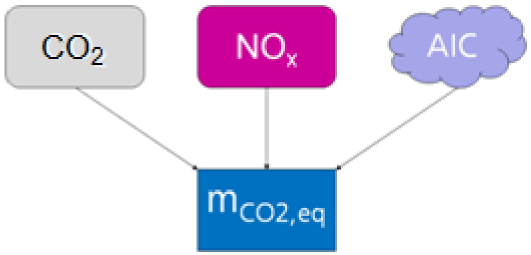
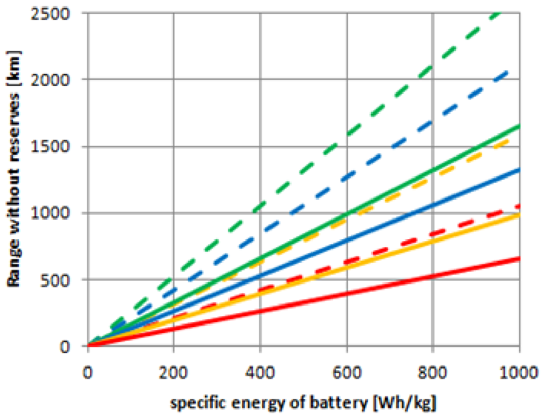
Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)



Passenger Aircraft Design towards Lower Emissions with SAF, LH2, and Batteries (Pros & Cons)

Dieter Scholz Hamburg University of Applied Sciences



RAeS Conference: Alternative Propulsion Systems –

The Challenges and Opportunities for Aircraft Design

London, UK / Hybrid, 01.–02.12.2021

https://doi.org/10.5281/zenodo.5904292

https://doi.org/10.48441/4427.409

Contents

Abstract

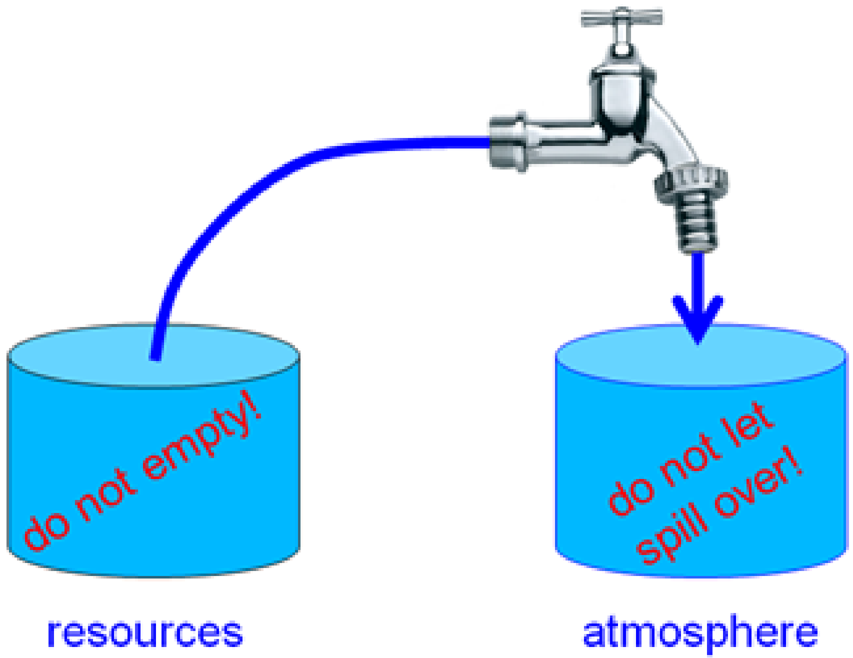
We consider that use of SAF is mainly a question of its availability and price. For engineers, it is a matter of sourcing primary energy involved in producing SAF – not to forget that SAF is only sustainable, if the CO2 is really taken out of the atmosphere in fuel production, which is intended to be put back into the atmosphere during flight. LH2 requires new (or modified) aircraft that are less efficient than conventional aircraft. Calculations show about 40% more fuel consumption (by energy) for LH2. This adds to the demand of LH2 for sourcing more primary energy. Batteries for electric flights suffer from their weight (as we already know). In addition, there are interesting aircraft design questions arising from issues such as: higher number of propellers and propeller integration into the airframe. It is explained, why hybrid electric or turbo electric solutions have clear disadvantages. There are also the non-CO2 effects. Here we shall consider flying lower with LH2 and also kerosene/SAF aircraft.

The video to this presentation: https://youtu.be/bHTpsDqtPqI

Introduction

Introduction

Resources or Atmosphere – What is the Problem?



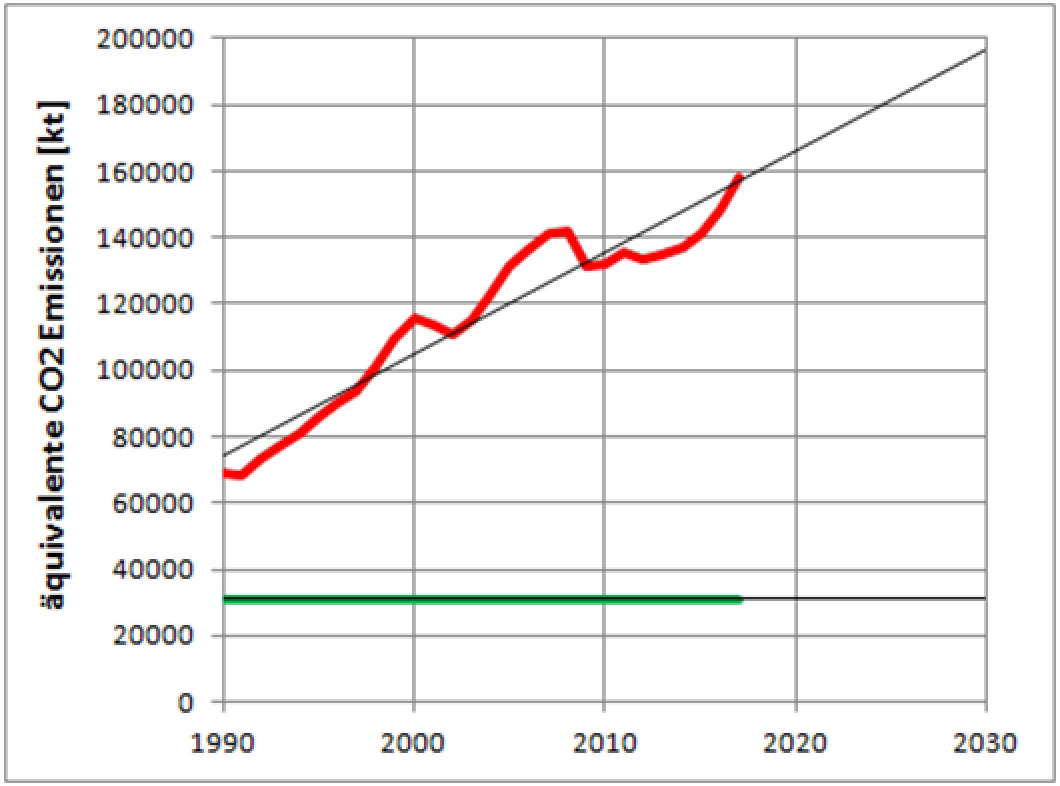
Two barrels symbolize:

- left: the finite fossil energy reserves and
- right: the finite capacity of the atmosphere to absorb.

It does not work to open the tap more each year.
It also does not work to set the tap at constant flow. It needs to be closed!

Introduction

"Green Deal" (2050) and "Fit for 55" (2030)



The equivalent CO2 emissions (in 1000 tonnes or kt) of international aviation in the EU are rising continuously (red line). According to the "Green Deal" of the EU, they have to go to 45% of the 1990 value (by 2030) (green line). Diagram created with data from. EEA 2019 (https://perma.cc/2EZ6-DQBN)

80% of humans on earth never flew and will probably never fly.

Global warming from aviation is a "rich world's problem"!

Two "Schools" Marching towards Zero Emission

1.) The traditional school: "We have to increase efficiency."
Critique: "You will never make it to zero emission!"

2.) The new school: "We have to apply new fuels and do not care about their overall inefficiency, because all energy will be renewable energy, which is without harm."
Critique: "You will run out of energy resources!"

The Way towards Zero Emission

Zero Emission can be achieved by a combination of these principles:

1. apply new technologies to increase efficiency, and:
2. apply new fuels and with new means of propulsion/flying with no or less emissions, and:
3. apply the carbon (CO2) cycle with biofuels or SAF from PtL, and:
4. compensate remaining emissions.

The Problems with Zero Emission Measures

Efficiency: **Mathematical fact**: Adding measures with improved efficiency on top of each other does not lead to zero emissions. Example: If you take an aircraft that burns only 50% of the fuel on a magic ATM system that reduces the distance by 50% you do not get zero emission, but 25% emission of the reference.

Experience: The rebound effect teaches us that in the long run increased efficiency leads to a lower price, which leads to more demand, which leads to more emissions.

Fuels: It is not so easy. Electricity does not just come from the socket. The energy production needs to be considered with a Life Cycle Analyses (LCA). Hydrogen combustion does not produce CO2, but has non-CO2 effects. *Details later*.

CO2 Cycle: A biofuel carbon cycle is not 100% efficient. It reduces CO2 by about 50%.

Compensate: Compensating emissions may not be sustainable. A new forest that is cut after 30 years is not a long term carbon sink. Compensation comes with philosophical questions. No one likes to pay for compensation.

Aircraft Design Basics

First Law of Aircraft Design

Maximum Take-Off mass is a combination of PayLoad and Fuel mass (to reach maximum useful load) plus the Operating Empty mass of the aircraft:

$$m_{MTO} = m_{PL} + m_F + m_{OE}$$

$$m_{MTO} - m_F - m_{OE} = m_{PL}$$

$$m_{MTO} \cdot \left(1 - \frac{m_F}{m_{MTO}} - \frac{m_{OE}}{m_{MTO}}\right) = m_{PL}$$

$$\boxed{m_{MTO} = \frac{m_{PL}}{1 - \frac{m_F}{m_{MTO}} - \frac{m_{OE}}{m_{MTO}}}}$$

m_{MTO} : Maximum Take – Off mass

m_F : Fuel mass

m_{OE} : Operating Empty mass

m_{PL} : PayLoad

In case of electric propulsion fuel mass is meant to be battery mass.

Maximum Take-Off mass is a surrogate parameter for cost !

Breguet Range Equation (for Jets)

Note: The Thrust Specific Fuel Consumption, c = SFC_T is not constant, rather a function of speed. Very roughly, we can write it as a linear function: $c \approx c_a V$

Is speed increasing range? No!

$$R = \frac{EV}{cg} \ln \frac{m_{MTO}}{m_L}$$

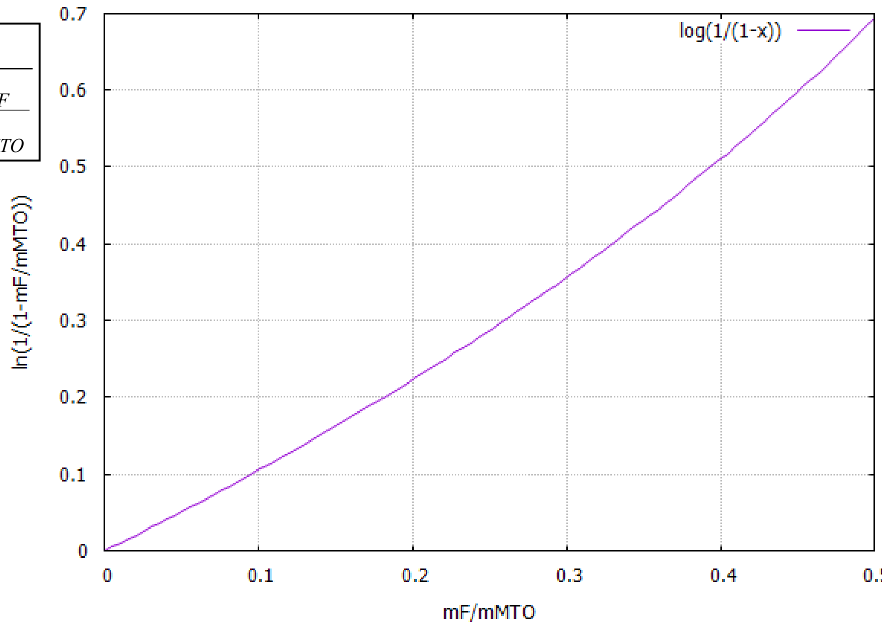
$$E = \frac{C_L}{C_D}$$

$$R \approx \frac{E}{c_a g} \ln \frac{m_{MTO}}{m_L}$$

$$R \approx \frac{E}{c_a g} \ln \frac{1}{1 - \frac{m_F}{m_{MTO}}}$$

$$R \approx \frac{E}{c_a g} \frac{m_F}{m_{MTO}}$$

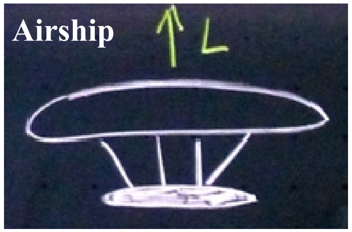
$$\ln \frac{1}{1 - \frac{m_F}{m_{MTO}}}$$



$$\frac{m_F}{m_{MTO}}$$

Force along the Way due to Lift or Weight: Induced Drag, D_i

Vehicle shows less resistence / drag

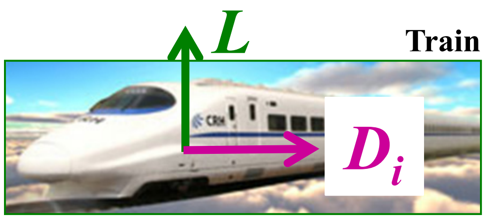


$D_i = L / \infty = 0$

$D = D_0 + D_i$

Force to push vehicle through the air

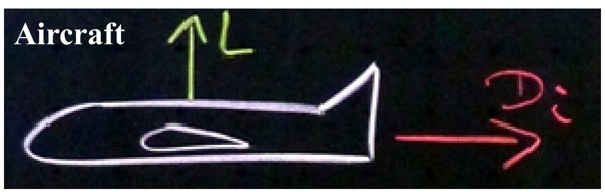
Train



$D_i = L / 700$

$D_i = L / 70$: Car on tarmac

$D_i = L / 20$: Car on sand



$D_i = L / 40$

$L = T$

Helicopter

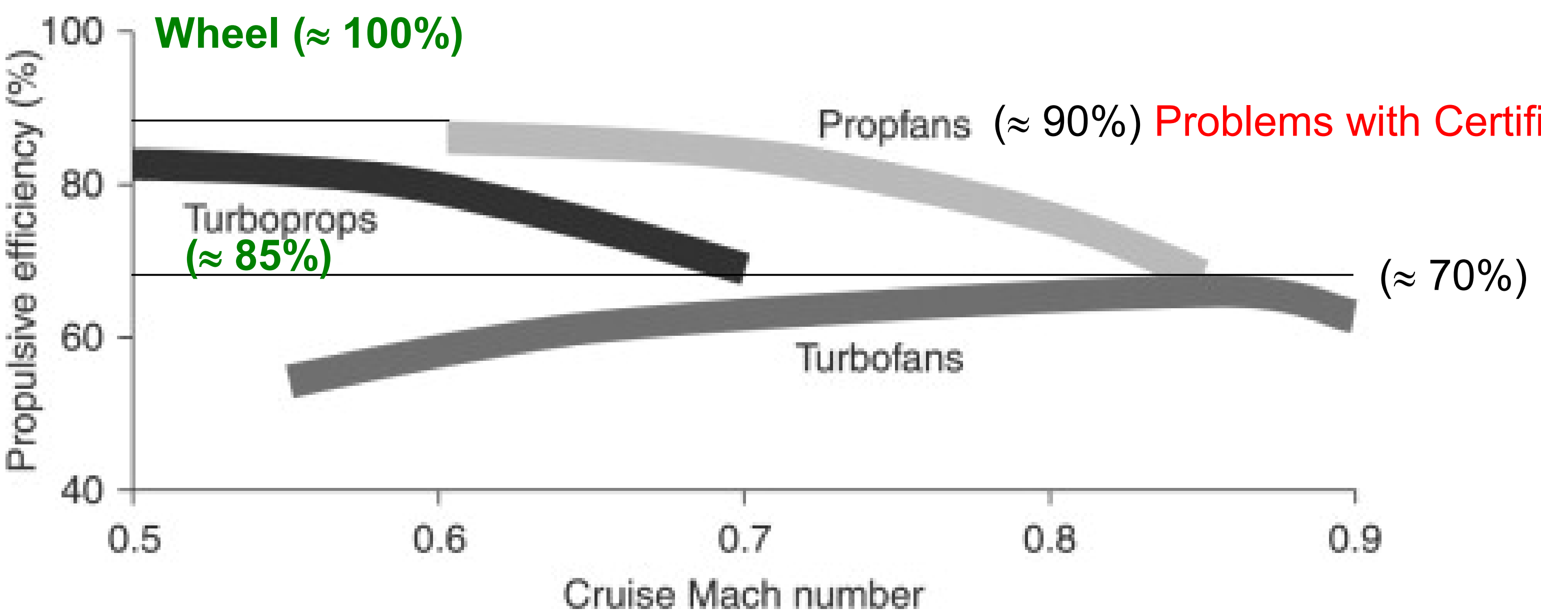
$D_i = T = L / 1$

D_i = induced Drag

L = Lift = Weight

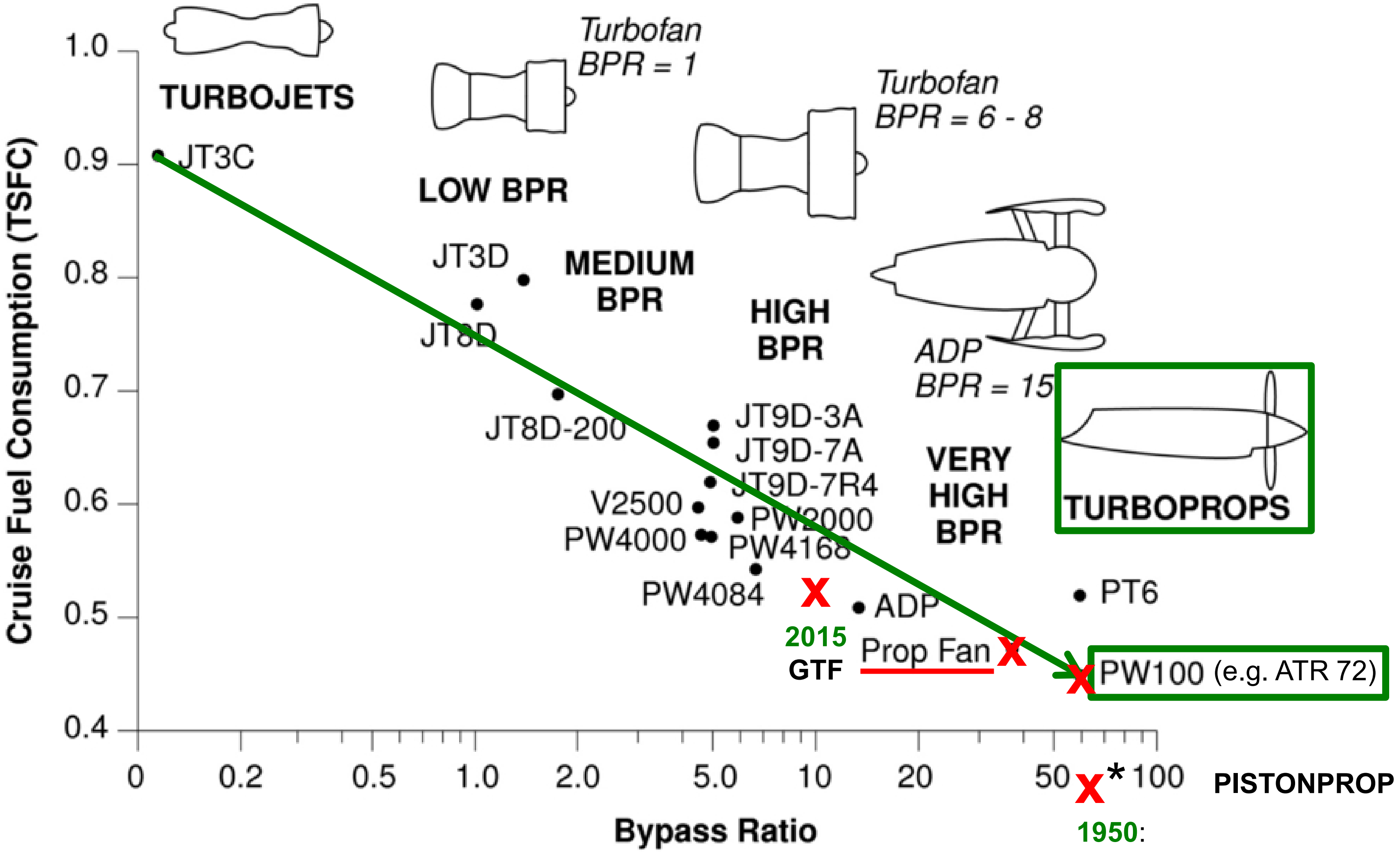
T = Thrust

Propulsive Efficiency



https://www.sciencedirect.com/topics/engineering/propulsive-efficiency

Specific Fuel Consumption



1950:
Wright R-3350
(Super Constellation)
* Bypass Ratio not defined

https://web.mit.edu/16.unified/www/FALL/thermodynamics/notes/node84.html

Desperately Needed: A Definition of the Aircraft's Fuel Consumption

Table 1: Summary of candidate metrics

	Full Mission Metrics				
Single parameter metric	Block Fuel ---------------- Range				
Two-parameter metric	Block Fuel ---------------- **Payload** * Range	Block Fuel ---------------- **Useful Load** * R	Block Fuel ---------------- **MTOW** * Range	Block Fuel ---------------- **Floor Area** * R	Block Fuel ---------------- **Av. Seats** * R
Three-parameter metric	Block Fuel ---------------- **Payload** * R.*Speed	Block Fuel ---------------- **Useful Load** * R.*Speed	Block Fuel ---------------- **MTOW** * R. *Speed	Block Fuel ---------------- **Floor Area***R.*Speed	Block Fuel ---------------- **Av. Seats** * R. *Speed
	Block Fuel ---------------- **Payload** * R./Time	Block Fuel ---------------- **Useful Load***R./Time	Block Fuel ---------------- **MTOW** * R./Time	Block Fuel ---------------- **Floor Area***R./Time	Block Fuel ---------------- **Av. Seats** * R./Time
	Instantaneous Performance Metrics				
Single parameter metric	1 ---------------- **Specific Air Range** = 1 ----- **SAR**				
Two-parameter metric	1 ---------------- SAR * **Payload**	1 ---------------- SAR * **Useful Load**	1 ---------------- SAR * **MTOW**	1 ---------------- SAR * **Floor Area**	1 ---------------- SAR * **Av. Seats**
Three-parameter metric	1 ---------------- SAR * **Payload** * Speed	1 ---------------- SAR * **Useful Load** * Speed	1 ---------------- SAR * **MTOW** *Speed	1 ---------------- SAR * **Floor Area*** Speed	1 ---------------- SAR * **Av. Seats** * Speed

Note: R = Range

http://partner.mit.edu/projects/metrics-aviation-co2-standard

PARTNER
Partnership for Air Transportation Noise and Emissions Reduction

Selecting a Fuel Metric:

$1/(SAR \cdot n_{seat})$

$$SAR = \frac{V \cdot L/D}{SFC \cdot m \cdot g} \;;\; g = 9.81 \text{ m/s}^2$$

Specific Air Range; 1/SAR=fuel consumption can be **measured** in flight **or calculated** from basic aircraft parameters:

- aircraft mass, *m*
- aerodynamic efficiency, *L/D*
- specific fuel consumption, *SFC*
- aircraft speed, *V*

or extracted from published **Payload Range Diagrams**

From Energy to Approximate Emission Comparison

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

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

Carnot Efficiency:

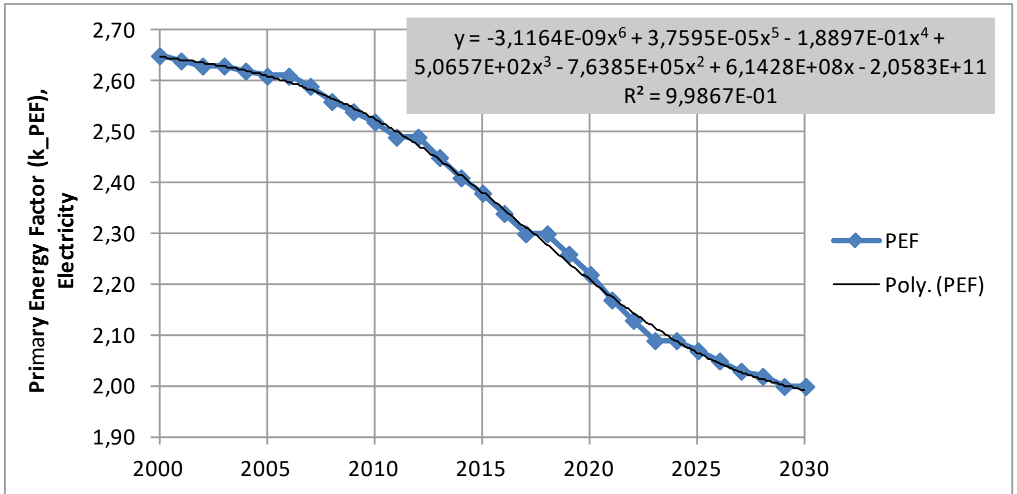
$\eta_C = 1 - T/(h) / T_{TET} =$

$= 1 - 216.65/1440 = 0.85$

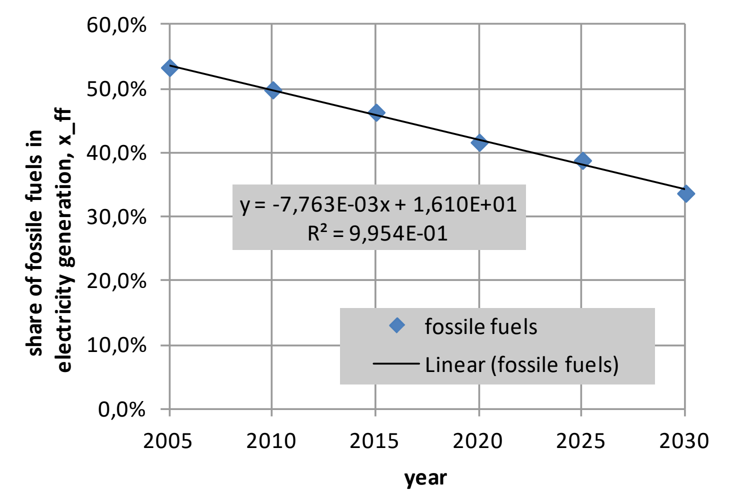
$\eta_{GT} = 0.35 \quad \eta_{EM} = 0.9$

Radiative Forcing Index:

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



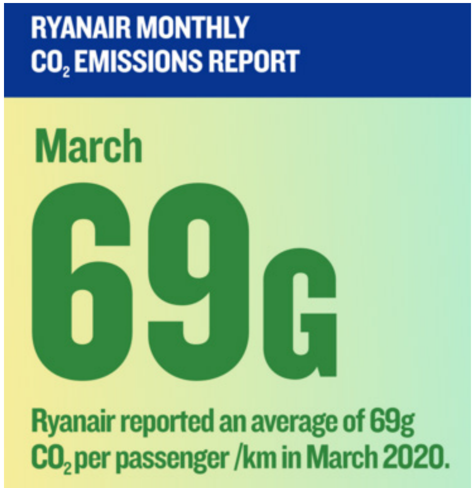
ESSER 2016, Table 73



ESSER 2016, Table 15

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

Pro & Con Low Cost Airline – Who Is Right?



ASA Ruling on Ryanair Ltd t/a Ryanair Ltd

Advertising Standards Athority, UK

Upheld | National press | 05 February 2020

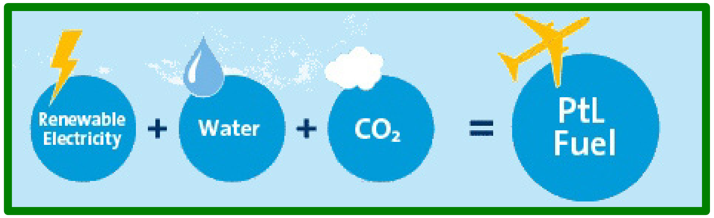
Ryanair Ltd said the metric they used to measure CO2 emissions was grams of CO2 per passenger-kilometre. Five key efficiency drivers: aircraft model, seating density, load factor, freight share and distance.

https://www.asa.org.uk/rulings/ryanair-ltd-cas-571089-p1w6b2.html

Many Possible Energy Paths for Aviation

1.	fossile fuel	=> jet engine		no future solution
2.	bio fuel (algae, ...)	=> jet engine		not sustainable
3.	regenerative electricity	=> aerial contact line	=> electric engine	not for aviation => train!
4.	regenerative electricity	=> battery	=> electric engine	**electric**: very short range
5.	regenerative electricity	=> **LH2**	=> jet engine	new infrastructure & planes
				but **2.7 times better efficiency than PtL**
6.	regenerative electricity	=> LH2 => fuel cell	=> electric engine	see 5.; heavy
7.	regenerative electricity	=> **PtL** (drop in fuel)	=> jet engine	same infrastructure & planes
8.	regenerative electricity	=> PtL => GT/Gen.	=> electric engine	**hybrid electric**, heavy
9.	regenerative electricity	=> PtL => GT/Pump	=> hydraulic motor	hybrid hydraulic , heavy

PtL: Power to Liquid **GT**: Gasturbine; **Gen.**: Generator



Additional conversions & major aircraft parts: Solutions 6 (one more component) and 8/9 (two more comp.)

Validation of Transport Options – Are We Doing the Right Thing?

- Physics favor trains over aircraft (*low drag due to weight*) => less energy, less CO2. Regenerative energy via aerial contact line efficiently fed into vehicle.
- PtL for jet/prop engines: Regenerative energy into aircraft NOW! But: Much primary energy needed!
- LH2 for jet/prop engines: Less efficient aircraft (40% more consumption), new or modified aircraft needed. New infrasturcture needed. Not as much primary energy needed for fuel production (2.7 times less than for PtL).
- Hybrid-electric propulsion has NO advantages for passenger aircraft.
- Unpredictable political environment for short range flights => high risk investment .
- Aircraft are the only means of transportation over oceans **long range.**
  Ships are too slow and hence no regular service, bridges and tunnels are limited in length.
- Trains beat aircraft on **short range** (*less access time to station, less waiting time in station, ...*).
- Trains beat aircraft to connect adjacent megacities over land up to **medium range** with high volume.
  A380 is too small and unfit, because designed for long range.
- Aircraft over land, if ...
  - **long range**,
  - **short range** and no train available due to low volume traffic
    - aircraft need less investment into infrastructure than (high speed) trains.
      Construction costs for high speed trains: 5 M€/km to 70 M€/km (2005, Campos 2009)
    - alternative: rail replacement bus service
  - over remote areas, if no train is available (mountains, desserts, polar regions).

Urban Aviation
Short / Medium / Long Range

Urban Aviation

Airtaxi Is Not the Solution to Save the Environment

based on Caldwell 2018

"Flying Taxi"?	......or "Flying Sports Car"?	Aircraft (Ryanair):
		CO2 = 69 g/km/person

1 kg fuel = 3.15 kg CO2

Ehang184	Lamborghini LP700	VW Golf TDI
Carbon fibre monocoque	Carbon fibre monocoque	4.2 l/100 km
360kg	1575kg	1440 kg
106kW	515kW peak	118 kW
= 0.29 kW/kg	**= 0.33 kW/kg**	**= 0.082 kW/kg**
CO2=1000g/km (in Dubai)	CO2=370g/km	CO2 = 106 g/km

CO2: ← (increasing)

Airtaxi: 200 $ for 24 km (7 €/km) – Taxi Hamburg: 1,80 €/km

GLOBAL TRAVELER

Uber's $200 helicopter taxi: Manhattan to JFK airport in 8 minutes flat

NEW YORK HELICOPTER

It won't get cheaper if batteries and electric motors are used!

Airtaxi for the Elite – Not for Mass Transportation

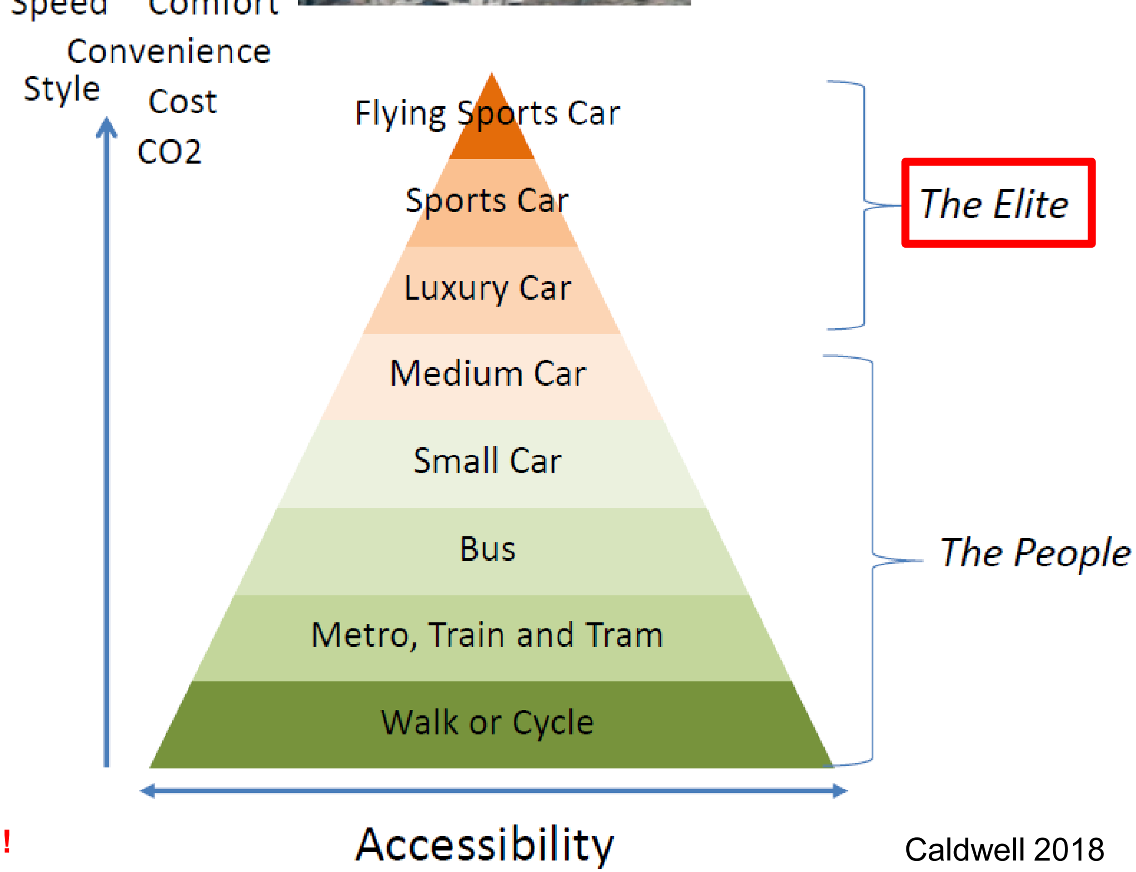
City Airbus, 4 Passengers, max: **15 min.**

Airtaxi: Not a technical solution!

Max Pixel, CC0

Waiting for the City Airbus?

Airtaxi: No solution to solve a traffic problem!



Caldwell 2018

Short Range

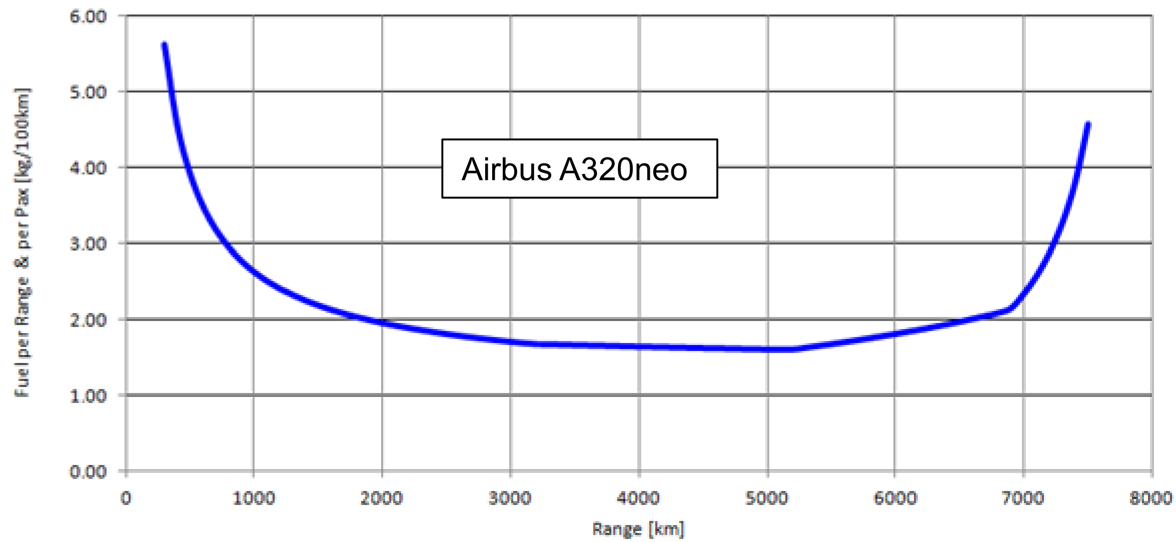
For Short Range We Take the Train!

Elektro mobility needs to be supplied from the grid. This is already invented: The train!

- Aircraft: *Induced drag* is drag due to Lift = Weight. Train: *Rolling Friction* is also drag due to Weight.
- Aircraft: For minimum drag, *induced drag* is 50% of total drag.
- For the same weight, rolling friction of a train is 5% of the induced drag of an aircraft!
- This means: For the same weight, drag of an aircraft is reduced by ≈ 47.5% if put on rails!

Aircraft Fuel Consumption – Short Range Not Efficient

Use the Train!



- **Train is about 3 times more energy-efficient** (certainly on short range)
- **Train uses 50% Eco Electricity Mix (factor 2)**
- **Aircraft Factor 3, because in addition non-CO2 effects from:**
  - **NOX and**
  - **H2O (AIC)**
- **3*2*3: aircraft is 18 times worse on global warming!**

<u>Simple Calculation of Aircraft Fuel Consumption with Public Data</u>:
See details: https://bit.ly/3mWHo6c

Fuel Consumption = (MTOW – MZFW) / (R · Seats) · 100

R: Range at maximum payload, from payload range diagram (Document for Airport Planning).

Example calculation with Airbus A320neo:

2.2 kg per 100 km per seat =
(73500 kg – 62800 kg) / (3180 km · 150) · 100

Medium Range

Medium Range between Megacities: We Take the Train!

Example: Two Megacities – Beijing & Shanghai – Comparison Aircraft versus Train

Time	Location	Mode
08:20	Beijing Capital Times Square	Walk
08:30	Xidan	
08:40		
08:50		Metro Line 4
09:00	Xuanwumen	
09:10		
09:30		Metro Line 2
09:40	Dongzhimen	
09:50		Metro Airport Line
10:00	Beijing Capital International Airport	
10:10		
...	...	
11:20		
11:30	Beijing Capital International Airport	
11:40		
11:50		
...	**Aircraft**	Air China 1557
13:20		
13:30		
13:40	Shanghai Hongqiao	
13:50	Pick-up luggage	

(a) Travel mode: metro + aircraft

Time	Location	Mode
08:20	Beijing Capital Times Square	Walk
08:30	Xidan	
08:40	Beijing South Railway Station	Metro Line 4
08:50		
09:00	Beijing South Railway Station	
09:10		
09:20		
09:30		
09:40		
09:50		
10:00		
...	**Train**	
11:20		
11:30		
11:40		
11:50		
13:10		
13:20		
13:30		
13:40		
13:50 **new: 13:28**	Shanghai Hongqiao	

(b) Travel mode: metro + high-speed rail

China High Speed Rail (CHR)
Beijing to Shanghai:
- 1200 passengers per train
- **1200 km distance**
- 350 km/h
- ≈ every 20 min. (an A380 every 10 min.)
- usually fully booked
- 88000 passengers per day (both directions)

Example: Train number G1

Sun 2017

- Comparison **air transportation versus high-speed rail** for a trip from Beijing Capital Times Square to Shanghai Hongqiao in China.
- Despite the large spatial distance of more than 1200 km, **passengers** using either mode **arrive** approximately **at the same time**. Probability of delays is less on the train.

A Propeller Driven Aircraft for 180 Passengers with Two Engines of the A400M ?

… saves lots of fuel!

Airbus A400M

ATR 72

Q400

	m_MTO	M_CR	P_eq	Pax
A320	78 t	0,76	xxx	180
A400M	141 t	0,70	4 x 8250 kW	xxx
ATR 72	23 t	0,46	2 x 1950 kW	72
Q400	29 t	0,60	2 x 3780 kW	78
Smart TP	56 t	0,51	2 x 5000 kW	180

"Smart Turboprop", Design see next pages!

A Larger Propeller Aircraft Is Discussed for 10 Years!

FLIGHT INTERNATIONAL

05/2011:

PROPULSION JOHN CROFT WASHINGTON DC

90-seat turboprop beckons to P&WC

Engine manufacturer to begin assembling next-generation powerplant to prepare for possible creation of bigger airframes

01/2013:

AIRFRAMES MAVIS TOH SINGAPORE

ATR keen to satisfy 90-seat audience

Turboprop manufacturer yet to convince shareholders despite Asian regional carriers' interest in potential larger aircraft

01/2013:

ANALYSIS MURDO MORRISON LONDON

ATR ascends as Bombardier suffers

Growing demand from lessors helps Franco-Italian airframer beat Canadian rival in turboprop orders and deliveries race

01/2013:

WHO WILL LAUNCH AN ALL-NEW 90-SEAT TURBOPROP?

The chances are, nobody will – but pressure from airline customers might conjure up a 2013 launch of a product that regional aircraft makers agree will eventually be a necessity.

01/2011:

DEVELOPMENT DAVID KAMINSKI-MORROW TOULOUSE

Demand for big turboprops will grow, says ATR

Airframer seeks 'convergent' solution with engine manufacturers to develop future 90-seat models

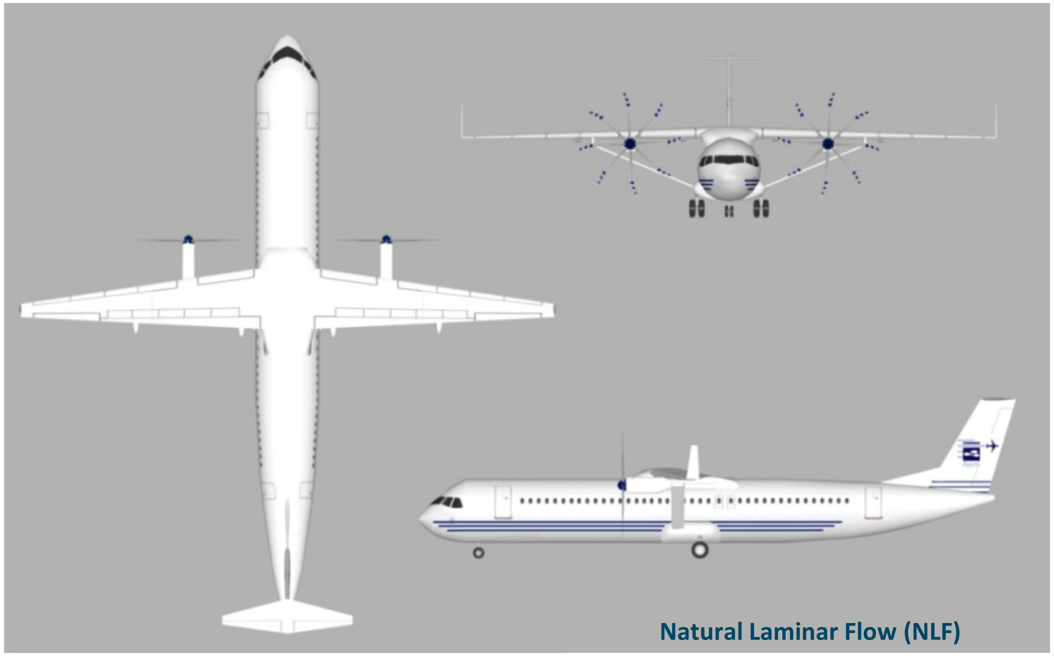
"I'm insisting on one point. The priority is cost-effectiveness, not spending money on speed"

FILIPPO BAGNATO
Chief executive, ATR

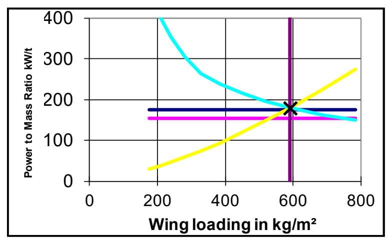
"Smart Turboprop": Large Propellers, Braced Wing, Partial Laminar Flow

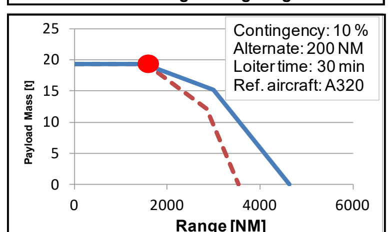
http://Airport2030.ProfScholz.de

"Smart Turboprop": Fly Slow and Low for Reduced Global Warming!



Parameter	Value	Deviation from A320*
Requirements		
m_{MPL}	19256 kg	0 %
R_{MPL}	1510 NM	0 %
M_{CR}	0.51	- 33 %
max(s_{TOFL} , s_{LFL})	1770 m	0 %
n_{PAX} (1-cl HD)	180	0 %
m_{PAX}	93 kg	0 %
SP	29 in	0 %

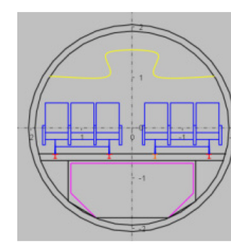




Parameter	Value	Deviation from A320*
Main aircraft parameters		
m_{MTO}	56000 kg	- 24 %
m_{OE}	28400 kg	- 31 %
m_F	8400 kg	- 36 %
S_W	95 m²	- 23 %
$b_{W,geo}$	36.0 m	+ 6 %
$A_{W,eff}$	14.9	+ 57 %
E_{max}	18.8	≈ + 7 %
$P_{eq,ssl}$	5000 kW	------
d_{prop}	7.0 m	------
η_{prop}	89 %	------
$PSFC$	5.86E-8 kg/W/s	------
h_{ICA}	23000 ft	- 40 %
s_{TOFL}	1770 m	0 %
s_{LFL}	1300 m	- 10 %
t_{TA}	32 min	0 %

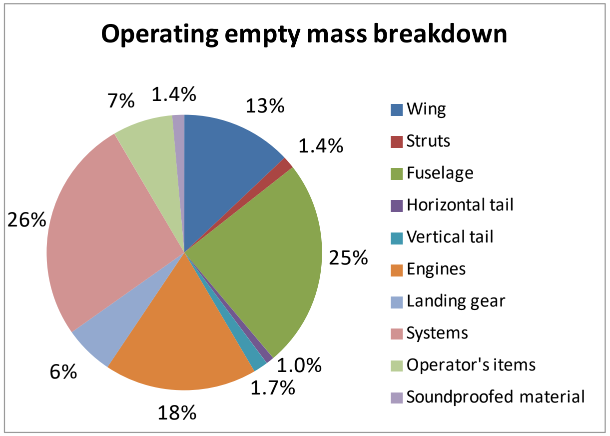
36 % less fuel

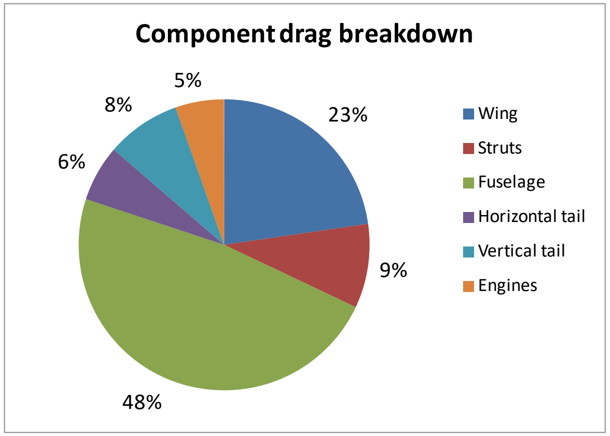
In 23000 ft altitude: no radiative forcing due to Aviation Induced Cloudiness (AIC)

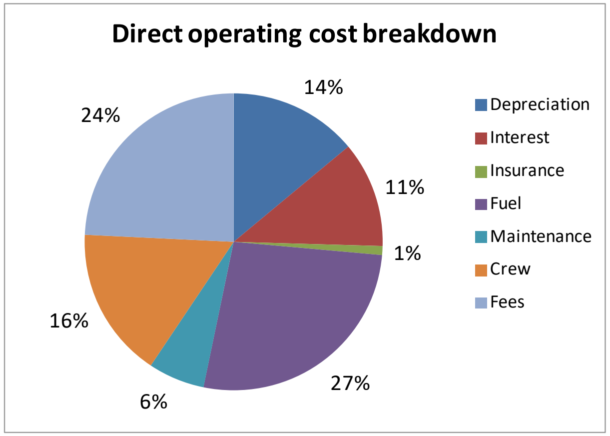


"Smart Turboprop": 17% Less Operating Costs!

Parameter	Value	Deviation from A320*
DOC mission requirements		
R_{DOC}	755 NM	0 %
$m_{PL,DOC}$	19256 kg	0 %
EIS	2030	-----
c_{fuel}	1.44 USD/kg	0 %
Results		
$m_{F,trip}$	3700 kg	- 36 %
$U_{a,f}$	3600 h	+ 5 %
DOC (AEA)	83 %	- 17 %





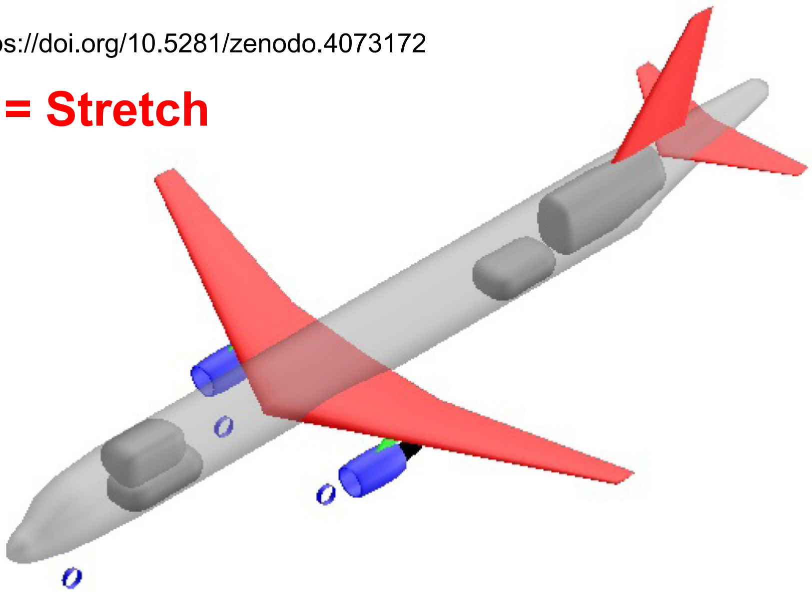


A320 Converted to Hydrogen

Comparison A321-HS with A320-200

https://doi.org/10.5281/zenodo.4073172

S = Stretch



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
DOC (AEA) [€/NM/t]	1.68	+26.7
DOC (TUB) [€/NM/t]	1.49	+29.3
l_F [m]	49.4	+28.8
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

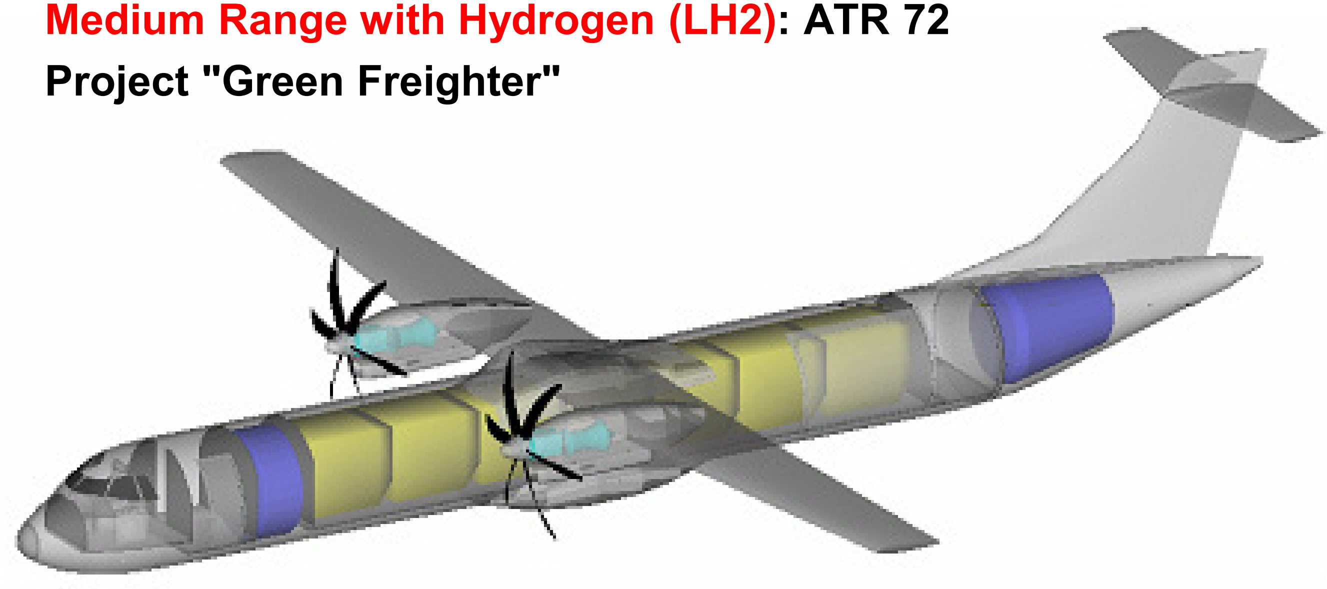
energy up 46 %

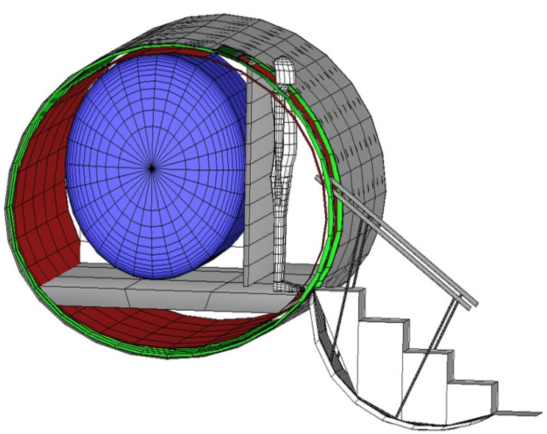
A321: l_F = 44.5 m
Delta fuselage length: **4.9 m.**
Further **stretch** or A319 cabin required.

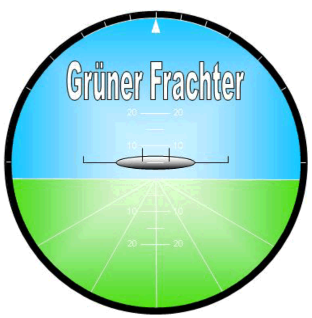
To do:
"Smart Turboprop" with LH2 to combine best of both solutions.

Example: Freighter for Medium Range with Hydrogen (LH2): ATR 72

Project "Green Freighter"

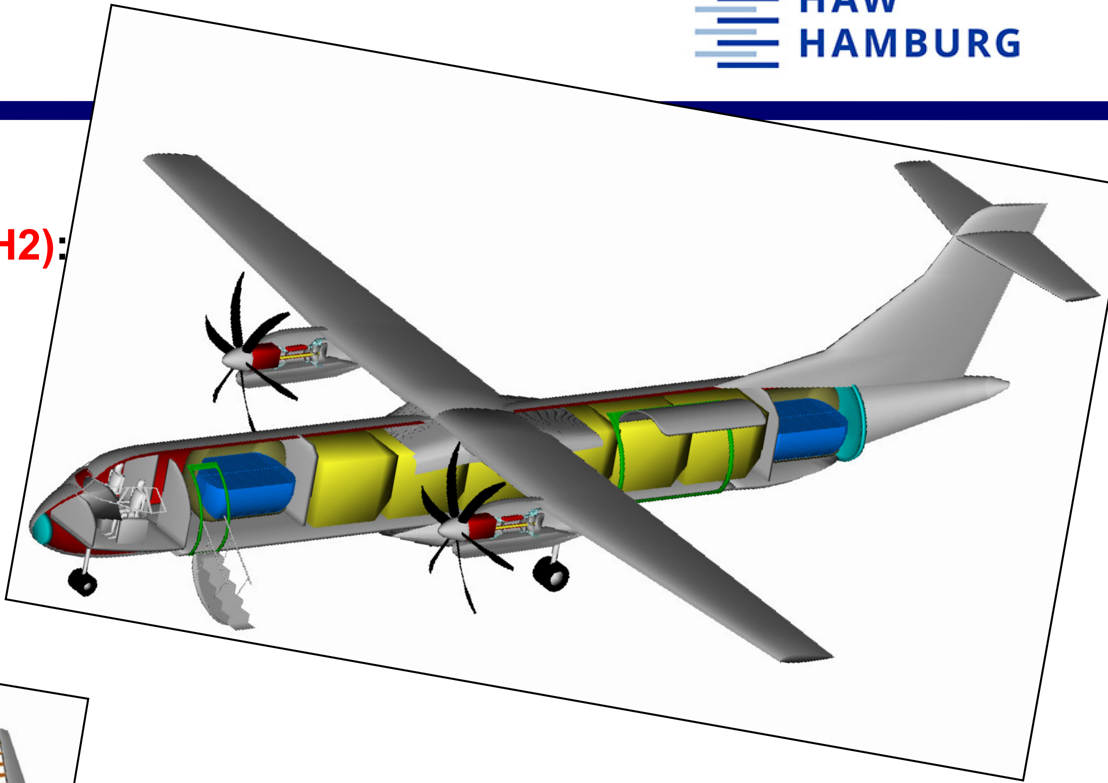


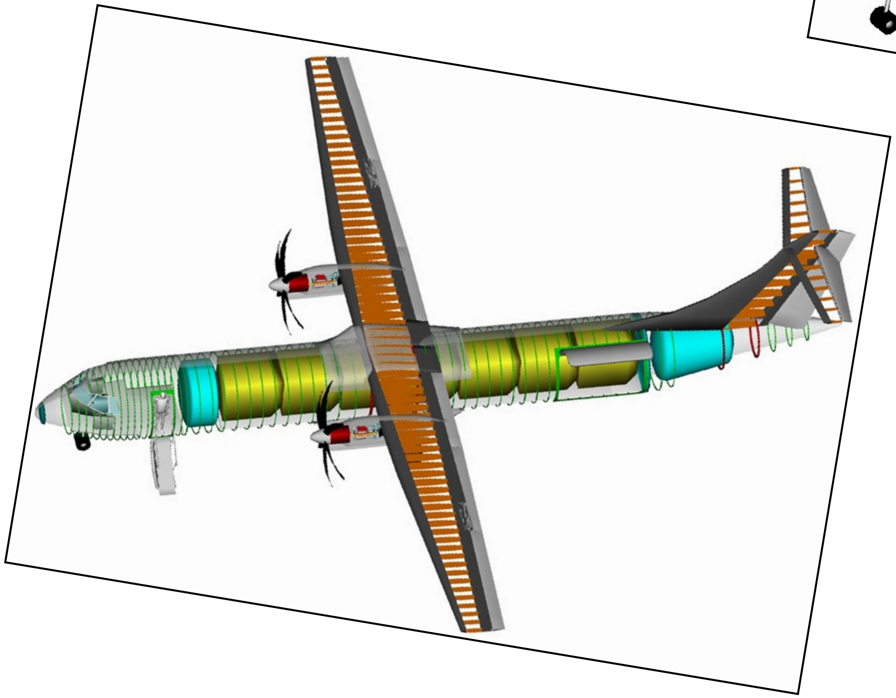


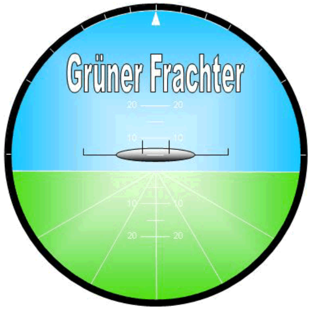


http://GF.ProfScholz.de

Example: Freighter for Medium Range with Hydrogen (LH2): ATR 72



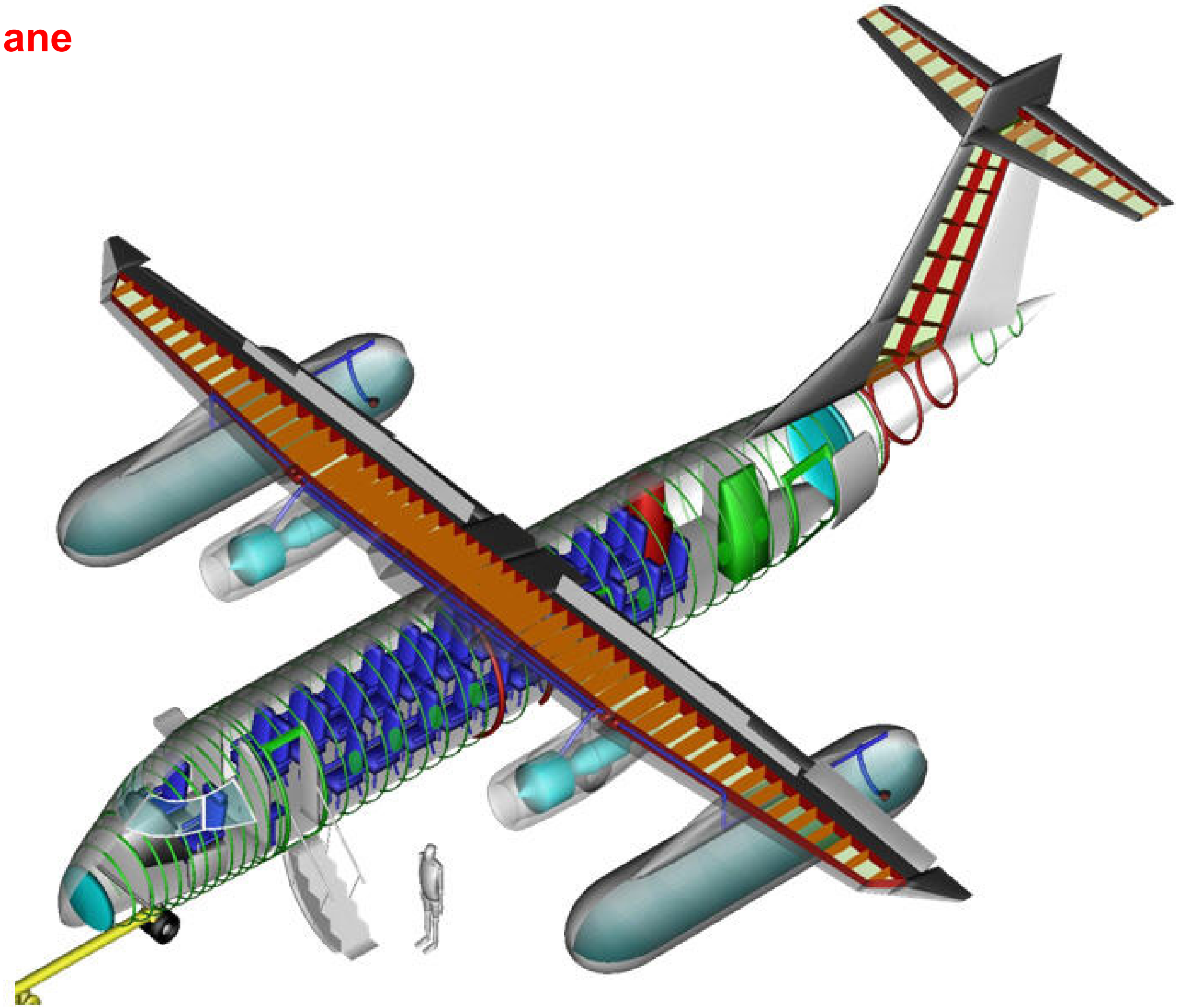


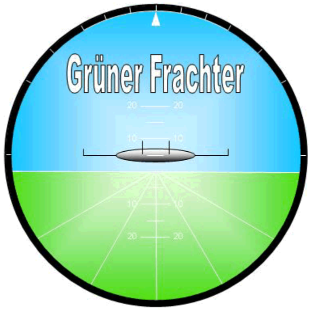


HEINZE, TU Braunschweig, 2009
see http://GF.ProfScholz.de

Example: Passenger Airplane for Medium Range with Hydrogen (LH2)

Project "Green Freighter"



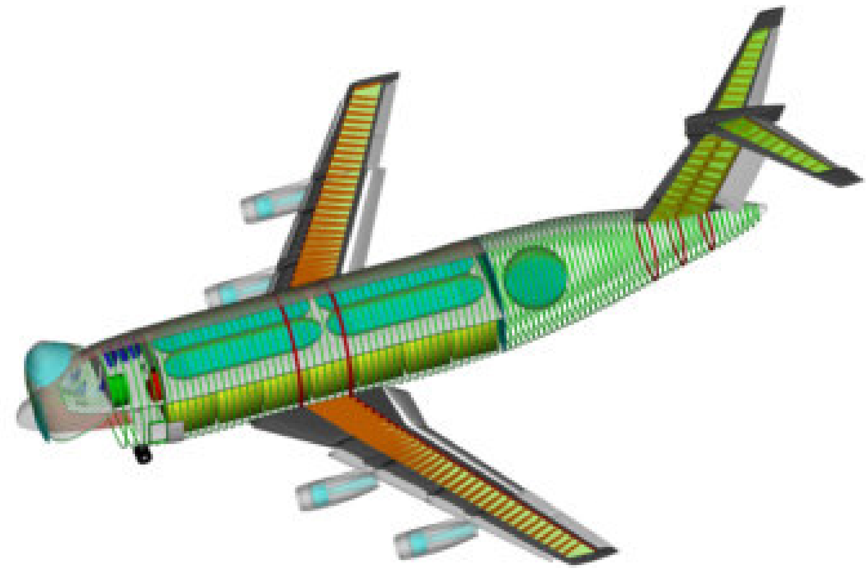


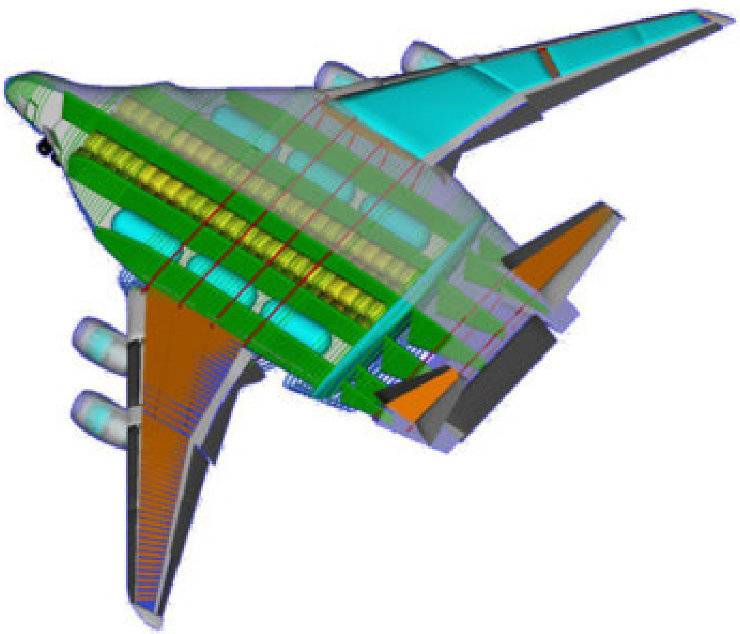
HEINZE, TU Braunschweig, 2009
see http://GF.ProfScholz.de

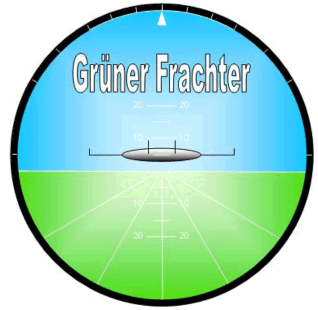
Long Range

Example: Freighter for Long Range with Hydrogen (LH2)

Project "Green Freighter"







HEINZE, TU Braunschweig, 2009
see http://GF.ProfScholz.de

Large Passenger Aircraft for LH2 and Extreme Long Range

Lockheed 1976

DESIGN GROSS WT - 266.429 KG

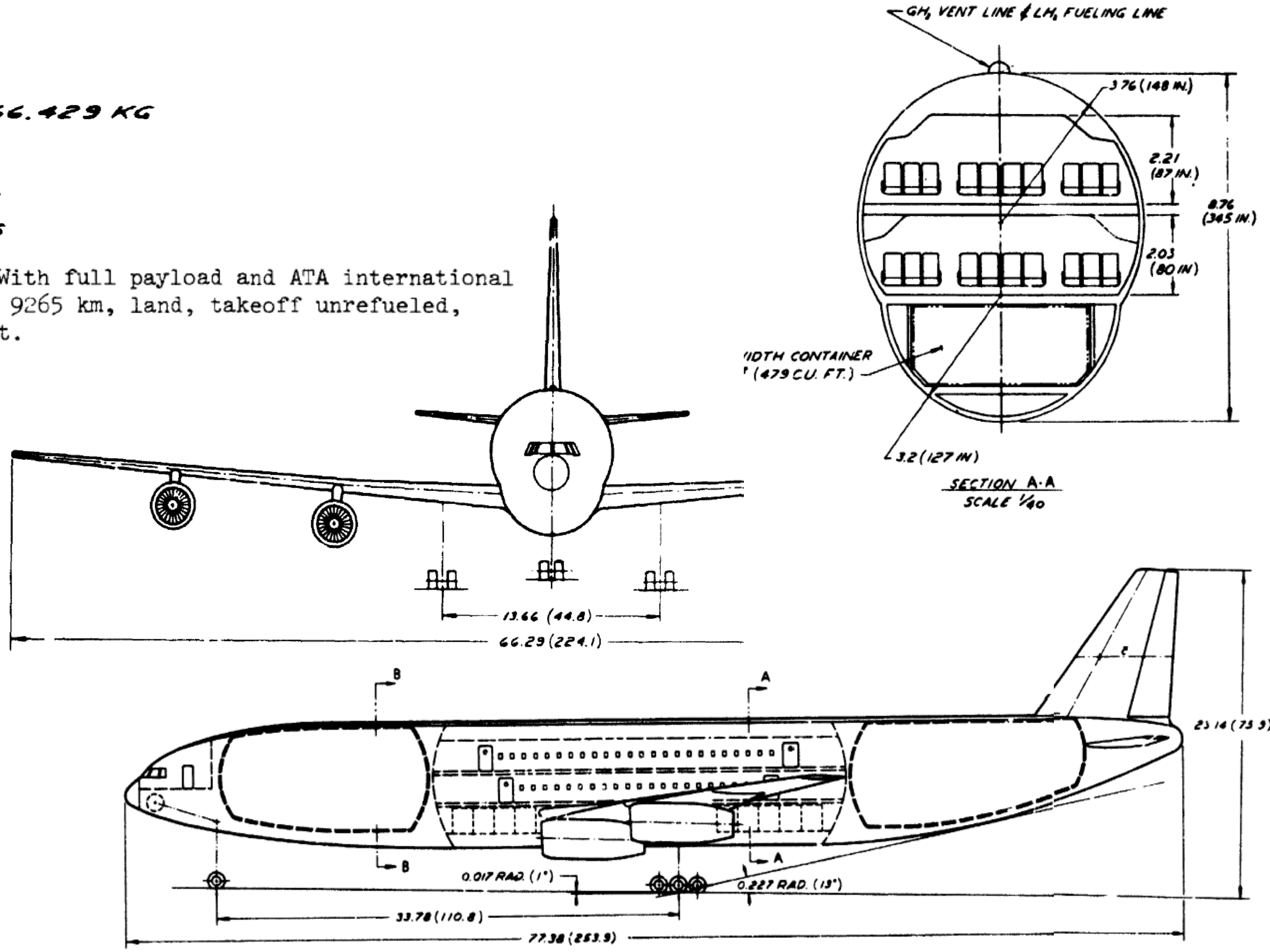
PASSENGERS - 400

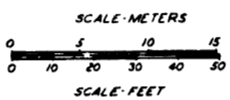
FUEL (LH_2) - 68,424 KG.

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

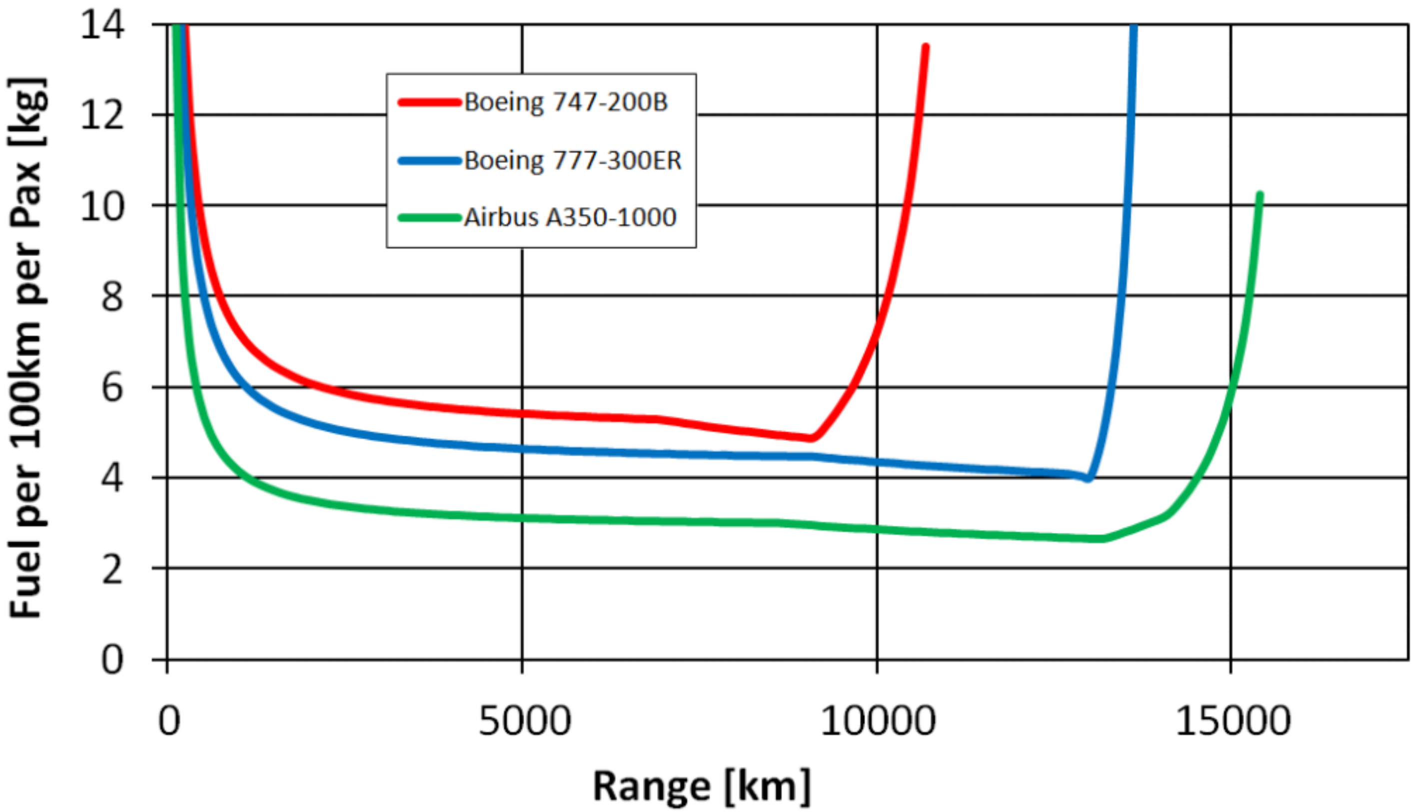




BREWER, G.D., MORRIS, R.E., 1976. *Study of LH2 Fueled Subsonic Passenger Transport Aircraft*. Lockheed, NASA CR-144935. Available from: https://ntrs.nasa.gov/citations/19760012056

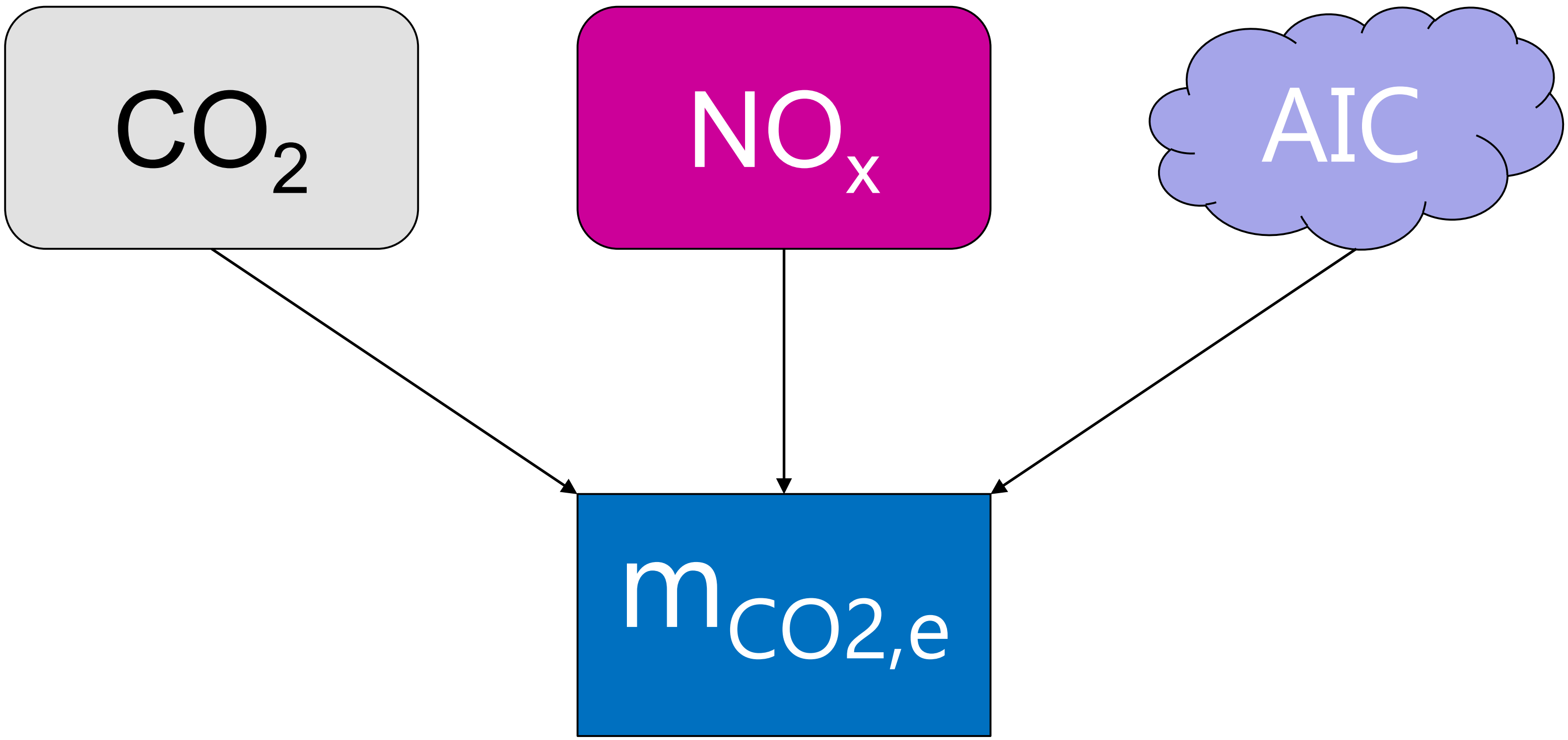
Environmental Evaluation

Fuel Consumption per 100 km and Person Depends on Flight Distance!



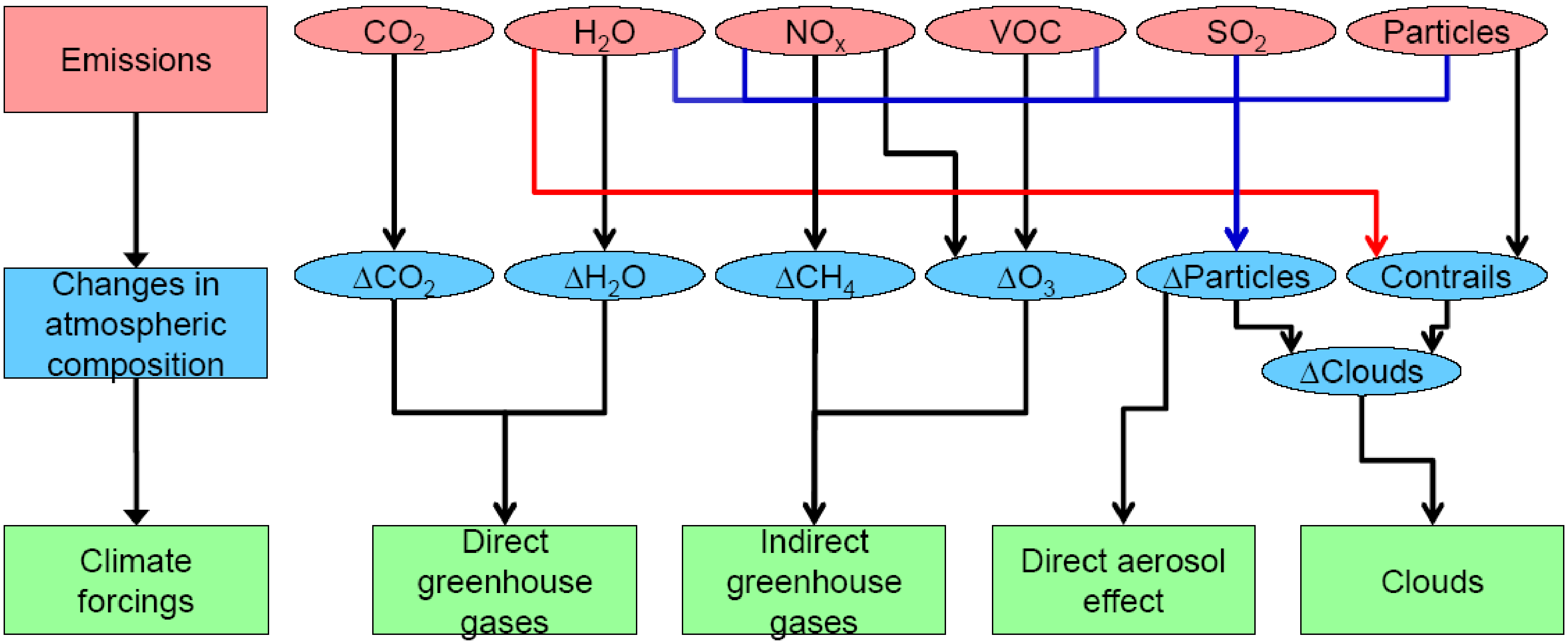
BURZLAFF, Marcus, 2017. *Aircraft Fuel Consumption - Estimation and Visualization*. Project. Hamburg University of Applied Sciences, Aircraft Design and Systems Group (AERO). Available from: https://nbn-resolving.org/urn:nbn:de:gbv:18302-aero2017-12-13.019

Equivalent CO2



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

Emissions, Change in Atmosphere, Climate Forcing



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

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

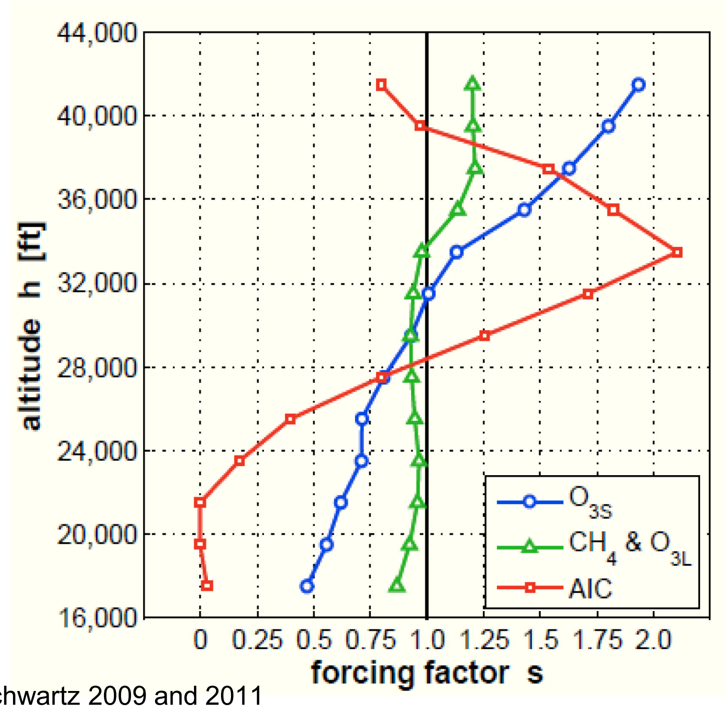
AIC aviation-induced cloudiness

Altitude-Dependent Equivalent CO2 Mass

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

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

↓ units only

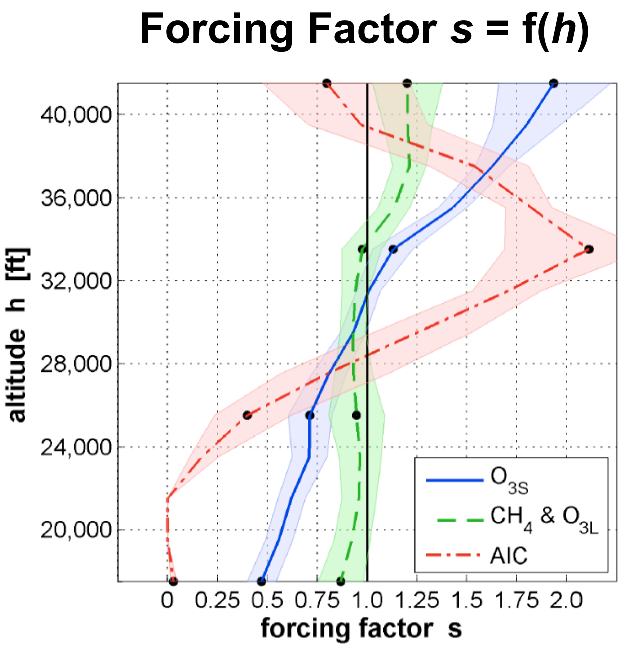
$$\frac{kg\ CO2}{NM \cdot n_{seat}} =$$

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

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



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

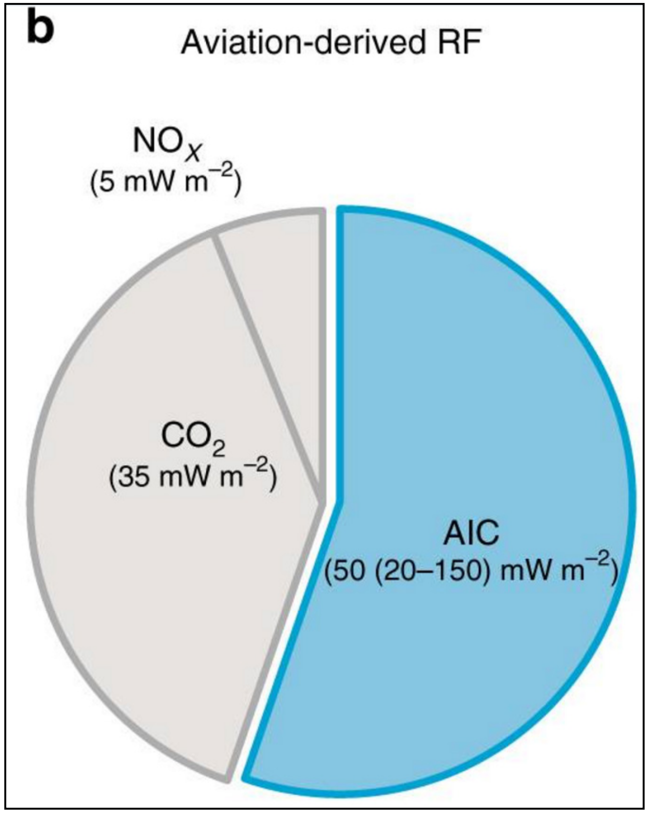
Based on KÖHLER 2008 and RÄDEL 2008.

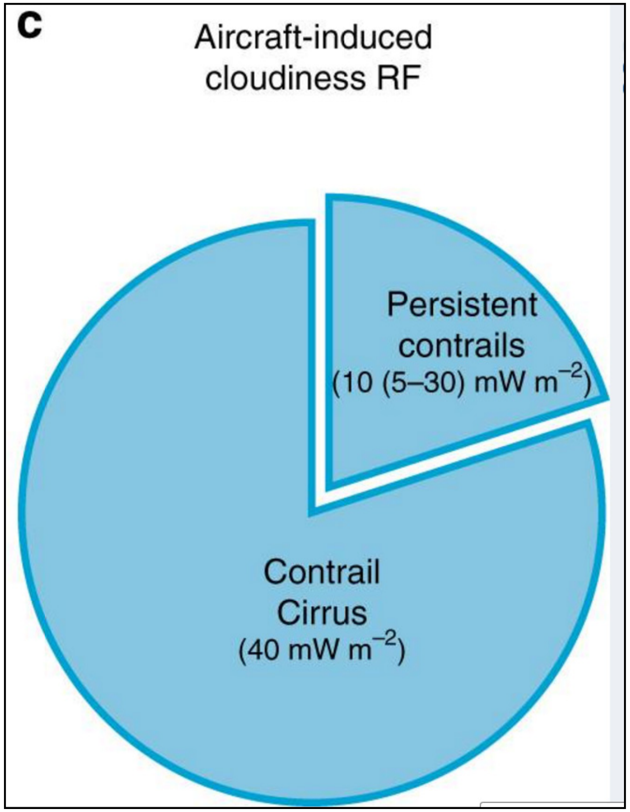
SCHWARTZ DALLARA, Emily, 2011. *Aircraft Design for Reduced Climate Impact*. Dissertation. Stanford University. Available from: http://purl.stanford.edu/yf499mg3300

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



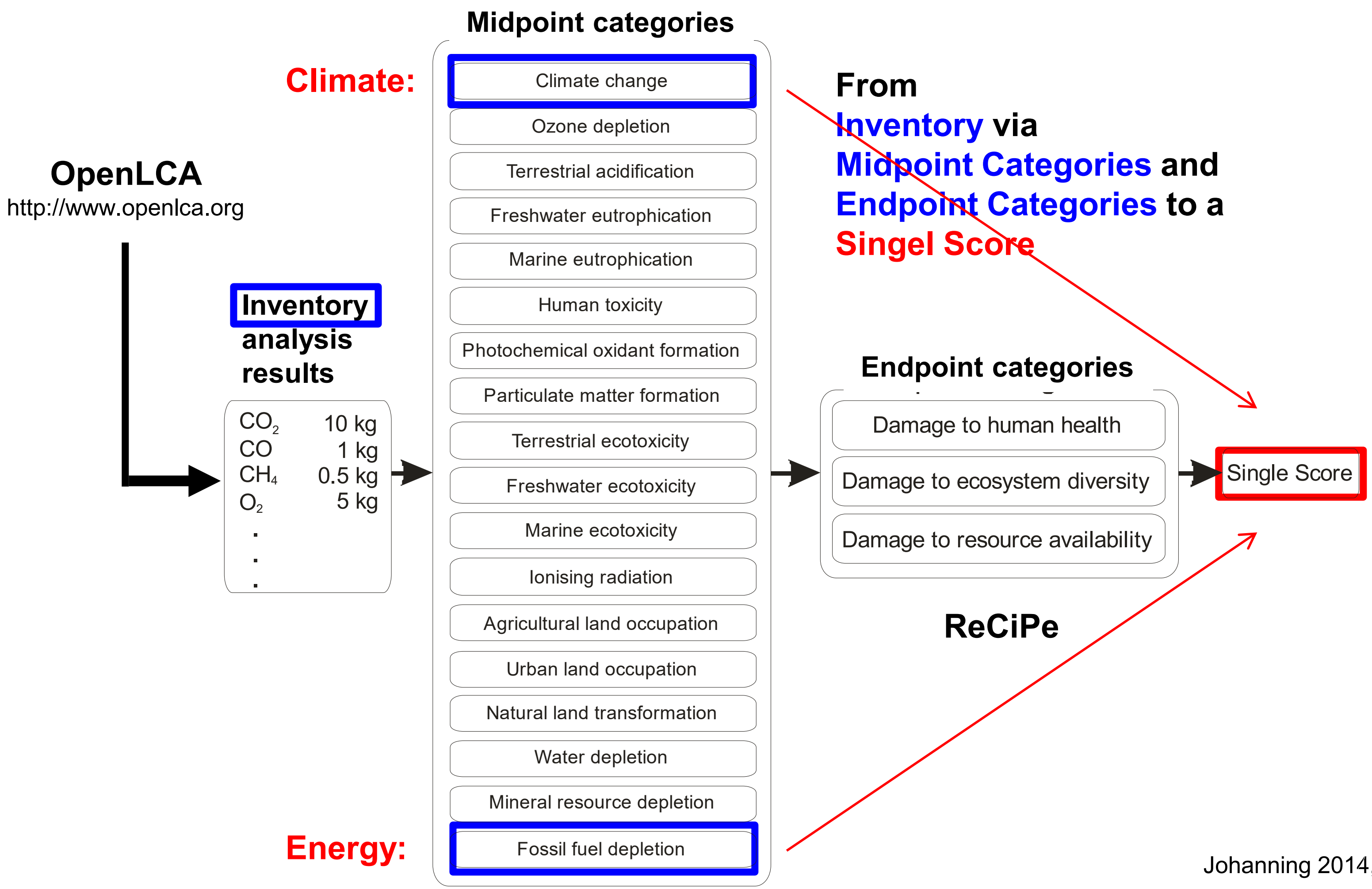


Cirrus/Contrails = 4.0

(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

Life Cycle Assessment (LCA)



Johanning 2014, 2016, 2017

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

Positive Effect for the Environment: Fly 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

Positive Effect for the Environment: Fly Lower!

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

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

  The increase of fuel consumption is mostly influenced by

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

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

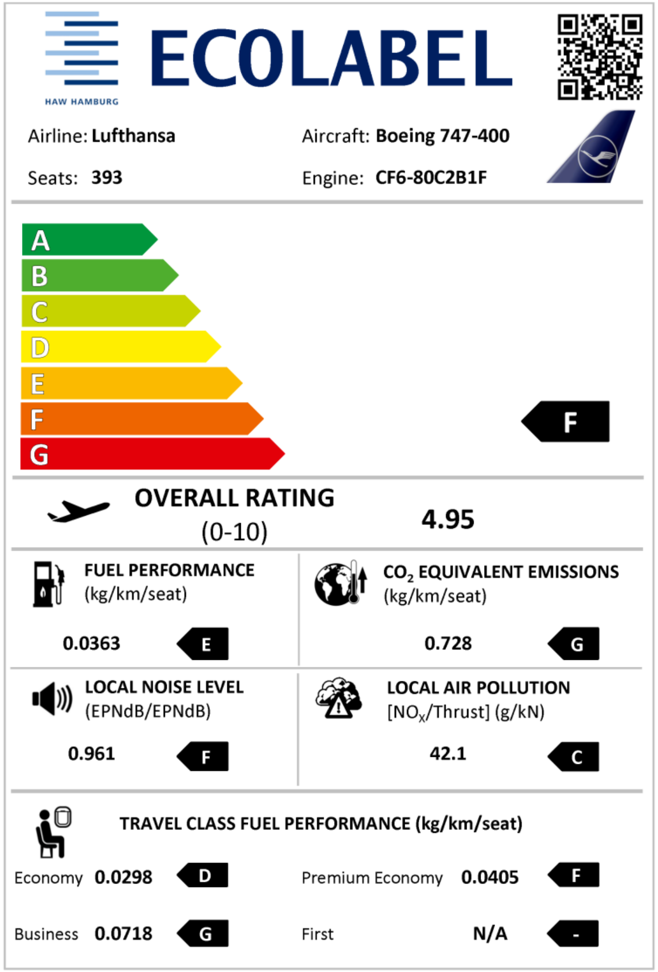
As the Mach number is kept constant, DOC are only effected by fuel consumption and increase by only 0.6%.

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

From Life Cycle Assessment to Ecolabel

Each Aircraft of an Airline gets an Ecolabel

Comparison among all Passenger Aircraft (A to G)



Fuel consumed is allocated according to used cabin floor area for each class.

http://ecolabel.ProfScholz.de

SCHOLZ, Dieter, 2017. *An Ecolabel for Aircraft*. German Aerospace Congress 2017 (DLRK 2017), Munich, Germany, 05.-07.09.2017. Available from: https://doi.org/10.5281/zenodo.4072826

New Energies, Propulsion, and Aircraft

Hydrogen (LH2)

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

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

Beware! "Zero-emission" is never possible; not for aircraft, not for animals/humans (CO2, CH4).
For details: SCHOLZ, Dieter, 2020. *Design of Hydrogen Passenger Aircraft – How much 'Zero-Emission' is Possible?*

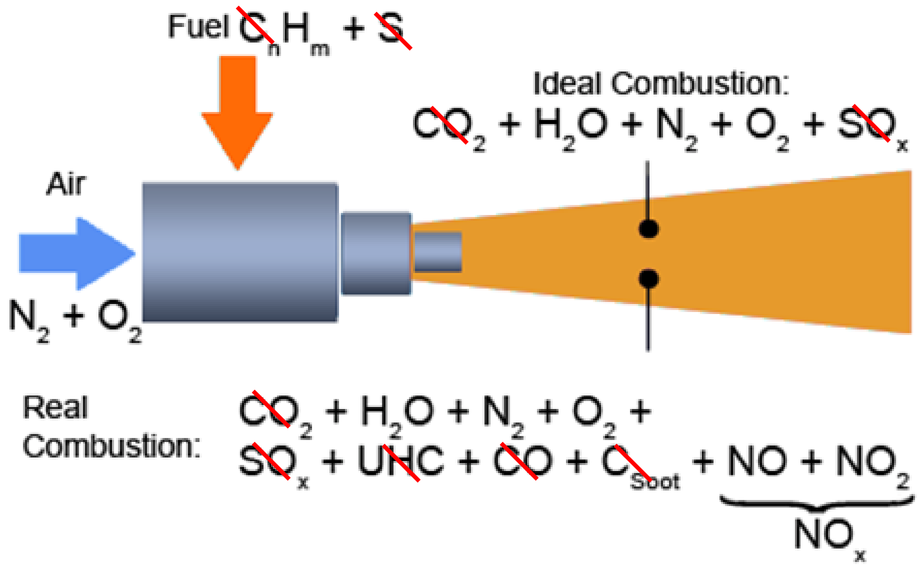
How Many Passengers Go into this Airplane (Intended for 200 Pax)?

Answer:

If you assume its the largest type door (Type A): max. 110 Pax are allowed.

If you look at the proportions of the aircraft: ≈ 20 Pax !?

Kerosene and LH2 Combustion



EI_{NOx} ↑ *m_F* ↑

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

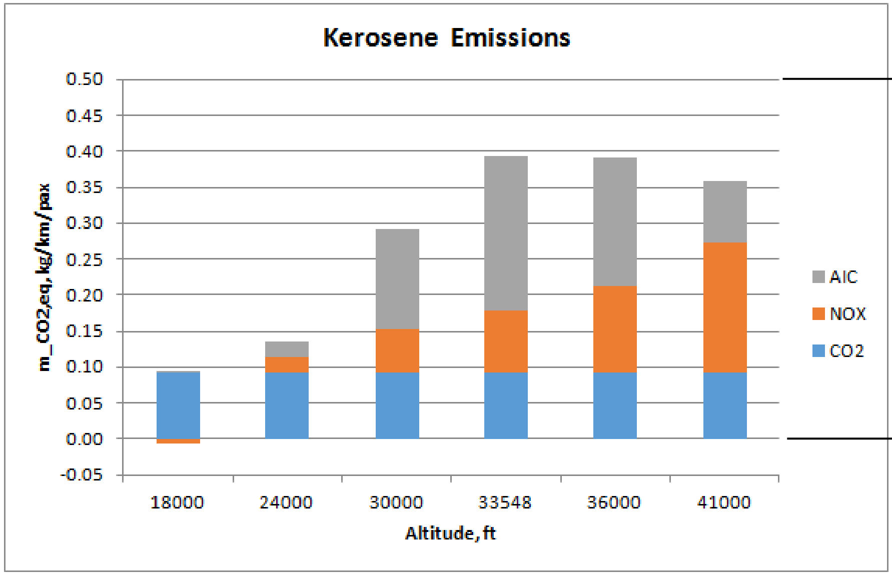
Own Fuel Calculation

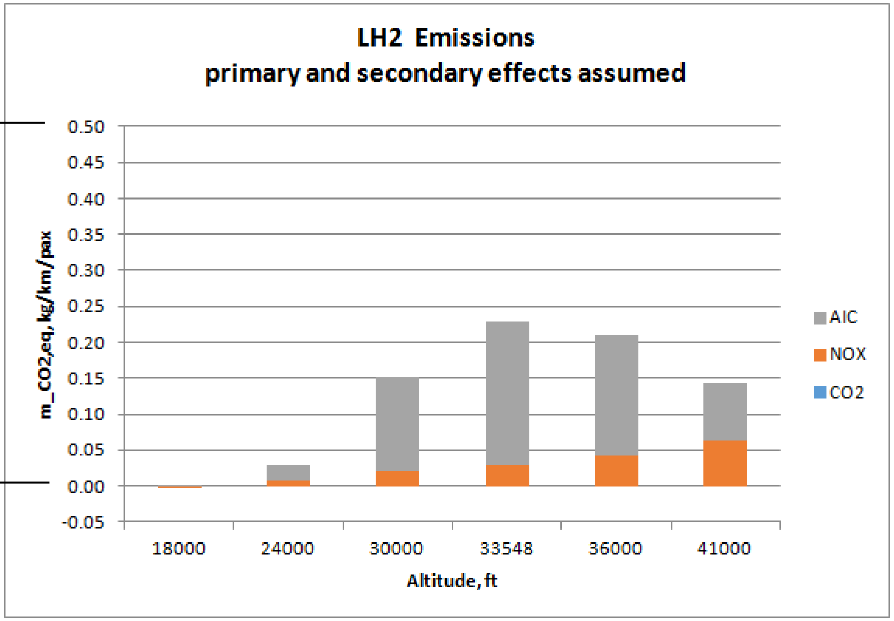
\ not included in LH2 combustion

Comparing the Emissions of Kerosene and Hydrogen Aircraft

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%





Airbus – Past Technology Timeline for Hydrogen

FlightGlobal 1995-08-30

DASA plans to fly Dornier 328 with hydrogen power in 1998

https://perma.cc/RF4R-LS8R

... but nothing happend!

Airbus – Future Technology Timeline for Hydrogen

Airbus' EU Briefing, 2021-02-09

Indicative overview of where CO_2 measures could be deployed globally

	2020	2025	2030	2035	2040	2045	2050	
Commuter » 9-50 seats » <60 minute flights » <1% of industry CO_2	SAF	Electric and/or SAF	Electric and/or SAF	Electric and/or SAF	Electric and/or SAF	Electric and/or SAF	Electric and/or SAF	~27% of CO_2 emissions
Regional » 50-100 seats » 30-90 minute flights » ~3% of industry CO_2	SAF	SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF	
Short-haul » 100-150 seats » 45-120 minute flights » ~24% of industry CO_2	SAF	SAF	SAF	SAF	Electric, hydrogen combustion and/or SAF	Electric, hydrogen combustion and/or SAF	Electric, hydrogen combustion and/or SAF	
Medium-haul » 100-250 seats » 60-150 minute flights » ~43% of industry CO_2	SAF	SAF	SAF	SAF	SAF	SAF	SAF potentially some Hydrogen	~73% of CO_2
Long-haul » 250+ seats » 150 minute + flights » ~30% of industry CO_2	SAF	SAF	SAF	SAF	SAF	SAF	SAF	

www.aviationdefenseuniverse.com AIRBUS

https://perma.cc/2G6J-76DA

Hydrogen (LH2) and SAF

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%**

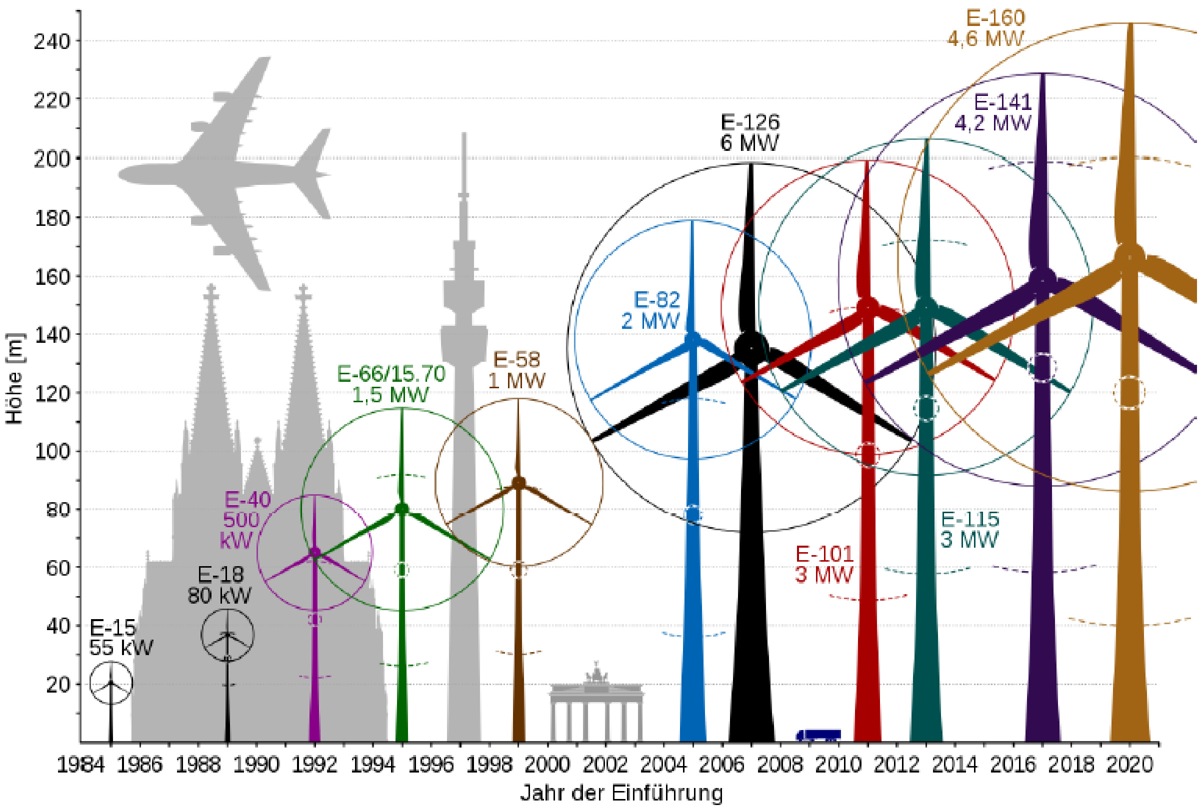
≠ 0%

Energy / Primary Energy

	Production well-to-tank %				Total efficiency %	primary energy factor
LH_2 from electrolysis and lique-faction on site	100 Renewable energy	x 70 Electrolysis	x	83 Distribution & liquefaction	= 58	1.7
Synfuel from direct air carbon capture	100 Renewable energy	x 70 Electrolysis	x 32 FT-Production	x 99 Transport & distribution	= 22	4.6

PtL needs 2.7 times more energy than LH2!

Refueling One A350 Once per Day:
52 of the Larges Wind Power Plants (4.6 MW each) Are Needed!



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%)

I 47 I © Bauhaus Luftfahrt e. V. I 11.11.2020 I Deutsches Museum // RAeS Munich Branch Willy-Messerschmitt-Lecture

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.)

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

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 needed 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.

Best Use Renewable Energy to Replace Coal Power Plants (PtL)

Substituting coal
is better by a factor of 0.9/0.057 = 15.7

The idea using PtL fuels in aviation

http://ptl.ProfScholz.de

1.

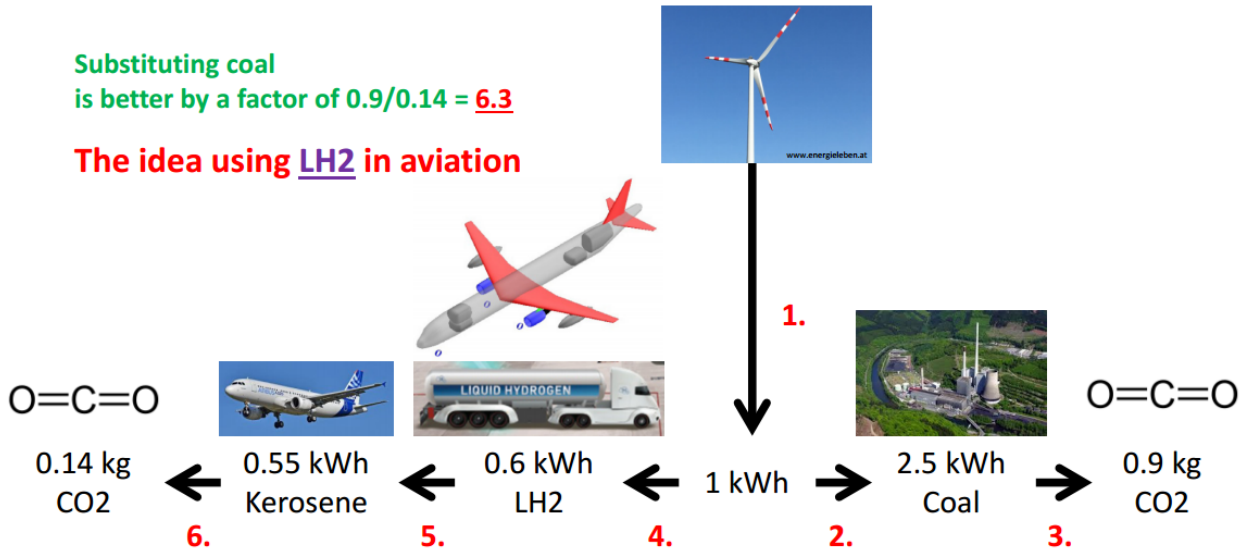
O=C=O (0.057 kg CO2) ← 5. ← 0.22 kWh PtL fuel ← 4. ← 1 kWh → 2. → 2.5 kWh Coal → 3. → 0.9 kg CO2 (O=C=O)

1.) 1 kWh of renewable energy ...
2.) ... can replace 2.5 kWh lignite in coal-fired power plants (efficiency 40%);
3.) This corresponds to 0.9 kg of CO2 (0.36 kg of CO2 for 1 kWh of energy from lignite *).
4.) ... converted into Sustainable Aviation Fuel (SAF) only 0.22 kWh remain (efficiency: 70% electrolysis, 32% Fischer-Tropsch), 99% transport; https://perma.cc/BJJ6-5L74
5.) which save only 0.057 kg of CO2 (0.26 kg of CO2 for 1 kWh of kerosene *).

* UBA, 2016: CO2 Emission Factors for Fossil Fuels. https://bit.ly/3r8avD1

Best Use Renewable Energy to Replace Coal Power Plants (LH2)

http://ptl.ProfScholz.de



1.) 1 kWh of renewable energy ...

2.) ... can substitute 2,5 kWh of coal (lignite, brown coal) in a coal power plant (efficiency of a coal power plant: 40%) this is

3.) ... equivalent to 0.9 kg CO2 (0.36 kg CO2 for 1 kWh of energy burning lignite*)

4.) ... but if used in an aircraft it generates LH2 with energy of 0.6 kWh (efficiencies: 70% electrolysis, 83% liquefaction & transport)

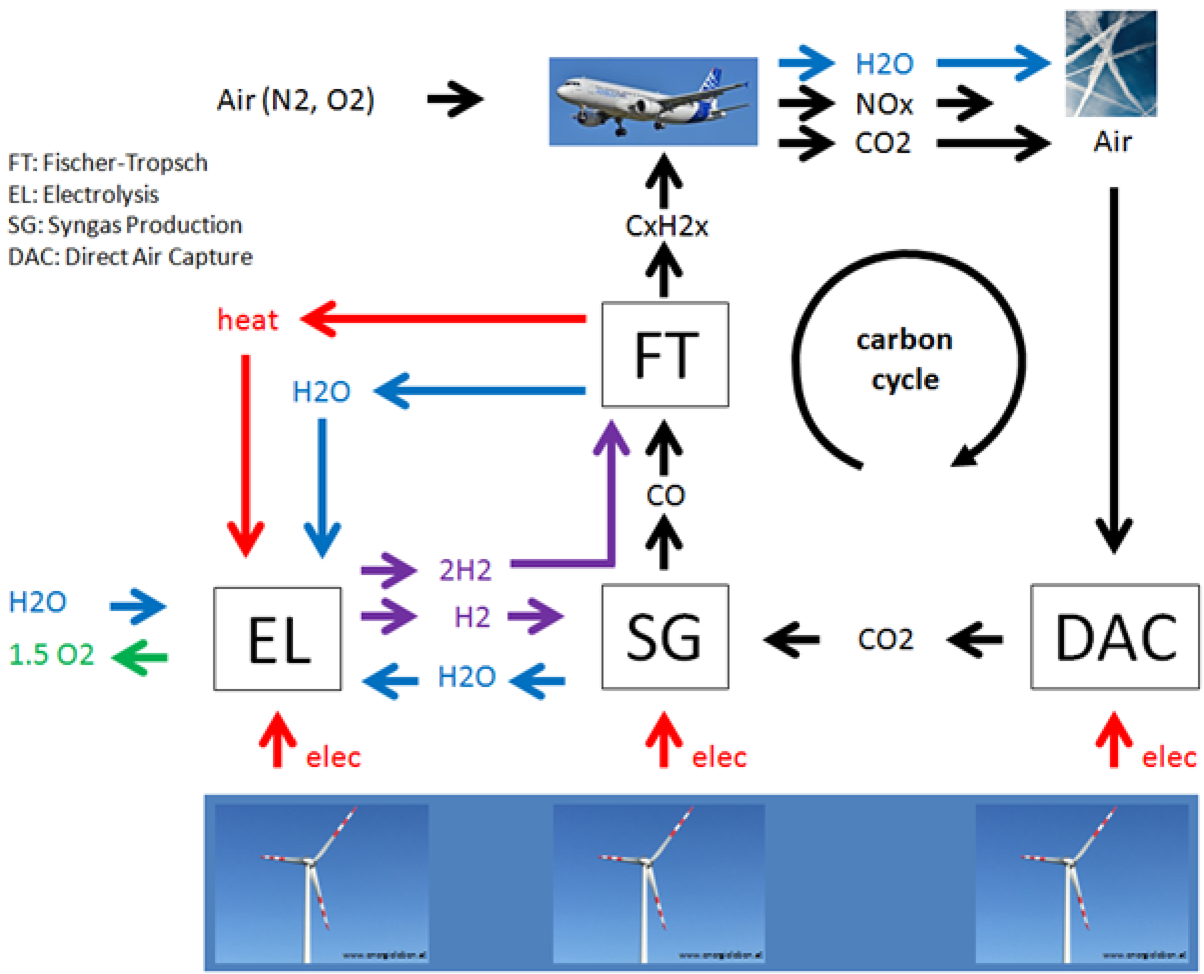
5.) LH2 aircraft consume (say) 10% more energy (higher operating empty mass, more wetted area); so a kerosene aircraft needs ...

6.) only 0.55 kWh, which can be substituted. This is equivalent to 0.14 kg CO2 (0.26 kg CO2 for 1 kWh of energy burning kerosene*).

7.) Note: Not considered is that hydrogen aircraft may come with higher non-CO2 effects than kerosene aircraft.

* UBA, 2016. CO2 Emission Factors for Fossil Fuels. Available from: https://bit.ly/3r8avD1

The Carbon Cycle (PtL)



- **SAF need DAC (Direct Air Capure) to compensate for CO2 ("cabon cycle")**
- **In addition: SAF and BioFuel need <u>more DAC</u> to compensate for the global warming effect due to**
  - **NOX and**
  - **H2O (AIC)**

Production of synthetic kerosene (e-fuel) with power-to-liquid (PtL). Taking CO_2 from the air (Direct Air Capture, DAC) enables a carbon cycle.

Electric Flight ?

Calculating Maximum Range for Battery–Electric Flight

$$e_{bat} = \frac{E_{bat}}{m_{bat}} \qquad L = W = m_{MTO}\, g \qquad E = \frac{L}{D} \qquad D = \frac{m_{MTO}\, g}{E}$$

$$P_D = D V = \frac{m_{MTO}\, g}{E} V = P_T = P_{bat}\, \eta_{prop}\, \eta_{elec} \qquad V = \frac{R}{t}$$

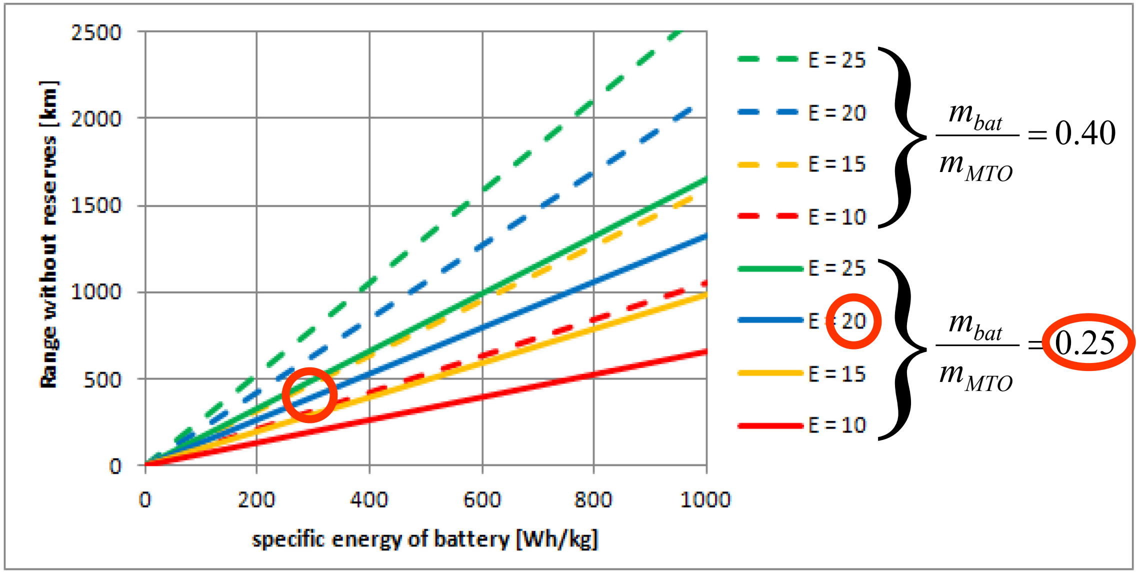
$$P_{bat} = \frac{E_{bat}}{t} = m_{bat}\, e_{bat} \frac{V}{R}$$

$$m_{bat}\, e_{bat} \frac{V}{R} \eta_{elec}\, \eta_{prop} = \frac{m_{MTO}\, g}{E} V$$

$$\boxed{R = \frac{m_{bat}}{m_{MTO}} \frac{1}{g} e_{bat}\, \eta_{elec}\, \eta_{prop}\, E}$$

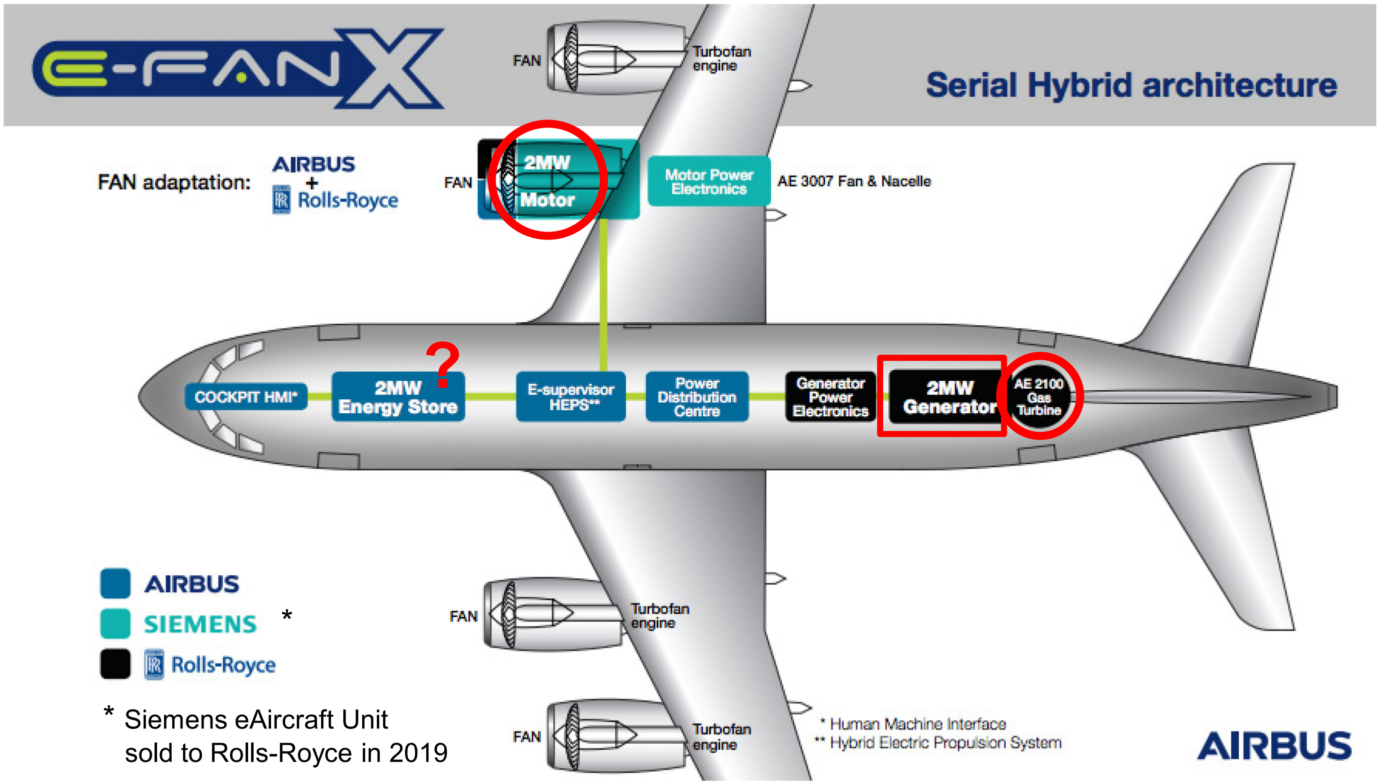
$$\eta_{elec} = 0.9; \qquad \eta_{prop} = 0.8$$

e_{bat} : specific energy
E_{bat} : energy in battery
E : glide ratio (aerodynamic efficiency)
L : lift
D : drag
W : weight
V : flight speed
R : range
t : time
g : earth acceleration
P : power
η : efficiency (prop : propeller)



○ : realistic parameters

Airbus / Rolls-Royce: E-Fan X: Hybrid–Electric Flight



- 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 Flight

https://www.airbus.com/innovation/zero-emission/electric-flight.html
Archived at: https://perma.cc/9ZPP-ULRS
https://www.airbus.com/newsroom/stories/our-decarbonisation-journey-continues.html
Archived at: https://perma.cc/CPS5-RB94

For more on hybrid-electric flight see Bibliography:

SCHOLZ 2018, https://doi.org/10.15488/3986
SCHOLZ 2019, https://doi.org/10.5281/zenodo.3265212
SCHOLZ 2019, https://doi.org/10.5281/zenodo.4072283

Savings due to a Large Number of (Electric) Engines? – Climb OEI: sin γ

CS 25.121 Climb: one-engine-inoperative

(b) *Take-off; **landing gear retracted**.*

In the take-off configuration existing at the point of the flight path at which the landing gear is fully retracted, ... the **steady gradient of climb** may **not be less than**

sin γ ↓

2.4% for **two-engined** aeroplanes,

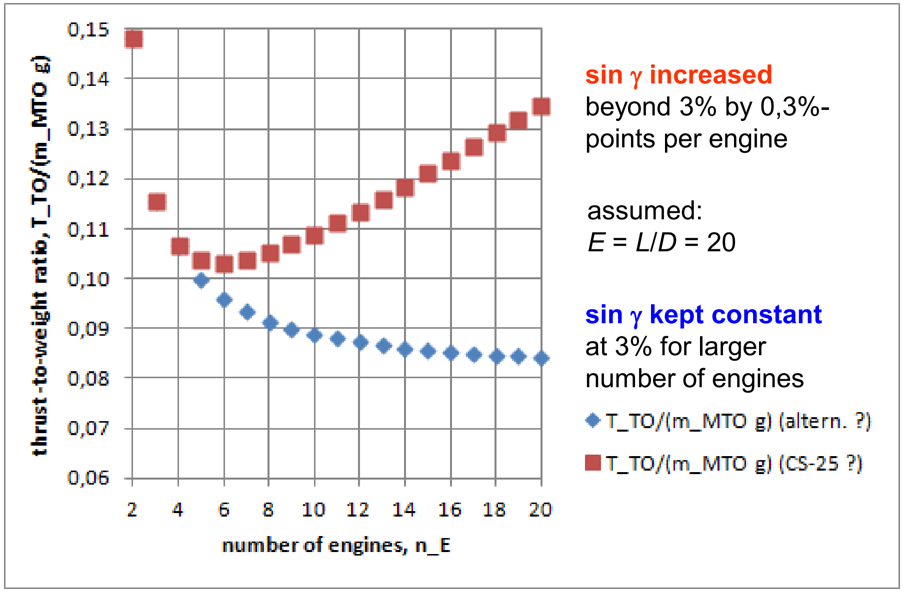
2.7% for **three-engined** aeroplanes and

3.0% for **four-engined** aeroplanes,

at V2 and with -

(1) The critical engine inoperative and the remaining engines at the available maximum continuous power or thrust

$$\frac{T_{TO}}{m_{MTO}\cdot g} = \left(\frac{n_E}{n_E-1}\right)\cdot\left(\frac{1}{E}+\sin\gamma\right)$$



- It depends on the required climb gradient, **sin γ**.
- It is not defined today, how a One-Engine-Inoperative (OEI) climb is treated by CS-25 with respect to sin γ.
- Many engines could also lead to increased thrust requirements!?

T_{TO} : Take – Off thrust

m_{MTO} : Maximum Take – Off mass

g : earth acceleration

n_E : number of engines

$\sin\gamma$: climb gradient

Savings due to a Large Number of (Electric) Engines? – One Engine Inop or More?

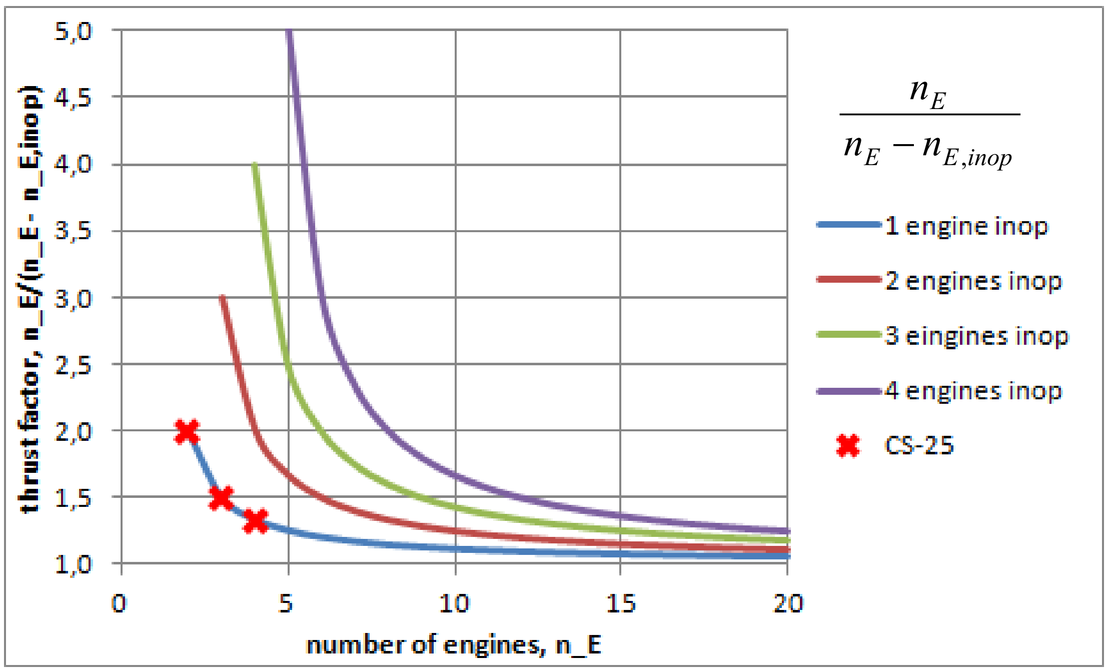
CS 25.107 Take-off speeds

(a)(1) V_{EF} is the calibrated airspeed at which **the [one]** critical engine is assumed to fail.

CS 25.109 Accelerate-stop distance

(a)(1)(ii) Allow the aeroplane to accelerate ... assuming **the [one]** critical engine fails at V_{EF}

CS 25.121 Climb: one-engine-inoperative



$$\frac{T_{TO}}{m_{MTO} \cdot g} = \left(\frac{n_E}{n_E - 1}\right) \cdot \left(\frac{1}{E} + \sin\gamma\right)$$

general thrust factor: $\frac{n_E}{n_E - n_{E,inop}}$

- For a design with very many engines n_E, EASA / FAA could re-define the thrust factor.
- The number of engines assumed inoperative $n_{E,inop}$ could be increased:
  $n_{E,inop} > 1$, for larger n_E
- 4 engines with 1 failed need a thrust factor of 1.33. 20 engines with 4 failed need a thrust factor of 1.25 – only slightly less. However, probability for 4 engines failed from 20 is very low.
- Applied, this could reduce the advantage of many engines.

An Infinite Number of Engines Reduces the Propeller Area to Zero!

The more propellers are put on the wing the smaller their diameter. As the number of propellers goes to infinity the propeller area is only a line on the wing and the propeller area goes to zero.

To maximize the total propeller area, an optimum number of propellers may be 4.

Rolls-Royce (NAS 2016)

Flying Less !

Le Monde

To log in

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Sharing

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

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

Google translation of French webpage.

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

Largest Reduction of Emissions in Aviation History from the Corona–Pandemic

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

STAY GROUNDED

Traffic reduction is more efficient than technology

https://stay-grounded.org

Saving the World Starts in Our Mind: Video "The Bill"

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

The video may make you think about how we live and what (how much flying) we really need.

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

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

Summary

Summary

- Urban Air Mobility is for the rich. No benefit to the environment. No reduction of congestion.
- Short Range is for the train.
- Medium Range between Megacities is for the train.
- For other Medium Range operation: Propeller aircraft with smart design. Hydrogen could be used.
- Long Range: Drop-in fuel from renewable energy (SAF, E-Fuel), but: high primary energy needs. Hydrogen possible, but inefficient aircraft design.
- Published fuel consumption and an ecolabel for all aircraft would be beneficial.
- Decisions should be based on a Life Cycle Analysis (LCA).
- Aviation has a water problem (AIC). Less so a CO2 problem.
- But: CO2 dominates in the long run.
- Flying lower has substancial environmental benefits. Similar other options exist.
- Battery-electric flight only works on short range (where it is generally not needed).
- Hybrid-electric flight has no advantages for passenger aircraft.
- Burning hydrogen has the same radiative forcing like kerosene, but avoids the accumulation of CO2.
- Aviation to the extend as today (2019) may face problems to be supplied with renewable energy. Aviation must not use renewable energy already allocated for other use (e.g. the substitution of coal power plants).
- Flying less needs to be considered.

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Bibliography / Literature

Cryoplane: Reports, Licentiate, Paper

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

SCHOLZ, Dieter; SEECKT, Kolja, 2010: *Schlussbericht - FH3-Projekt "Grüner Frachter"*. HAW Hamburg, Department F&F, AERO. Berichts-Nr.: GF_WT0.1_AB. Download: http://GF.ProfScholz.de

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

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

SEECKT, Kolja, HEINZE, Wolfgang, SCHOLZ, Dieter, 2008. The Green Freighter Project – Objectives and First Results. In: *CD Proceedings: ICAS 2008 - 26th Congress of the International Council of the Aeronautical Sciences including the 8th AIAA Aviation Technoloy, Integration, and Operations (ATIO) Conference* (Anchorage, Alaska, USA, 14.-19.09.2008). Edinburgh, UK: Optimage Ltd. Paper: ICAS 2008-4.10.3. Download: http://GF.ProfScholz.de

SEECKT, Kolja, SCHOLZ, Dieter, 2009. Jet versus Prop, Hydrogen versus Kerosene for a Regional Freighter Aircraft. In: DGLR: *Deutscher Luft- und Raumfahrtkongress 2009 : Tagungsband - Ausgewählte Manuskripte* (DLRK, Aachen, 08.-10.09.2009). Download: http://GF.ProfScholz.de

HEINZE, W., HANSEN, L.-U., WERNER-SPATZ, C., HORST, P., 2009. *Gesamtentwurfsuntersuchungen zu BWB-Frachtflugzeugen mit alternativen Treibstoffen* (Deutscher Luft- und Raumfahrtkongress, Aachen, 08.-10.09.2009). Download: http://GF.ProfScholz.de

SEECKT, Kolja, SCHOLZ, Dieter, 2010. Application of the Aircraft Preliminary Sizing Tool PreSTo to Kerosene and Liquid Hydrogen Fueled Regional Freighter Aircraft. In: DGLR: *Deutscher Luft- und Raumfahrtkongress 2010: Tagungsband - Ausgewählte Manuskripte* (DLRK, Hamburg, 31.08.-02.09.2010). Download: http://GF.ProfScholz.de

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.-24.09.2015. Available from: https://doi.org/10.5281/zenodo.4073172

DIB, Leon, 2015. *The Aviation Fuel and the Passenger Aircraft for the Future – Hydrogen*. Master Thesis. HAW Hamburg. Available from: http://Library.ProfScholz.de

SCHOLZ, Dieter, 2020. *Design of Hydrogen Passenger Aircraft – How much 'Zero-Emission' is Possible?* Hamburg Aerospace Lecture Series, HAW Hamburg (online), 19.11.2020. Available from: https://doi.org/10.5281/zenodo.4301104

Green Aviation and Aviation Ethics

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

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)

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

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

Evaluation of Aircraft Configurations

SCHOLZ, Dieter, 2006. Die Blended Wing Body Flugzeugkonfiguration. Hamburg Aerospace Lecture Series, 2006-09-28. Available from: https://bit.ly/3leyyMr (PDF)

JOHANNING, Andreas, SCHOLZ, Dieter, 2012. Novel Low-Flying Propeller-Driven Aircraft Concept For Reduced Direct Operating Costs And Emissions. In: *CD Proceedings: ICAS 2012 - 28th Congress of the International Council of the Aeronautical Sciences* (ICAS, Brisbane, 23.-28.09.2012). Edinburgh, UK: Optimage Ltd, 2012. Paper: ICAS2012-1.10.5. Download: http://Airport2030.ProfScholz.de

SCHOLZ, Dieter, JOHANNING, Andreas, 2014. *Smart Turboprop – A Possible A320 Successor*. 4th Symposium on Collaboration in Aircraft Design (25.-27.11.2014, Toulouse, France). Presentation. Download: http://Airport2030.ProfScholz.de

JOHANNING, Andreas, SCHOLZ, Dieter, 2014. *Airport2030, AP4.1: Evolutionäre Flugzeugkonfigurationen - Schlussbericht*. HAW Hamburg, Department F&F, AERO. Berichts-Nr.: Airport2030_AB_Schlussbericht. Download: http://Airport2030.ProfScholz.de

Hybrid-Electric Aircraft

SCHOLZ, Dieter, 2018. Evaluating Aircraft with Electric and Hybrid Propulsion. In: *UKIP Media & Events: Conference Proceedings : Electric & Hybrid Aerospace Symposium 2018* (Cologne, 08.-09.11.2018). Available from: https://doi.org/10.15488/3986. Available from: http://EHA2018.ProfScholz.de (PDF)

SCHOLZ, Dieter, 2019. *Electric and Hybrid Aviation – From Media Hype to Flight Physics*. Hamburg Aerospace Lecture Series, 2019-04-25. Available from: https://doi.org/10.5281/zenodo.3265212

SCHOLZ, Dieter, 2019. *Limits to Principles of Electric Flight*. German Aerospace Congress 2019 (DLRK 2019), Darmstadt, 30.09.-02.10.2019. Available from:https://doi.org/10.5281/zenodo.4072283

Life Cycle Analysis (LCA): Dissertation, Paper

JOHANNING, Andreas, 2017. *Methodik zur Ökobilanzierung im Flugzeugvorentwurf*. München: Verlag Dr. Hut. Dissertation. ISBN 978-3-8439-3179-3. Download: http://Airport2030.ProfScholz.de

JOHANNING, Andreas, 2016: *Life Cycle Assessment in Conceptual Aircraft Design – Excel Tool LCA-AD*. Available from: http://doi.org/10.13140/RG.2.1.1531.0485

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

JOHANNING, Andreas; SCHOLZ, Dieter, 2014. Conceptual Aircraft Design Based on Lifecycle Assessment. In: *ICAS 2014 - 29th Congress of the International Council of the Aeronautical Sciences* (St. Petersburg, 07.-12.09.2014). Paper: ICAS2014-9.10.1. Download: http://Airport2030.ProfScholz.de

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

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

Environmental Impact

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

SCHWARTZ DALLARA, Emily, 2011. *Aircraft Design for Reduced Climate Impact*. Dissertation. Stanford University. Available from: http://purl.stanford.edu/yf499mg3300 – Forcing Factor s(h) based on: KÖHLER 2008 and RÄDEL 2008.

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

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

SCHOLZ, Dieter, 2020. *Calculation of the Emission Characteristics of Aircraft Kerosene and Hydrogen Propulsion*. Excel table. Available from: https://doi.org/10.7910/DVN/DLJUUK

Aircraft Design

SCHOLZ, Dieter, 2015: *Aircraft Design*, 2015. Lecture notes and more as part of "Hamburg Open Online University (HOOU)". Webpage: http://HOOU.ProfScholz.de

DOC

SCHOLZ, Dieter, THORBECK, Jürgen, 2013. *TU Berlin DOC Method*. 3rd SCAD - Symposium on Collaboration in Aircraft Design, (Linköping University, 19.-20.09.2013). Hamburg: AERO, 2013. – Download: http://reports-at-aero.ProfScholz.de, http://www.fzt.haw-hamburg.de/pers/Scholz/Aero/TU-Berlin_DOC-Method_with_remarks_13-09-19.pdf

Further References

CALDWELL, Niall, 2018. Digital Displacement: Hydraulic Power for the Digital Age. In: UKIP Media & Events: *Conference Proceedings : Electric & Hybrid Aerospace Symposium 2018* (Cologne, 08.-09. November 2018)

CANNON, Frank, 2016. Aircraft Cabin Air Contamination and Aerotoxic Syndrome – A Review of the Evidence. In: Collegium Basilea: *Nanotechnology Perceptions*, Vol. 12 (2016), pp. 73-99. Available from: https://doi.org/10.4024/N08CA16A.ntp.12.02. Download: URL: http://skybrary.aero/bookshelf/books/3594.pdf

SUN, X., ZHANG, Y., WANDELT, S., 2017. Air Transport versus High-Speed Rail – An Overview and Research Agenda. In: *Journal of Advanced Transportation*, Vol. 2017, Article ID 8426926. Available form: https://doi.org/10.1155/2017/8426926