contrail Cirrus. In: *Nature Communications*, Vol. 9, Article Number: 1824. Available from: <https://doi.org/10.1038/s41467-018-04068-0>

Schmidt-Appleman Criterion for Contrail Formation

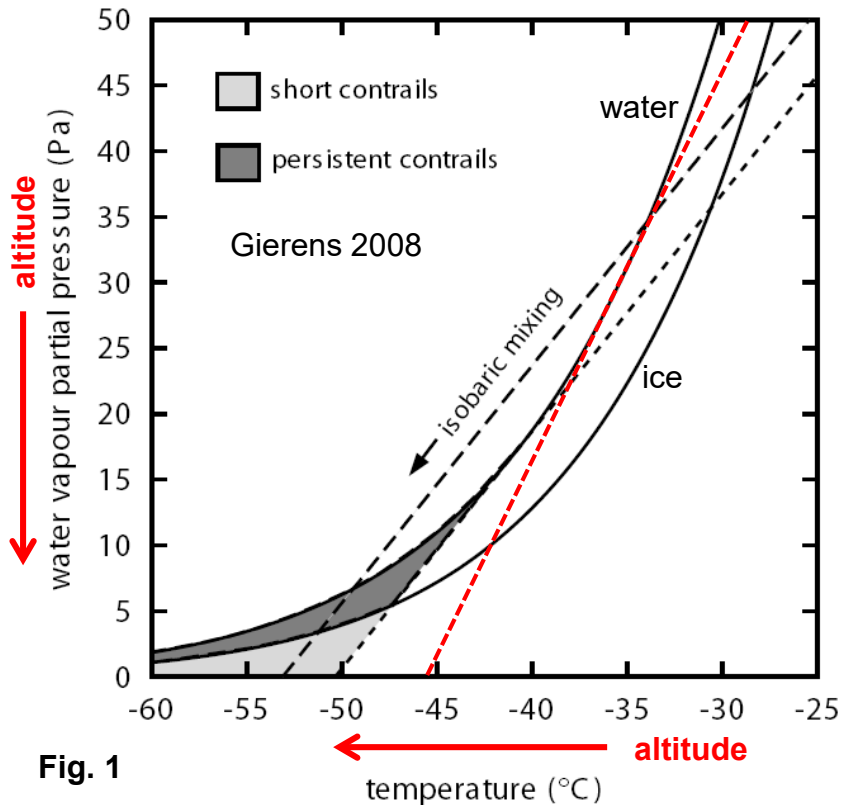


Fig. 1

G is the slope of the dotted line.
The dotted line is tangent to the water saturation line.

The mixing process is assumed to take place isobarically, so that on a T - e diagram the mixing (phase) trajectory appears as a straight line (e is the partial pressure of water vapour in the mixture, T is its absolute temperature, see Fig. (1)). The slope of the phase trajectory, G (units Pa/K), is characteristic for the respective atmospheric situation and aircraft/engine/fuel combination. G is given by

$$G = \frac{EI_{H_2O} p c_p}{\varepsilon Q (1 - \eta)}$$

where ε is the ratio of molar masses of water and dry air (0.622), $c_p = 1004$ J/(kg K) is the isobaric heat capacity of air, and p is ambient air pressure. G depends on fuel characteristics (emission index of water vapour, $EI_{H_2O} = 1.25$ kg per kg kerosene burnt; chemical heat content of the fuel, $Q = 43$ MJ per kg of kerosene), and on the overall propulsion efficiency η of aircraft. Modern airliners have a propulsion efficiency (η) of approximately 0.35.

A steep dotted line (large G) means:
Contrails more often and also at lower altitudes.

GIERENS, Klaus, LIM, Limg, ELEFATHERATOS, Kostas, 2008. A Review of Various Strategies for Contrail Avoidance. In: The Open Atmospheric Science Journal, 2008, 2, 1-7. Available from: <https://doi.org/10.2174/1874282300802010001>

Heating Value Q, Emission Index EI, and Slope G

fuel	Q [MJ/kg]	EI _{H₂O} [kg/kg]	EI _{H₂O} /Q [kg/MJ]	G _{H₂} /G _{Jet-A1}
H ₂	120	8,94	0,0745	2,58
Jet –A1	43	1,24	0,0288	

The **slope G** of the dotted line is **2,58 times steeper** in case of LH₂ combustion. This means: **Contrails more often** and **also at lower altitudes**.

2,58 times more water vapor is produced with LH₂ combustion compared to kerosene combustion (for the same energy used).

Literature Review: Hydrogen and Water Emissions

Types of water based emissions:

- water **vapor** emissions
- aviation-induced cloudiness (AIC)
 - line-shaped **contrails**
 - **cirrus clouds** (aged contrails)

*the **water vapour** RF [radiative forcing] increases in the cryoplane case, but by absolute magnitude this **contribution** remains the **smallest**.*

Ponater, 2006, <https://doi.org/10.1016/j.atmosenv.2006.06.036>

*For H₂ turbines and fuel cells, as they use H₂ as fuel, **2.55 times more water vapor** is formed compared to kerosene combustion [for the same energy content].*

*H₂ turbines emit **less soot** compared to kerosene; therefore, their emission leads to **optically thinner ice crystals** and thus lower climate impact. [Reduction assumed down to **60%** (40% reduction). See table on page 76 in report.]*

EU, 2020. Hydrogen-Powered Aviation. <https://doi.org/10.2843/471510>. Archived at: <https://perma.cc/BJJ6-5L74>

Literature Review: Hydrogen and Water Emissions

Current *state of knowledge does not allow a conclusive assessment* whether the net radiative impact of cryoplane contrails will be smaller or larger than that of conventional contrails. Uncertainty with respect to radiative forcing arises mainly from insufficient knowledge regarding the mean effective ice crystal radius for both conventional and, especially, cryoplane contrails.

it would be *strongly desirable* to compare model results to observations, i.e., *measurements* taken in the wake of a *prototype cryoplane*, which presently *does not exist*.

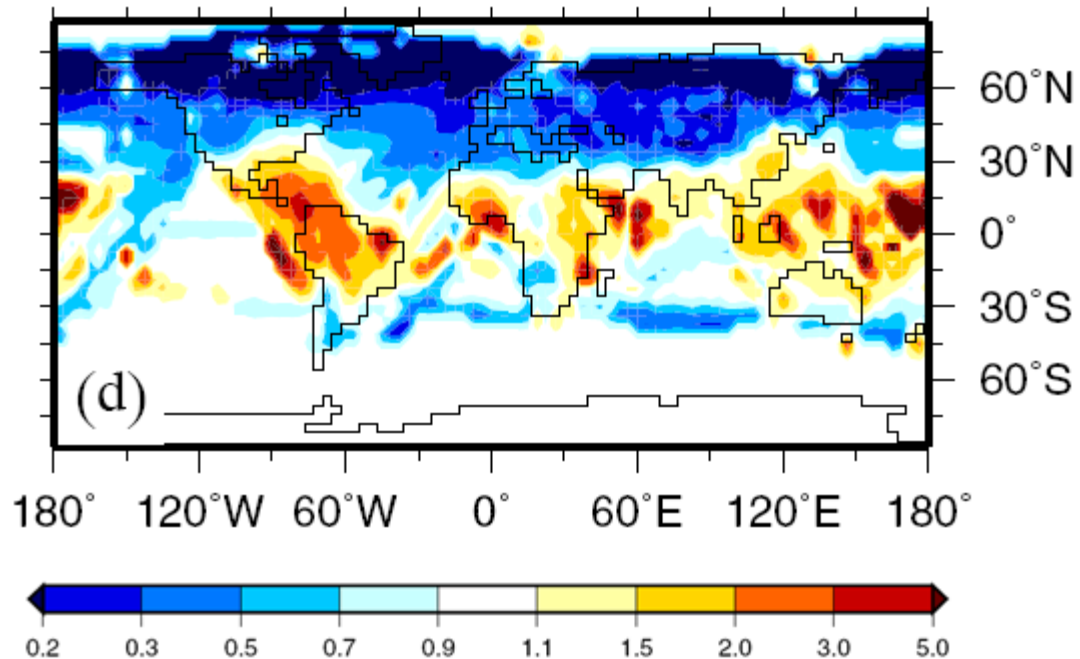
crystal radius is about a *factor of 0.3 smaller* for conventional contrails than for cryoplane contrails. [Hence, the radius of cryoplane's ice crystals is 3.33 times larger and the volume is 37 times larger. That means with 2.58 the amount of water there are only 7% of the ice crystals by numbers compared to kerosene. The area of the ice crystals is 11 time larger and the *coverage of the sky is only 77% of that for kerosene*. Everything calculated from simple geometry.]

the substitution of conventional aviation by a fleet of cryoplanes would lead to ... *increase* in the *coverage* with all contrails by a *factor of 1.2*

However, contrails are only visible (from satellite or an Earth-bound observer) if their optical depth exceeds a certain threshold value. In our studies, we have used a visibility-threshold of 0.02 and, therefore, have distinguished between the "visible" contrail cover and the cover with "all" contrails. Though, as just explained, the *coverage with all contrails increases all over the world* in our cryoplane simulations, the *coverage with visible contrails decreases over a substantial part of the globe*

Marquart 2005, <https://doi.org/10.1127/0941-2948/2005/0057>

Literature Review: Hydrogen and Water Emissions



Change in annual mean total *contrail cover* for the time slice 2015 if the *conventional fleet of aircraft is replaced by a fleet of cryoplanes*. (d) *ratio cryoplane/conventional for visible contrails*.

Marquart 2005, <https://doi.org/10.1127/0941-2948/2005/0057>

Literature Review: Hydrogen and Water Emissions

the global mean radiative forcing of cryoplane contrails is simulated to be by about ... 30% [lower] in 2050 compared to the radiative forcing of conventional contrails. The global mean decrease in radiative forcing results from the decrease in contrail optical depth, which outweighs the effect of increased contrail cover due to the higher specific emission of water vapour. However, in tropical regions, where it is often too warm for contrail formation in the case of conventional aircraft, the increase in contrail cover for the cryoplane case is found to be relatively strong, leading to an increase in radiative forcing there.

Marquart 2005, <https://doi.org/10.1127/0941-2948/2005/0057>

Contrail cirrus, consisting of linear contrails and the cirrus cloudiness arising from them, yields the largest positive net (warming) ERF term followed by CO₂ and NO_x emissions.

Lee, 2020, <https://doi.org/10.1016/j.atmosenv.2020.117834>

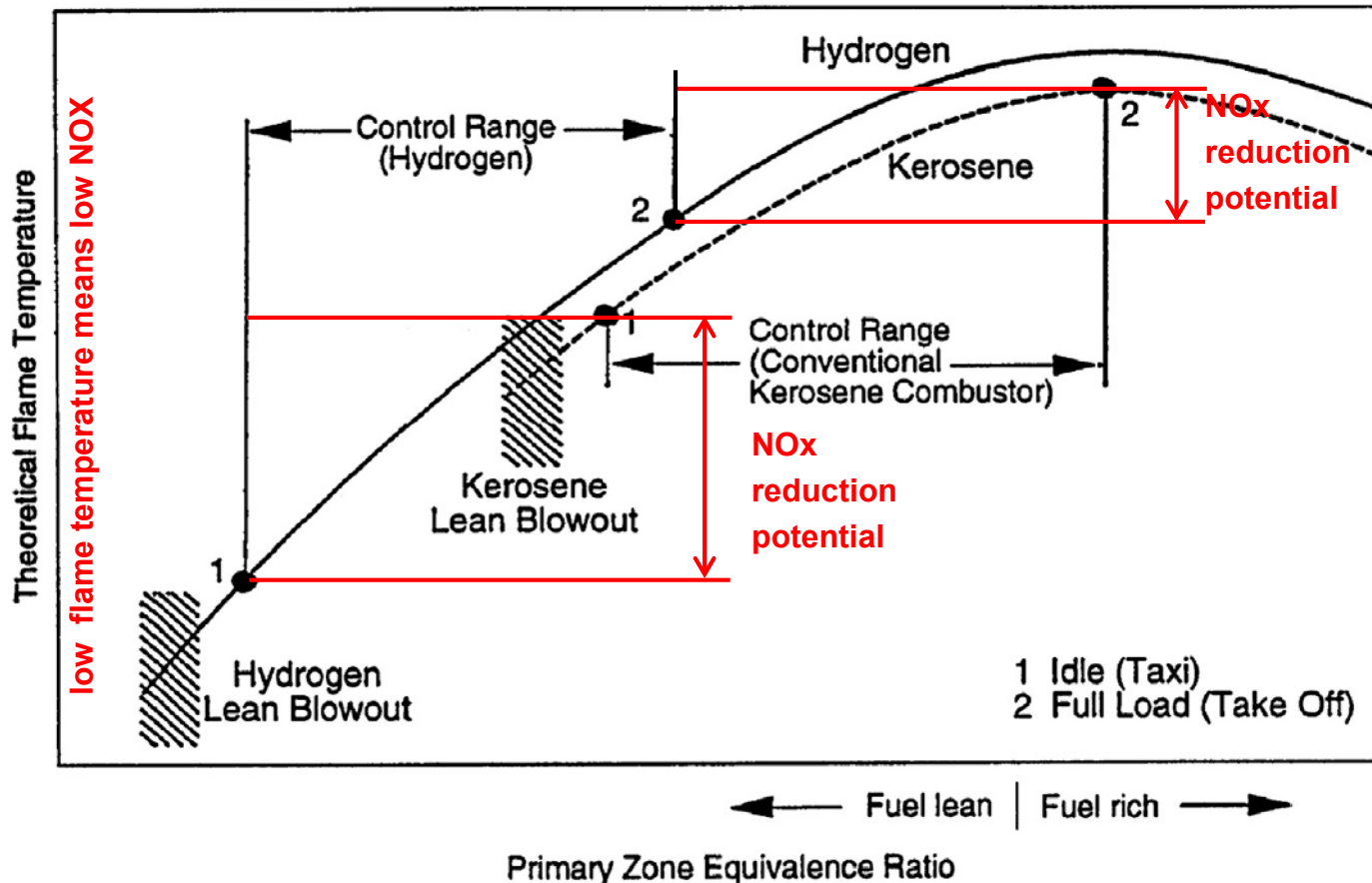
Flying at lower altitudes can also lead to contrail reduction in the mid-latitudes.

Gierens, 2008, <https://doi.org/10.2174/1874282300802010001>

Cryoplanes should cruise at an altitude of about 2–3 km below where conventional aircraft cruise today. At this reduced flight level, the contribution to global warming from the cryoplane is slightly less than about 15% of that of the conventional aircraft cruising at the datum level. In addition to the aspects considered here, reducing the flight altitude will help to avoid the formation of contrails. Inevitably, this change in cruise altitude causes increased aircraft investments and operating costs.

Svensson, 2004, <https://doi.org/10.1016/j.ast.2004.02.004>

Hydrogen: Less NOx in Lean Combustion



Primary effect:
Hydrogen burn **hotter** and produces **more NOx**.

Secondary effect:
Hydrogen allows **leaner** combustion for **less NOx**.

NOx reduction potential, but **not zero NOx** for LH2 combustion.

KHANDELWAL et al., 2013. Hydrogen powered aircraft: The future of air transport. In: *Progress in Aerospace Sciences*. Vol. 60, July 2013, pp. 45-59. Available from: <https://doi.org/10.1016/j.paerosci.2012.12.002>

Literature Review: Hydrogen and NOx Emissions

For H2 turbines (vs. kerosene), hydrogen's *wider flammability limits* enable *leaner combustion* that results in *lower flame temperatures*. In addition, higher burning velocities and diffusivity allow for higher reaction rates and faster mixing respectively, resulting in lower residence time. These factors cumulatively contribute to lower thermal NOx and allow for shorter combustor designs. As the total amount of *NOx reduction* is *promising but still uncertain*, a range of 50 percent to 80 percent compared to kerosene was considered. Translating this to GWP and in reference to kerosene aircraft, we used a range of GWP for NOx from H2 turbines of 10 percent (lower limit) to 75 percent (upper limit), *resulting in an average GWP value of 35 percent*.

EU, 2020. Hydrogen-Powered Aviation. <https://doi.org/10.2843/471510>. Archived at: <https://perma.cc/BJJ6-5L74>

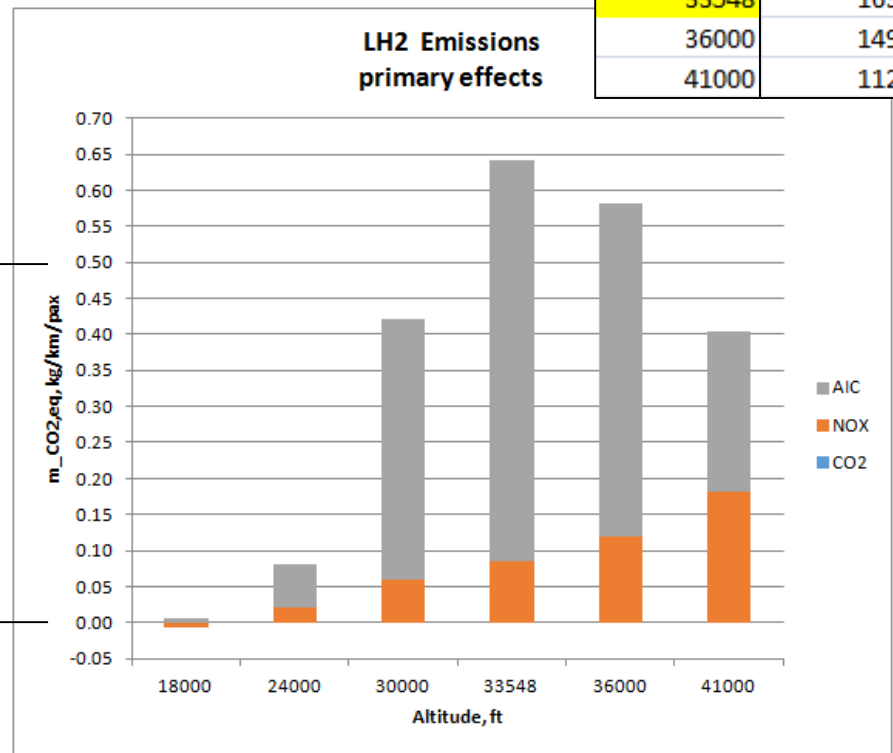
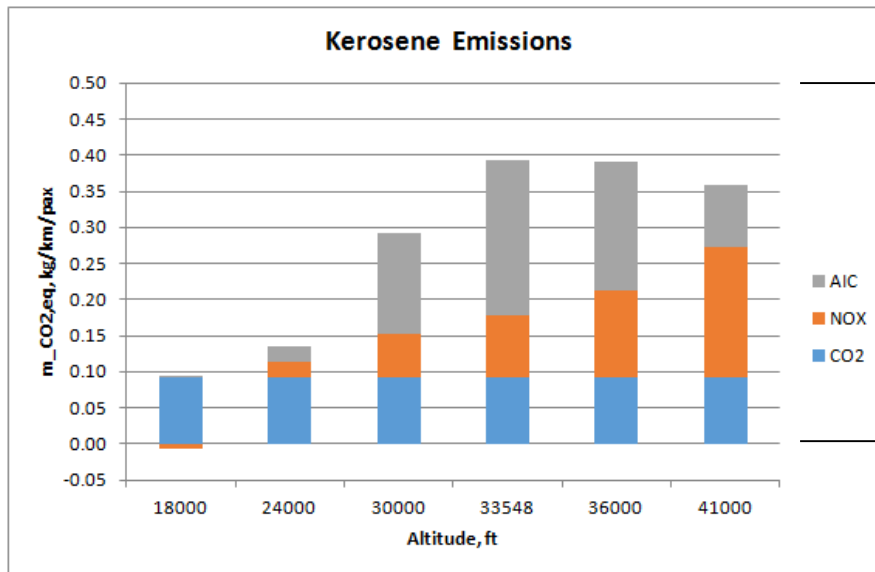
As for the NOx emissions when burning hydrogen, *theoretically* there is, in spite of the *higher stoichiometric flame temperature of hydrogen*, a potential to achieve lower emissions as compared with engines using kerosene. The main reason for this is that the hydrogen flame has a *wider flammability range*; particularly the *lean limit is substantially lower* than that encountered for kerosene flames. Therefore the entire operating range may be shifted further into the lean region, with considerably *reduced NOx emissions* as a consequence.

Svensson, 2004, <https://doi.org/10.1016/j.ast.2004.02.004>

Calculation of the Emission Characteristics of Aircraft Kerosene and Hydrogen Propulsion – A Comparison with Primary Effects

The method from SCHWARTZ 2009 was applied and adapted. Hydrogen combustion has 2.58 times more water emissions. If this primary effect is applied to aviation-induced cloudiness (AIC) with its line-shaped contrails and cirrus clouds, the equivalent CO₂ mass would be 50% higher than for kerosene. Hydrogen flame temperature is higher (without applying special technologies) and as such NO_x would be higher. It is assumed here that NO_x are the same as for kerosene. Results are calculated with an Excel table: <https://doi.org/10.7910/DVN/DLJUUK>

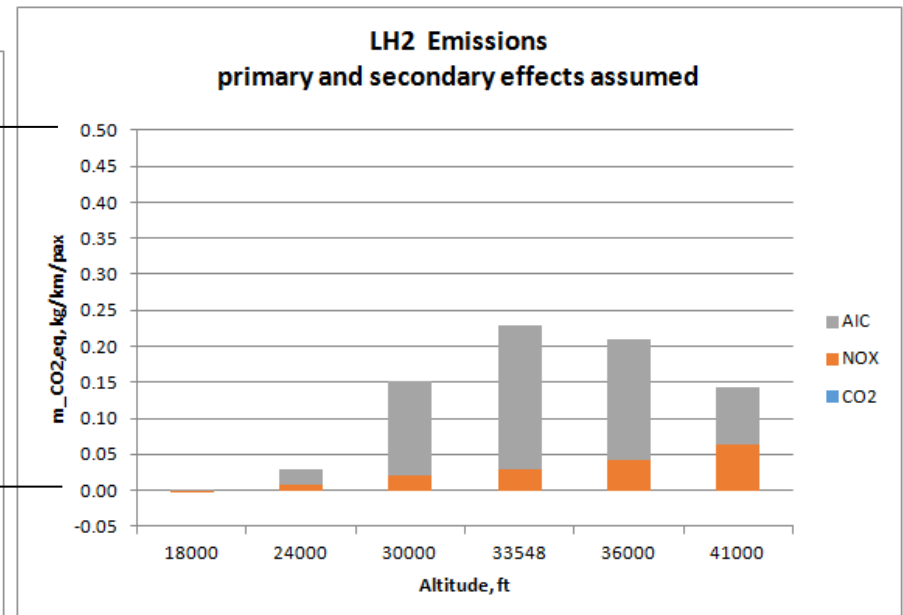
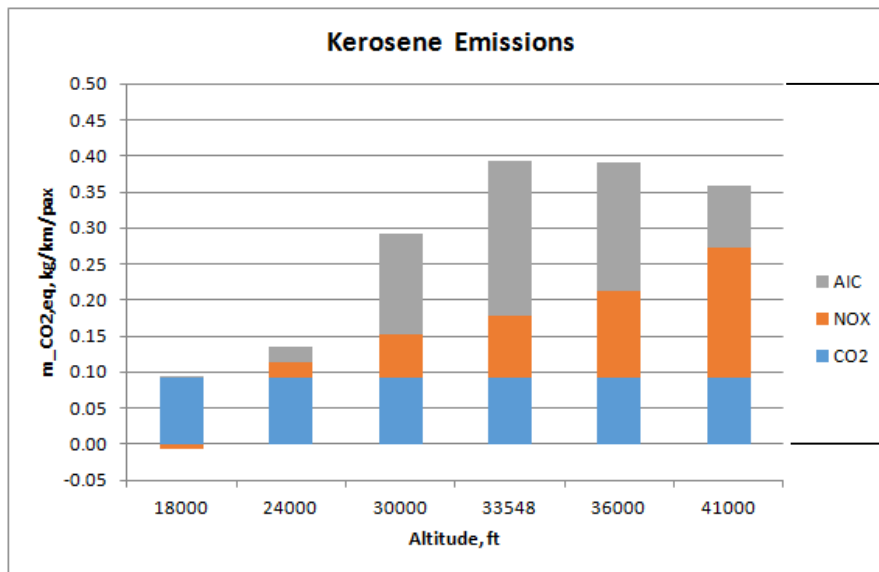
Altitude [ft]	rel. to kero
18000	-1%
24000	59%
30000	144%
33548	163%
36000	149%
41000	112%



Calculation of the Emission Characteristics of Aircraft Kerosene and Hydrogen Propulsion – A Comparison with Secondary Effects

Now **secondary effects** are applied on top of the primary effect for **contrails** due to 3.333-fold larger ice crystals (factor 0.774) and for increased coverage (factor 1.2) leading all together to a **reduction factor** of $0.774 \cdot 1.2 = 0.929$. Note: This **factor** already **includes** the **2.58** for more water emissions. If the "2.58" are kept separately, the **reduction factor is 0.358!** The **same factor is assumed** for cirrus clouds. For NOx a factor of 0.35 is **assumed** due to lean combustion and low flame temperature. With that **equivalent CO2 mass is now below that for kerosene propulsion**. See Excel table: <https://doi.org/10.7910/DVN/DLJUUK>

Altitude [ft]	rel. to kero
18000	0%
24000	21%
30000	52%
33548	59%
36000	53%
41000	40%





AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

Conditions for Passenger Aircraft Minimum Fuel Consumption, Direct Operating Costs and Environmental Impact

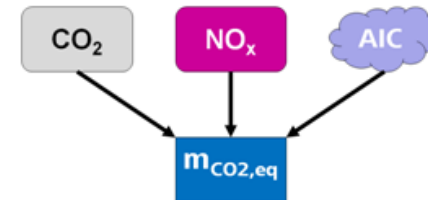
Brecht Caers Hamburg University of Applied Sciences
Dieter Scholz

<https://doi.org/10.5281/zenodo.4068135>

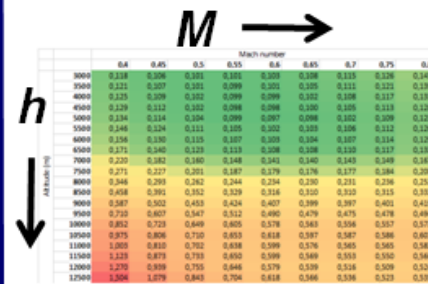
Deutscher Luft- und Raumfahrtkongress 2020

German Aerospace Congress 2020

Online, 01 - 03.09.2020



$$m_{CO_2,eq} = f(M, h)$$



Environmental Impact – Flying Lower

		Mach number									
		0,4	0,45	0,5	0,55	0,6	0,65	0,7	0,75	0,8	
Altitude (m)	3000	0,053	0,023	0,012	0,011	0,018	0,035	0,058	0,092	0,155	
	3500	0,062	0,027	0,012	0,008	0,013	0,026	0,047	0,078	0,135	
	4000	0,072	0,032	0,013	0,006	0,008	0,019	0,037	0,064	0,117	
	4500	0,083	0,038	0,015	0,005	0,005	0,013	0,028	0,052	0,100	
	5000	0,097	0,046	0,018	0,006	0,002	0,008	0,020	0,042	0,085	
	5500	0,114	0,057	0,025	0,009	0,003	0,006	0,016	0,035	0,074	
	6000	0,133	0,068	0,032	0,012	0,003	0,004	0,012	0,028	0,065	
	6500	0,155	0,083	0,041	0,018	0,006	0,004	0,009	0,023	0,057	
	7000	0,192	0,110	0,062	0,035	0,020	0,015	0,018	0,030	0,061	
	7500	0,231	0,140	0,087	0,054	0,036	0,029	0,030	0,039	0,066	
	8000	0,282	0,180	0,119	0,082	0,060	0,050	0,048	0,055	0,079	
	8500	0,349	0,233	0,164	0,121	0,095	0,082	0,077	0,082	0,103	
	9000	0,425	0,294	0,215	0,166	0,135	0,118	0,111	0,112	0,131	
	9500	0,502	0,354	0,265	0,209	0,173	0,153	0,142	0,141	0,157	
	10000	0,589	0,422	0,320	0,256	0,215	0,190	0,176	0,172	0,184	
10500	0,675	0,481	0,364	0,289	0,241	0,211	0,193	0,186	0,196		
11000	0,685	0,483	0,361	0,284	0,234	0,203	0,185	0,178	0,189		
11500	0,769	0,535	0,394	0,305	0,247	0,211	0,188	0,178	0,186		
12000	0,867	0,591	0,426	0,322	0,255	0,211	0,184	0,170	0,175		
12500	1,000	0,677	0,485	0,364	0,285	0,234	0,201	0,183	0,184		

“Neutral” mix of 50 – 50 resource depletion and engine emissions

Clear altitude boundary from $m_{CO2,eq}$ visible

Fuel consumption shape visible

Fly low and slow

Units: normalized value between 0 and 1

Environmental Impact – Flying Lower

Changing the regular cruise altitude of an Airbus A320-200 of about 11500 m to an altitude of 6500 m at a constant Mach 0.78 would result in:

- a decrease of equivalent CO₂ mass of 78 % and
- an increase of fuel consumption of 5.6 %.

The increase of fuel consumption is mostly influenced by

- an increase of TSFC of 6.0 % and
- a decrease of the aerodynamic efficiency of 5.4 %.

Combining equivalent CO₂ mass and resource depletion (fuel consumption) into the environmental impact would result in a decrease of 70 % in environmental impact.

As the Mach number is kept constant, DOC are only effected by fuel consumption and increase by only 0.6%.

However, for the atmosphere this is an exchange of considerable less short term non-CO₂ warming potential versus more CO₂ long term warming potential. This exchange can be questioned, because it is not good for future generations.

Literature Review: Operational Measures to Avoid Contrails

Contrails cool the surface during the day and heat the surface during the night... Whereas the longwave (terrestrial) radiative forcing varies only little over the day, the shortwave (solar) forcing displays a strong diurnal cycle due to the variation of the sun's position (zenith angle). Hence... altering the time for aircraft traffic has the potential for reducing the radiative forcing due to contrails.

that most of the RF from contrails can be attributed to night-time flights. Even though only 25% of aircraft movements occur at night, they account for 60-80% of the contrails' RF.

although 22% of annual air traffic movements are winter flights, they contribute about half of the annual mean RF from contrails.

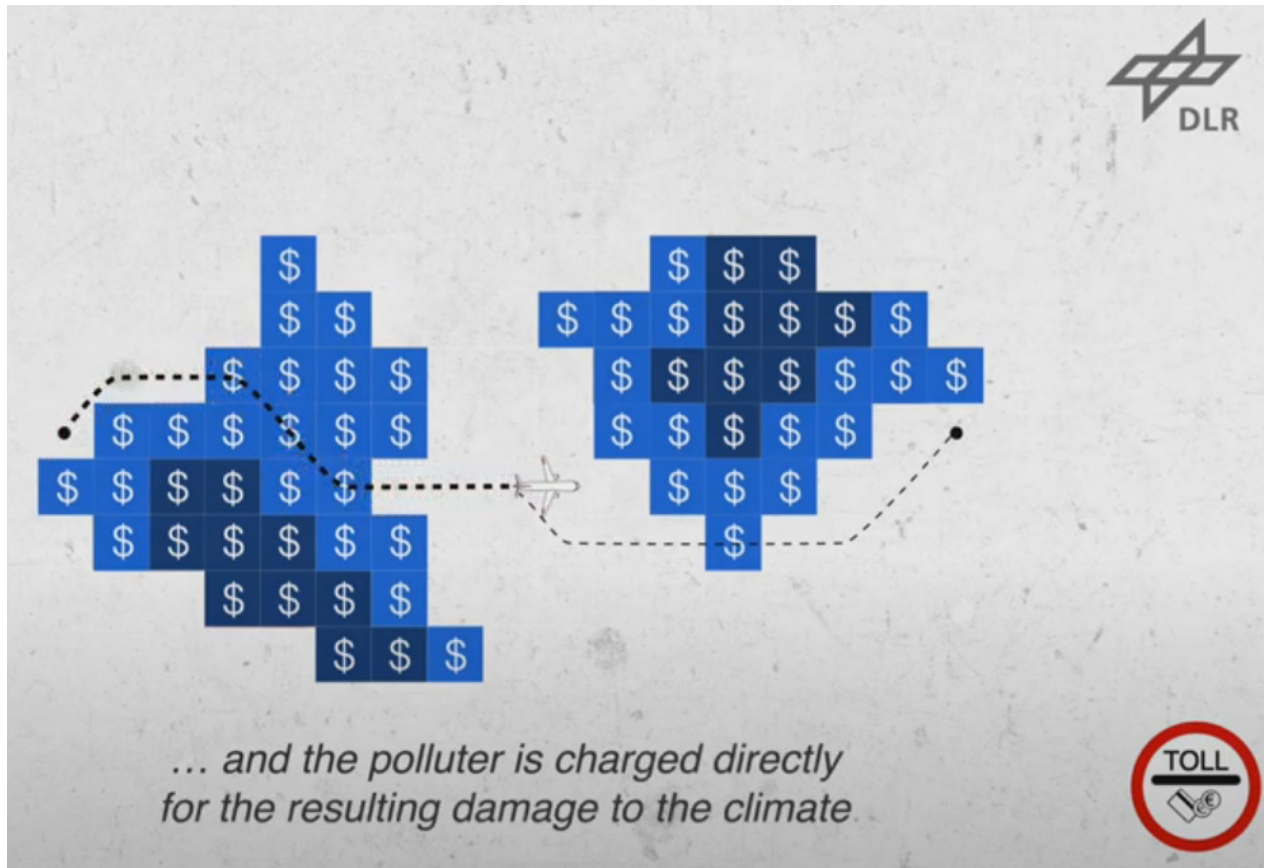
A strategy [can be] designed to achieve environmentally optimum flight routings (avoiding ice supersaturated air masses) especially for flights in the evening and night hours... As air traffic density is lower during the night, when contrails have a large individual radiative forcing, there is a greater opportunity for redirecting flights out of ice supersaturated regions without dramatically enhancing the work load of air traffic controllers.*

Gierens, 2008, <https://doi.org/10.2174/1874282300802010001>

* Redirecting flights can be done either laterally or vertically.

Hence, **only a small number of flights need to be redirected** e.g. to lower altitudes to achieve still a significant effect.

Redirecting Flights



The concepts of **climate-restricted airspaces** (regulatory approach) and **climate-charged airspaces** (price-based approach) show their mitigation potential. A trajectory simulation in the North Atlantic shows that more than 90% of the maximum mitigation potential of eco-efficient flying can be achieved by these concepts. The concepts resolve the existing conflict of objectives between ecology and economy in aviation. **Climate-friendly flying becomes economically attractive.**

Climate Charged Airspaces, <https://youtu.be/BZbOANbAG-A>

NIKLAß, Malte, 2019. *Ein systemanalytischer Ansatz zur Internalisierung der Klimawirkung der Luftfahrt*. Dissertation. Available from: <https://elib.dlr.de/126415>

Design of Hydrogen Passenger Aircraft – How much 'Zero-Emission' is Possible?

Summary (1 of 2)

- When fossil fuels come to an end, **we need an efficient energy carrier** to bring renewable energies (electricity) into the aircraft.
- At the same time we need to **make sure that flying is done with as little emissions** as possible.
- Aircraft have no aerial contact line, batteries are too heavy, **PtL needs 2.7 times more electrical energy than hydrogen for its production.**
- An **A319 LH2 cryoplane** (based on an A321 fuselage) flies its max payload at its max range with **40% more energy, 20% more DOC and about 27% less environmental burden** (considering emissions and energy based on a LCA) **if(!)** hydrogen is from **electrolysis** and electricity from **renewable sources.**
- An **aircraft flying with PtL compared with one flying on hydrogen needs $2.7/1.4 = 1.9$, or roughly two times more primary energy.**
- **Very long range aircraft** (in case they are needed at all) would require a prohibitively large LH2 tank and are thus bound to PtL.
- **Cryoplanes** need lean combustion for low NOx and **should fly lower** to limit contrails. Research in contrail forming behind a hydrogen aircraft is needed.
- For decades to come we will have an electricity energy mix including fossil fuels and renewable energies. No one should claim the clean energy and leave the dirty energy to others.
- With **all measures** together, cryoplanes can **reduce emissions** (tank to wake) down to $44\% \cdot 1.4 = 62\%$ compared to kerosene planes (**38%** reduction). **Considering** however **the energy mix**, cryoplanes are **as polluting as the kerosene planes.** All the efforts do not pay off related to **overall** emissions!

Design of Hydrogen Passenger Aircraft – How much 'Zero-Emission' is Possible?

Summary (2 of 2)

- Cryoplane emission are more short term than the CO2 long term emissions from kerosene aircraft. This means that **in the long term, cryoplanes burden future generations less with global warming**. If we fly cryoplanes today, less CO2 piles up. Future generations could decide to stop (or reduce) flying and will see an immediate effect when cutting the short term non-CO2 effects.
- **Renewable energy** will by far **not** be **sufficient to maintain flying at the level we know today** (2019).
- It is therefore paramount to **reduce flying** as it happened already during the Corona pandemic. If we do not gently start changing the aviation industry now (while change takes place), the laws of physics will tell us later, with the consequence that our children will later struggle harder to make this transformation.
- Everyone needs to abide in a basic **ethic code**. "**Do not lie**" is something we have learned from childhood. It should not be limited to private life, it needs to extend to business as well.
- We need to find a **sincere way of communication**. Otherwise our society will drift apart even more than it has already: aviation industry versus citizen; old generation versus young generation.
- In the end **everything can be traced back to money**. Too many have some kind of financial stake in the aviation industry and their narrative is compromised. This has caused already a tremendous **truth decays** in the aviation industry – not only limited to this topic "zero emission".
- The aviation industry has to maintain the physically implausible goal of "*zero emission*" by technology, because otherwise the credo "aviation needs growth" will not convince politics and society, and aviation could face restrictions.
- This is why a **technical debate** with industry about: "**How much 'zero emission' is possible?**" **is impossible!**

Video "The Bill"

Watch "The Bill", a short video (4:21).

The video may make you think about how we live and what we really need.

<https://youtu.be/EmirohM3hac> (German)

<https://youtu.be/rWfb0VMCQHE> (English Subtitles)



Design of Hydrogen Passenger Aircraft – How much 'Zero-Emission' is Possible?

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Update on 2021-01-06 of pages 123 and 124.

Design of Hydrogen Passenger Aircraft – How much 'Zero-Emission' is Possible?

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