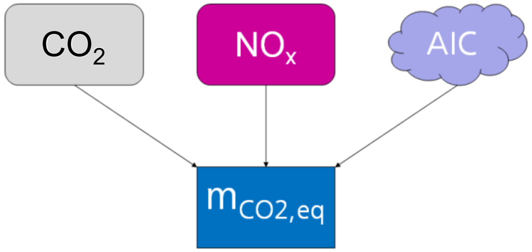
Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

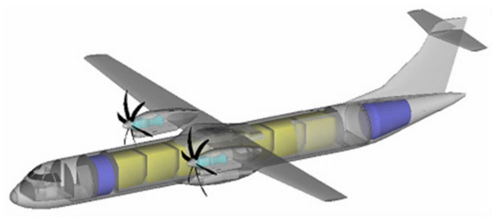
AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

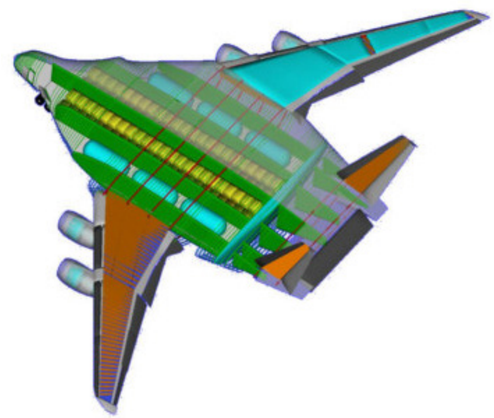


SONDERVORTRAG zum 50. Geburtstag der DGLR Bezirksgruppe Hamburg:

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

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
DGLR
VDI
ZAL
HAW HAMBURG
Hamburg Aerospace Lecture Series
Hamburger Luft- und Raumfahrtvorträge
http://www.AeroLectures.de

Deutsche Gesellschaft für Luft- und Raumfahrt Lilienthal-Oberth e.V.
DGLR Bezirksgruppe Hamburg

ROYAL AERONAUTICAL SOCIETY
HAMBURG BRANCH e.V.

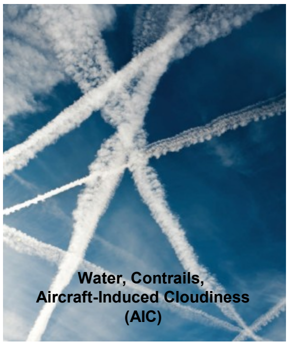
ZAL

VDI Verein Deutscher Ingenieure
Hamburger Bezirksverein e.V.
Arbeitskreis Luft- und Raumfahrt

HAW HAMBURG

Hamburg Aerospace Lecture Series
Hamburger Luft- und Raumfahrtvorträge

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



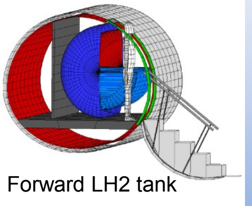
SONDERVORTRAG zum 50. Geburtstag der DGLR Bezirksgruppe Hamburg:

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

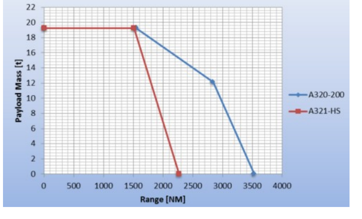
Prof. Dr.-Ing. **Dieter Scholz**, MSME, HAW Hamburg

Date: **Thursday, 19 November 2020, 18:00**

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

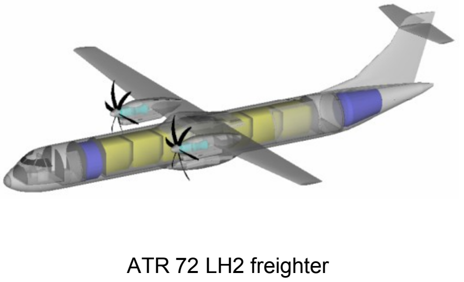


Forward LH2 tank

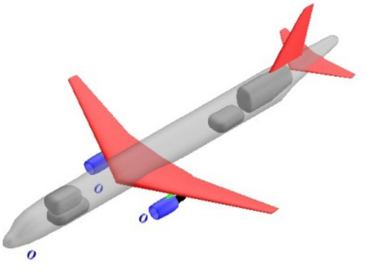


"Zero-emission" is not possible! Hydrogen combustion emits 2.6 times more water per energy than kerosene. This leads to contrails forming already at lower altitudes and hence more often. Hydrogen is an energy carrier that is responsible for as much CO2 as its production has emitted. It is not only about 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

HAW/DGLR	Prof. Dr.-Ing. Dieter Scholz	Tel.: (040) 42875-8825	info@ProfScholz.de
RAeS	Richard Sanderson	Tel.: (04167) 92012	events@raes-hamburg.de

Hamburg Aerospace Lecture Series – DGLR, HAW Hamburg, RAeS, VDI, ZAL

DGLR Bezirksgruppe Hamburg https://hamburg.dglr.de
RAeS Hamburg Branch https://www.raes-hamburg.de
ZAL TechCenter https://www.zal.aero
VDI Hamburg, Arbeitskreis L&R https://www.vdi.de

Die ***Hamburg Aerospace Lecture Series*** (http://www.AeroLectures.de) wird gemeinsam veranstaltet von DGLR, RAeS, ZAL, VDI und HAW Hamburg (Praxis-Seminar Luftfahrt, PSL). Der Besuch der **Veranstaltung ist steuerlich absetzbar**. Bringen Sie dazu bitte eine ausgefüllte Teilnahmebestätigung zur Unterschrift zum Vortrag mit. Mittels **E-Mail-Verteilerliste** wird über aktuelle Veranstaltungen informiert. **Vortragsunterlagen** vergangener Veranstaltungen, aktuelles **Vortragsprogramm**, Eintrag in E-Mail-Verteilerliste, Vordrucke der Teilnahmebestätigung: Alle Services über das Internet: http://www.AeroLectures.de .

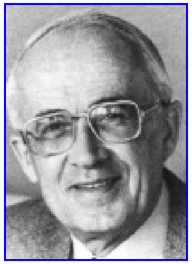
Hamburg Aerospace Lecture Series

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.

50 YEARS

Deutsche Gesellschaft für Luft- und Raumfahrt Lilienthal-Oberth e.V.
Bezirksgruppe Hamburg
DGLR

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.

Contents

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

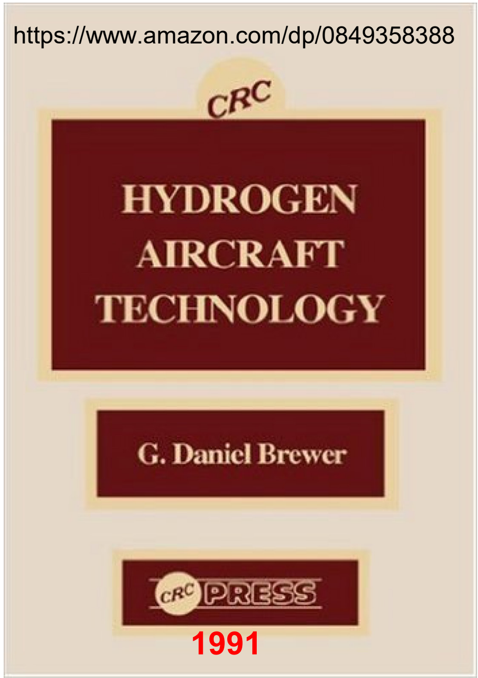
Brecht Caers (HAW Hamburg, Master Thesis)

Funding from HAW Hamburg, up to 2020

... and many others.

Introduction

Literature / Previous Projects



In 2012: Dan BREWER at 93.

FINAL TECHNICAL REPORT
(PUBLISHABLE VERSION)

CONTRACT N°: G4RD-CT-2000-00192

PROJECT N°: GRD1-1999-10014

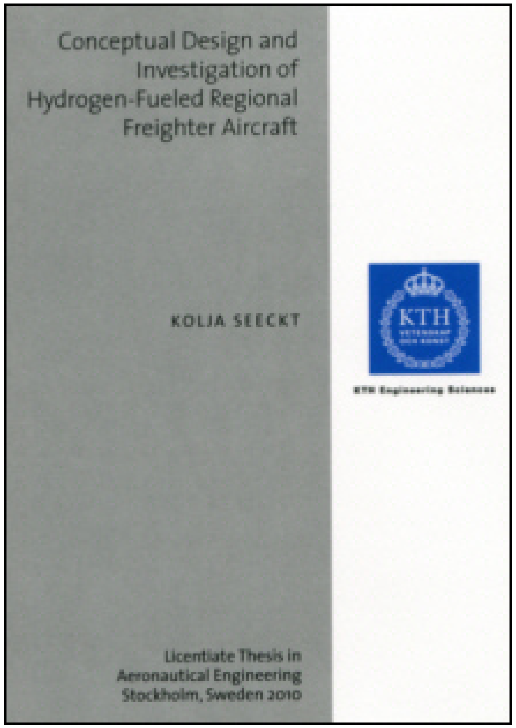
ACRONYM: CRYOPLANE

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



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

Grüner Frachter

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

Federal Ministry of Education and Research

Airport2030

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

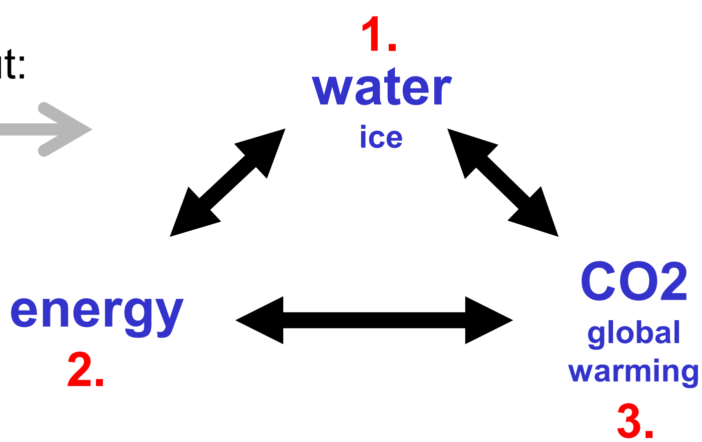
Federal Ministry of Education and Research

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: CO_2, Global Warming, Climate Change, but:
- There are **more issues than CO_2** & global warming
- **Needed:** Balanced look with **Life Cycle Assessment**



Ensure with 2. priority (after water):

Future availability of energy (in aviation) !

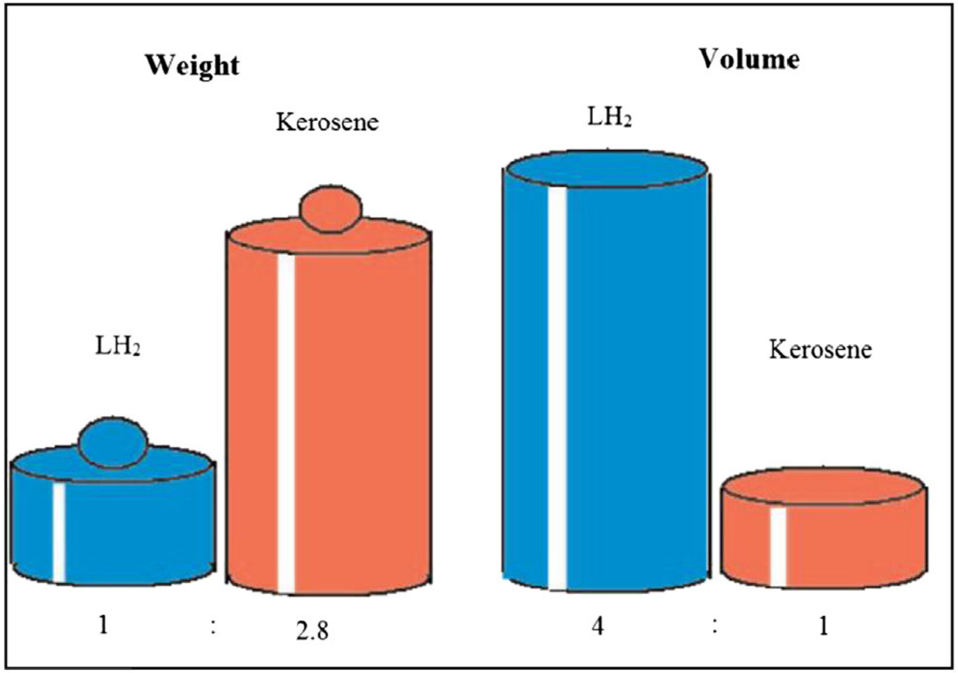
(or tell your kids the party is over)

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

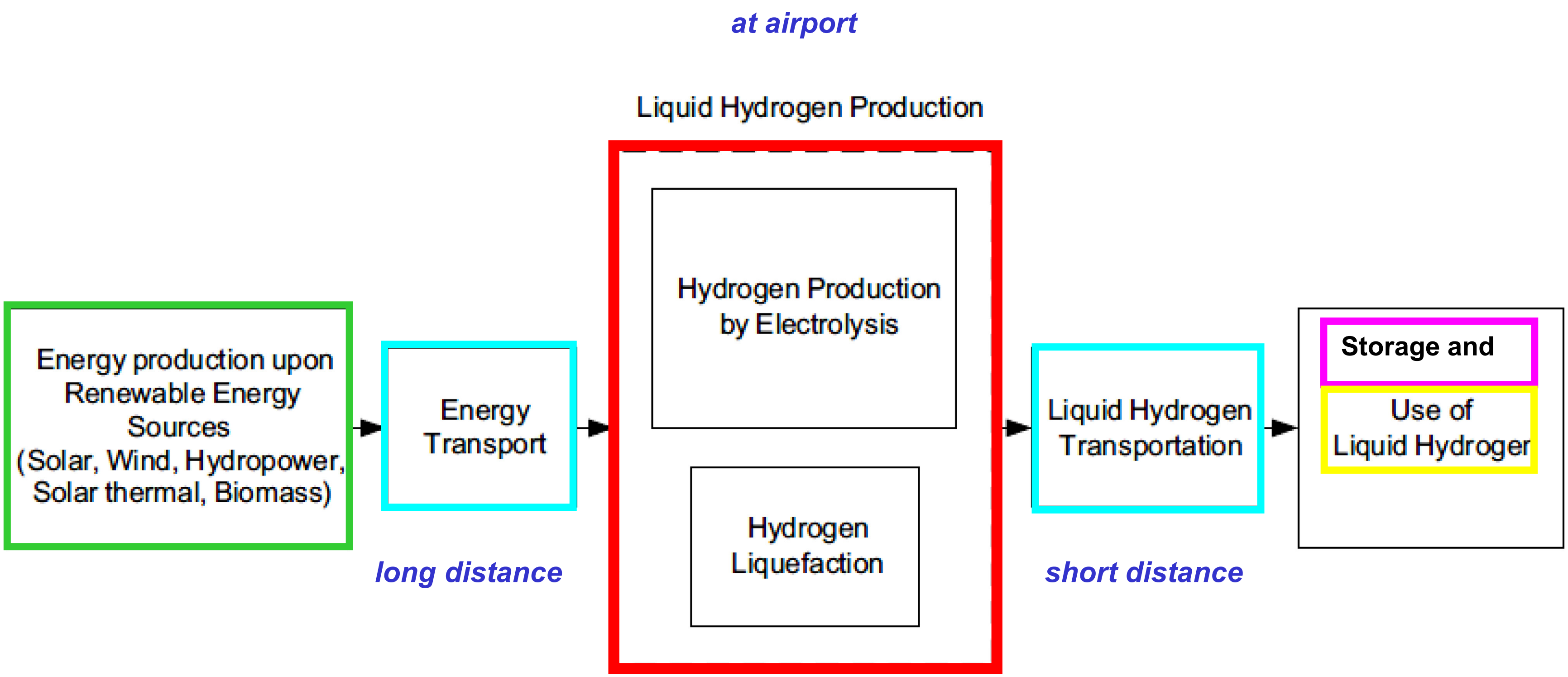
- **LH2 comparison at equal energy (20 K = -253 °C):**



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"

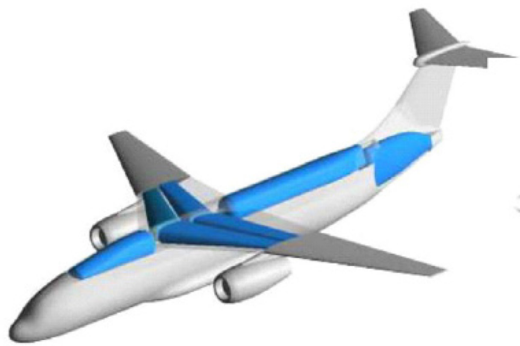


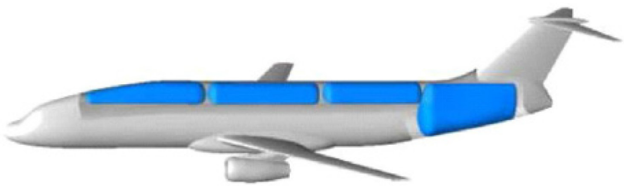
EU, 2020. Hydrogen-Powered Aviation. Available from: https://doi.org/10.2843/471510

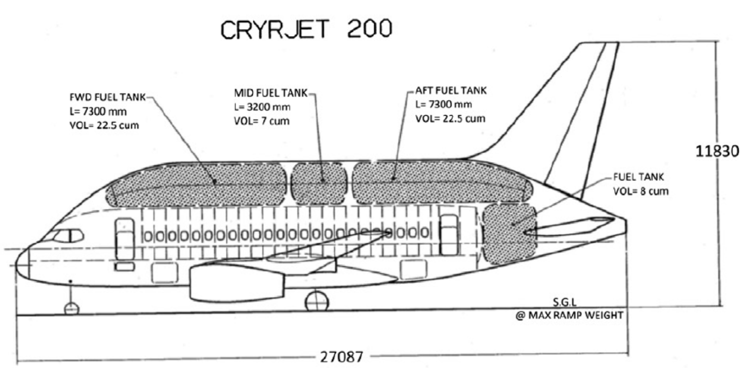
Liquefaction should be at the airport. To avoid unnecessary boil-off, distances to the aircraft are kept short. Refueling has to be done directly before take-off.

Hydrogen Aircraft Configurations

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

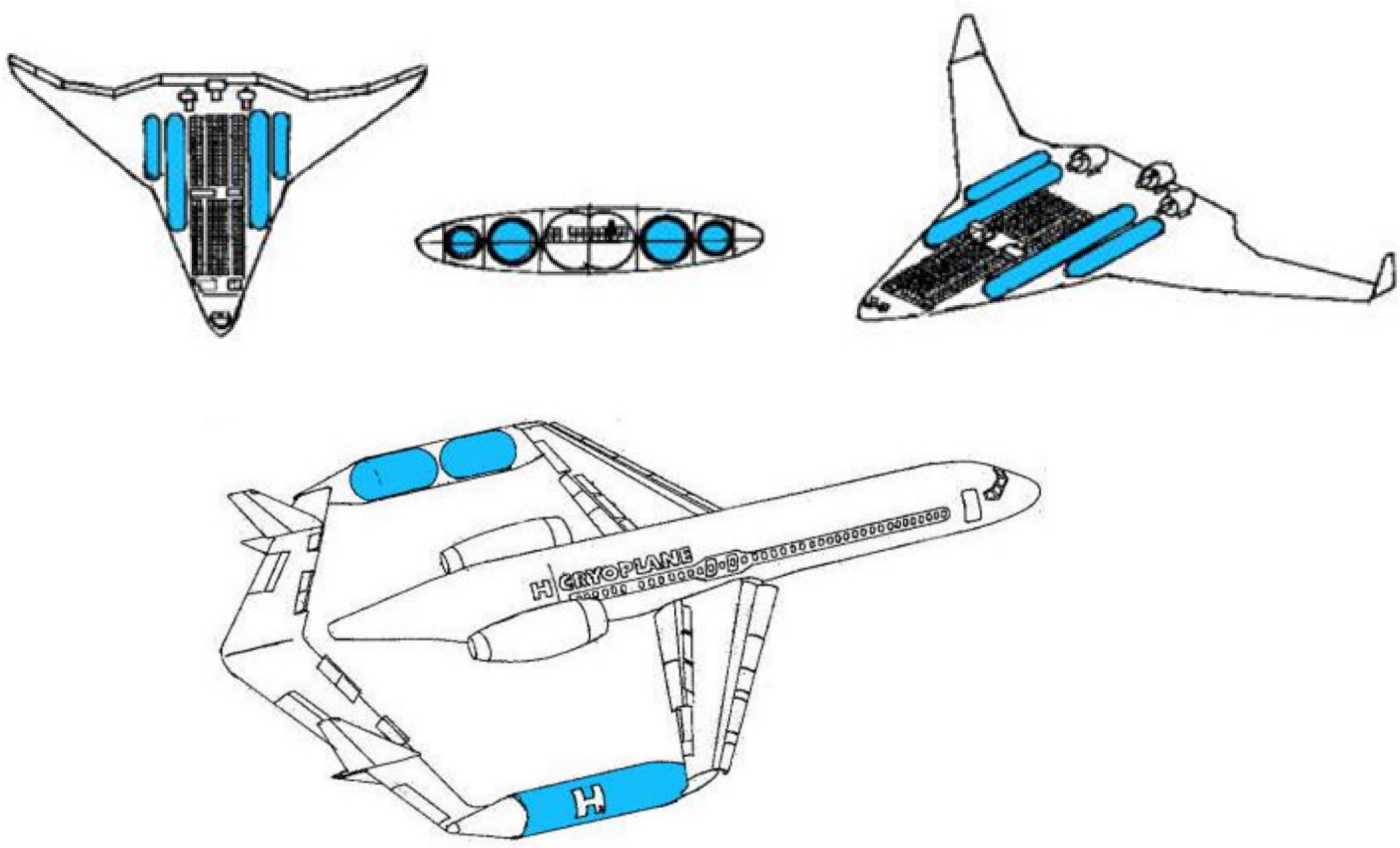






WESTENBERGER, 2003

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

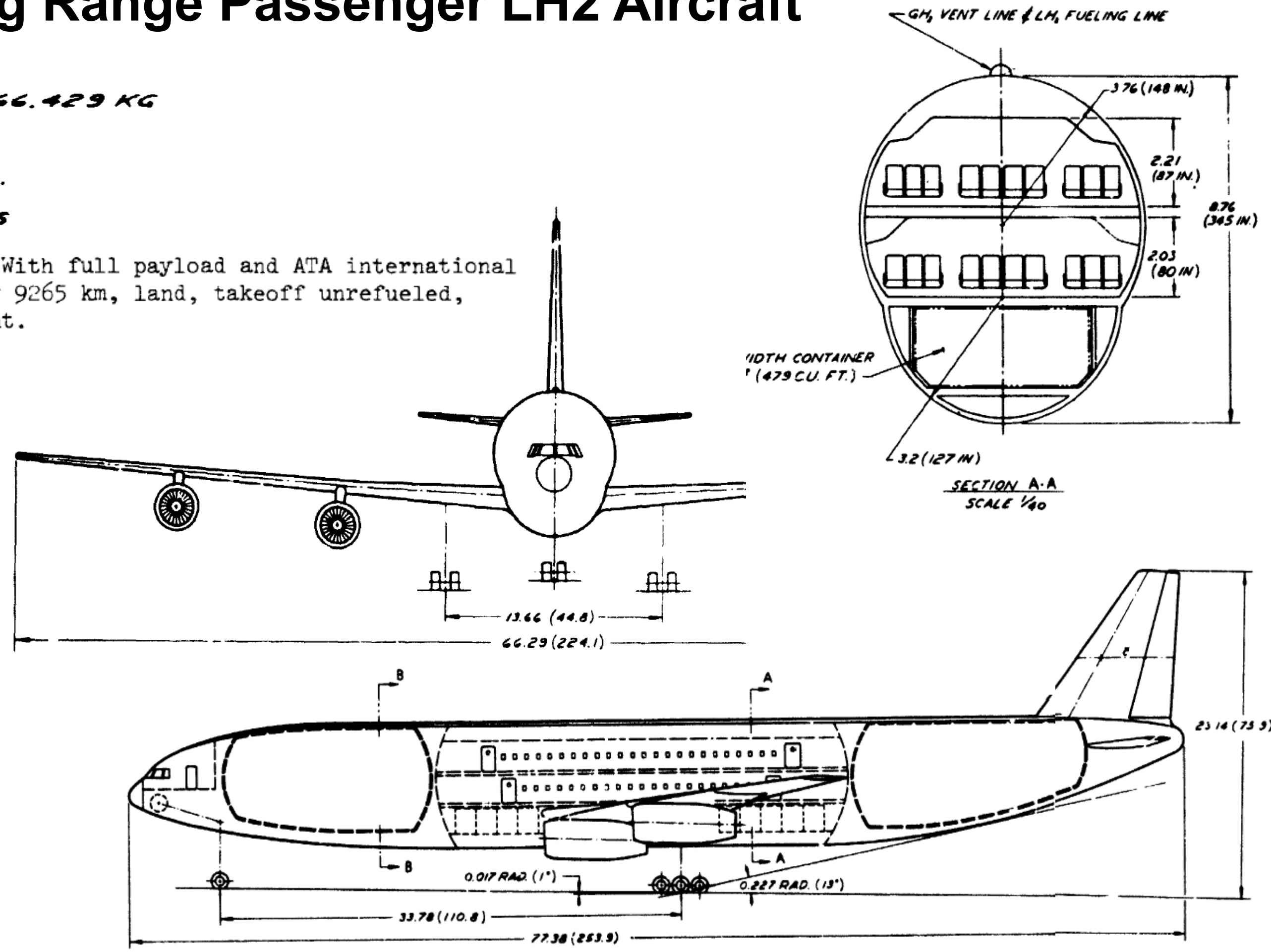
PASSENGERS - 400

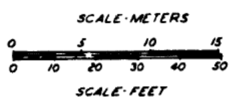
FUEL (LH_2) - 68,424 KG.

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

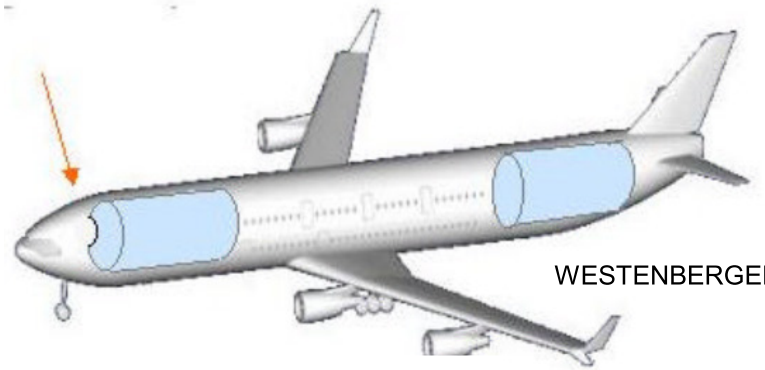




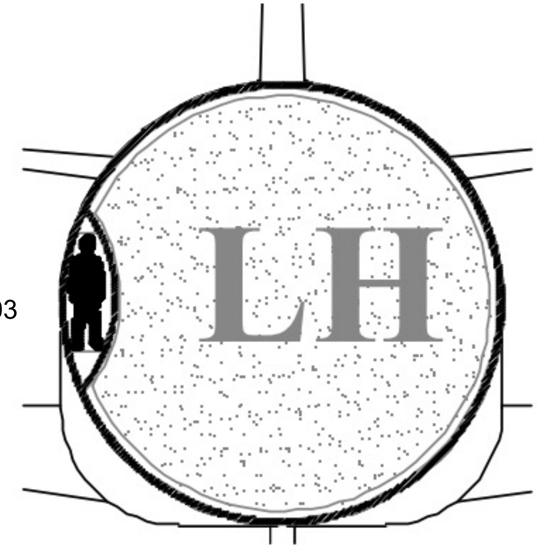
BREWER, G.D., MORRIS, R.E., 1976. *Study of LH2 Fueled Subsonic Passenger Transport Aircraft*. Lockheed, NASA CR-144935. Available from: https://ntrs.nasa.gov/citations/19760012056

Cockpit Integration – Passageway to Cabin?

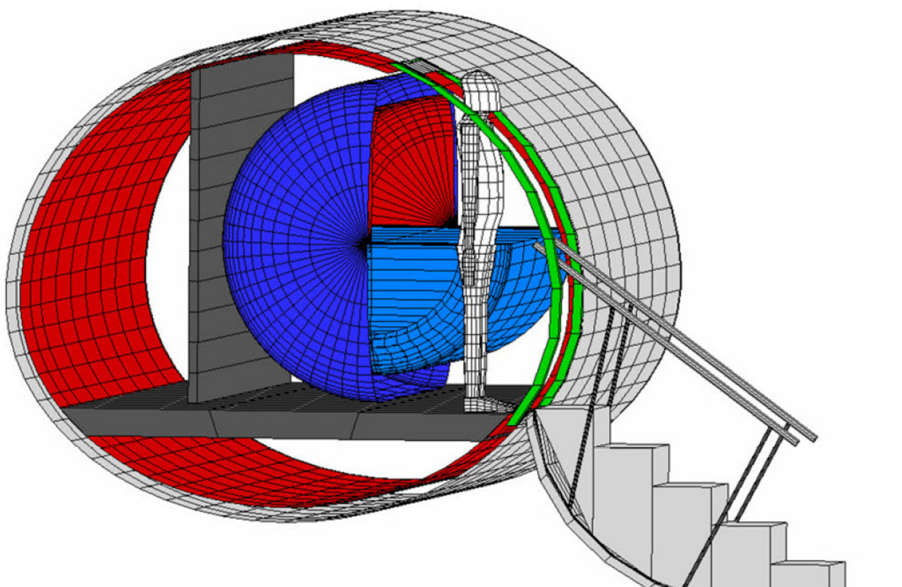
Yes:



WESTENBERGER, 2003

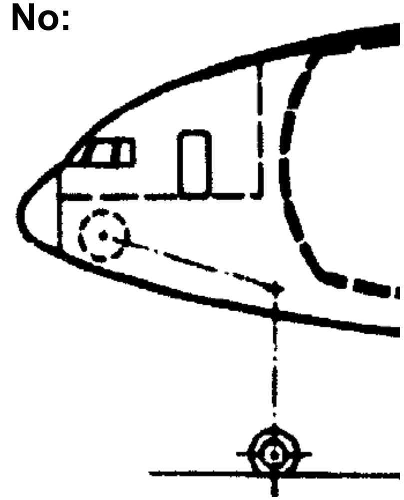


Yes:



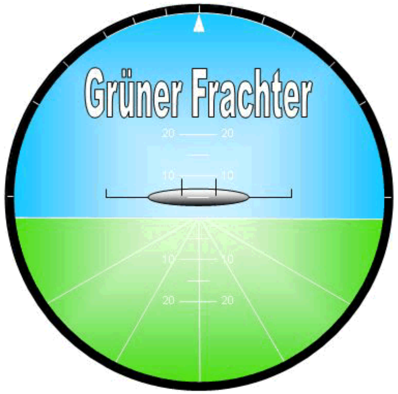
SEECKT, HAW Hamburg, 2010

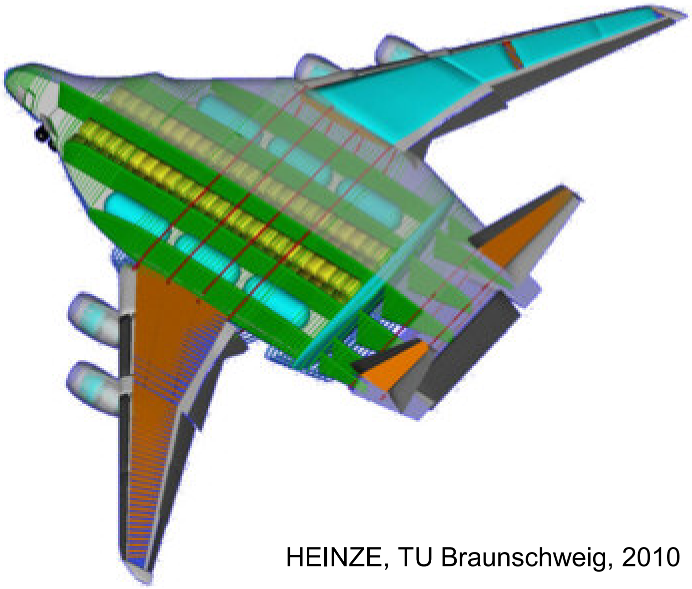
No:



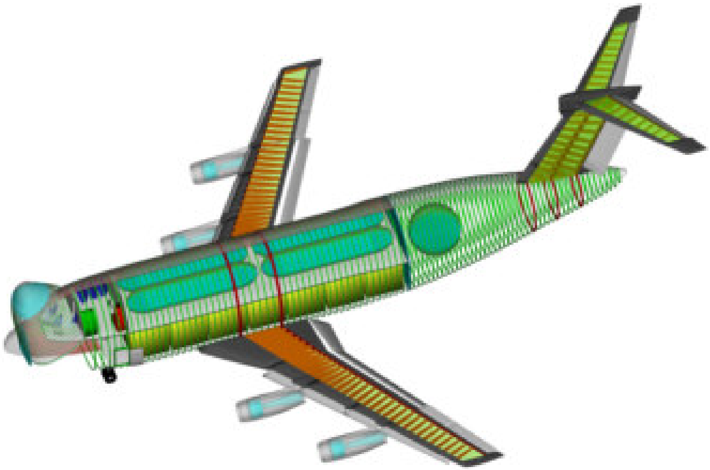
BREWER 1976

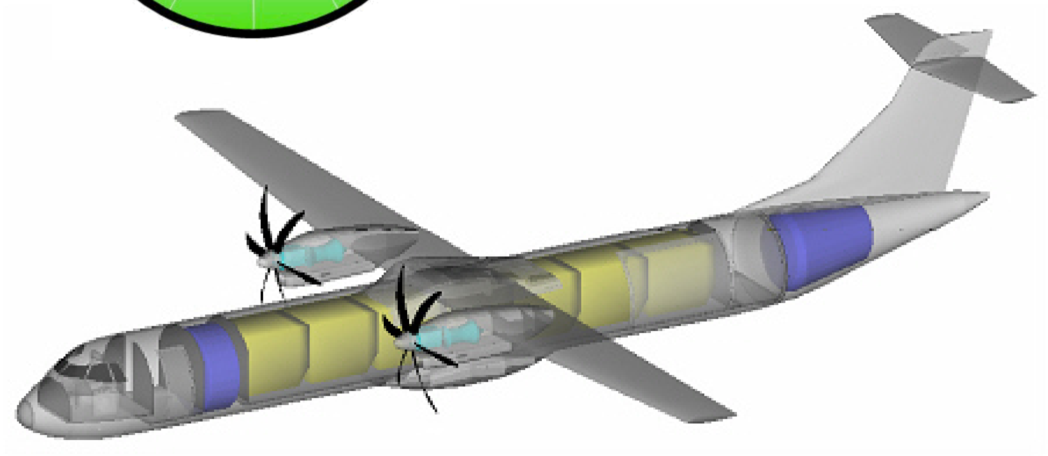
Configurations From the "Green Freighter" Project





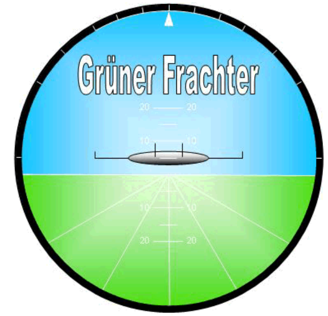
HEINZE, TU Braunschweig, 2010





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

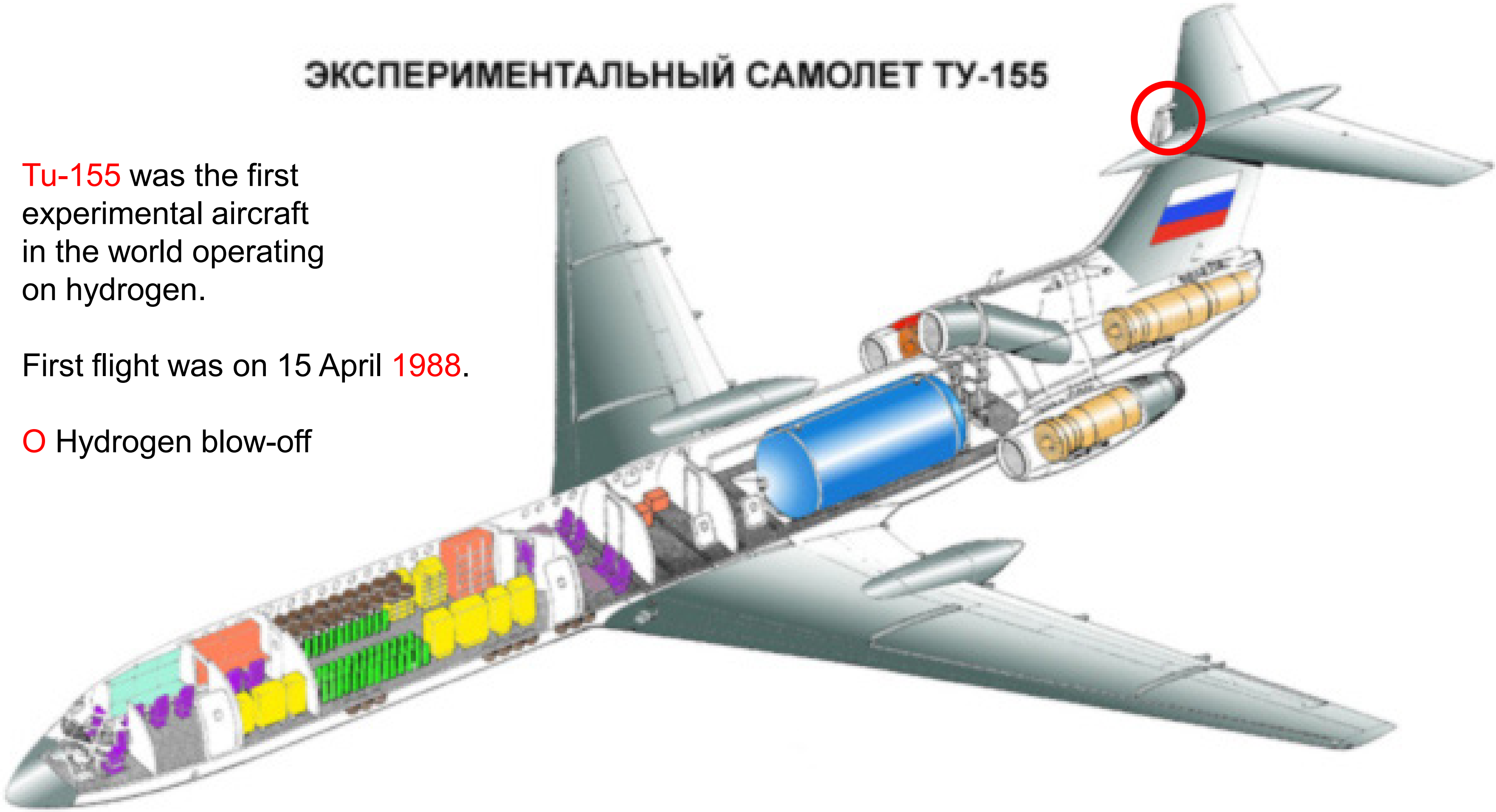
https://www.airbus.com/innovation/zero-emission/hydrogen/zeroe.html
Archived at: https://perma.cc/HJ6L-3HUB

Airbus First? Tu-155 First Experimental Hydrogen Aircraft

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

First flight was on 15 April 1988.

O Hydrogen blow-off



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

HAW HAMBURG

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

ZEROAVIA

2020 SUMMIT | MISSION | MEDIA | NEWS | PROBLEM | SOLUTION | OPPORTUNITY

ZeroAvia Completes World First Hydrogen-Electric Passenger Plane Flight

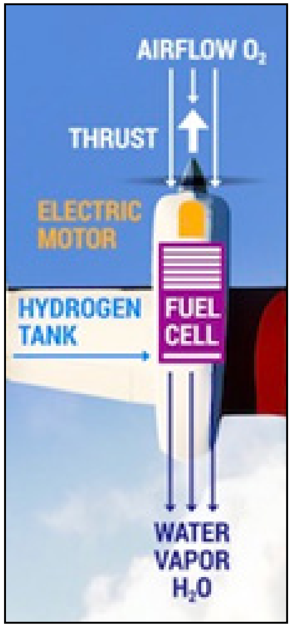
25 September, 2020, 08:00 BST

— 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 Fight



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 (CO_2, NO_x, H_2O, 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

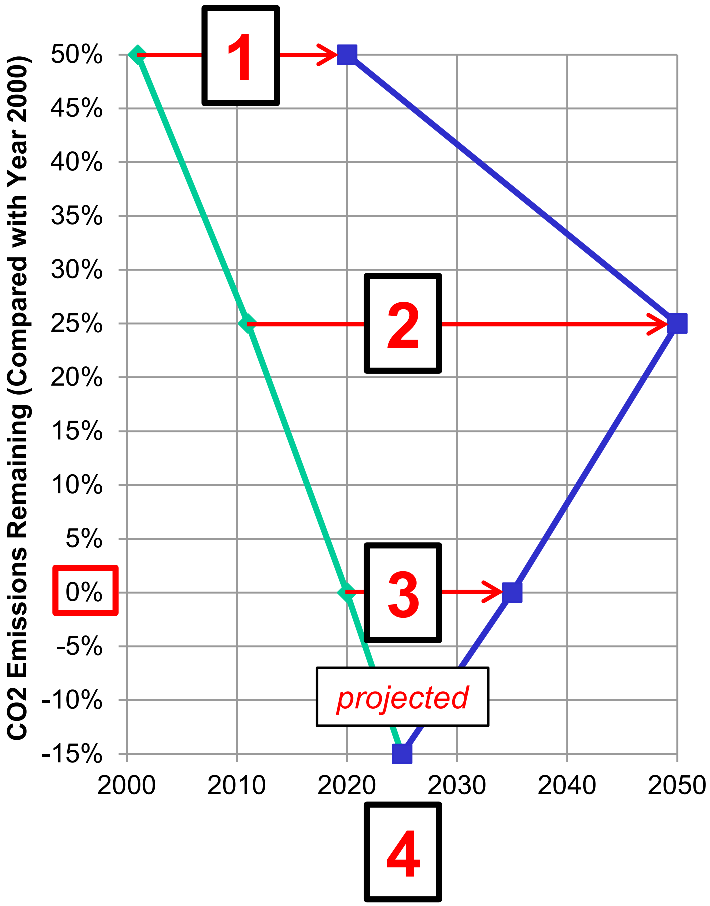
VANCOUVER - The International Air Transport Association (IATA) issued four challenges to drive the air transport industry towards its vision of zero emissions.

"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?

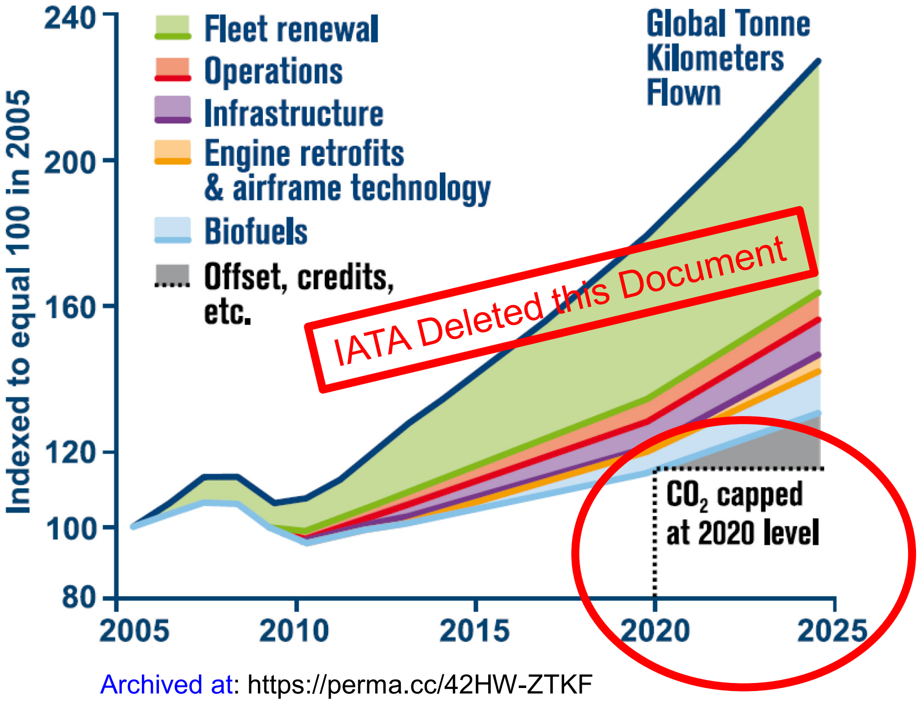
Please compare with the statement on previous page: "reduce aircraft emissions by up to 50%" versus "reduce aviation's CO2 emissions by up to 50%". "aircraft emissions" or "aviation's emissions"? "emissions; 50%" or "CO2 emissions; 50%"?

"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-emisson**" 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?



Archived at: https://perma.cc/42HW-ZTKF

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?

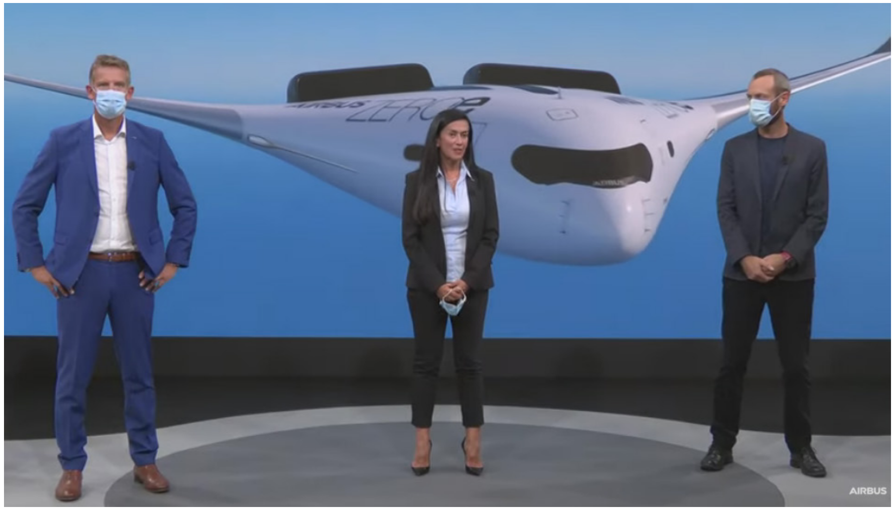
- IATA (and ATAG) wanted to achieve "Carbon-Neutral Growth" (CNG) from 2020 onwards.
- This is only possible with CO2 compensation (carbon offset schemes).
- In 2020 the goal of "Carbon-Neutral Growth" (CNG) was swept under the carpet.
- Some may point to CORSIA, but CORSIA does not deliver CNG.
- The 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 potentail ... has some work to do but [hydrogen] is really the most promising vector to deliver ultemately zero emission flight. [1]

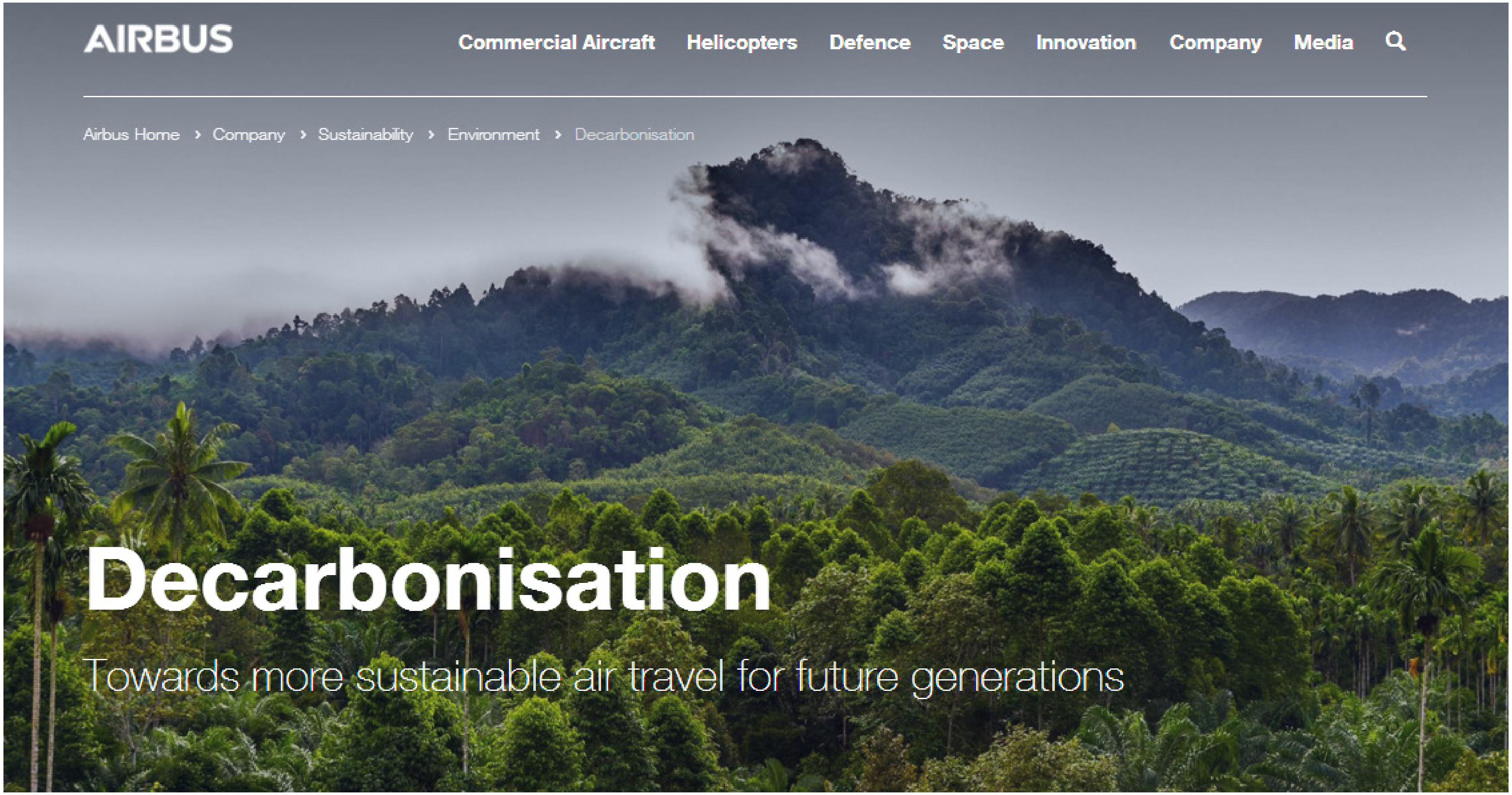
Dr. Sandra Bour-Schaeffer (Head of Airbus Group Demonstrators, CEO of Airbus UpNext):
We will be producing more vapor and probably more contrails ... Yes there remain open questions we have to look on and contrails are one of them. [2]

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]



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).

[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



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)	$m_{CO2,eq} = m_{CO2} (k_{RFI} + 0.1)$	$m_{CO2,eq} = m_{CO2}$

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

Carnot Efficiency:

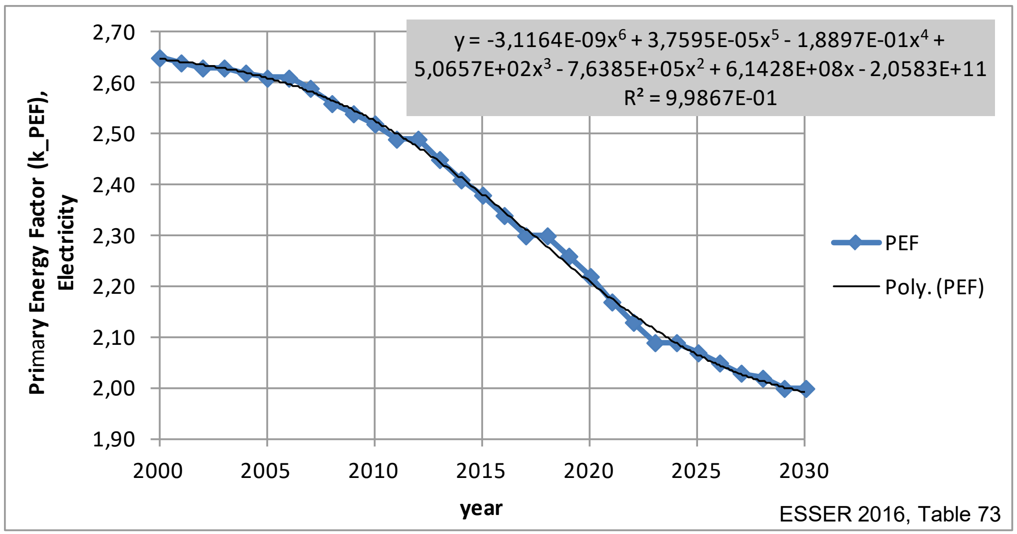
$\eta_C = 1 - T/(h)/T_{TET} =$

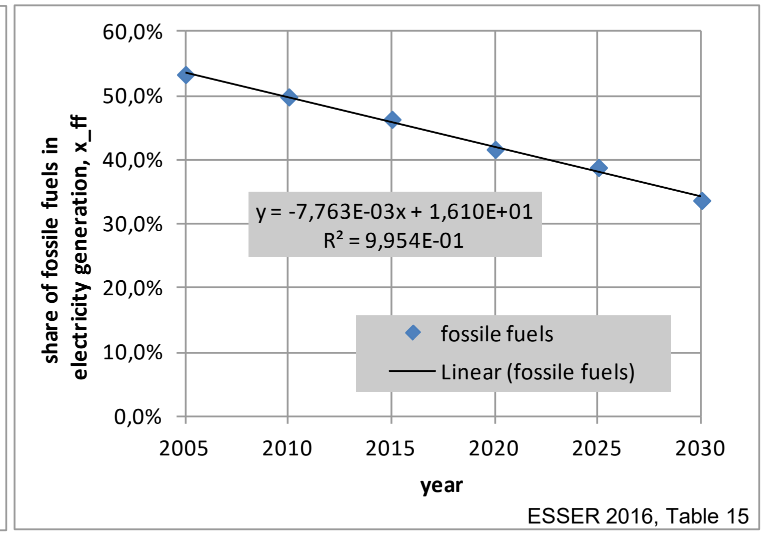
$= 1 - 216.65/1440 = 0.85$

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

Radiative Forcing Index:

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





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

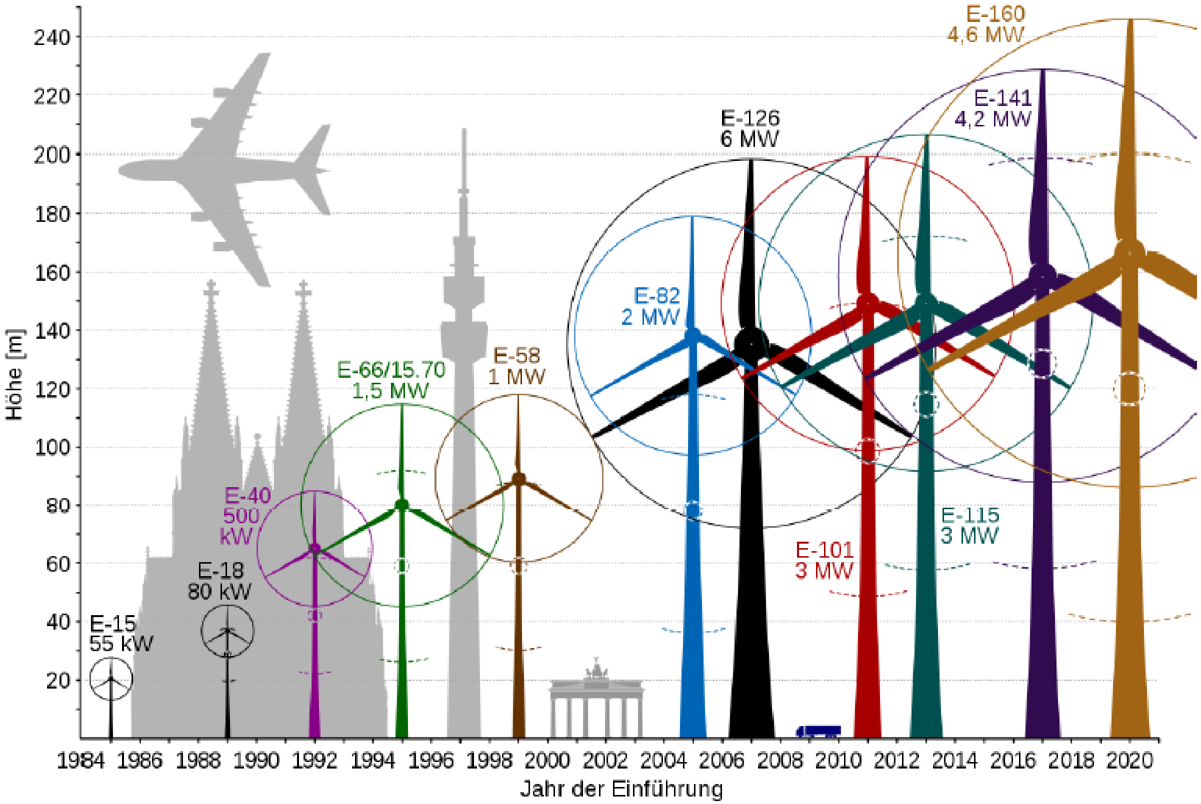
Average values	CO_2	NO_x	Water vapor	Contrails	Total
Kerosene	100%	100%	10%	100%	**310%**
Synfuel	0%	100%	10%	75%	**185%**
H_2 turbine	0%	35%	25%	60%	**120%**
H_2 fuel cell	0%	0%	25%	30%	**55%**

≠ 0%

Energy / Primary Energy

	Production well-to-tank %								Total efficiency %	energy factor compared to electricity and kerosene
LH_2 from electrolysis and lique-faction on site	100 Renewable energy	x	70 Electrolysis			x	83 Distribution & liquefaction	=	58	1.7 3.4 !!!
Synfuel from direct air carbon capture	100 Renewable energy	x	70 Electrolysis	x	32 FT-Production	x	99 Transport & distribution	=	22	4.6 9.2 !!! PtL: 2.7 times more than LH2!

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%, η_{PtL} = 0.45%)

Bauhaus Luftfahrt
Neue Wege.

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

The full global demand for LH_2 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

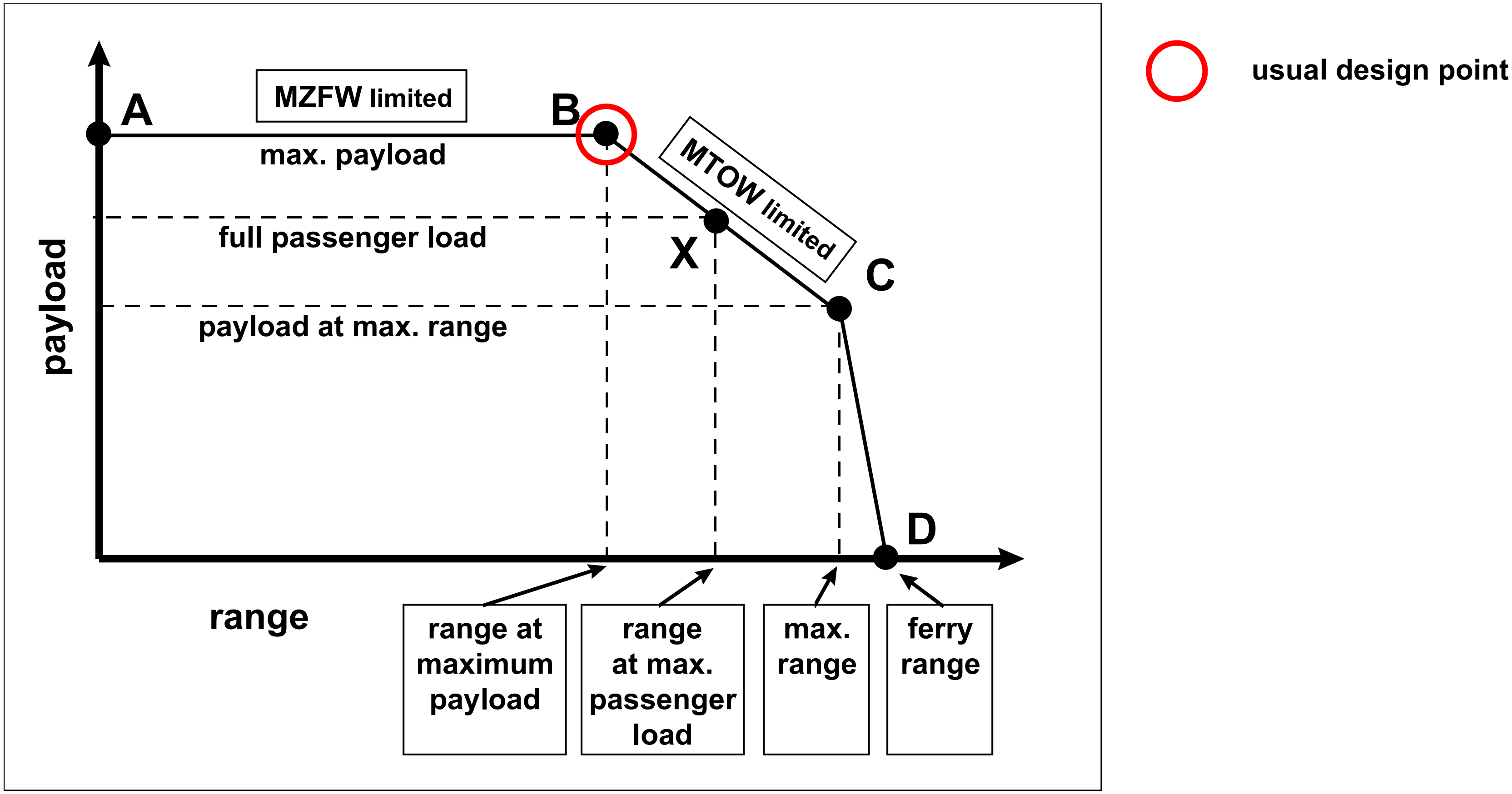
Aviation's energy demand today is too high: Minium all wind or solar energy available today!

First we need to reduce the amount of air travel.

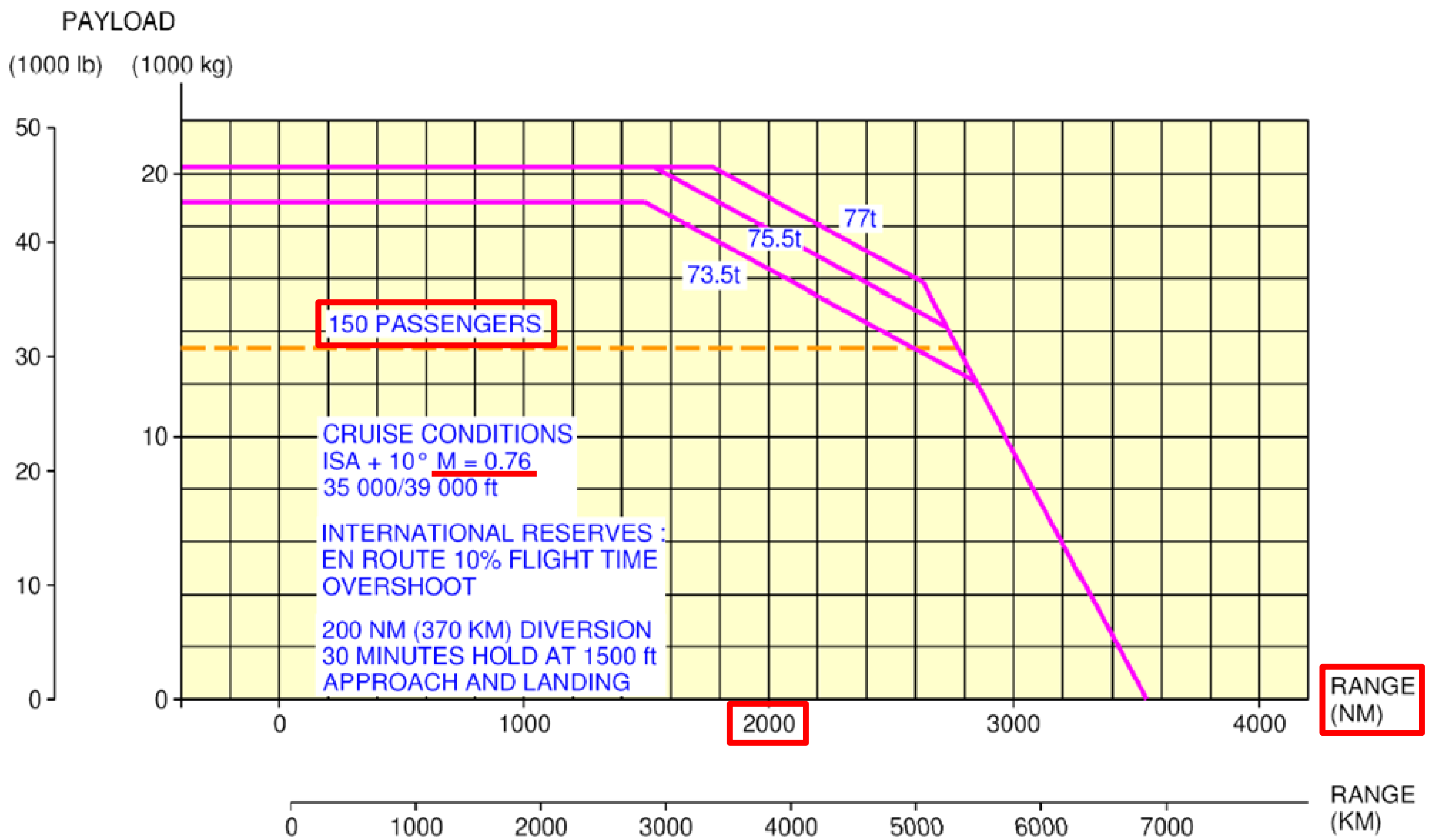
Then we may have a chance to power aviation with renewable energy.

Airbus Hydrogen Concept Planes: Payload and Range

Payload-Range Diagram – Fundamentals



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

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

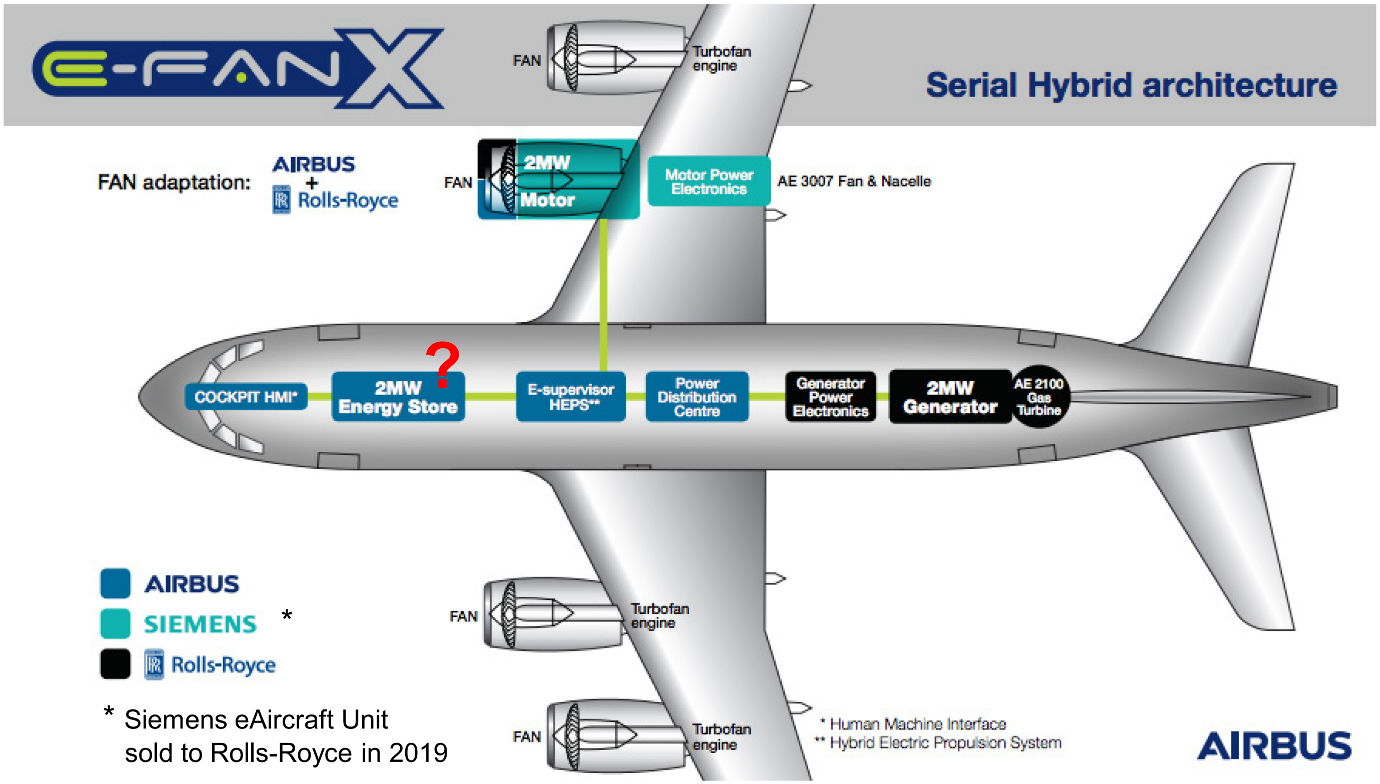
E-Fan X project lead Olivier Maillard

- 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 CO_2 by 75%, reduction of NOx by 90% and noise reduction by 65%)." (https://bit.ly/2UB4D6v)

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/935443638137622528
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

Airbus 2018

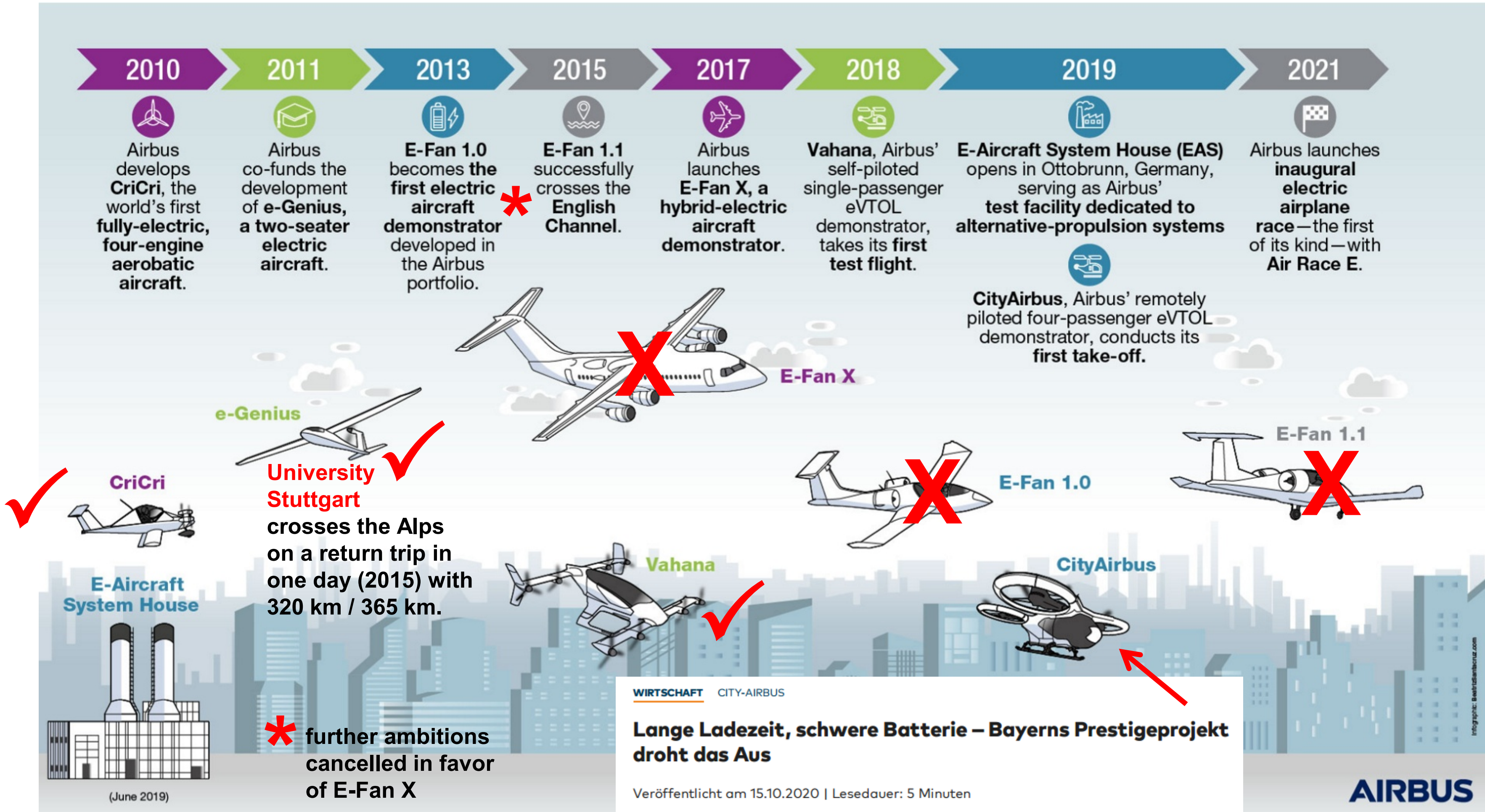
https://www.airbus.com/innovation/zero-emission/electric-flight.html
Archived at: https://perma.cc/9ZPP-ULRS

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



WIRTSCHAFT CITY-AIRBUS

Lange Ladezeit, schwere Batterie – Bayerns Prestigeprojekt droht das Aus

Veröffentlicht am 15.10.2020 | Lesedauer: 5 Minuten

Von **Gerhard Hegmann**
Wirtschaftsredakteur

https://perma.cc/YCA2-2DWW

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

HAW HAMBURG

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

Le Monde

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Sharing

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

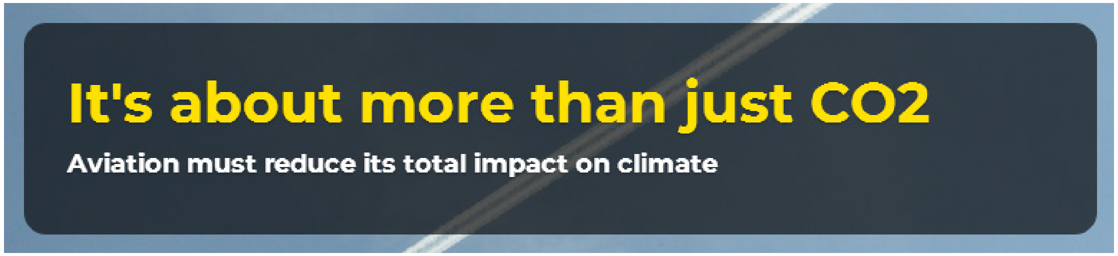
Biggest Emission Reduction in Aviation History Thanks to the Corona Pandemic

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

STAY
GROUNDED

Traffic reduction is more efficient than technology

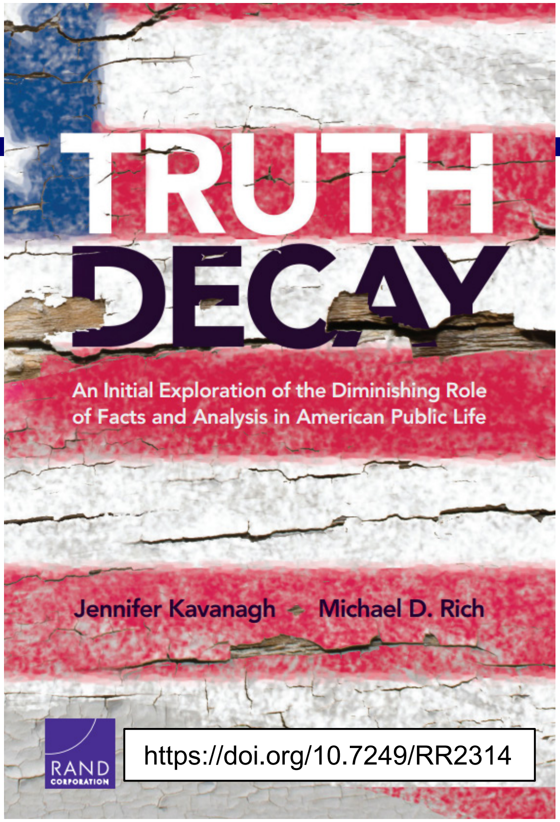
https://stay-grounded.org



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:

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

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 futher 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 fascility 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**

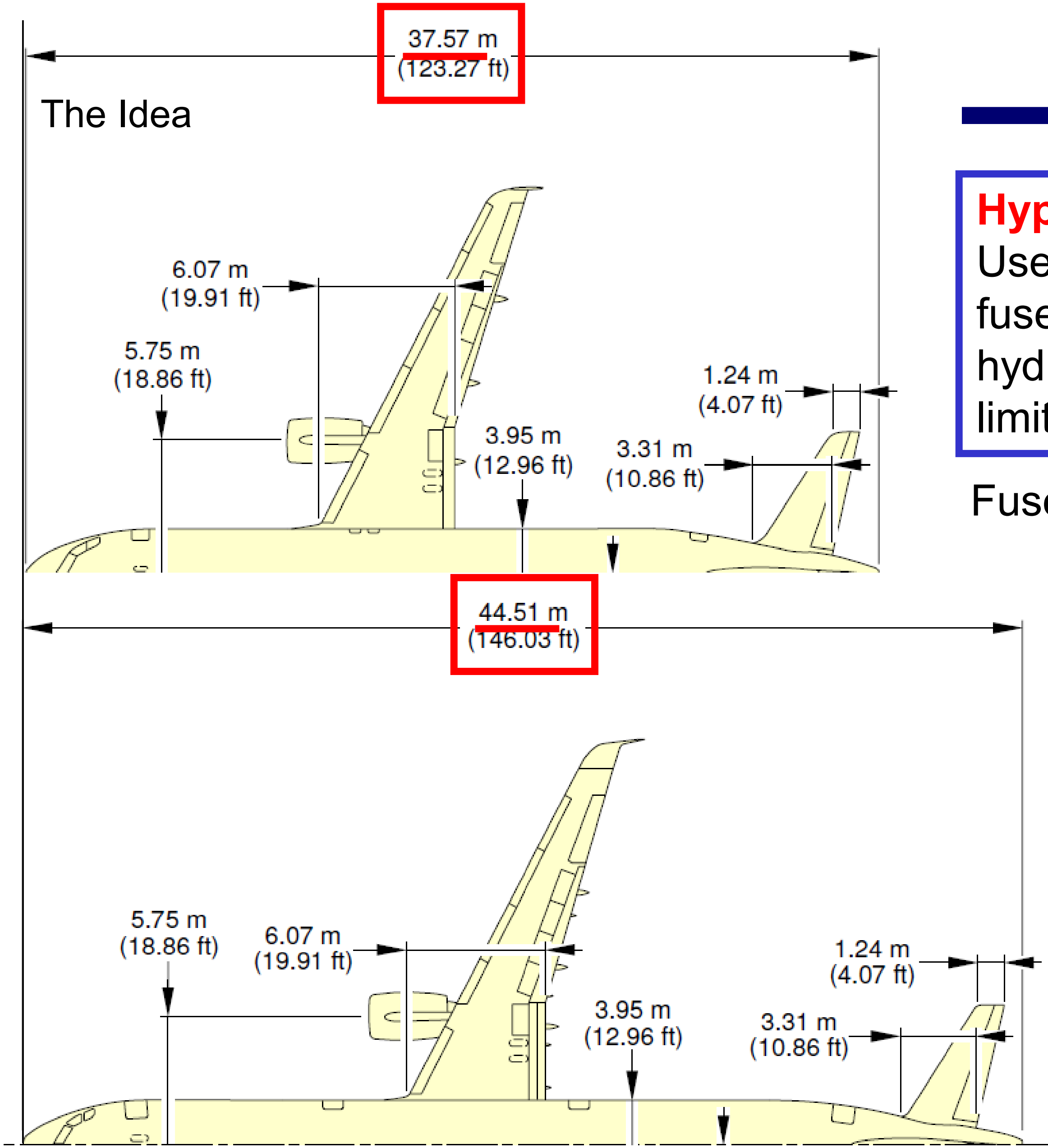
1.) in new aircraft

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



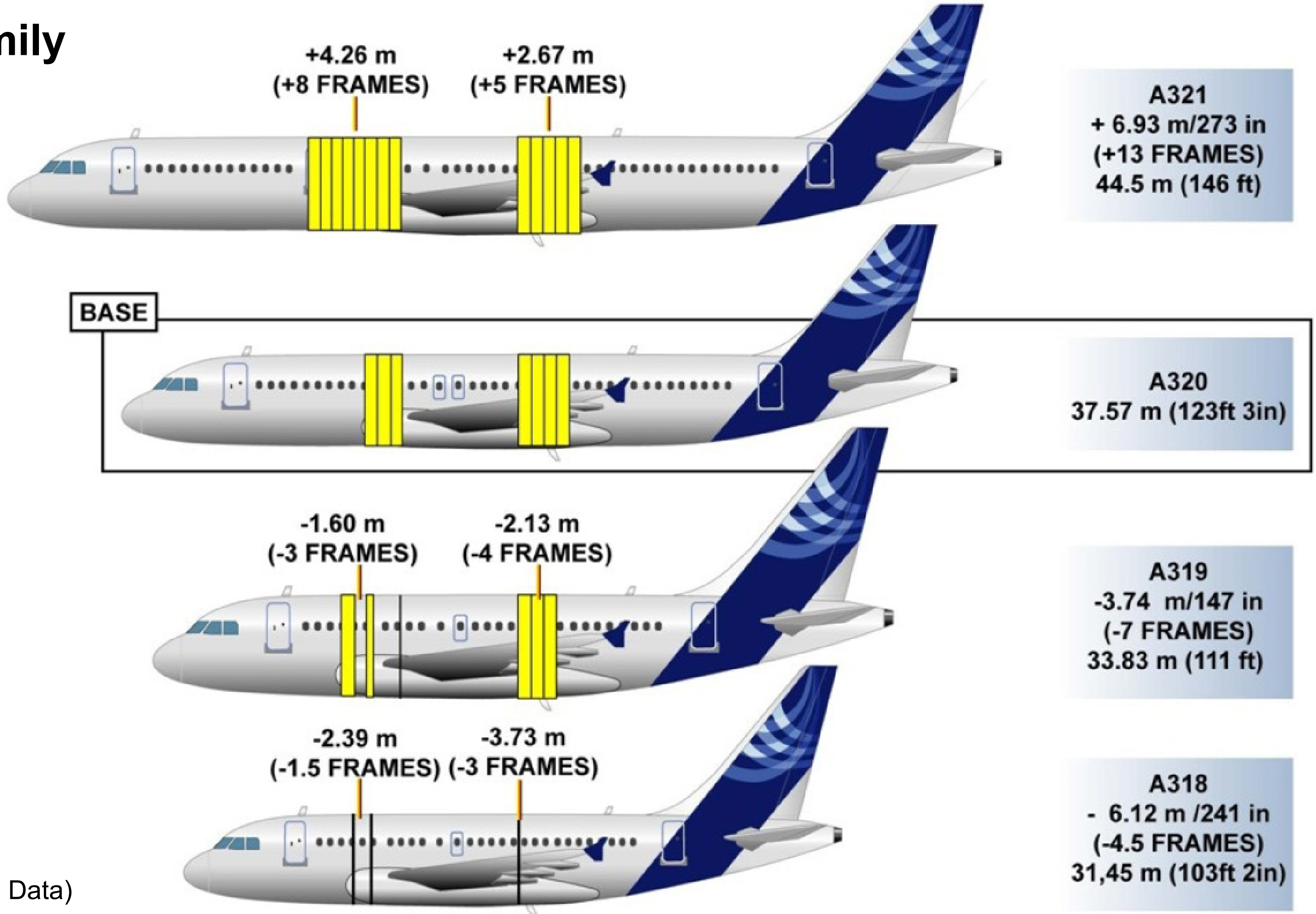
Hypothesis:
Use an existing (longer) fuselage to integrate the hydrogen tanks to limit investment!

Fuselage Length Compared:

A320

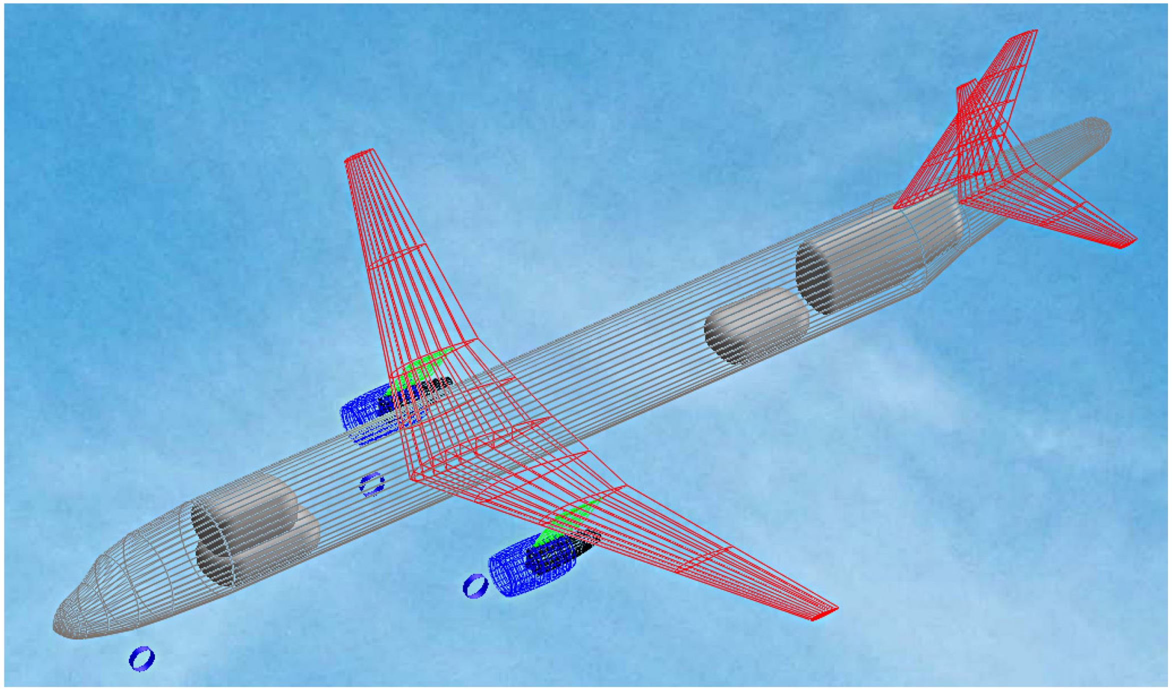
A321

A320 Family



Dimensions of
the A320 family
(Airbus Technical Data)

Hydrogen Storage in the Fuselage (Front and Rear)

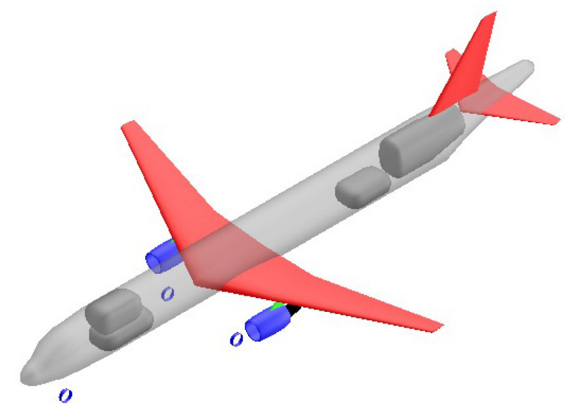


Distribution of the tank in the front and in the back to **balance CG**.

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 protion of front and aft **cargo compartment**.



Trade-Off for Tank Location in Fuselage

Not compatible with simple fuselage stretch.

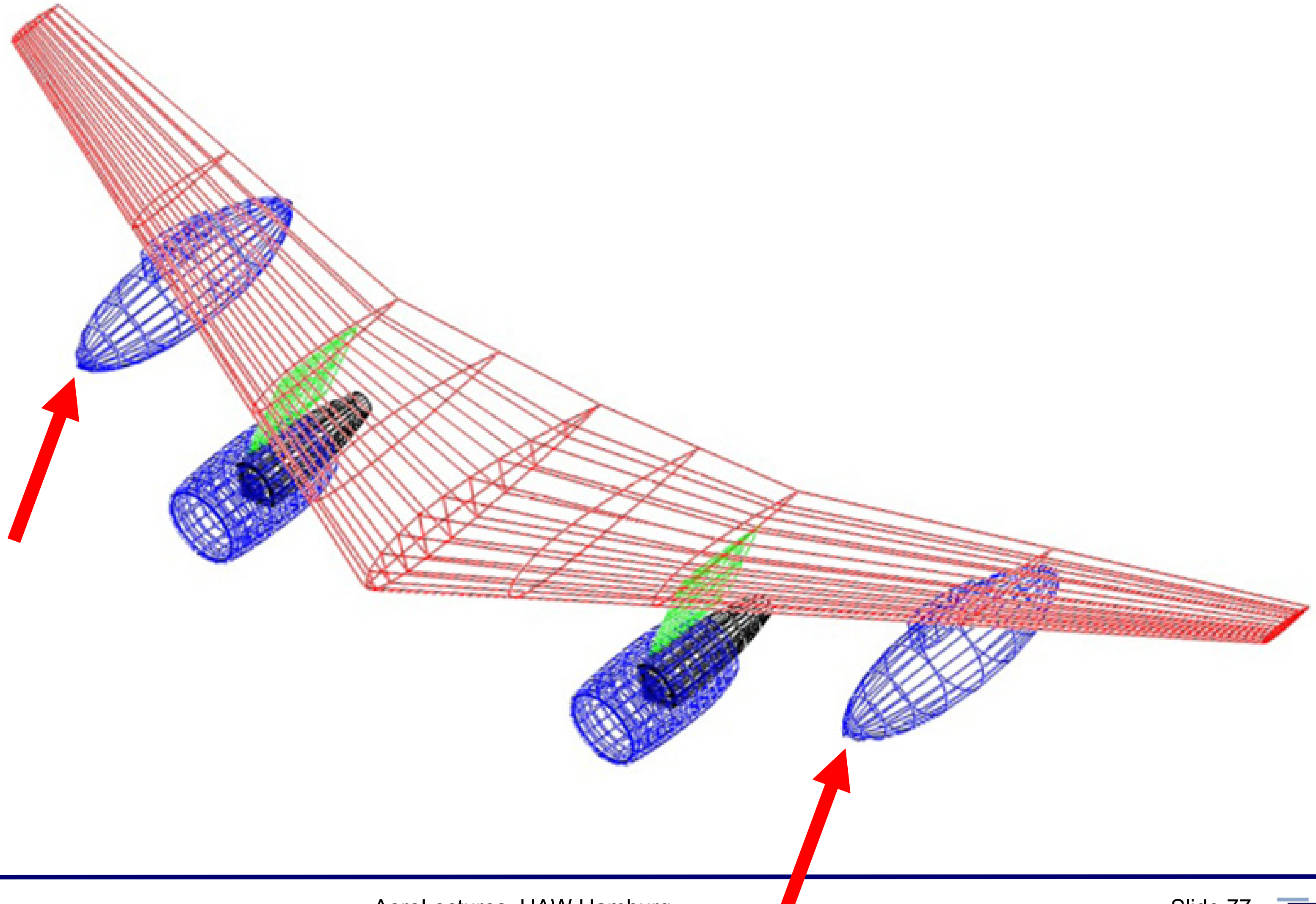
	CONFIGURATION	
FEATURE	Over the fuselage	Front and Rear
Access for crew and passengers	3†	1
Surface to volume considerations	1	3
Control of C.G.	2	3
Security in case of damage	3	2
Drag Increase	1	3
Weight increase	2	2
Manufacturing process consideration	1	3
TOTAL	**13**	**17**

† 3 is High; 2 is Medium; 1 is Low

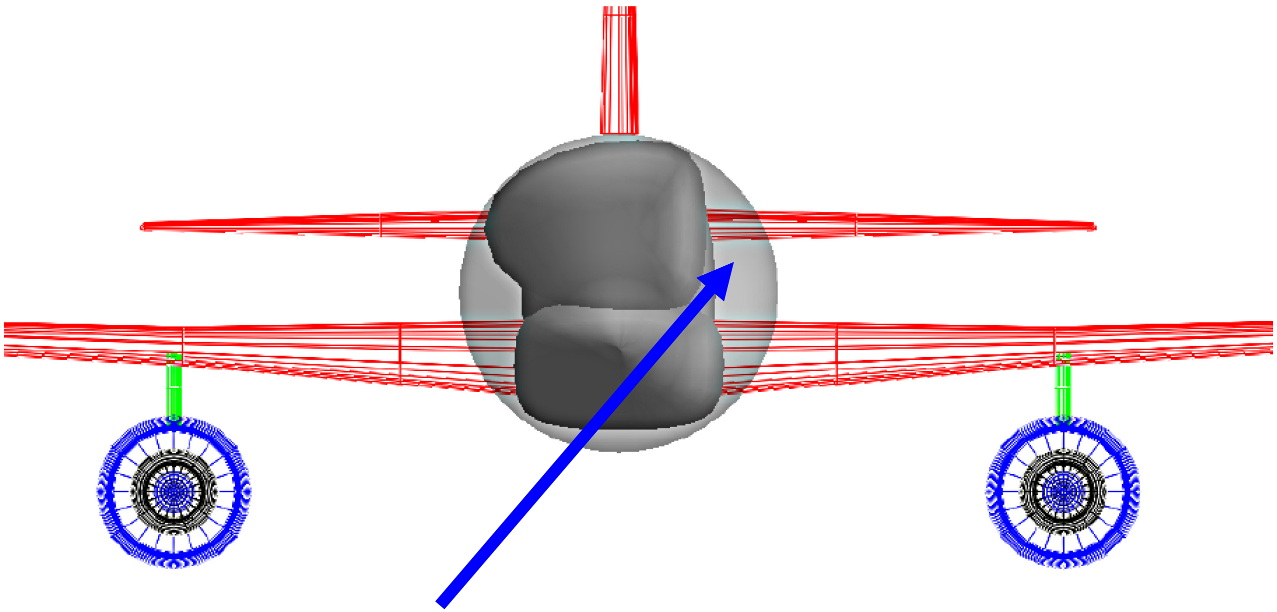
Scoring Model

The winner!

Additional (!) Hydrogen Storage in Underwing Pods

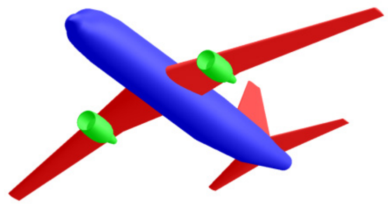


Passage Way for Cockpit Crew to Reach the Cabin



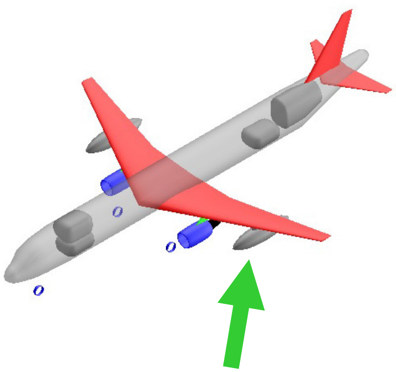
- For certification: No need for **passage** way from cockpit to cabin (according to Roskam)
- Passage way selected here for convenience.
  But: Reduces tank volume in the front tank leads to longer fuselage.

Overview of Aircraft Configurations

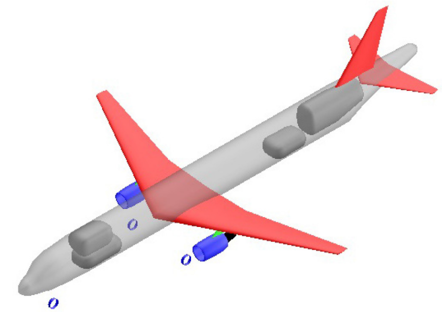


Baseline
A320-200

A321-HW



A321-HS



A321-H19
A319 Cabin

H: LH2 Aircraft
W: A321 with addtional 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

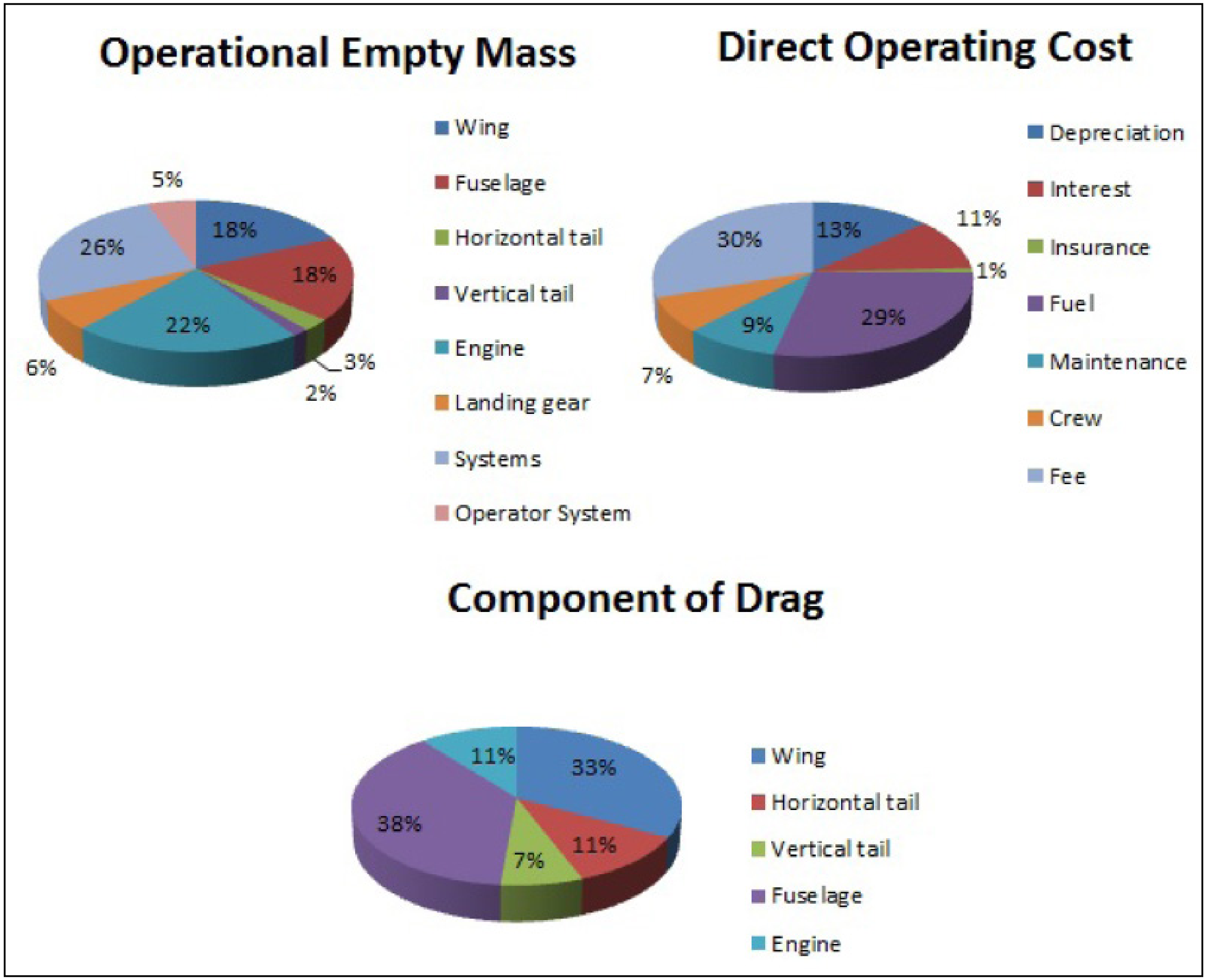
List of fundamentag aircraft and cabin variables with the values of the reference aircraft

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

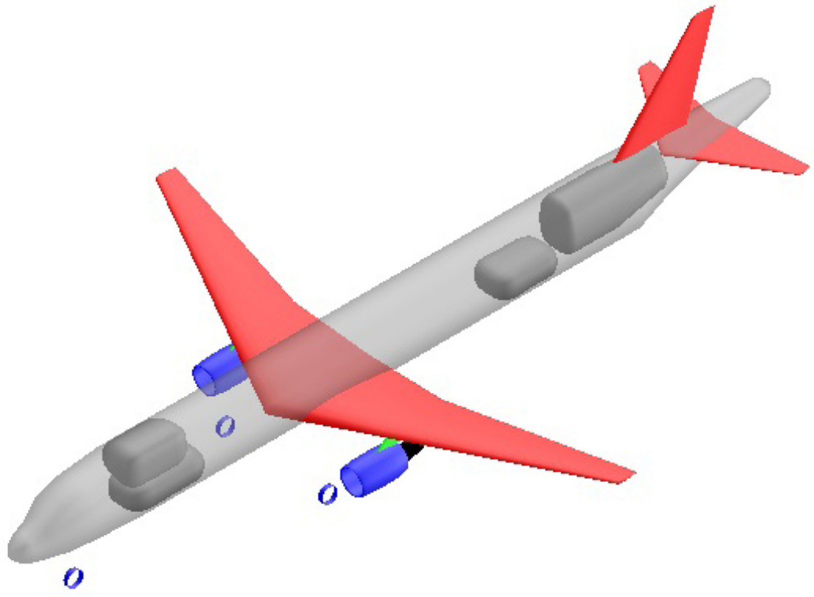
Calculation tool adapted and used:
OPerA – Optimization in Preliminary Aircraft

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_{sear}	0.51
Armrest width [m]	$w_{armrest}$	0.051
Sidewall Clearance (at armrest) [m]	$s_{clearence}$	0.015

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



Comparison of A321-HS with A320-200

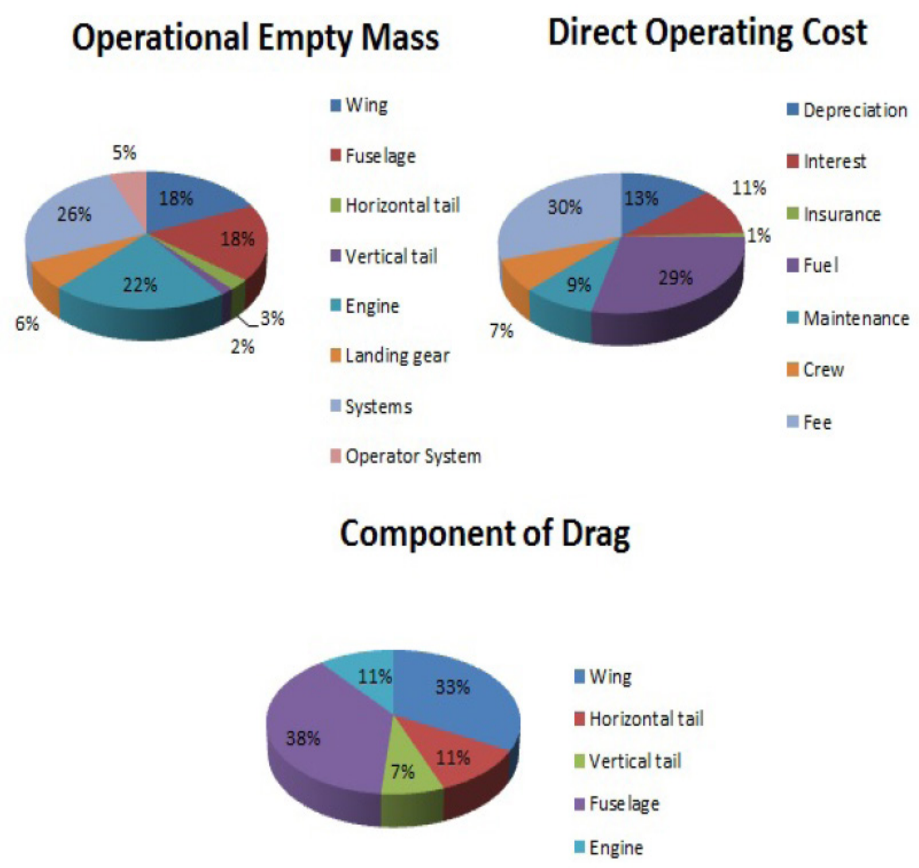


Details of the tanks for the A321-HS

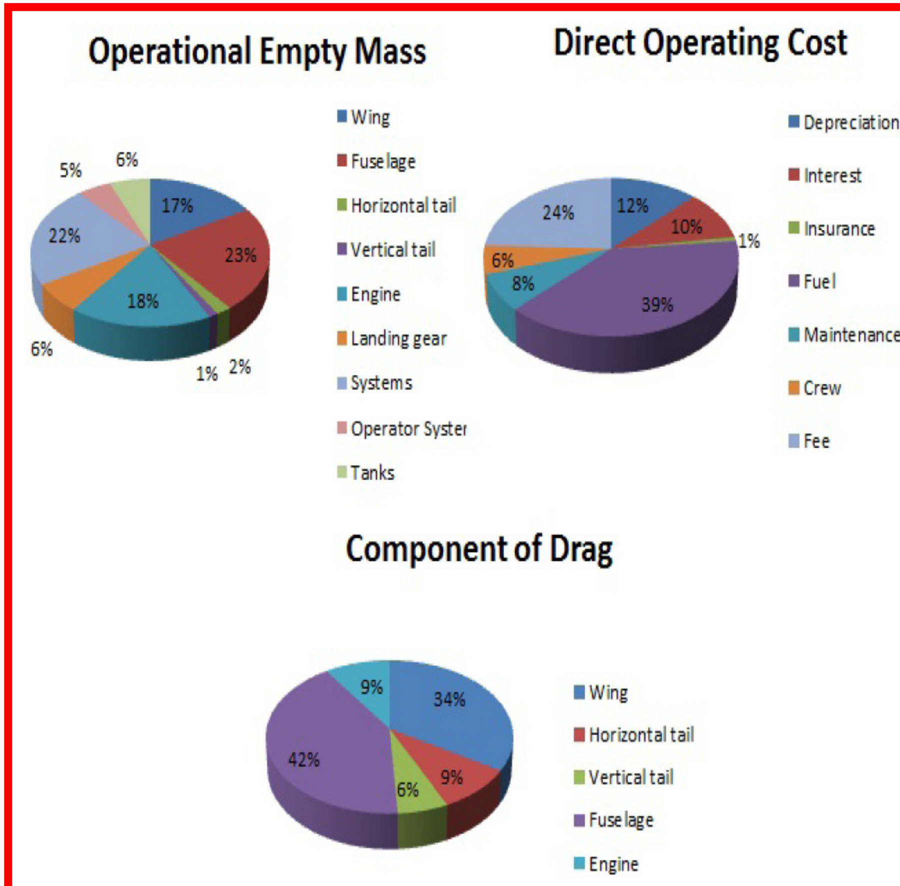
	Length [m]	Mass of tank [kg]	Mass of fuel [kg]
Rear upper tank	4.14	581.6	1600
Rear lower tank	5.24	315.4	1225
Back upper tank	6.92	1385	2874.4
Back lower tank	4.16	249.3	967.8
Total [kg]		2531.3	6667.2

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	

Aircraft Design for Hydrogen

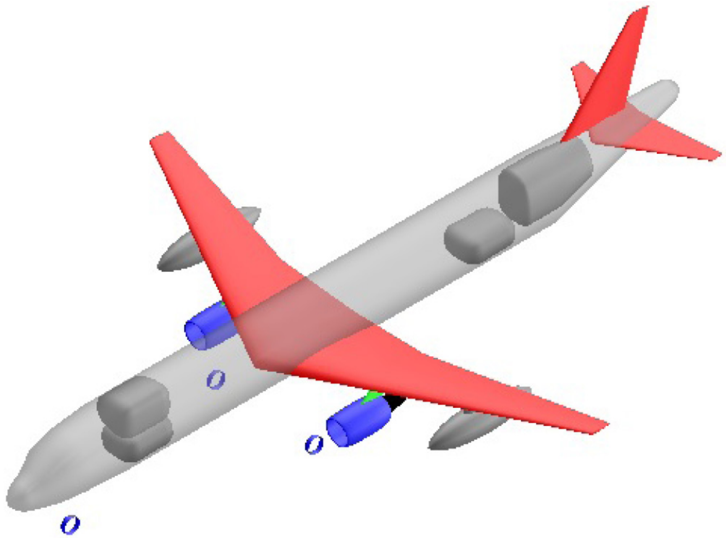


A320-200



A321-HS

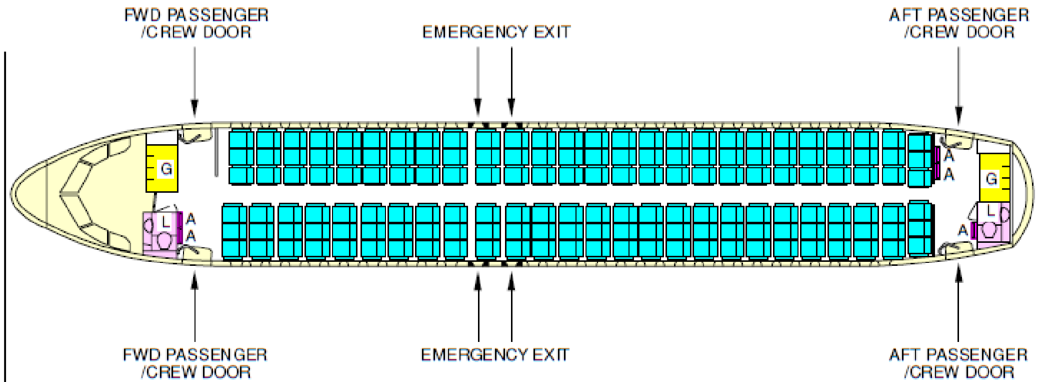
Comparison of A321-HW with A320-200



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

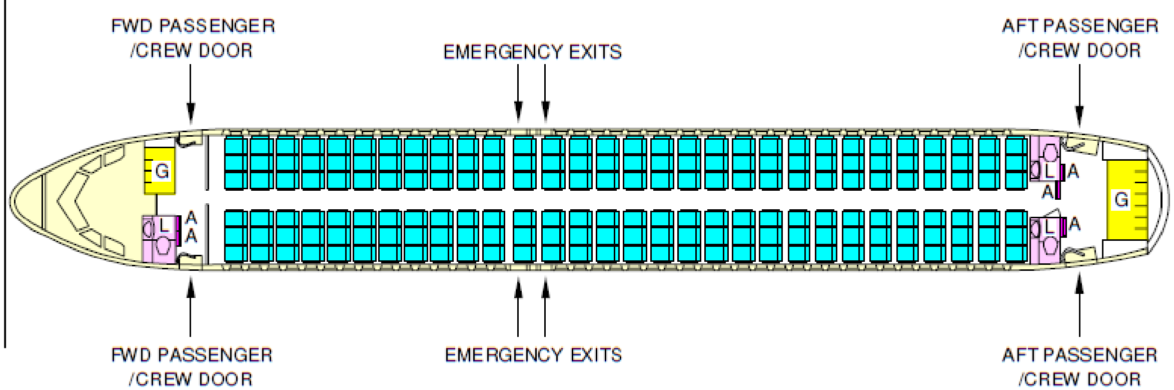
Parameter	A321-HW	Variation (A320)	
m_{MTO} [kg]	70716	-2.2	
m_{OE} [kg]	44871	+11.6	
m_F [kg]	6588	-48.6	energy up 44 %
DOC (AEA) [€/NM/t]	1.63	+23.3	
DOC (TUB) [€/NM/t]	1.45	+25.9	
l_F [m]	45.2	+18.0	A321: l_F = 44.5 m Delta: 0.7 m
S_W $[m^2]$	126.1	+4.8	
$b_{W,geo}$ [m]	34.6	+2.4	
$A_{W,eff}$	9.5	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	



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

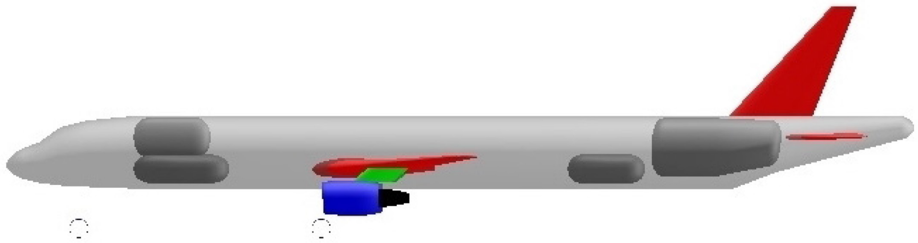


A320, 180 pax

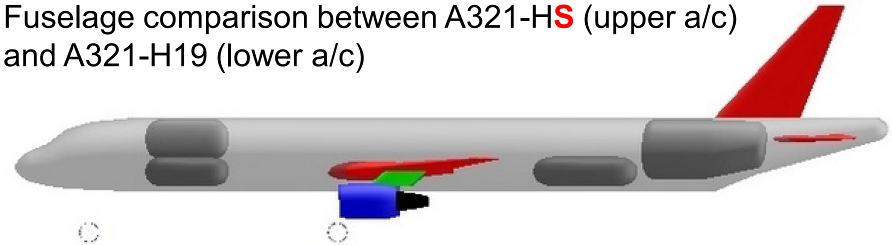
ITEM	DESIGNATION	
G	GALLEY	(2)
L	LAVATORY	(3)
A	ATTENDANT SEAT	(5)

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

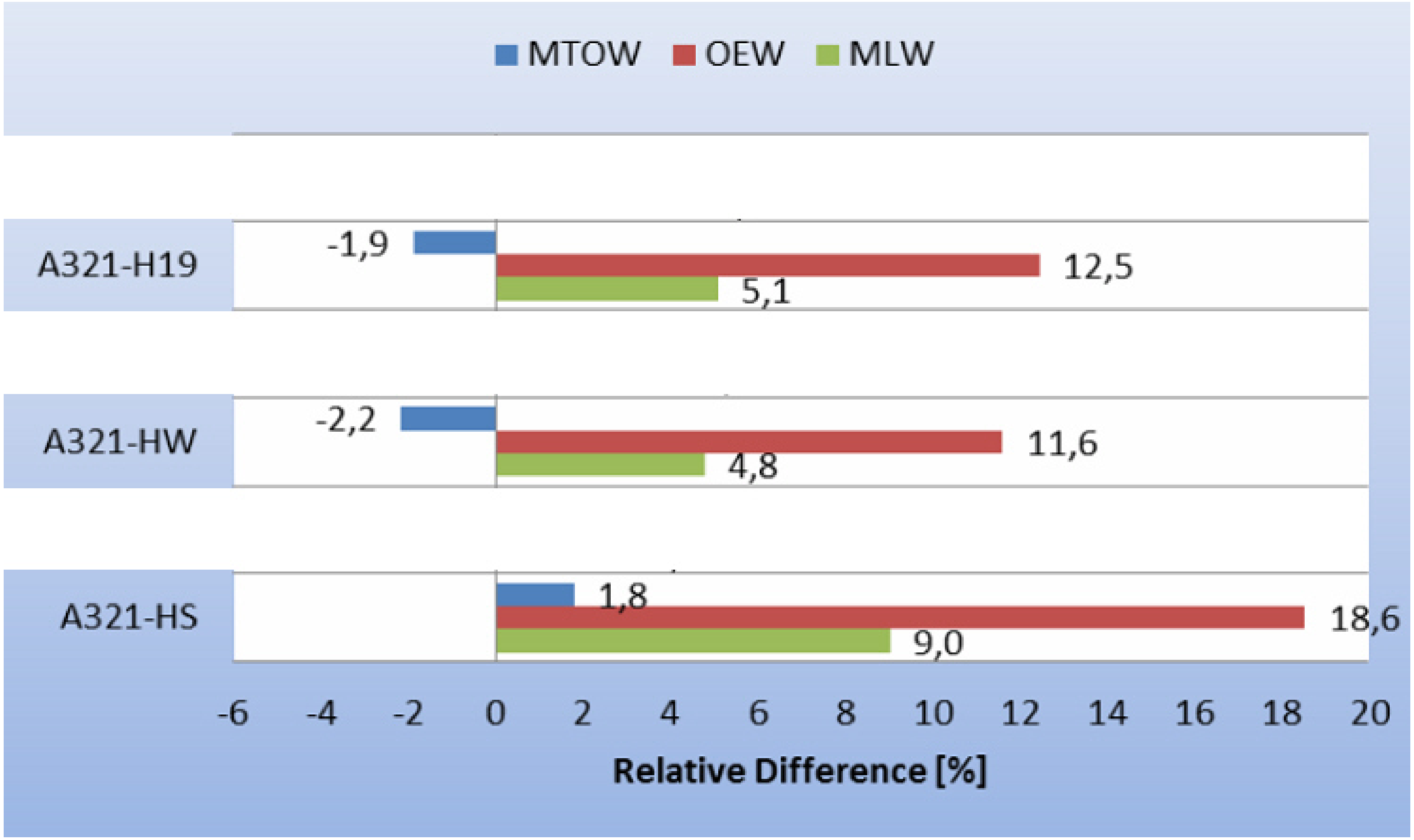
If DOC are based on A319:
DOC (AEA) +17%
DOC (TUB) +21%

Overall Comparison

	A320-200	A321-HS	A321-HW	A321-H19
l_F [m]	38.4	49.4	45.2	46.2
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

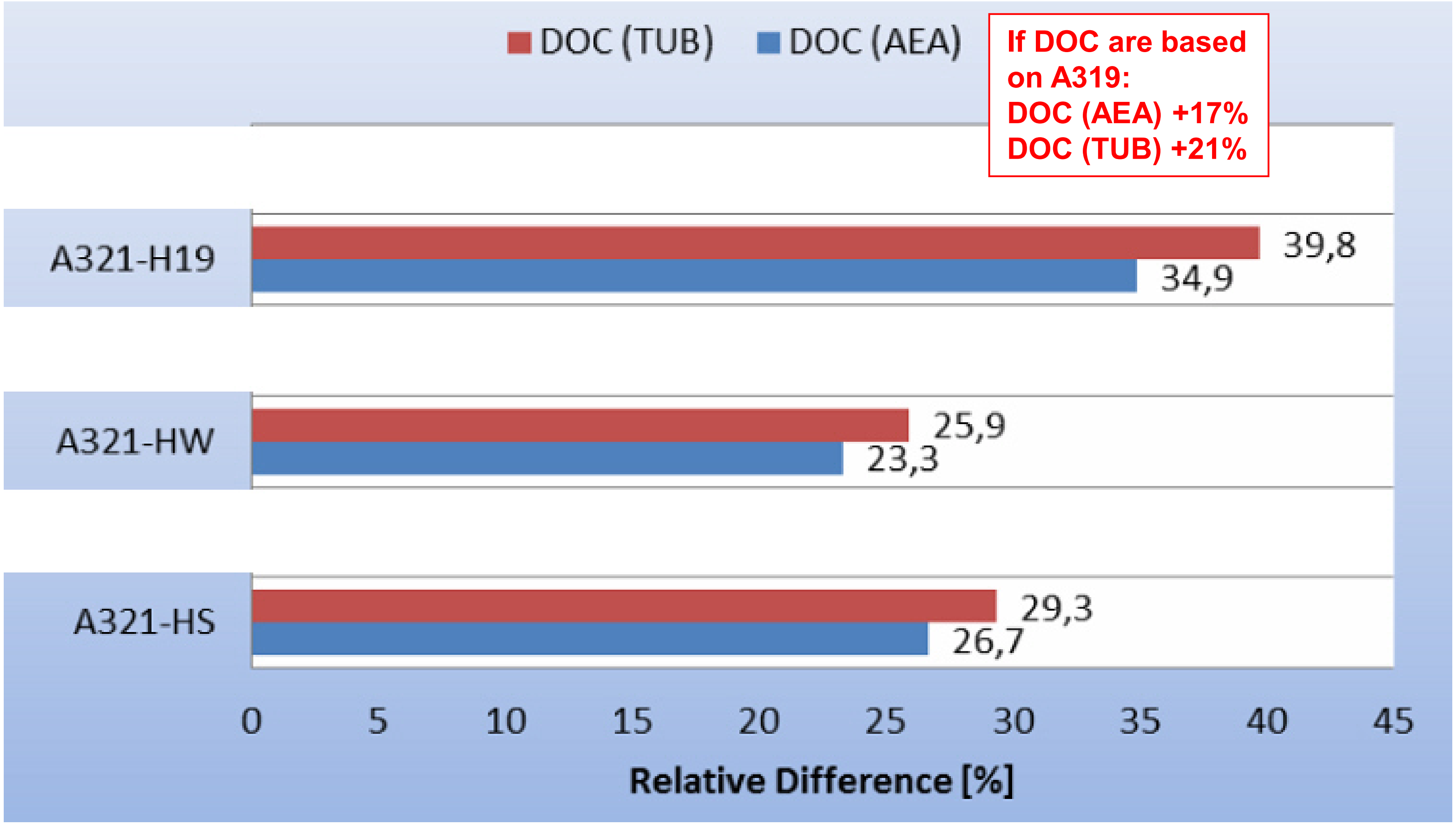
A321: l_F = 44.5 m

Overall Comparison



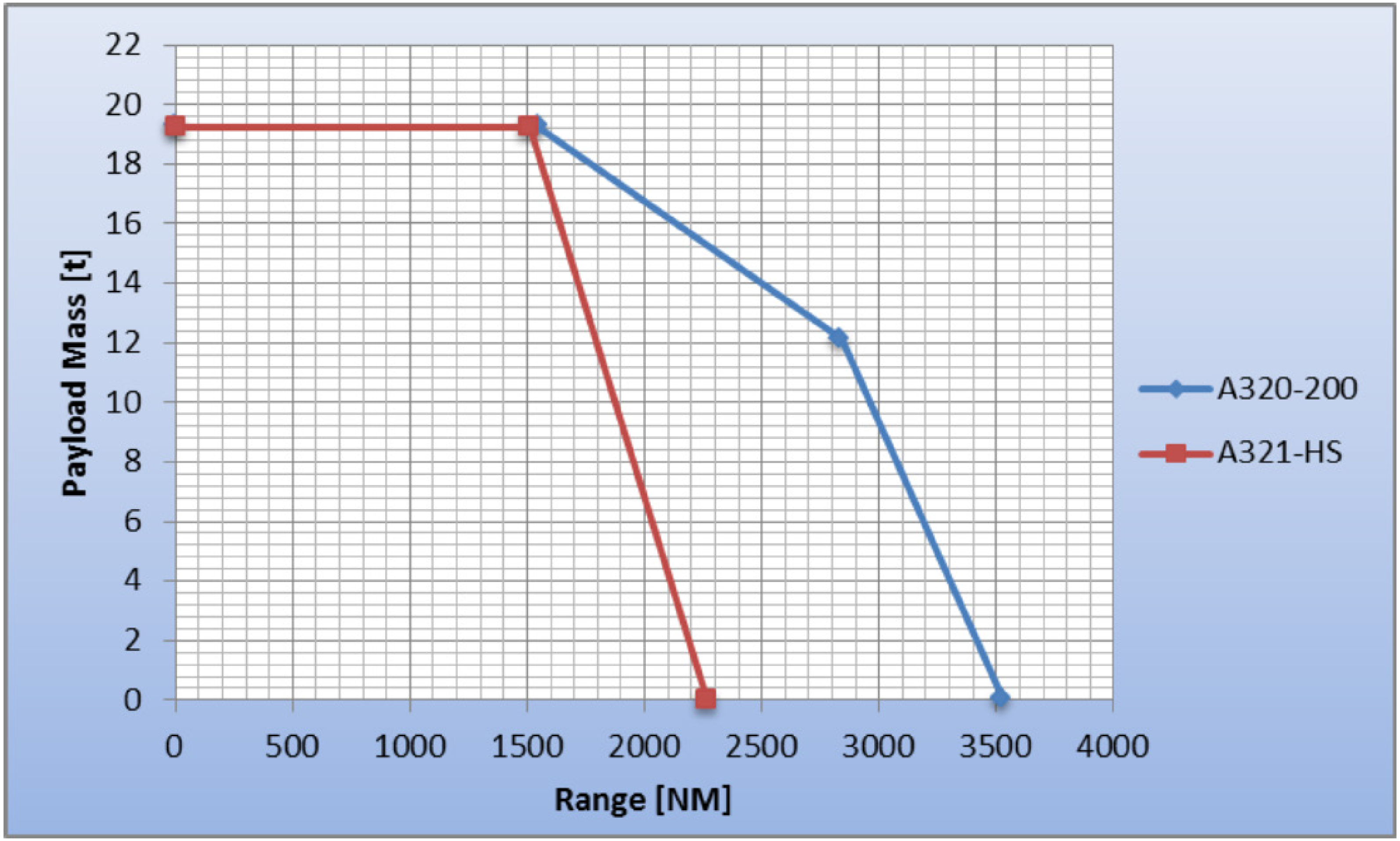
Comparison of MTOW, OEW, MLW related to the original A320-200

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

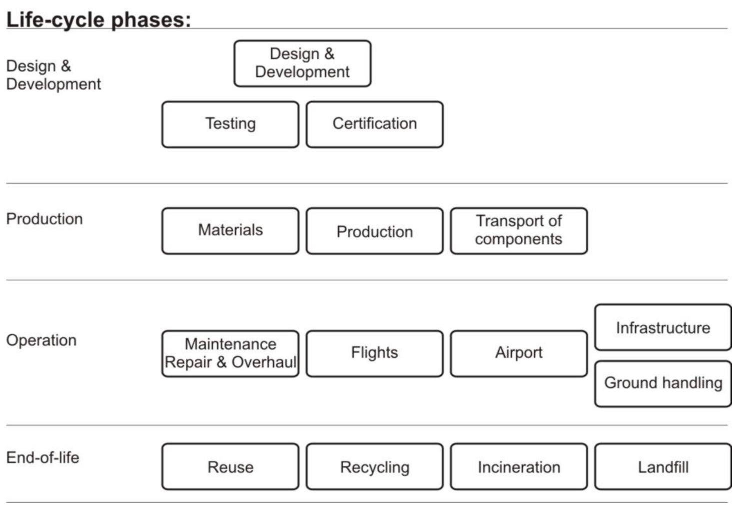
INTERNATIONAL STANDARD ORGANISATION, 2006. ISO 14040: *Environmental management — Life cycle assessment — Principles and framework*. Second edition, July 2006. Available from: https://www.iso.org/standard/37456.html

Life Cycle Assessment (LCA)

4 Phases

1) **Goal and scope definition**

- Goal
- System boundaries



- 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

Fluss	Menge	Einheit
Aggregate, natural	0.07139	kg
Air	23.58890	kg
Antimony	6.68042E-13	kg
Barite	0.00556	kg
Basalt, in ground	0.00369	kg
Bauxite	1.67932	kg
biomass; 14.7 MJ/kg	1.98174	MJ
Borax, in ground	0.00062	kg
brown coal; 11.9 MJ/...	6.07284	MJ
Cadmium	5.47330E-9	kg
Calcium carbonate, i...	0.63251	kg
Calcium chloride	1.34285E-11	kg
Carbon	1.61338E-7	kg
Carbon dioxide, in air	0.10779	kg
Cerium, in ground	3.15583E-18	kg
Chromium	3.01517E-5	kg
Chrysotile, in ground	1.75039E-7	kg
Clay, bentonite, in gr...	0.00262	kg
Clay, unspecified, in ...	0.00218	kg
Cobalt, in ground	3.22670E-10	kg
Colemanite, in ground	0.10098	kg
Copper	6.24400E-5	kg
crude oil; 42.3 MJ/kg	18.68835	MJ
Diatomite, in ground	8.97114E-12	kg
Dolomite, in ground	0.18529	kg

Outputs

Fluss	Menge	Einheit
1,4-Butanediol	4.88175E-13	kg
1,4-Butanediol	1.95257E-13	kg
2,4-D	3.65852E-11	kg
4-Methyl-2-pentanone	1.20567E-14	kg
Acenaphthene	2.86861E-9	kg
Acenaphthene	7.19709E-11	kg
Acenaphthene	6.97969E-13	kg
Acenaphthene	8.14351E-12	kg
Acenaphthylene	2.82654E-11	kg
Acenaphthylene	1.08460E-9	kg
Acenaphthylene	5.08915E-13	kg
Acetaldehyde	1.54072E-6	kg
Acetaldehyde	2.75074E-10	kg
Acetic acid	6.87065E-5	kg
Acetic acid	6.59615E-9	kg
Acetic acid	1.62343E-7	kg
Acetic acid	4.41277E-9	kg
Acetone	7.30996E-6	kg
Acetone	1.65080E-6	kg
Acetonitrile	1.08866E-10	kg
Acidity, unspecified	5.83350E-9	kg
Acidity, unspecified	0.00034	kg
Acidity, unspecified	2.95993E-14	kg
Acidity, unspecified	1.04297E-6	kg
Aclonifen	1.22893E-11	kg

Life Cycle Assessment (LCA)

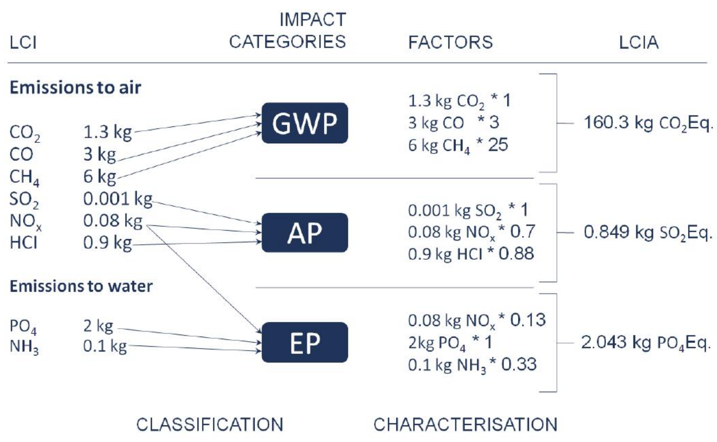
4 Phases

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]



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)

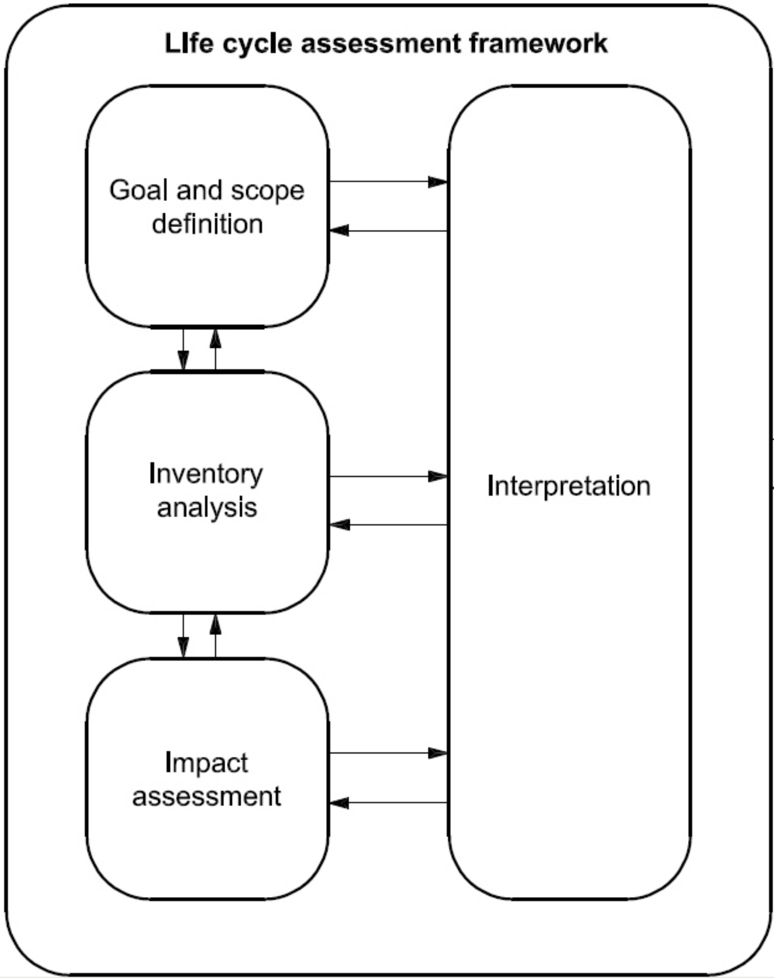
4 Phases

1) Goal and scope definition

2) Inventory analysis

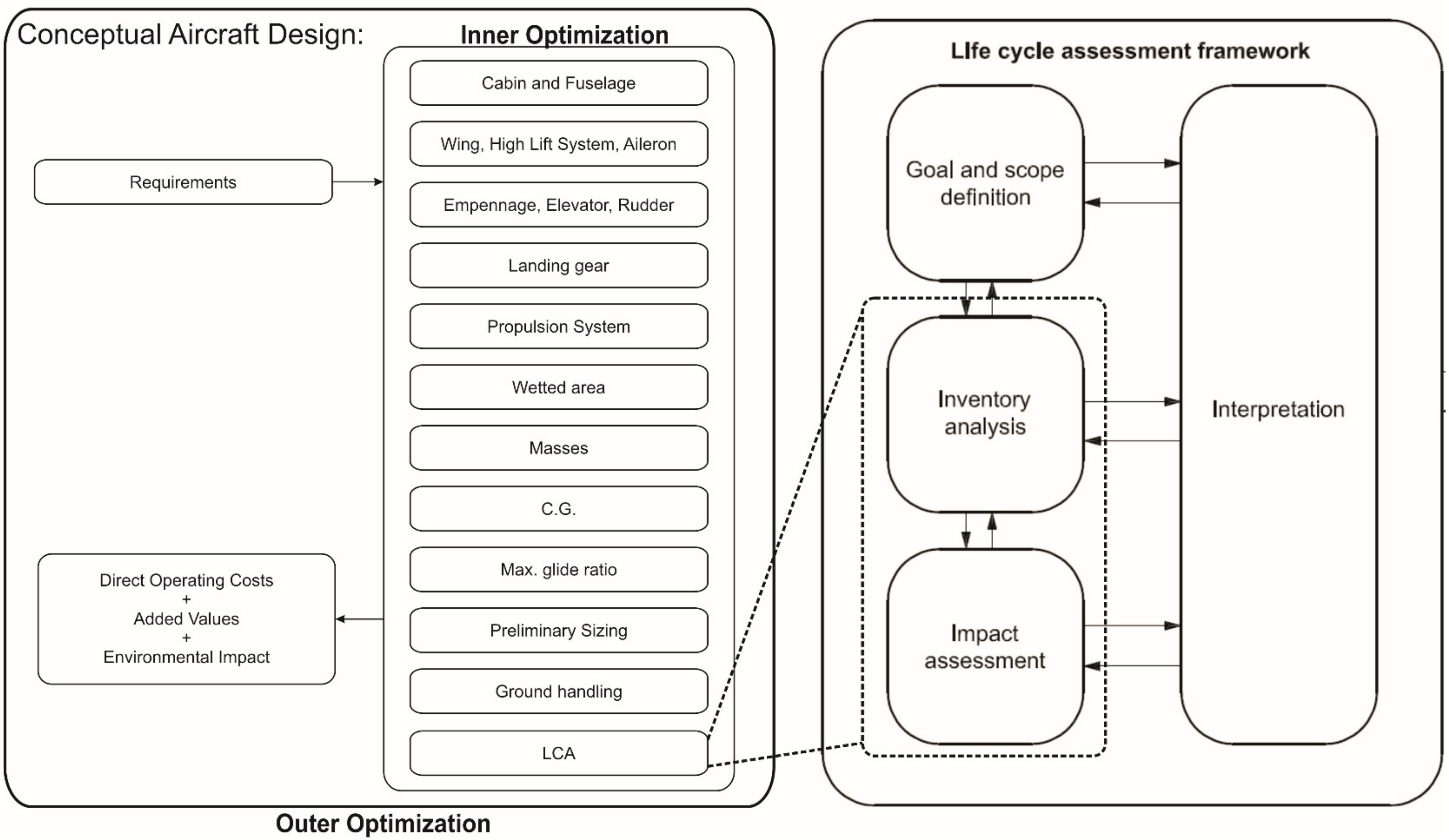
3) Impact assessment

4) Interpretation

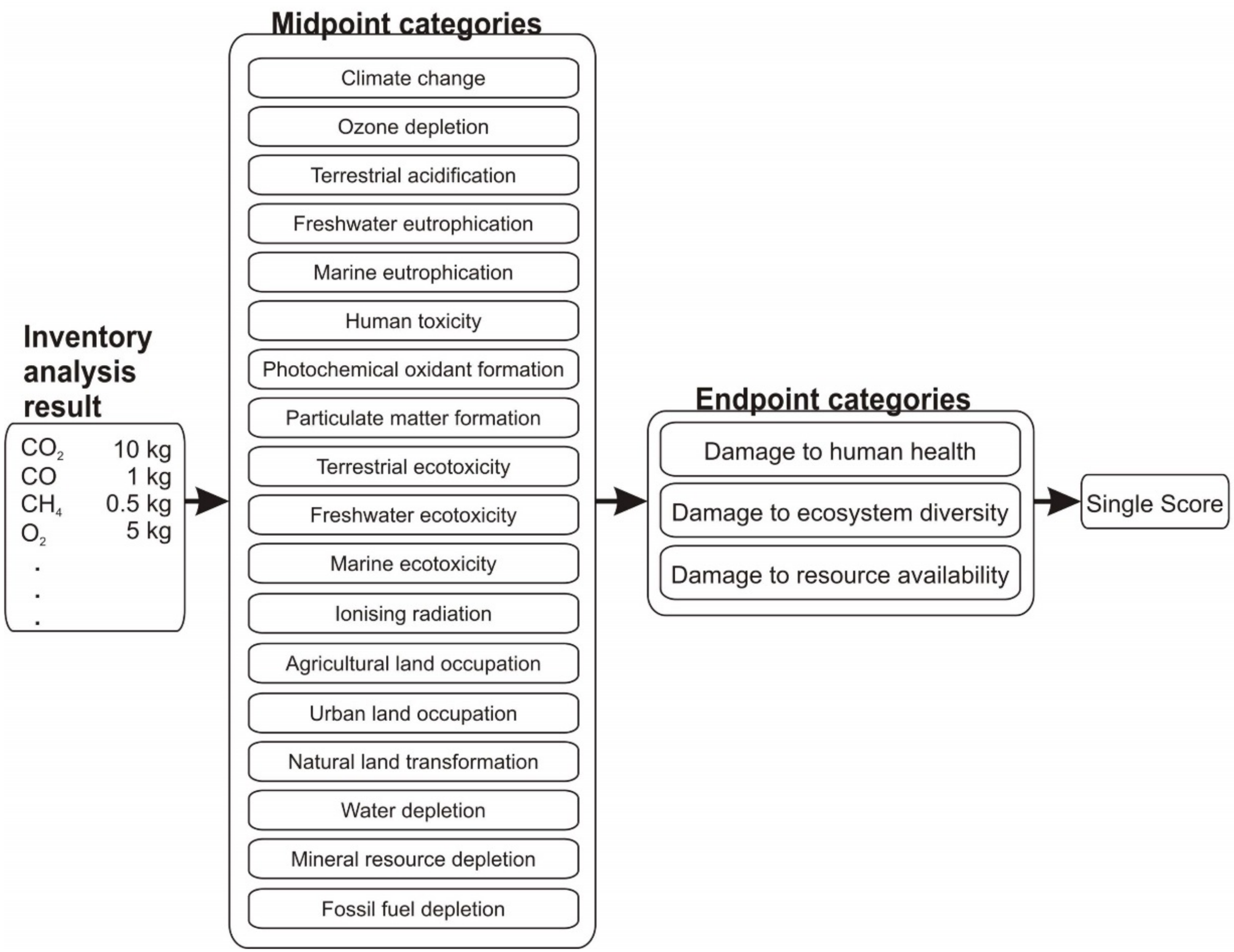


INTERNATIONAL STANDARD ORGANISATION, 2006. ISO 14040: *Environmental management — Life cycle assessment — Principles and framework*. Second edition, July 2006. Available from: https://www.iso.org/standard/37456.html

Integration into the Conceptual Aircraft Design Software "PrOPerA"



Impact Assessment Using the ReCiPe Method



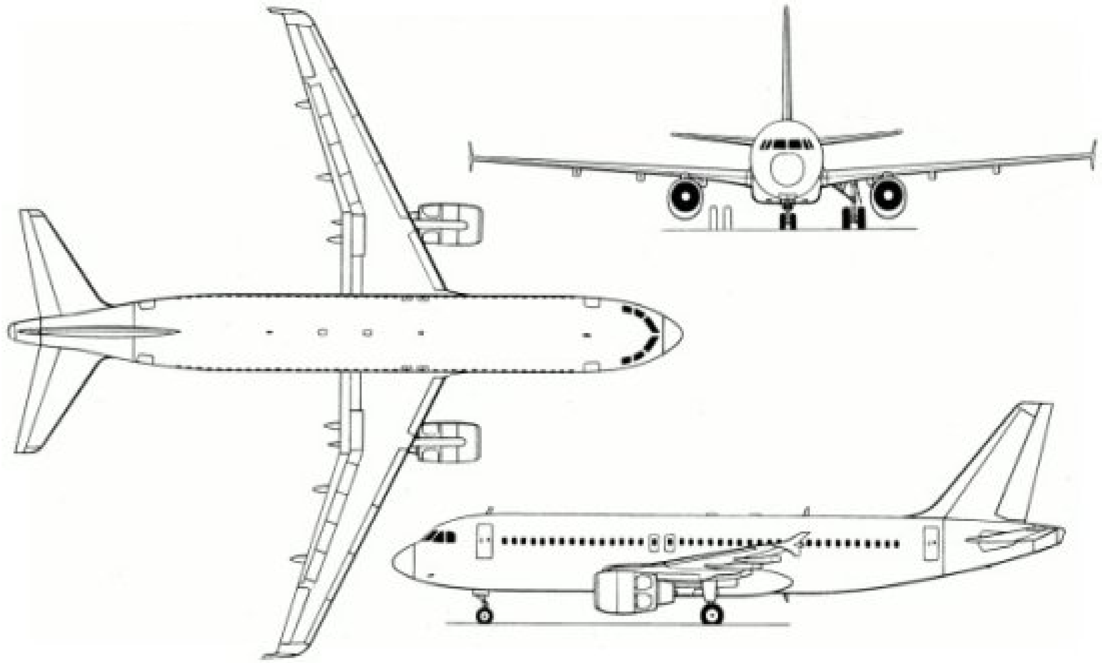
ReCiPe Method – Available from: https://www.leidenuniv.nl/cml/ssp/publications/recipe_characterisation.pdf

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

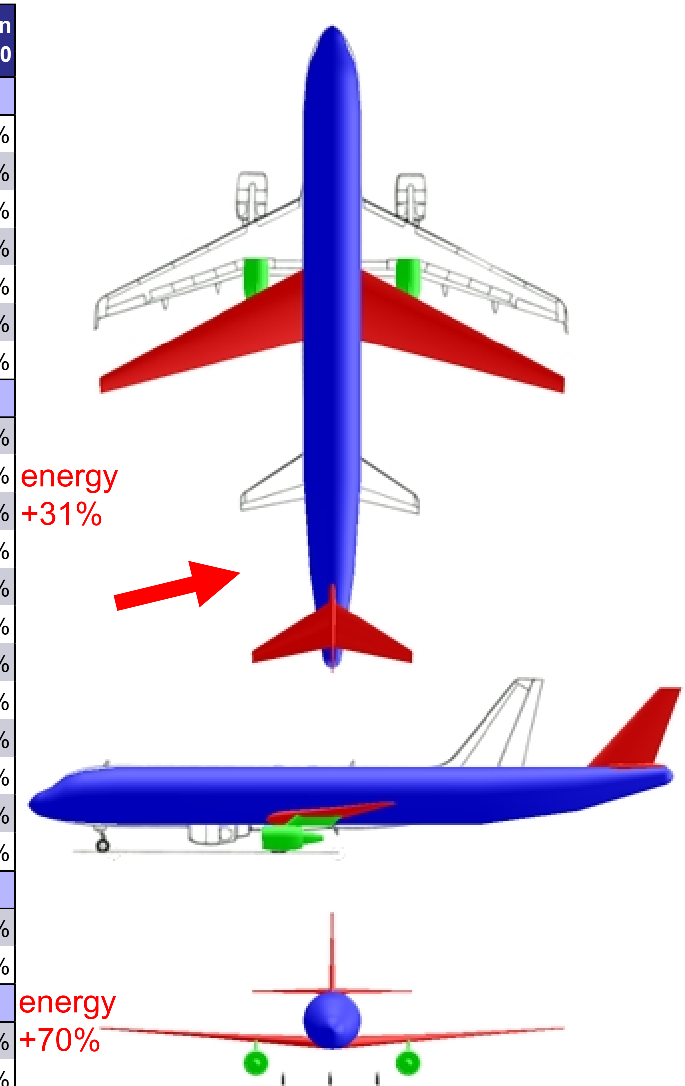
- Hydrogen is produced:
  1. using natural gas steam reforming and electricity mix
  2. using electrolysis and electricity from renewable sources
- Liquefaction of hydrogen is considered
- Transport of the liquid hydrogen from the production site to the airport is not considered
- It is considered that 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

HAW HAMBURG

Hydrogen Powered A320

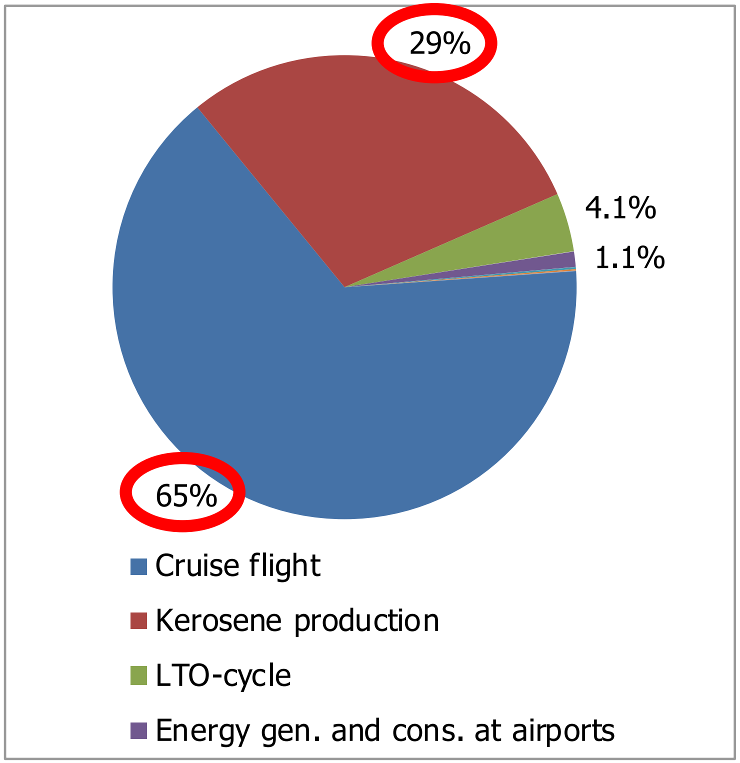
- Reduced hydrogen mass due to high mass energy density
- Stretched fuselage for additional tanks du to low volumetric energy density: 11 m
- In total: No improvement of the Maximum Take-Off Mass (MTOM)
- Steam reforming and electricity mix: SS = +300%
- Electrolysis and electricity from renewable sources: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

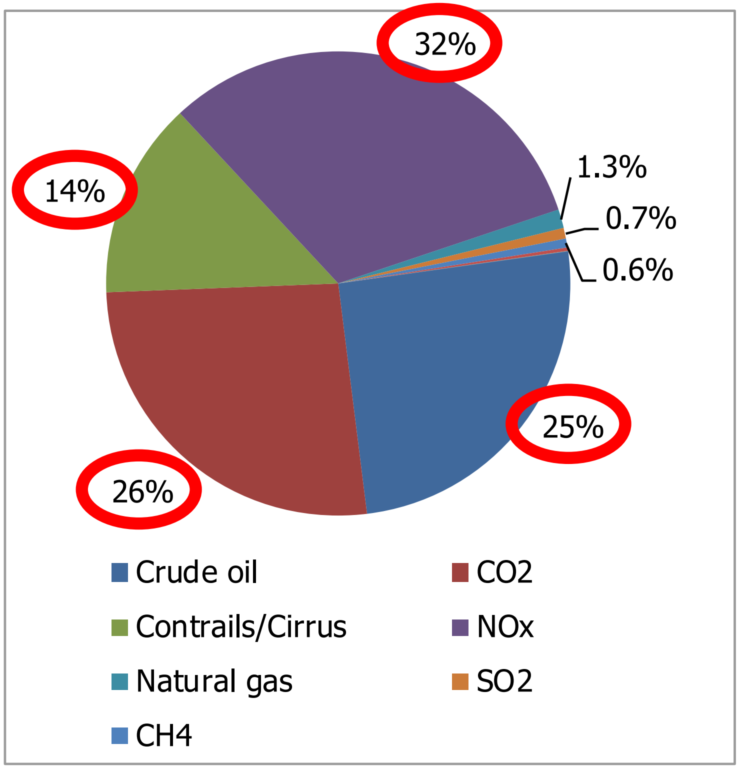
Parameter	Value	Deviation from A320
Requirements		
m_{MPL}	19256 kg	0%
R_{MPL}	1510 NM	0%
M_{CR}	0.76	0%
max(s_{TOFL} , s_{LFL})	1770 m	0%
n_{PAX} (1-cl HD)	180	0%
m_{PAX}	93 kg	0%
SP	29 in	0%
Main aircraft parameters		
m_{MTO}	74200 kg	1%
m_{OE}	48800 kg	18%
m_F	6200 kg	-53%
S_W	124 m²	1%
$b_{W,geo}$	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

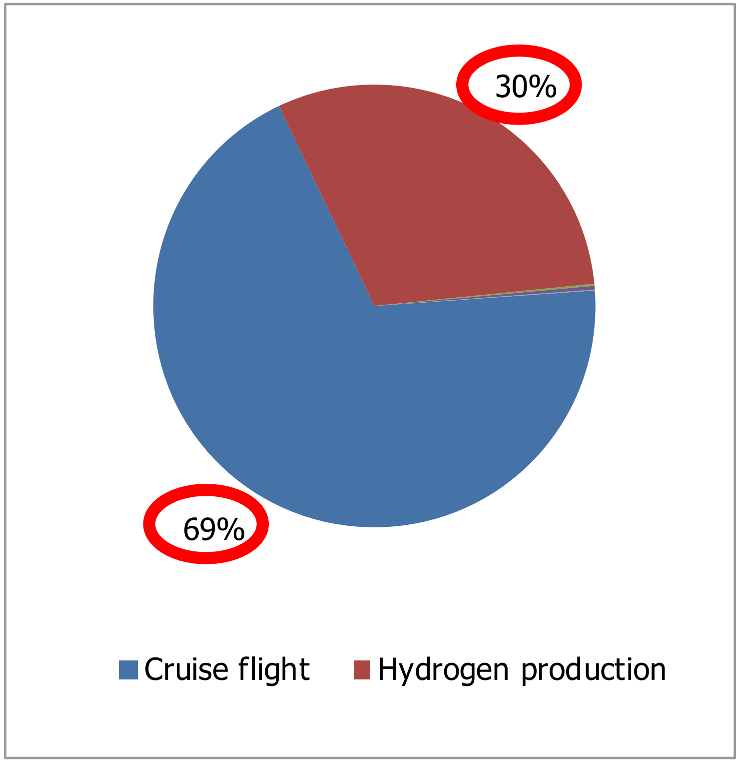
- Cruise flight and kerosene production dominate environmental impact
- CO_2, NO_x, crude oil and contrails/cirrus clouds have highest influence

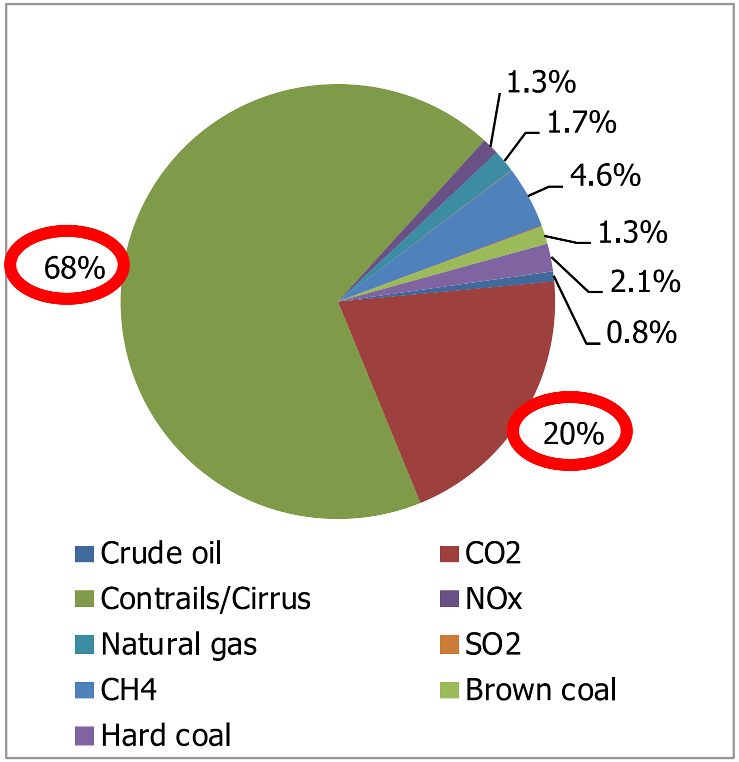




Hydrogen Powered A320 – Steam Reforming

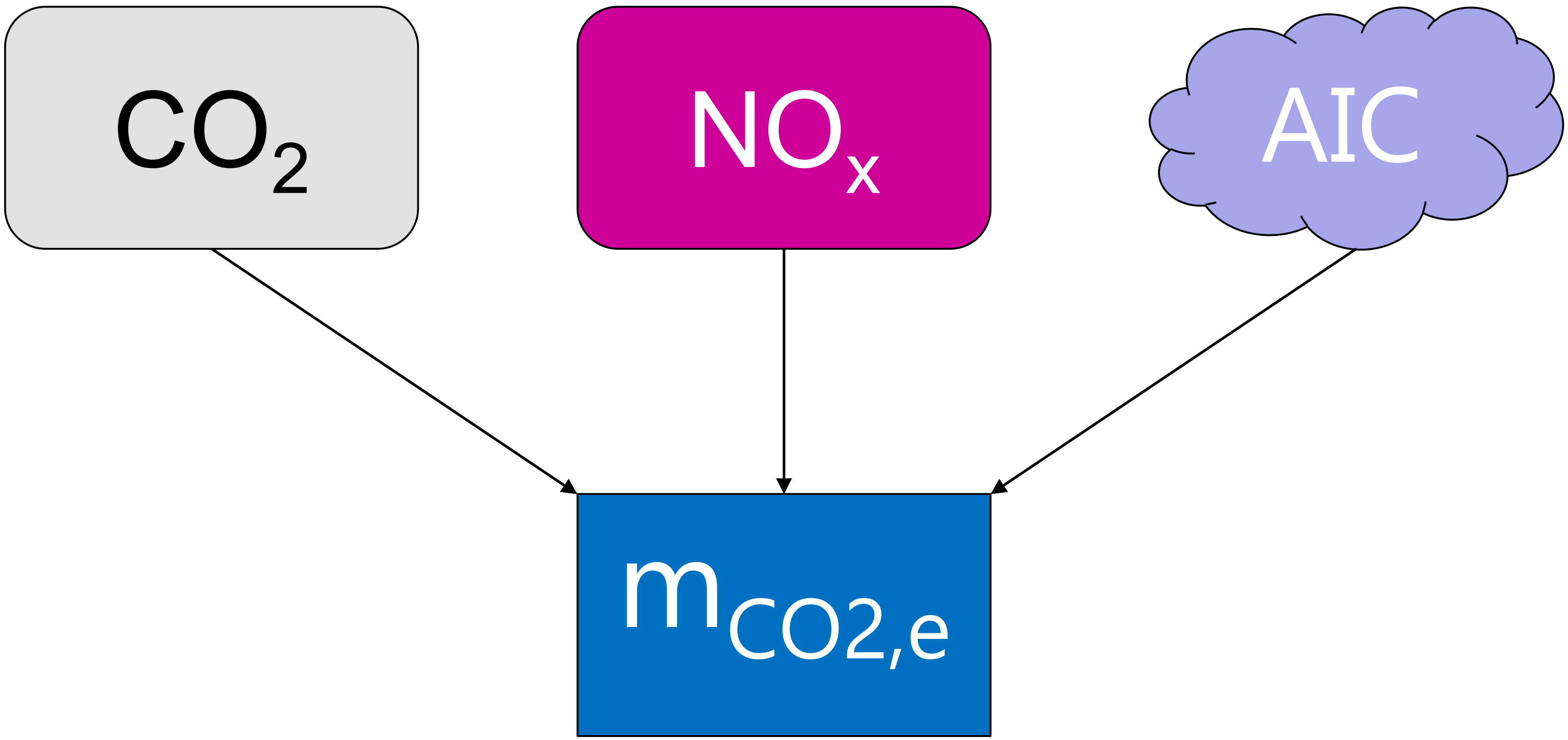
- Cruise flight and hydrogen production from steam reforming dominate environmental impact
- Contrails/cirrus clouds from the flight (2.6 times the amount of water compared with kerosene) and CO_2 from the production have highest influence





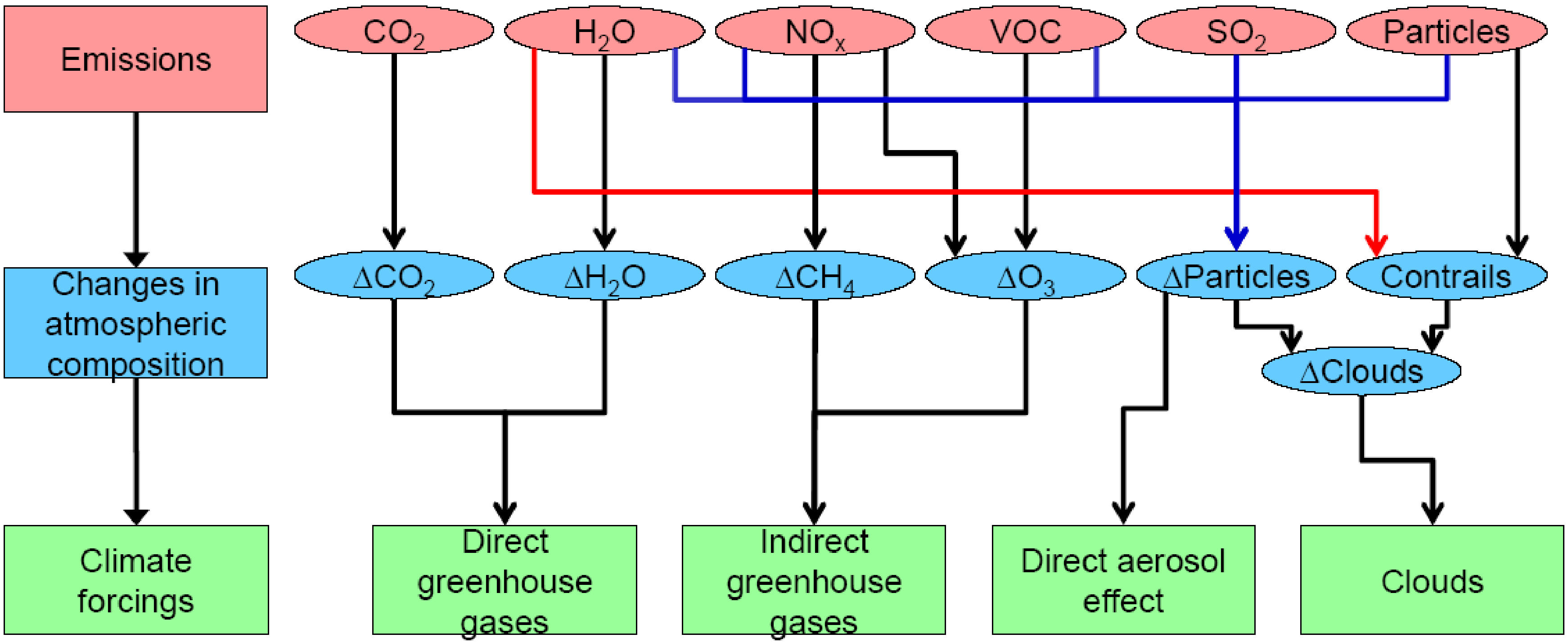
Equivalent CO2 Mass

Equivalent CO_2 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

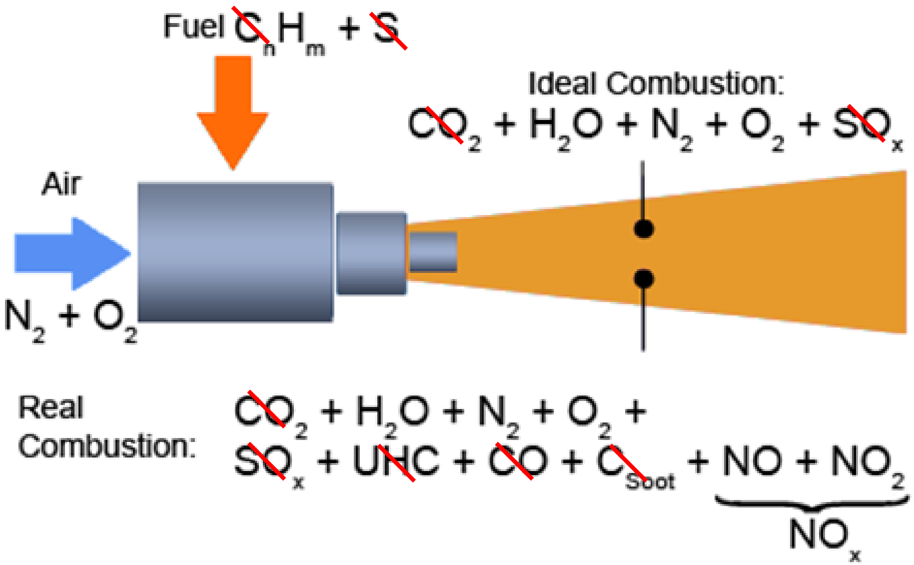


CO2: Long term influence

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



EI_{NOx}

m_F

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

Own Fuel Calculation

not included in LH2 combustion

Altitude-Dependent Equivalent CO2 Mass

$$m_{CO2,eq} = \frac{EI_{CO2} \cdot f_{NM}}{n_{seat}} \cdot 1 + \frac{EI_{NOx} \cdot f_{NM}}{n_{seat}} \cdot CF_{midpoint,NOx} + \frac{R_{NM}}{R_{NM} \cdot n_{seat}} \cdot CF_{midpoint,AIC}$$

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

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

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

Species	Emission Index, EI (kg/kg fuel)
CO_2	3,15
H_2O	1,23
SO_2	$2{,}00 \cdot 10^{-4}$
Soot	$4{,}00 \cdot 10^{-5}$

$$s_{O_3,L}(h) = s_{CH_4}(h)$$

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

Species	$SGTP_{i,100}$
CO_2 (K/kg CO_2)	$3{,}58 \cdot 10^{-14}$
Short O_3 (K/kg NO_x)	$7{,}97 \cdot 10^{-12}$
Long O_3 (K/NO_x)	$-9{,}14 \cdot 10^{-13}$
CH_4 (K/kg NO_x)	$-3{,}90 \cdot 10^{-12}$
Contrails (K/NM)	$2{,}54 \cdot 10^{-13}$
Contrails (K/km)	$1{,}37 \cdot 10^{-13}$
Cirrus (K/NM)	$7{,}63 \cdot 10^{-13}$
Cirrus (K/km)	$4{,}12 \cdot 10^{-13}$

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

Altitude-Dependent Equivalent CO2 Mass

$$m_{CO2,eq} = \frac{EI_{CO2} \cdot f_{NM}}{n_{seat}} \cdot 1 + \frac{EI_{NOx} \cdot f_{NM}}{n_{seat}} \cdot CF_{midpoint,NOx} + \frac{R_{NM}}{R_{NM} \cdot n_{seat}} \cdot CF_{midpoint,AIC}$$

$\downarrow$ units only

$$\frac{kg\ CO2}{NM \cdot n_{seat}} =$$

$$\frac{kg\ CO2/kg\ fuel \cdot kg\ fuel/NM}{n_{seat}} \cdot 1 + \frac{kg\ NOx/kg\ fuel \cdot kg\ fuel/NM}{n_{seat}} \cdot \frac{kg\ CO2}{kg\ NOx} + \frac{NM}{NM \cdot n_{seat}} \cdot \frac{kg\ CO2}{NM}$$

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

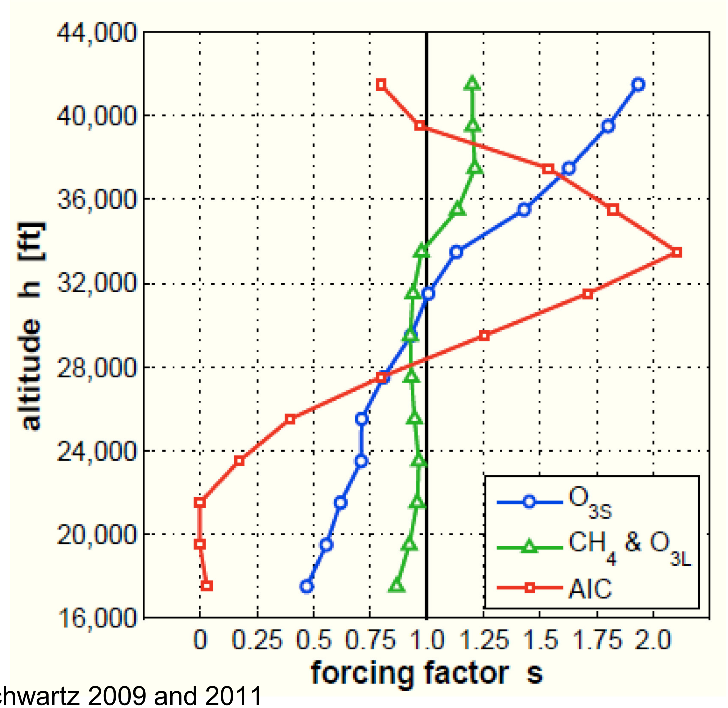
JOHANNING, Andreas, SCHOLZ, Dieter, 2014. *Adapting Life Cycle Impact Assessment Methods for Application in Aircraft Design*.
German Aerospace Congress 2014 (DLRK 2014), Augsburg, 16.-18.09.2014.
Available from: https://nbn-resolving.org/urn:nbn:de:101:1-201507202456. Download: http://Airport2030.ProfScholz.de

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*)

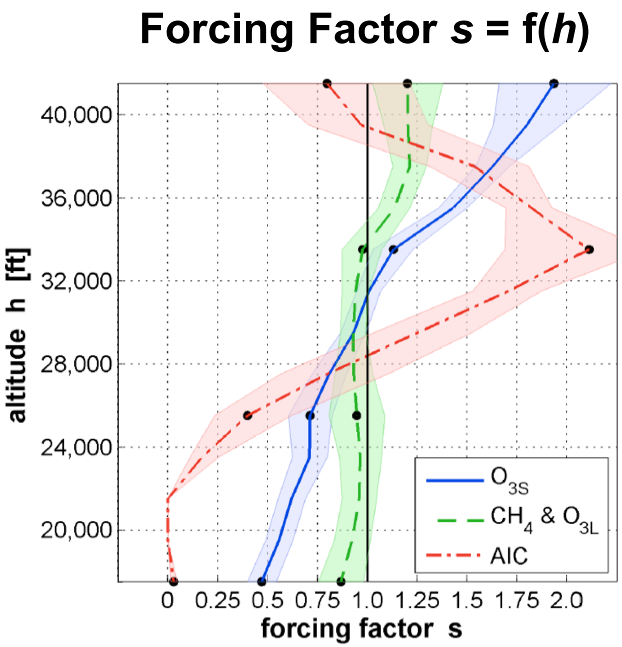


Schwartz 2009 and 2011

- The curves go along with the ICAO Standard Atmosphere (ISA) applicable for average lattitudes. With a first approximation, the curves could be adapted to other lattitudes 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 factors (lines) with **66% likelihood ranges** (shaded areas). Altitudes with forcing factors based on raditiave forcing data with independent probability distributions. (SCHWARTZ 2011)

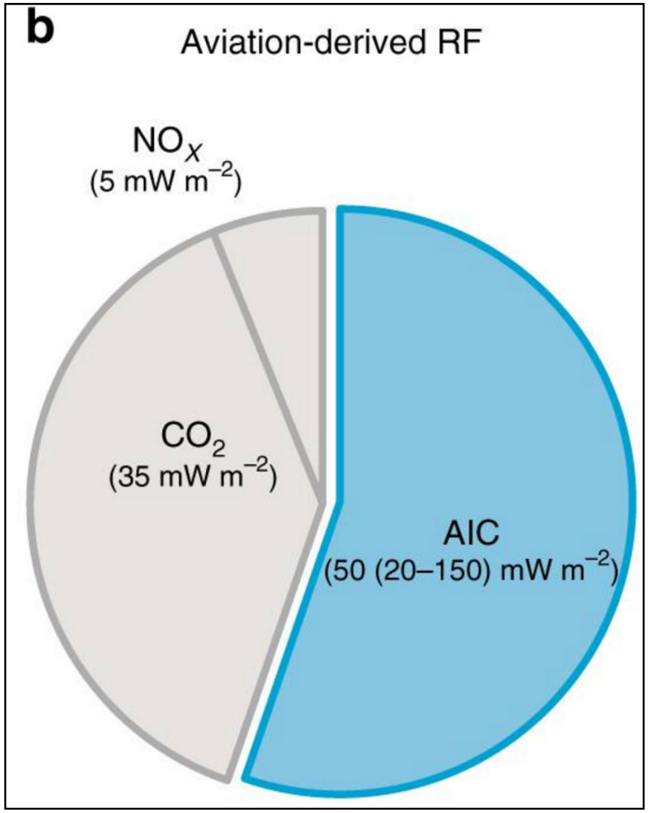
Based on KÖHLER 2008 and RÄDEL 2008.

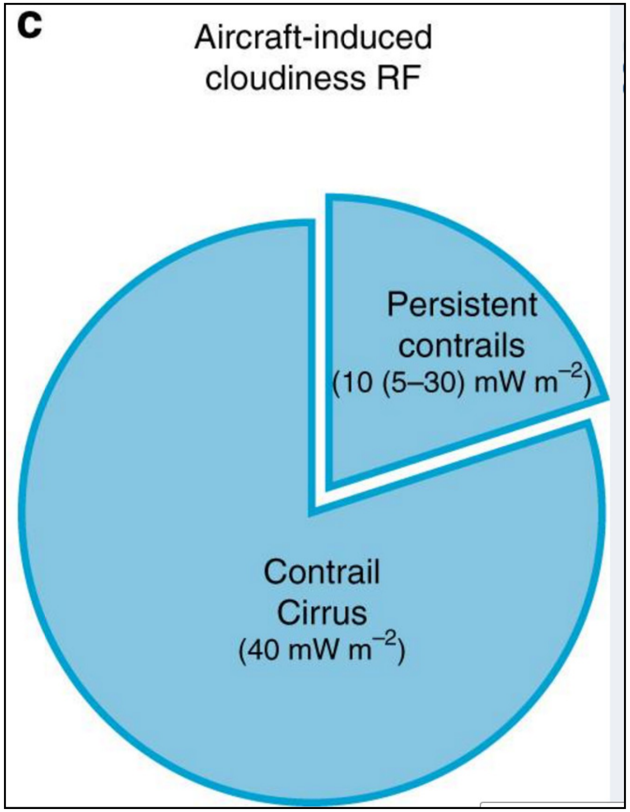
SCHWARTZ DALLARA, Emily, 2011. *Aircraft Design for Reduced Climate Impact*. Dissertation. Stanford University. Available from: http://purl.stanford.edu/yf499mg3300

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

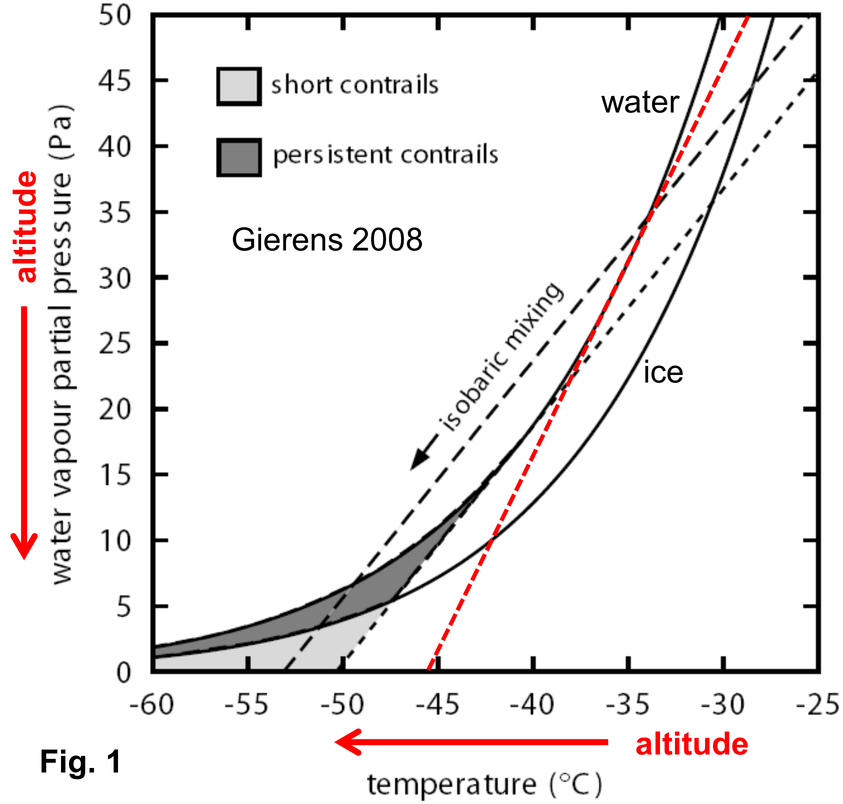


Fig. 1

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

$$G = \frac{EI_{H2O}\, p c_p}{\varepsilon Q(1-\eta)}$$

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_{H2O} = 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.

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

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

GIERENS, Klaus, LIM, Limg, ELEFTHERATOS, 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]	$G_{H2}/G_{Jet\text{-}A1}$
H2	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.

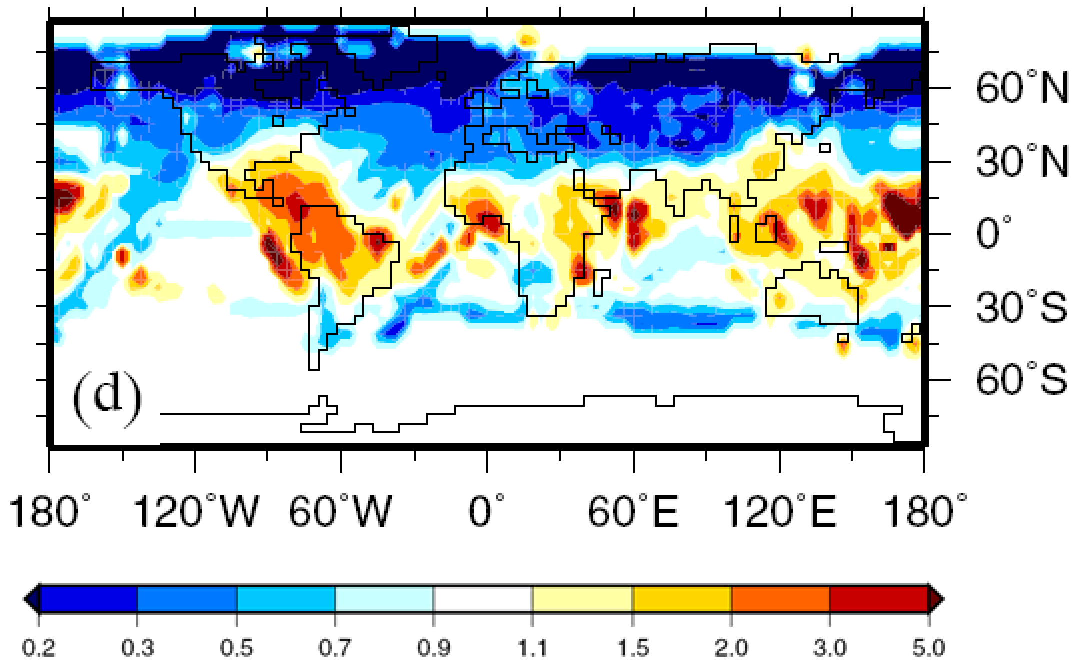
crystal radius is about a factor of 0.3 smaller for conventional contrails than for cryoplane contrails. [Hence, the radius of cryoplane's ice crystals is 3.33 times larger and the volume is 37 times larger. That means with 2.58 the amount of water there are only 7% of the ice crystals by numbers compared 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 leed 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 NOx emissions.

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

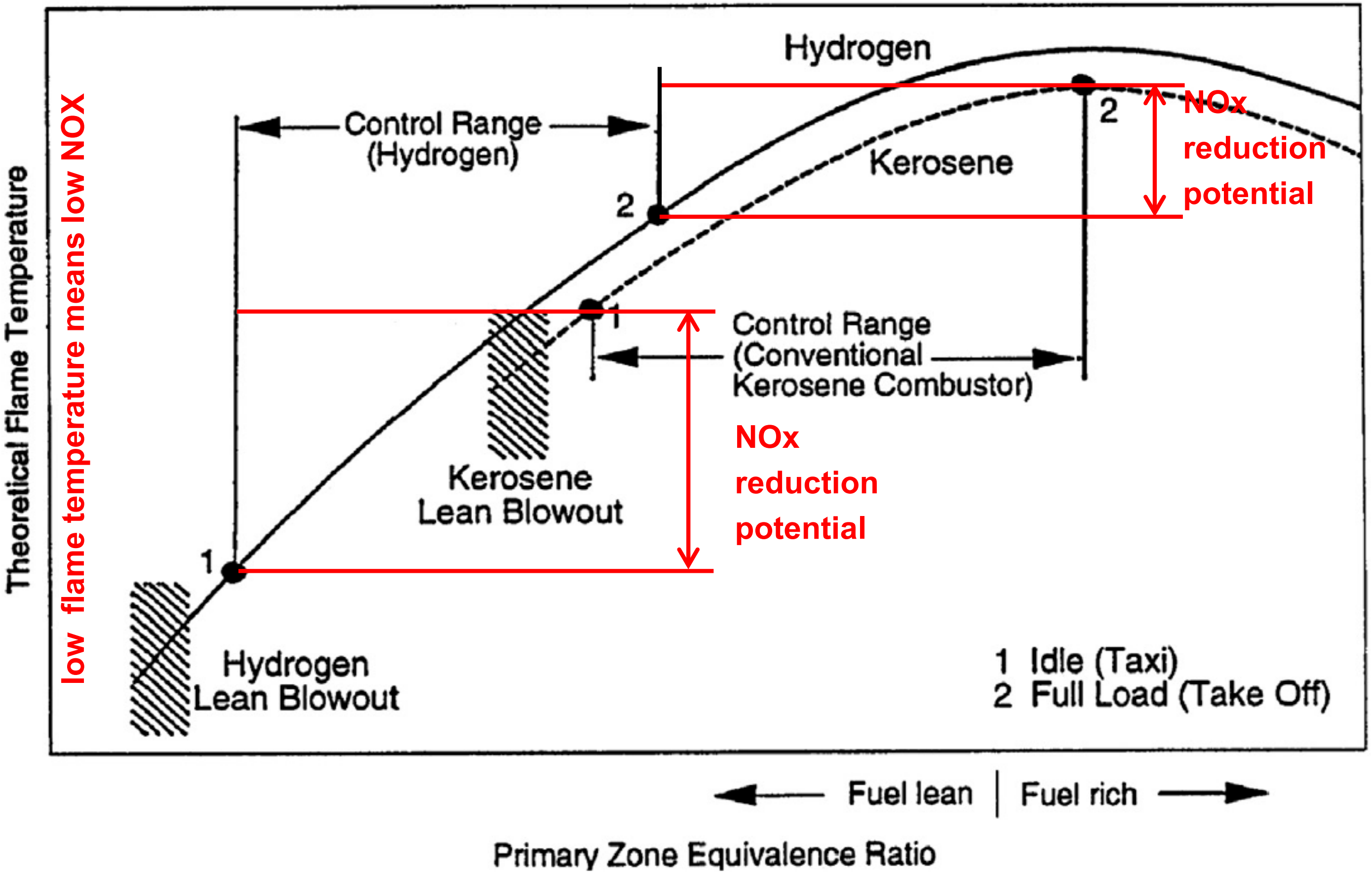
Flying at lower altitudes can also lead to contrail reduction in the mid-latitudes.

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 combuston 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

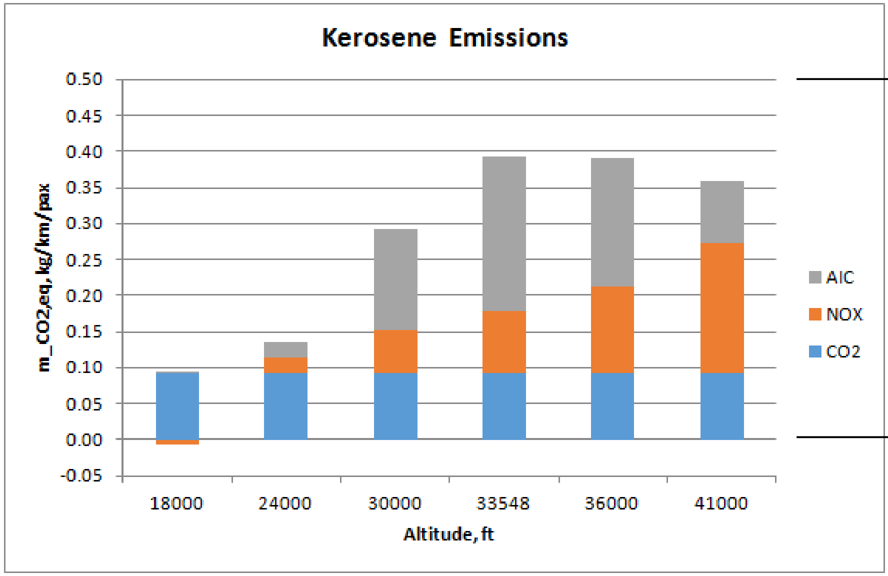
As for the NOx emissions when burning hydrogen, theoretically there is, in spite of the higher stoichiometric flame temperature of hydrogen, a potential to achieve lower emissions as compared with engines using kerosene. The main reason for this is that the hydrogen flame has a wider flammability range; 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.

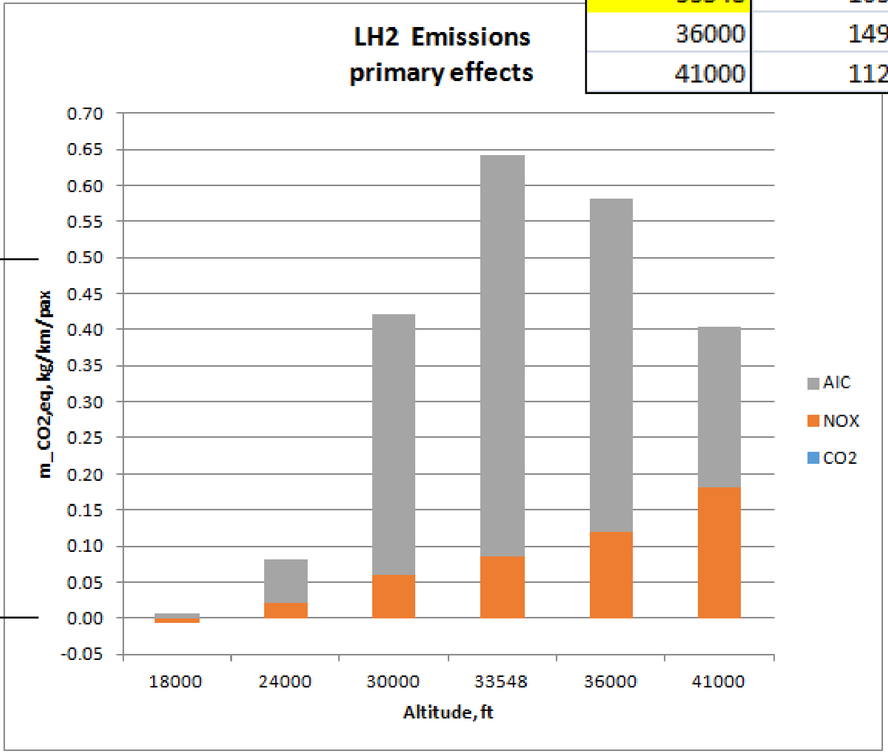
Svensson, 2004, https://doi.org/10.1016/j.ast.2004.02.004

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 NOx would be higher. It is assumed here that NOx 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%

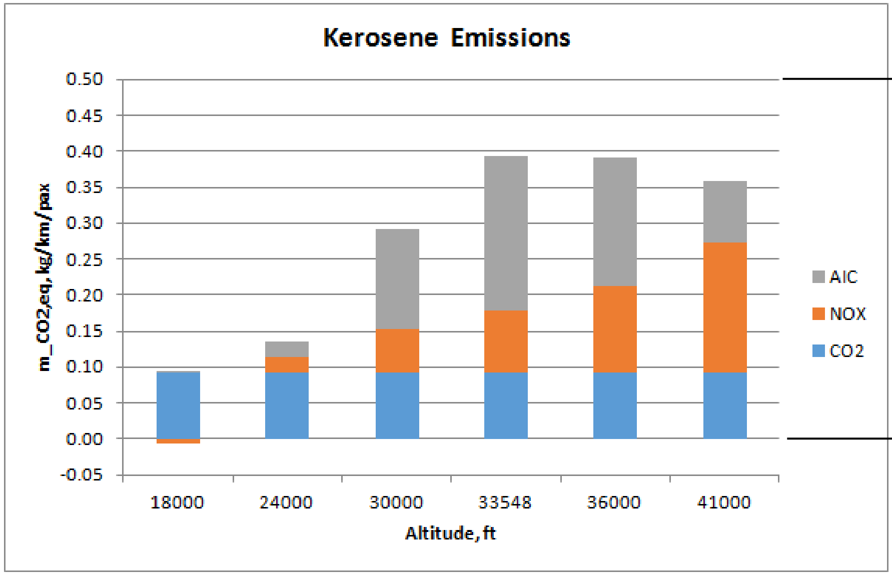


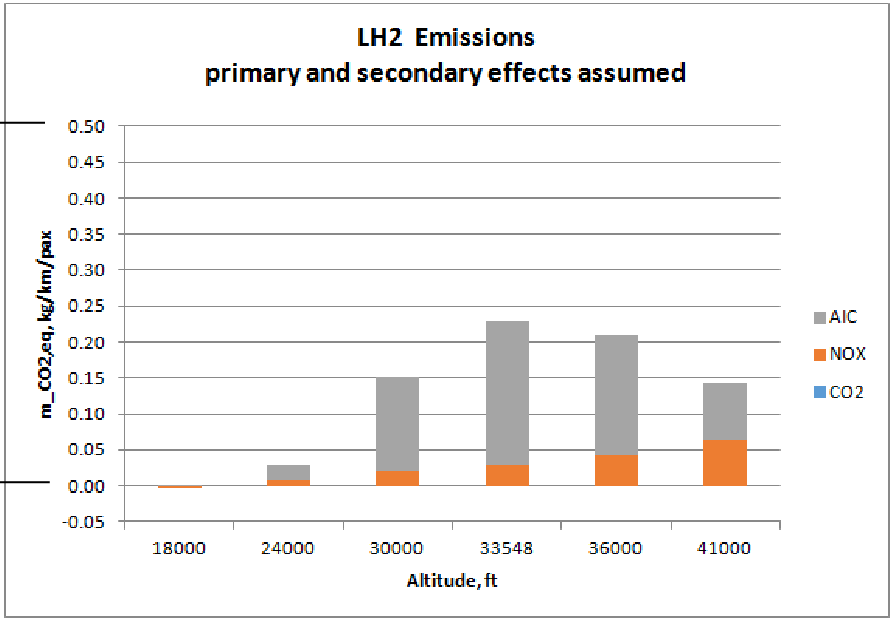


Calculation of the Emission Characteristics of Aircraft Kerosene and Hydrogen Propulsion – A Comparison with Secondary Effects

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*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%





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Hamburg University of Applied Sciences

AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

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

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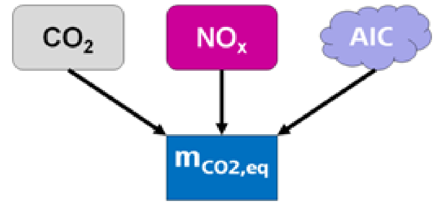
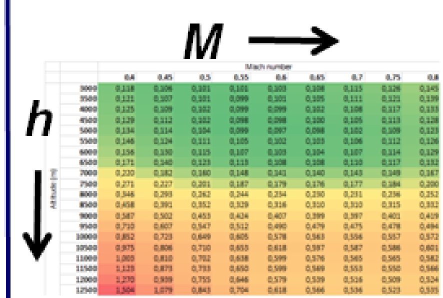
https://doi.org/10.5281/zenodo.4068135

Deutscher Luft- und Raumfahrtkongress 2020
German Aerospace Congress 2020
Online, 01 - 03.09.2020



$$m_{CO2,eq} = f\,(M,\ h)$$



Environmental Impact – Flying Lower

Altitude (m)	Mach number								
	0,4	**0,45**	**0,5**	**0,55**	**0,6**	**0,65**	**0,7**	**0,75**	**0,8**
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 CO_2 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 CO_2 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-CO_2 warming potential versus more CO_2 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.

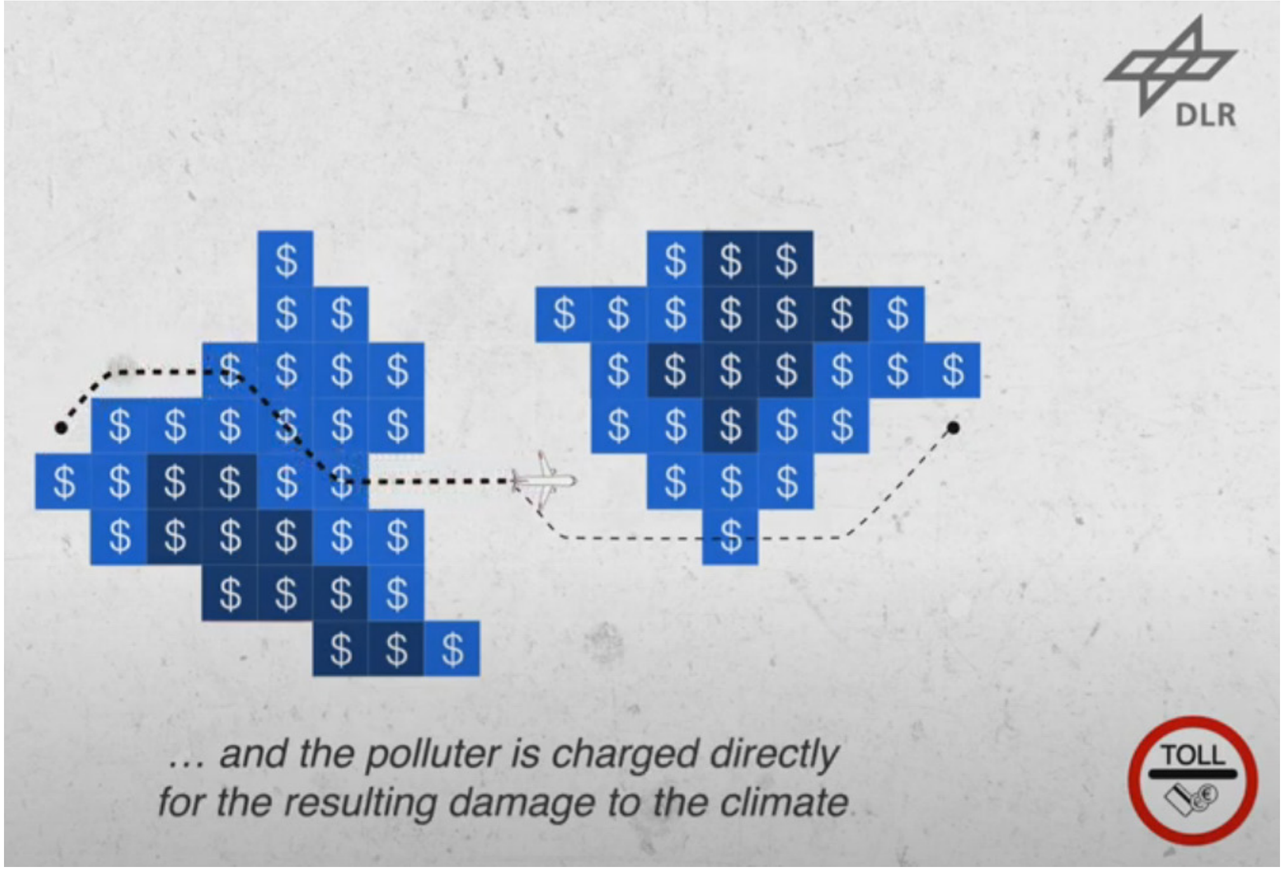
although 22% of annual air traffic movements are winter flights, they contribute about half of the annual mean RF from contrails.

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

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!

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)

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Quote this document:

SCHOLZ, Dieter, 2020. *Design of Hydrogen Passenger Aircraft – How much 'Zero-Emission' is Possible?*Hamburg Aerospace Lecture Series, HAW Hamburg, 19.11.2020.
Available from: https://doi.org/10.5281/zenodo.4301103

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

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