

AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

Luftverkehr: Energie, Klima, Technik

- Urban Aviation / Kurz- / Mittel- / Langstrecke
- Neue Energien, Antriebe und Flugzeuge

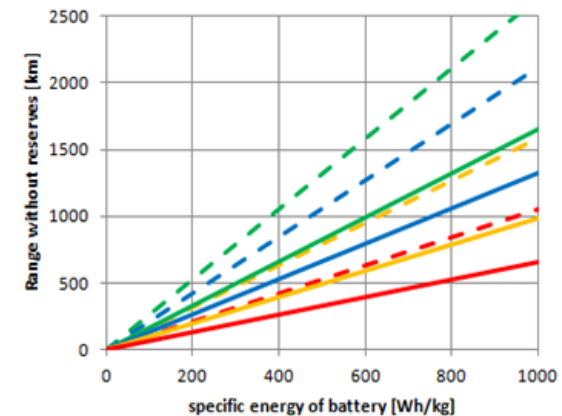
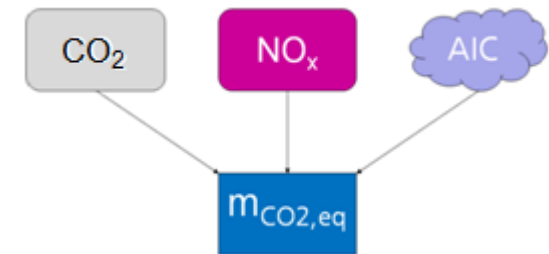
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Grüner Fachworkshop zum Thema Luftverkehr

Online, 05.12.2020, 13:00 – 17:00

<https://doi.org/10.5281/zenodo.4312988>



Abstract / Kurzreferat (Seite 1 von 2)

Zweck – Basierend auf wissenschaftlichen Grundlagen liefert der Vortrag einen Überblick hinsichtlich einsetzbarer Energien und deren Klimawirkung abhängig von der Technik heutiger und zukünftiger Fluggeräte und deren Antriebssysteme. Dabei werden die Einsatzgebiete der Fluggeräte unterschieden in Urban Aviation, Kurz-, Mittel- und Langstrecke. Ein Vergleich mit anderen Verkehrsträgern wird angedeutet.

Methodik – Der Vortrag basiert auf den Forschungsergebnissen und Literaturstudien des Autors in den letzten mehr als 15 Jahren.

Ergebnisse – Urban Air Mobility ist für die Reichen, bietet keine Vorteile für die Umwelt und ändert nichts an den Staus in der Stadt. Kurzstrecken sollten mit der Bahn zurückgelegt werden. Für Mittelstrecken zwischen Megacities bieten Hochgeschwindigkeitszüge viele Vorteile. Ansonst könnten neu entworfene Propellerflugzeuge in intelligenter Auslegung, evtl. mit Wasserstoff, deutliche Vorteile bringen hinsichtlich Ökonomie und Ökologie – insbesondere wenn diese auslegungsbedingt tiefer und evtl. auch langsamer fliegen. Wir haben in der Luftfahrt weniger ein CO₂-Problem als mehr ein Wasserproblem (Aviation-Induced Cloudiness, AIC). Letzteres kann durch tieferes Fliegen vermieden werden. Jedoch: CO₂ setzt sich auf lange Zeiten durch. Auf der Langstrecke bieten sich Drop-In-Kraftstoffe aus erneuerbaren Energien (PtL-Kraftstoffe) an, weil LH₂-basierte Flugzeuge mit zunehmender Reichweite weniger effizient werden aufgrund der großen Kraftstofftanks. Drop-In-Kraftstoffe können für existierende Flugzeug eingesetzt werden und gehen das Klimaproblem daher Jahrzehnte früher an als LH₂-Lösungen. Aber: PtL-Kraftstoffe erfordern einen ca. 2,7-fach höheren Primärenergieeinsatz. Wichtig ist es daher, PtL und LH₂ parallel einzuführen. Batterie-elektrisches Fliegen geht nur auf Kurzstrecke, wo es nicht benötigt wird. Hybrid-elektrisches Fliegen hat keine technischen Vorteile für Passagierflugzeuge. Die höhere Effizienz der sogenannten Billigfluggesellschaften hinsichtlich Kraftstoffverbrauch und Umweltwirkung pro Passagierkilometer ist anzuerkennen. Wenn geringerer Verbrauch zu günstigeren Tickets führt, kann sich der freie Wettbewerb sogar positiv auf umweltfreundlicheres Fliegen auswirken. Da es durch den Rebound-Effekt aber zu einer Verbrauchssteigerung kommt, muss objektiv über die Umweltwirkung der Luftfahrt informiert und gegengesteuert werden. Graswurzelbewegung (Flugscham, Stay Grounded) sind ausdrücklich zu unterstützen. Die Luftfahrt wie sie heute (2019) existiert(e) kann mit regenerativen Energien nicht versorgt werden. (*Fortsetzung auf nächster Seite*)

Abstract / Kurzreferat (Seite 2 von 2)

Daher kann eine grundlegende Problemlösung nur gelingen, wenn weniger geflogen wird. Hier kann auf den Tatsachen aufgebaut werden, die durch COVID-19 geschaffen wurden. Beim Umbau der Luftverkehrswirtschaft müssen die Arbeitnehmer mitgenommen werden. Genauso wie es zu einer Verlagerung der Verkehrsströme auf umweltfreundlichere Verkehrsträger kommt, kann auch ein Wechsel der Arbeitsplätze beobachtet werden. Wir haben in Zukunft nicht weniger Aufgaben, sondern andere Aufgaben. Finanzielle Begünstigungen des Luftverkehrs gegenüber anderen Verkehrsträgern müssen abgebaut werden. In der Luftfahrtforschung sollte nur noch das gefördert werden, was vorab über eine Ökobilanz seine Sinnfälligkeit gezeigt hat. Darüber hinaus sollte der gesellschaftliche und ökonomische Nutzen sichtbar werden (Socio-Eco-Efficiency). Statt Milliarden Euros an Runden Tischen bei unklaren Kriterien ("alte Stinker") zu verschieben, brauchen wir einen öffentlichen Diskurs über schwergewichtige Entscheidungen im Luftverkehr. Nur ein solches transparentes Vorgehen wird dem Anspruch an unsere Demokratie gerecht. Dazu müssen Parameter der Luftfahrt und der Flugzeuge offen gelegt werden. So ein Vorgehen beginnt bei einer abgestimmten Definition zum Kraftstoffverbrauch von Flugzeugen und könnte z. B. auf ein Ökolabel für Flugzeuge ausgedehnt werden. Die Industrie sollte verpflichtet werden, entsprechende Basisangaben zu machen. Die didaktische Aufarbeitung kann durch die Wissenschaft erfolgen (notfalls auch ohne Hilfe durch die Industrie). Die Digitalisierung ist in der Luftfahrt genauso wichtig wie in anderen Bereichen, stellt aber in der Luftfahrt keine Besonderheit dar.

Soziale Bedeutung – Bei den Themen "Kabinenbelüftung und SARS-CoV-2" sowie "Zero Emission" konnte eine ethisch unhaltbare Art der Beeinflussung der Bevölkerung durch die Luftverkehrswirtschaft bei gleichzeitiger Unterstützung durch die Regierung beobachtet werden. Die Verbreitung von unwahren Behauptungen steht in Deutschland nicht unter Strafe, sollte aber nicht von der Regierung praktiziert werden und nicht durch finanzielle Zuwendungen belohnt werden. Hier bedarf es dringend einer Kehrtwende. Ein Beispiel dazu: Die Ausbildung durch die Hochschule von Ingenieur*innen im Flugzeugbau für die Industrie wird schwierig, wenn sich die Hochschullehre von den "alternativen Fakten" der Industrie unterscheidet.

Inhalt

- **Einleitung: Corona und Fliegen / Kontaminierte Kabinenluft**
- **Urban Aviation / Kurz- / Mittel- / Langstrecke**
- **Neue Energien, Antriebe und Flugzeuge**
- **Digitalisierung in der Luftfahrt**
- **Zusammenfassung**
- Kontakt / Zitieren
- Bibliographie / Literaturhinweise
- Backup / Ergänzungen

Einleitung

Corona und Fliegen

<http://Corona.ProfScholz.de>

Luftfahrtindustrie lügt beim Thema "Kabinenbelüftung" während der Corona-Pandemie



What?

false statement (lie) of the aviation industry

Short form of the lie (in German)

air in the plane

"as clean as in an operating room" (through HEPA filter)

Operationssaal

air exchange

"COMPLETE in 2 to 3 minutes"

Frischluftquote *

air flow in the aircraft cabin

"only from top to bottom" or "no horizontal flows"

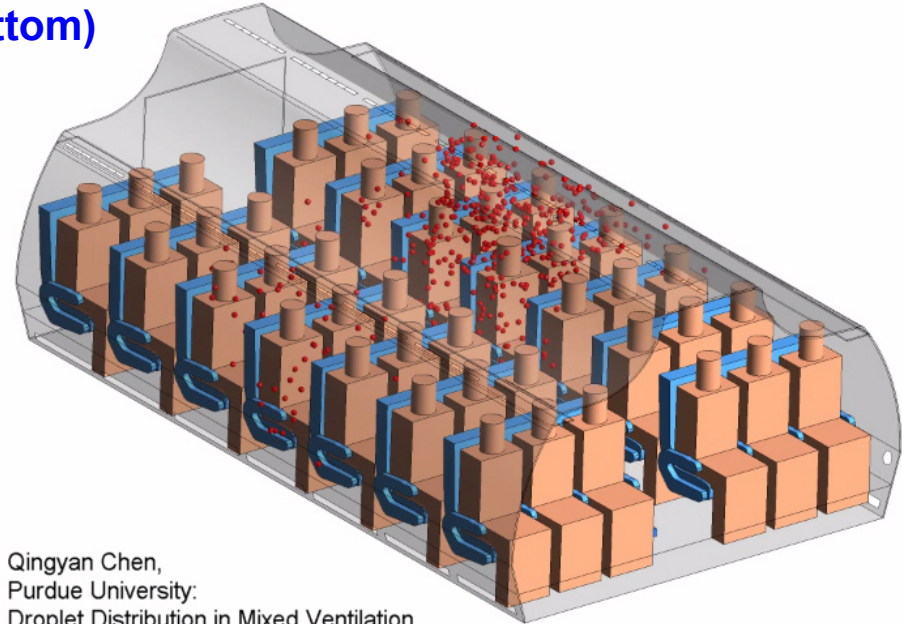
Klimavorhang *

* A. Scheuer, BMVI, <https://youtu.be/tGXNK9Y40AQ>

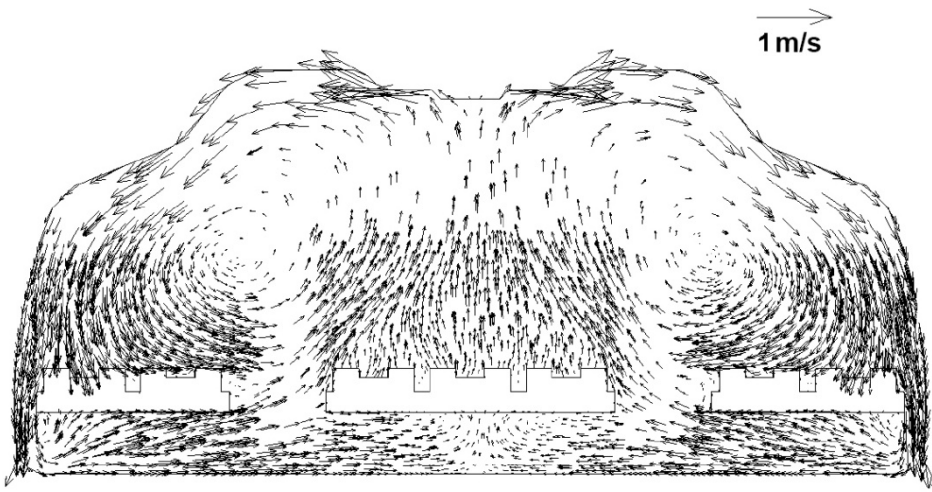
Lufftfahrtindustrie lügt beim Thema "Kabinenbelüftung" während der Corona-Pandemie

"Klimavorhang" (flow only from top to bottom)

The air conditioning system forms **circulation patterns** of the air and helps to distribute droplets among **several rows** in the aircraft cabin!



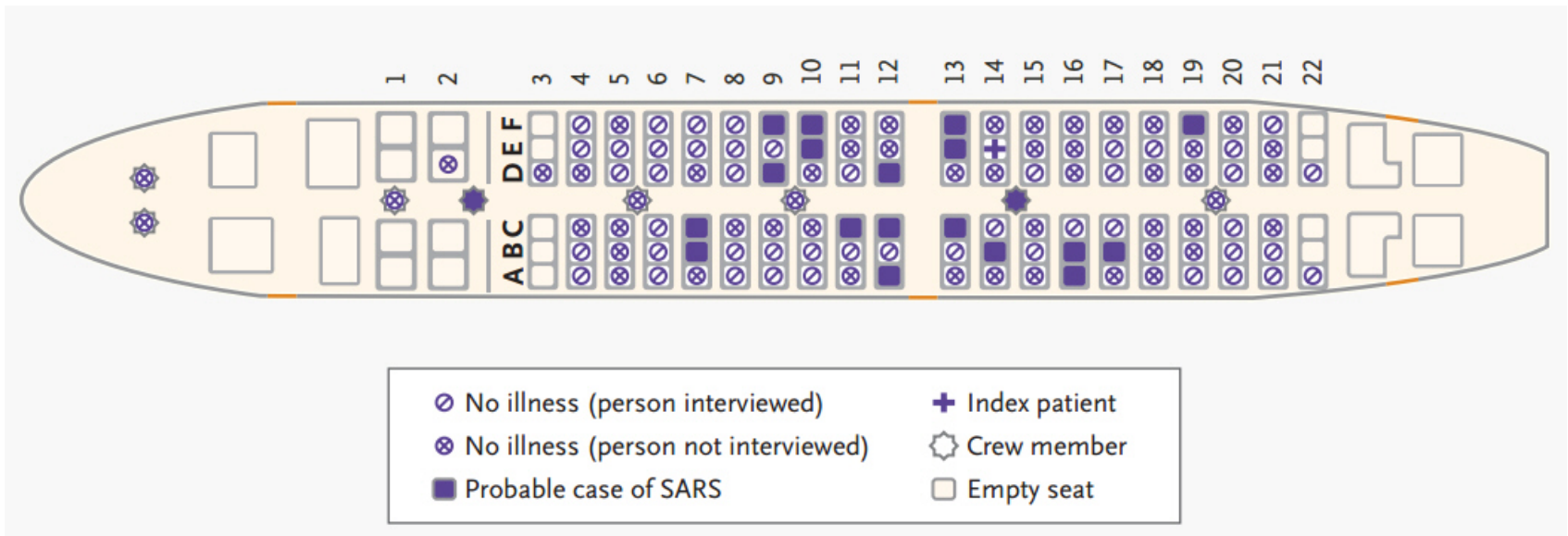
Qingyan Chen,
Purdue University:
Droplet Distribution in Mixed Ventilation



Aerosols are further distributed along the **length of the cabin** by turbulence, diffusion, and movement of persons in the cabin!

<http://purl.org/corona/N2020-06-17>

Ansteckung ist in der ganzen Kabine möglich



Boeing 737-300 auf dem Flug von Hong Kong nach Peking über 3 Stunden.
 "Index patient" ist die erkrankte Person auf Sitz 14E.

<https://doi.org/10.1056/NEJMoa031349>

Hohes Risiko der Ansteckung:

Viele Menschen zusammen
Menschen **dicht** zusammen
Über **lange Zeit** zusammen
Geringe **Belüftung** des Raumes

im Flugzeug?

ja

ja

ja

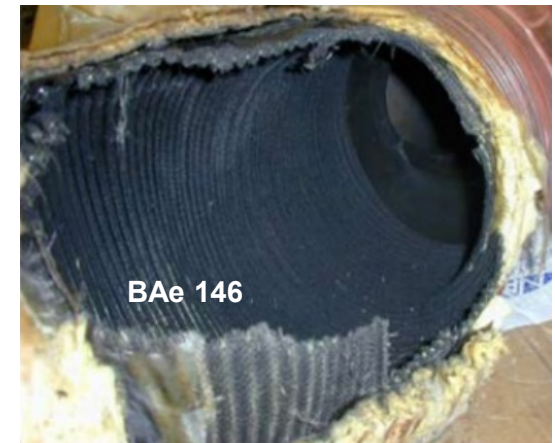
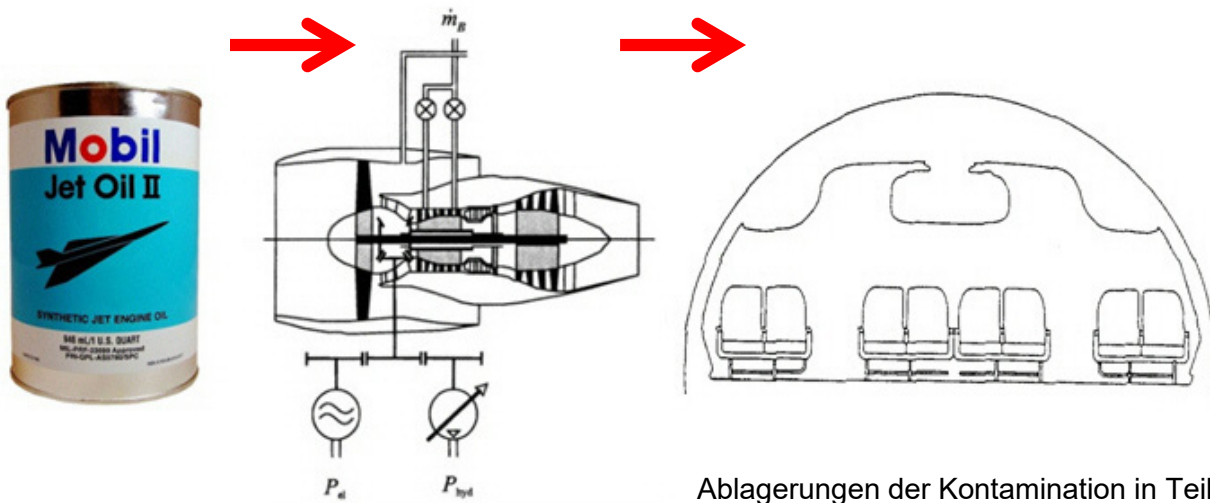
nein,

aber Situation ist problematisch

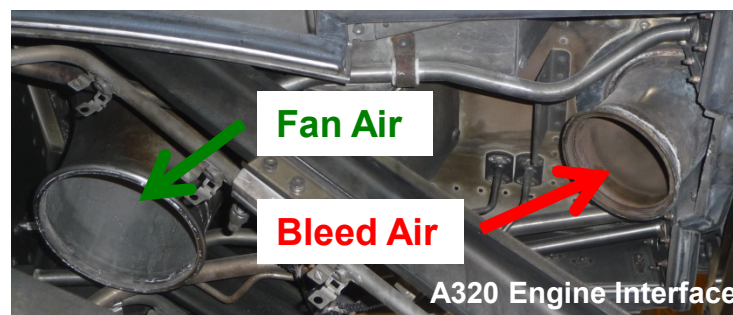
SCHOLZ, Dieter, 2020. *Sommer 2020, COVID-19, Fliegen: ja oder nein? Vorsicht: Gesundheitsrisiko und unklare Rechtslage!* Pressemitteilung.
Available from: <http://purl.org/corona/PR2020-06-05>

Kontaminierte Kabinenluft

<http://CabinAir.ProfScholz.de>



Ablagerungen der Kontamination in Teilen der Klima- und Zapfluftanlage an Bord.



warning:

contains **TCP**
tricresylphosphate.

Swallowing this product
 can cause nervous
 system disorders,
 including paralysis.
 Prolonged breathing of oil
mist, or prolonged or
repeated skin contact can
cause nervous system
effects.



Urban Aviation

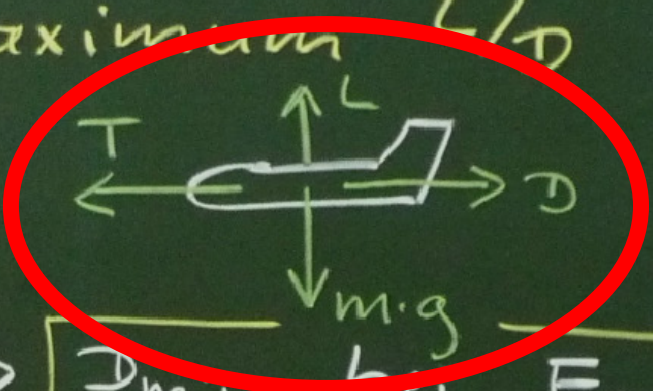
Kurz- / Mittel- / Langstrecke

Grundlagen

Aus der Vorlesung

drag D_{min} and der
 Gleitzahl maximum L/D E_{max}

Horizontalflug

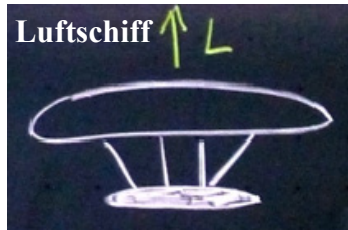


$D = \frac{L}{E} = \frac{m \cdot g}{E} \Rightarrow \boxed{D_{min} \text{ bei } E_{max}}$

$\frac{C_L}{C_D + C_L^2}$ also: $E = f(C_L)$

Kraftaufwand, um ein Fahrzeug während Fahrt bzw. Flug hoch zu halten, D_i

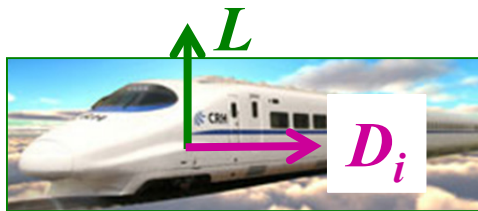
Fahrzeug ist widerstandsärmer



$$D_i = L / \infty = 0$$

$$D = D_0 + D_i$$

↑ Kraft, um Fahrzeug durch die Luft zu schieben

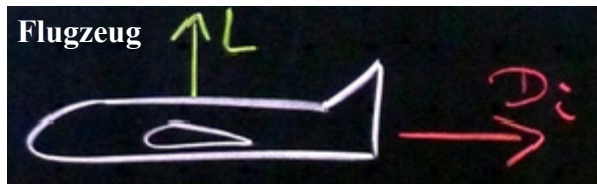


$$D_i = L / 700$$



$D_i = L / 70$: Auto auf Asphalt

$D_i = L / 20$: Auto auf Sand



$$D_i = L / 40$$



Hubschrauber

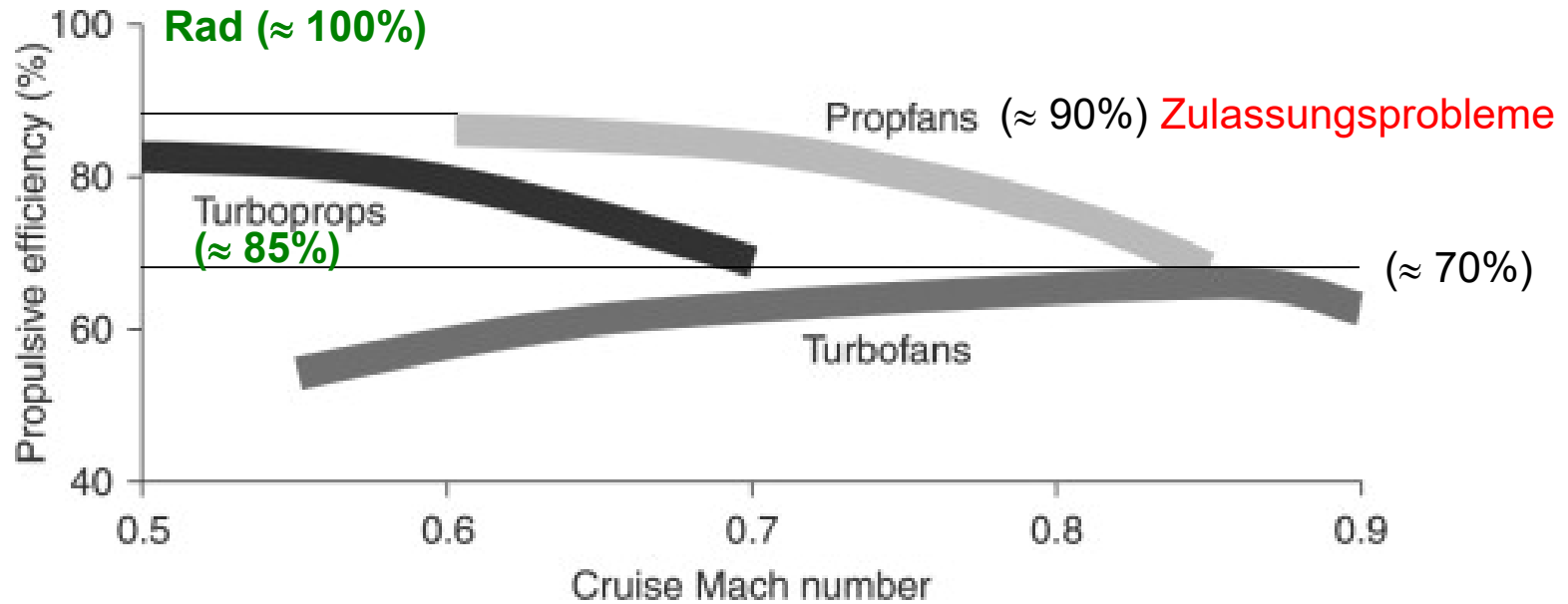
$$D_i = T = L / 1$$

D_i = induzierter Widerstand (Drag)

L = Auftrieb (Lift) = Gewicht

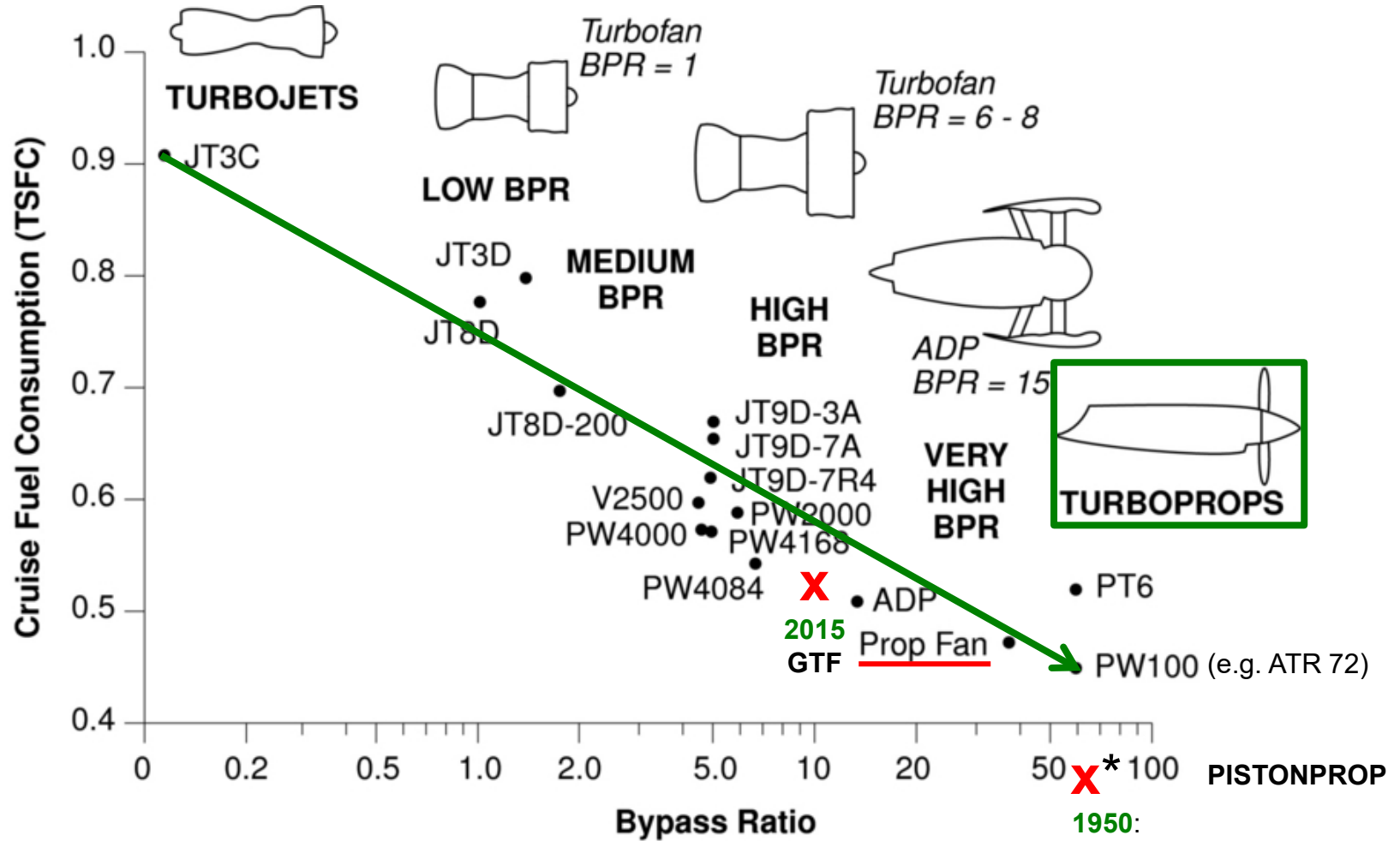
T = Schub (Thrust)

Vortriebswirkungsgrad des Antriebes



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

Spezifischer Kraftstoffverbrauch



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

Urban Aviation

Flugtaxi ist keine Lösung für die Umwelt

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

Carbon fibre monocoque
360kg
106kW
= 0.29 kW/kg

Lamborghini LP700

Carbon fibre monocoque
1575kg
515kW peak
= 0.33 kW/kg

VW Golf TDI

4.2 l/100 km
1440 kg
118 kW
= 0.082 kW/kg

CO2: CO2=1000g/km (in Dubai)

CO2=370g/km

CO2 = 106 g/km



Lufttaxi: 200 \$ für 24 km (10 €/km) – Taxi Hamburg: 1,80 €/km

GLOBAL TRAVELER

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

NEW YORK
HELICOPTER



Durch Einsatz von Batterien und Elektromotor wird es nicht preiswerter!

Flugtaxi für Eliten



City Airbus, 4 Passagiere, max: **15 min.**
Keine technische Lösung!

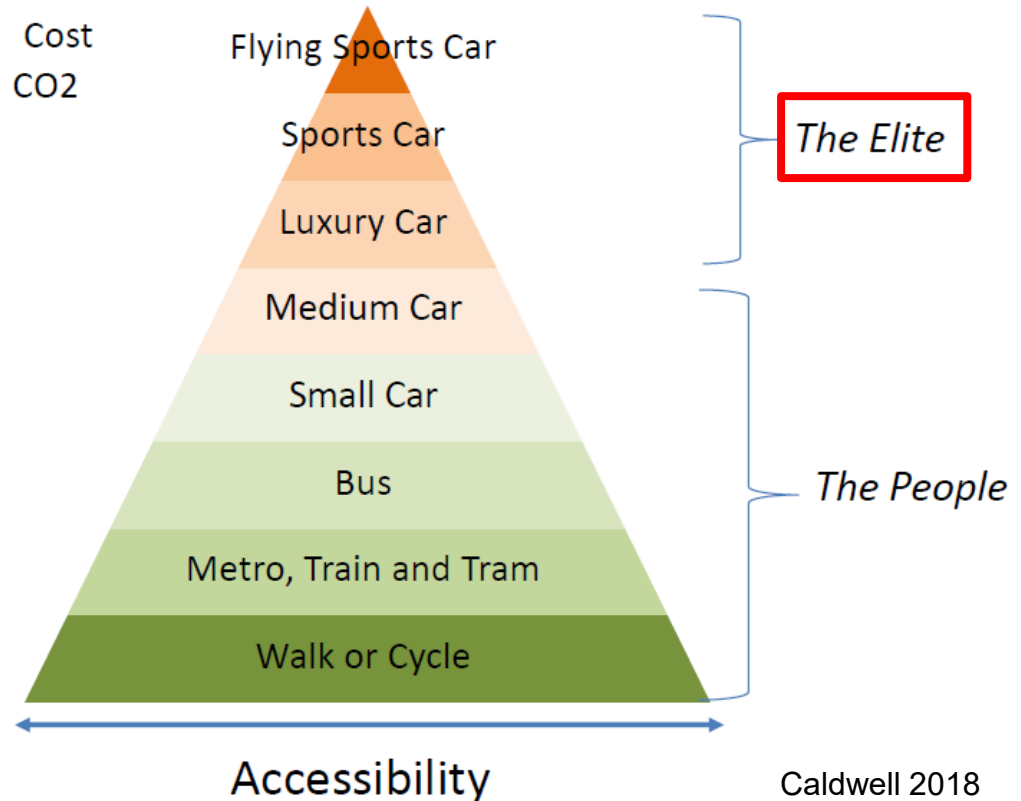


Max Pixel, CC0

Waiting for the City Airbus?
Keine Lösung der Verkehrsprobleme!



Speed
Comfort
Convenience
Style
Cost
CO2



Caldwell 2018

Kurzstrecke

Auf der Kurzstrecke nehmen wir die Bahn!

Elektromobilität, die am Netz betrieben wird gibt es bereits erfolgreich auf der Schiene!



- 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 $\approx 47.5\%$ if put on rails!**

Mittelstrecke

Auf der Mittelstrecke zwischen Megacities nehmen wir die Bahn!

Verbindung von benachbarten Megacities – Beijing & Shanghai – Vergleich Flugzeug und Zug

Time	Location	Mode
08:20	Beijing Capital Times Square	Walk
08:30	Xidan	
08:40		Metro Line 4
08:50		
09:00	Xuanwumen	Metro Line 2
09:10		
09:30		Metro Airport Line
09:40	Dongzhimen	
09:50		Metro Airport Line
10:00	Beijing Capital International Airport	
10:10		Aircraft
...	...	
11:20		Aircraft
11:30	Beijing Capital International Airport	
11:40		Aircraft
11:50		
...	...	Aircraft
13:20		
13:30		Aircraft
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	Train
09:10		
09:20		Train
09:30		
09:40		Train
09:50		
10:00		Train
...	...	
11:20		Train
11:30		
11:40		Train
11:50		
13:10		Train
13:20		
13:30		Train
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.**

Ein Propellerflugzeug für 180 Passagiere mit zwei Triebwerken der A400M ?

... spart erheblich Kraftstoff !



	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", Entwurf auf Seite 26 bis 28!

Ein größerer Propellerflug wird seit 10 Jahren diskutiert!

FLIGHT INTERNATIONAL

PROPULSION JOHN CROFT WASHINGTON DC

05/2011:

90-seat turboprop beckons to P&WC

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

AIRFRAMES MAVIS TOH SINGAPORE

01/2013:

ATR keen to satisfy 90-seat audience

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

ANALYSIS MURDO MORRISON LONDON

01/2013:

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"

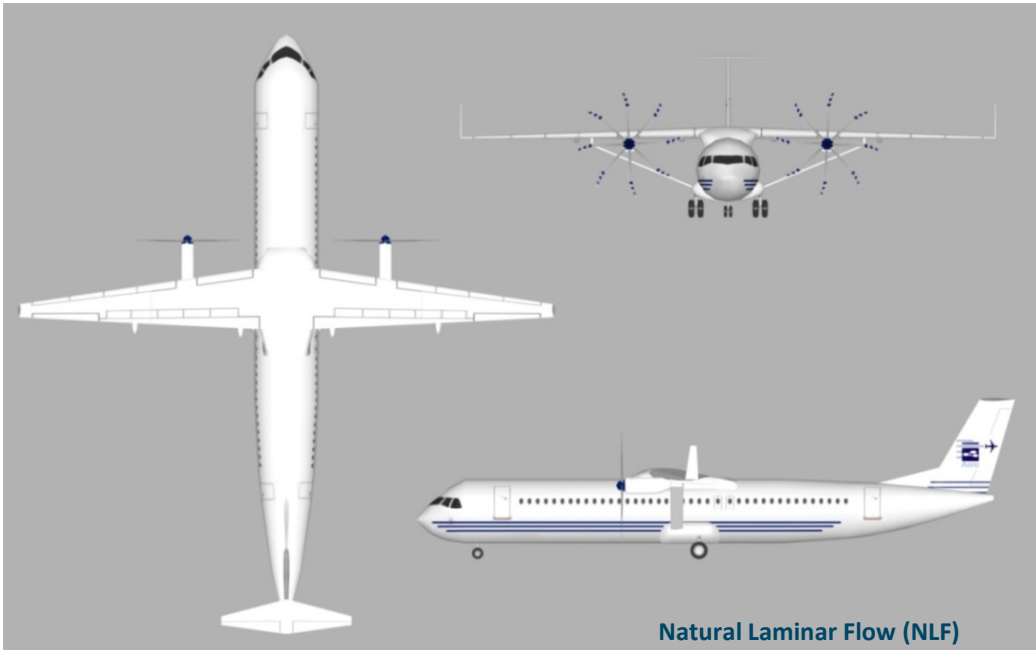
FILIPPO BAGNATO
Chief executive, ATR

"Smart Turboprop": Große Propeller, abgestreifter Flügel, teilweise Laminarströmung

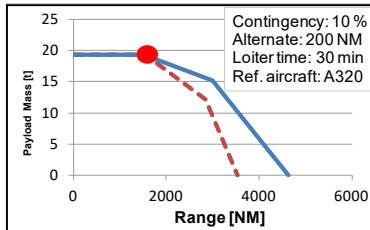
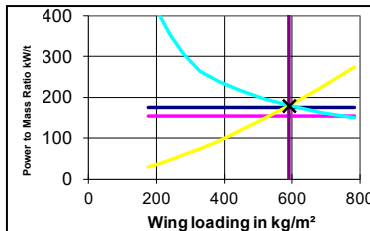


<http://Airport2030.ProfScholz.de>

"Smart Turbo prop": Langsamer und tiefer fliegen bedeutet erheblich umweltfreundlicher fliegen !



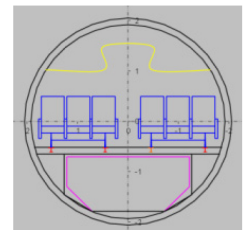
Parameter	Value	Deviation from A320*
Requirements		
m_{MPL}	19256 kg	0 %
R_{MPL}	1510 NM	0 %
M_{CR}	0.51	- 33 %
$\max(S_{TOFL}, S_{LFL})$	1770 m	0 %
n_{PAX} (1-cl HD)	180	0 %
m_{PAX}	93 kg	0 %
SP	29 in	0 %



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 m ²	- 23 %
$b_{W,geo}$	36.0 m	+ 6 %
$A_{W,eff}$	14.9	+ 57 %
E_{max}	18.8	$\approx + 7 \%$
$P_{eq,ssl}$	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 % weniger Kraftstoff.

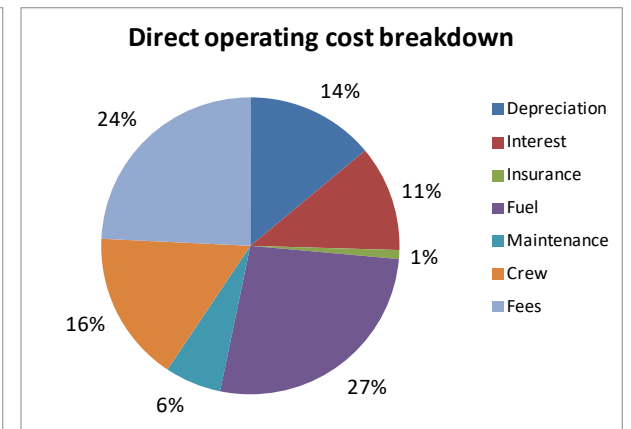
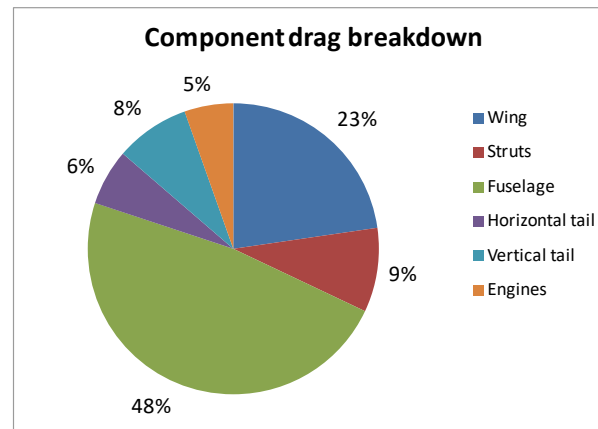
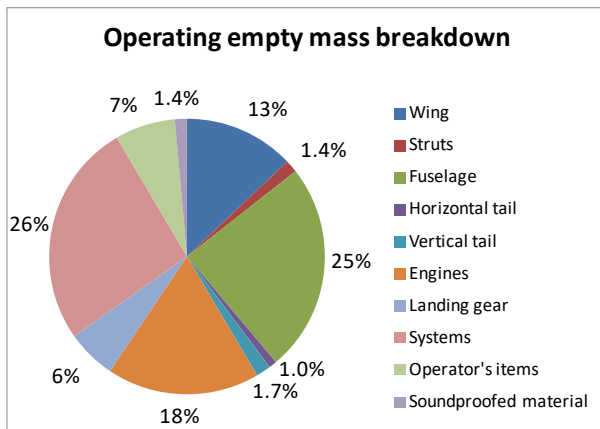
In 23000 ft Flughöhe: kein Strahlungsantrieb durch Aviation Induced Cloudiness (AIC)



"Smart Turboprop": 17 % weniger Betriebskosten !



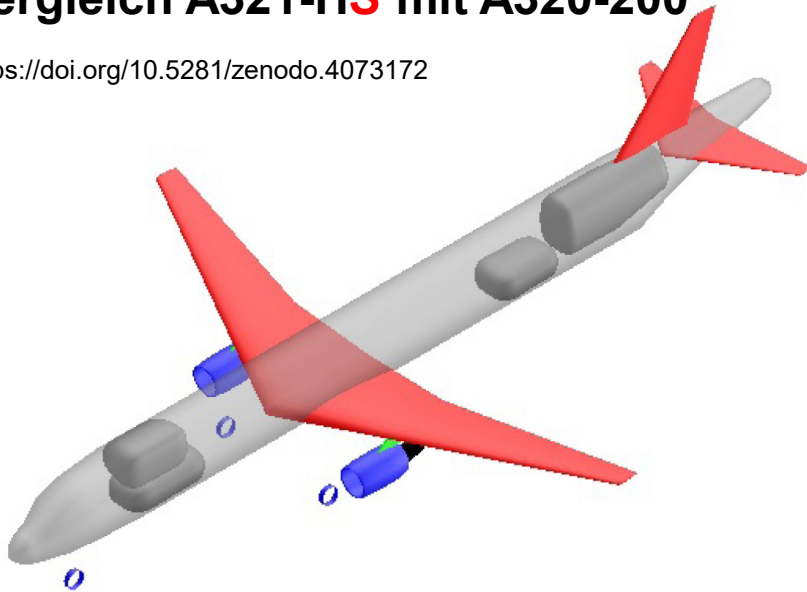
Parameter	Value	Deviation from A320*
DOC mission requirements		
R_{DOC}	755 NM	0 %
$m_{PL,DOC}$	19256 kg	0 %
EIS	2030	-----
c_{fuel}	1.44 USD/kg	0 %
Results		
$m_{F,trip}$	3700 kg	- 36 %
$U_{a,f}$	3600 h	+ 5 %
DOC (AEA)	83 %	- 17 %



A320 umgebaut für Wasserstoff

Vergleich A321-HS mit A320-200

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



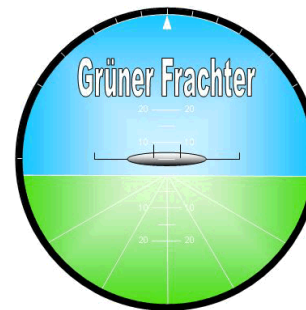
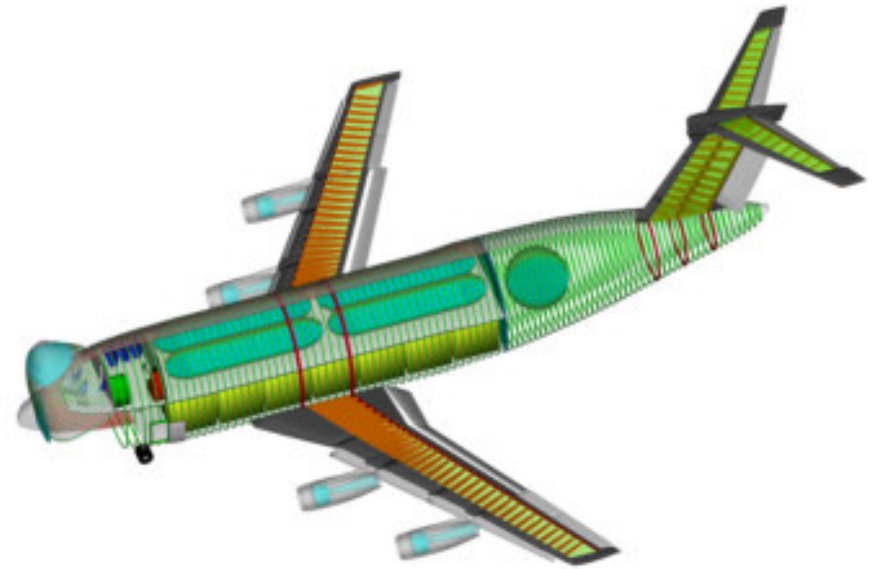
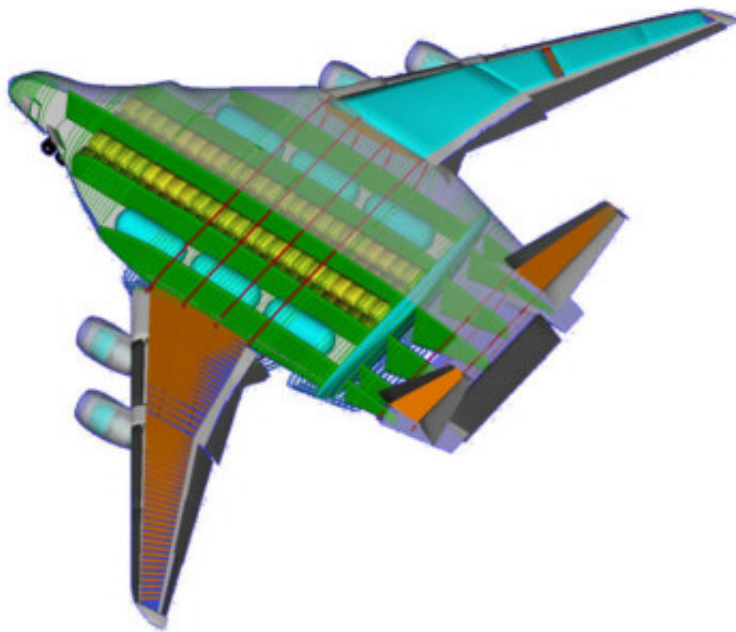
Details of the tanks for the A321-HS

	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
S_W [m ²]	131.1	+9.0	Delta fuselage length: 4.9 m.
$b_{W,geo}$ [m]	35.3	+4.4	Further stretch or A319 cabin required.
$A_{W,eff}$	9.5	0	
ϕ_{25} [°]	25	0	
λ	0.21	0	To do: "Smart Turboprop"
E_{max}	17.6	+0.4	with LH2 to combine best of both solutions.
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	

Langstrecke

**Frachtflugzeug für die Langstrecke
mit Wasserstoff (LH2) aus dem Projekt
"Grüner Frachter"**



HEINZE, TU Braunschweig, 2009
siehe <http://GF.ProfScholz.de>

Großes Passagierflugzeug für LH2 und extreme Langstrecke

Lockheed 1976

DESIGN GROSS WT - 266.429 KG

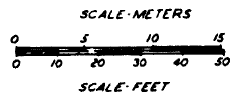
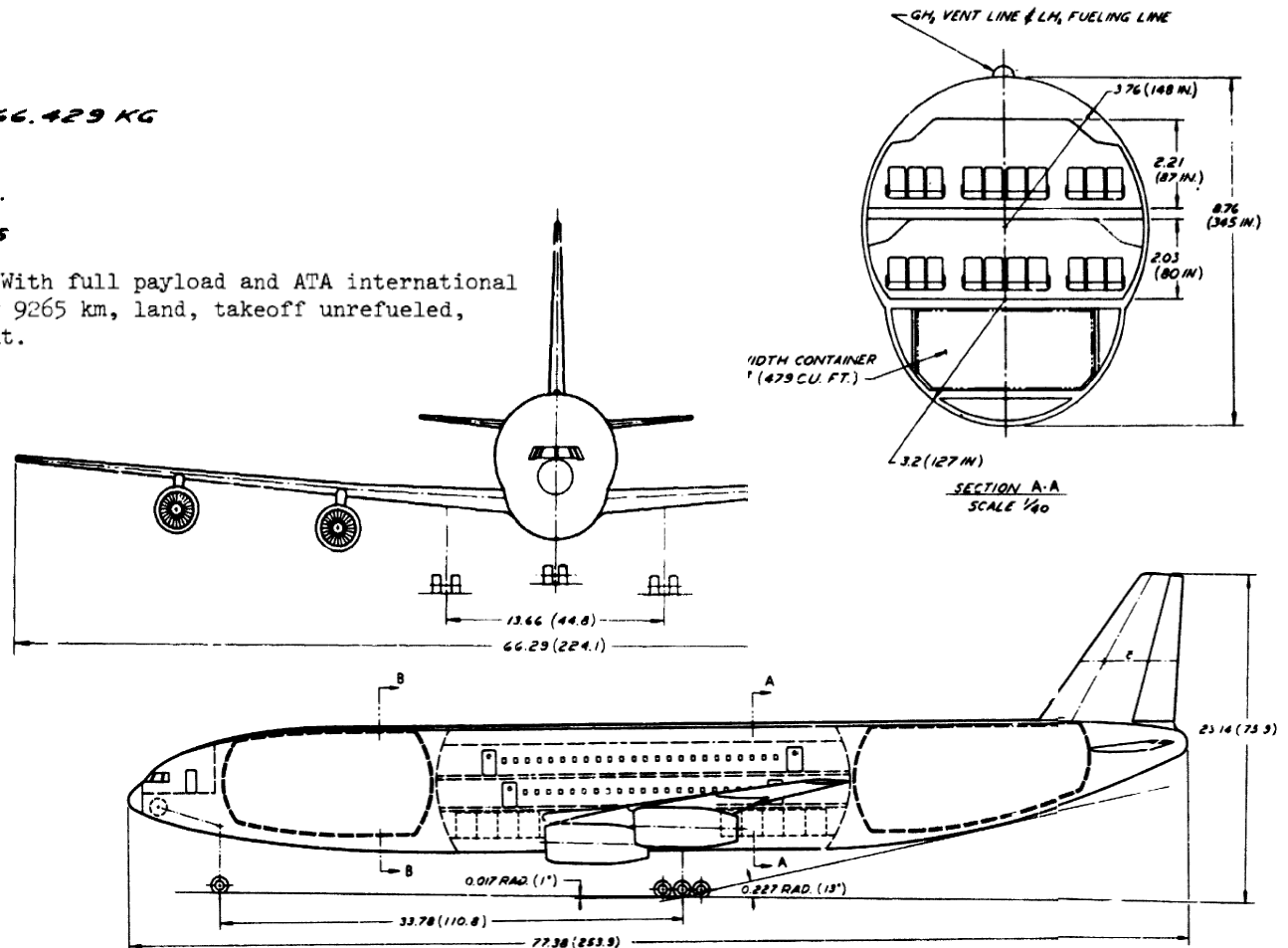
PASSENGERS - 400

FUEL (LH₂) - 68.424 KG.

RANGE - 9.265 KM RADIUS

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

Range: 18530 km = 10000 NM

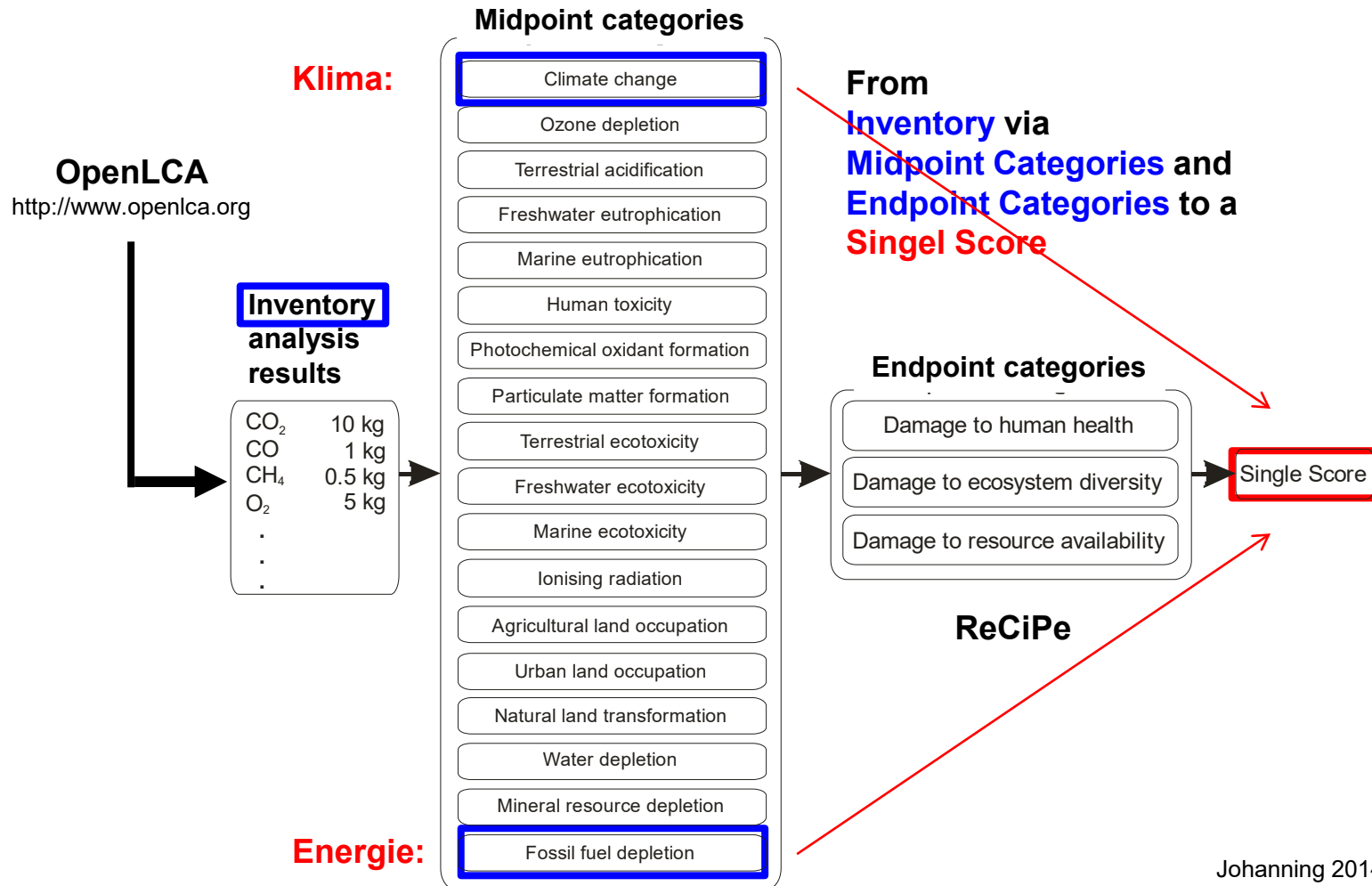


BREWER, G.D., MORRIS, R.E., 1976. *Study of LH2 Fueled Subsonic Passenger Transport Aircraft*. Lockheed, NASA CR-144935. Available from: <https://ntrs.nasa.gov/citations/19760012056>

Neue Energien, Antriebe und Flugzeuge

Grundlagen

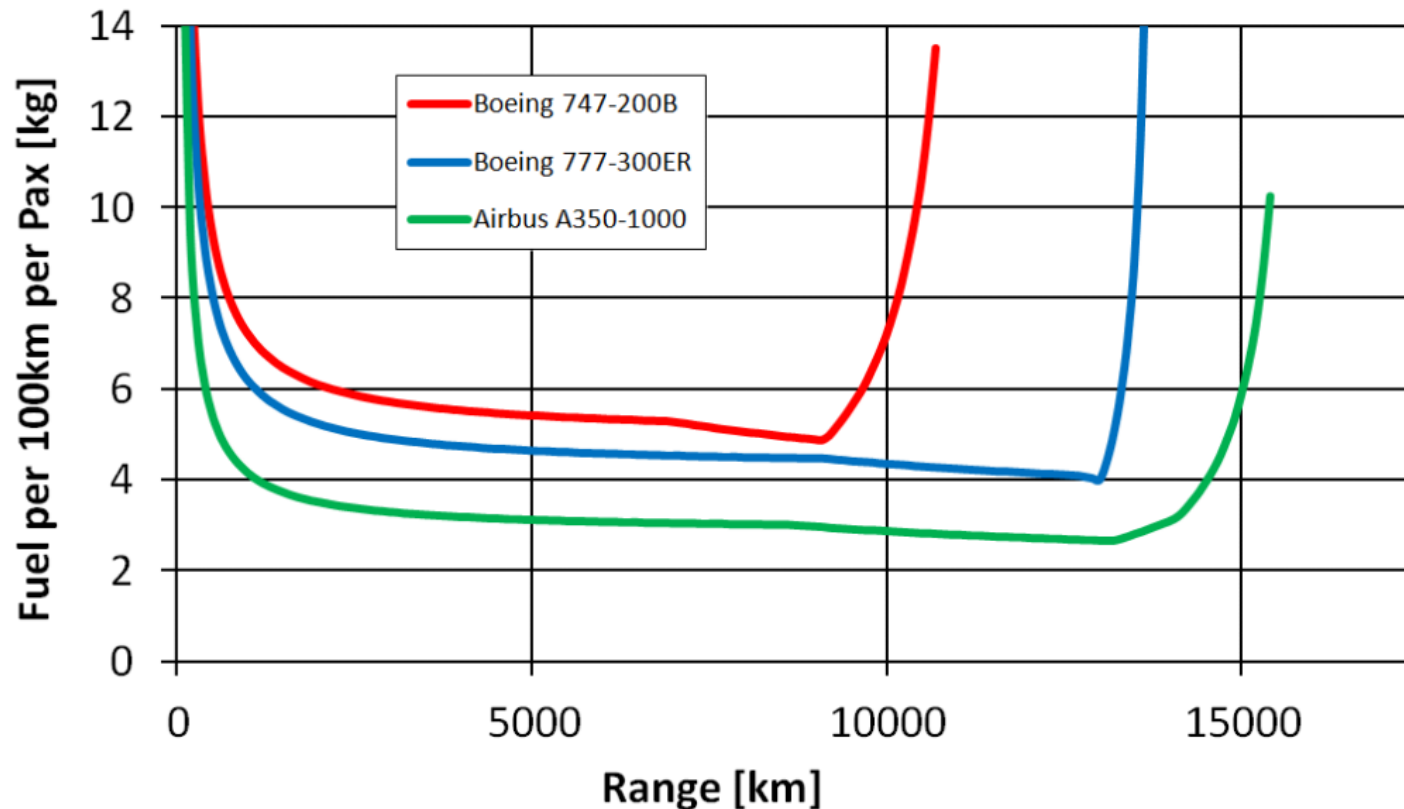
Ökobilanz = Life Cycle Assessment (LCA)



Johanning 2014, 2016, 2017

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

Der Kraftstoffverbrauch pro 100 km und Person hängt von der Flugdistanz ab!



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>

Objektiv über Kraftstoffverbrauch reden!

Forderung: **Der Kraftstoffverbrauch von Flugzeugen muss definiert und angegeben werden!**

Ansonsten bleiben die Bürger uninformiert darüber,
was "alte Stinker" (T. Jarzombek) sind und
warum für ein "Abwrackprogramm" bzw. eine Flottenerneuerung
1 Mrd. Euro ausgegeben werden.

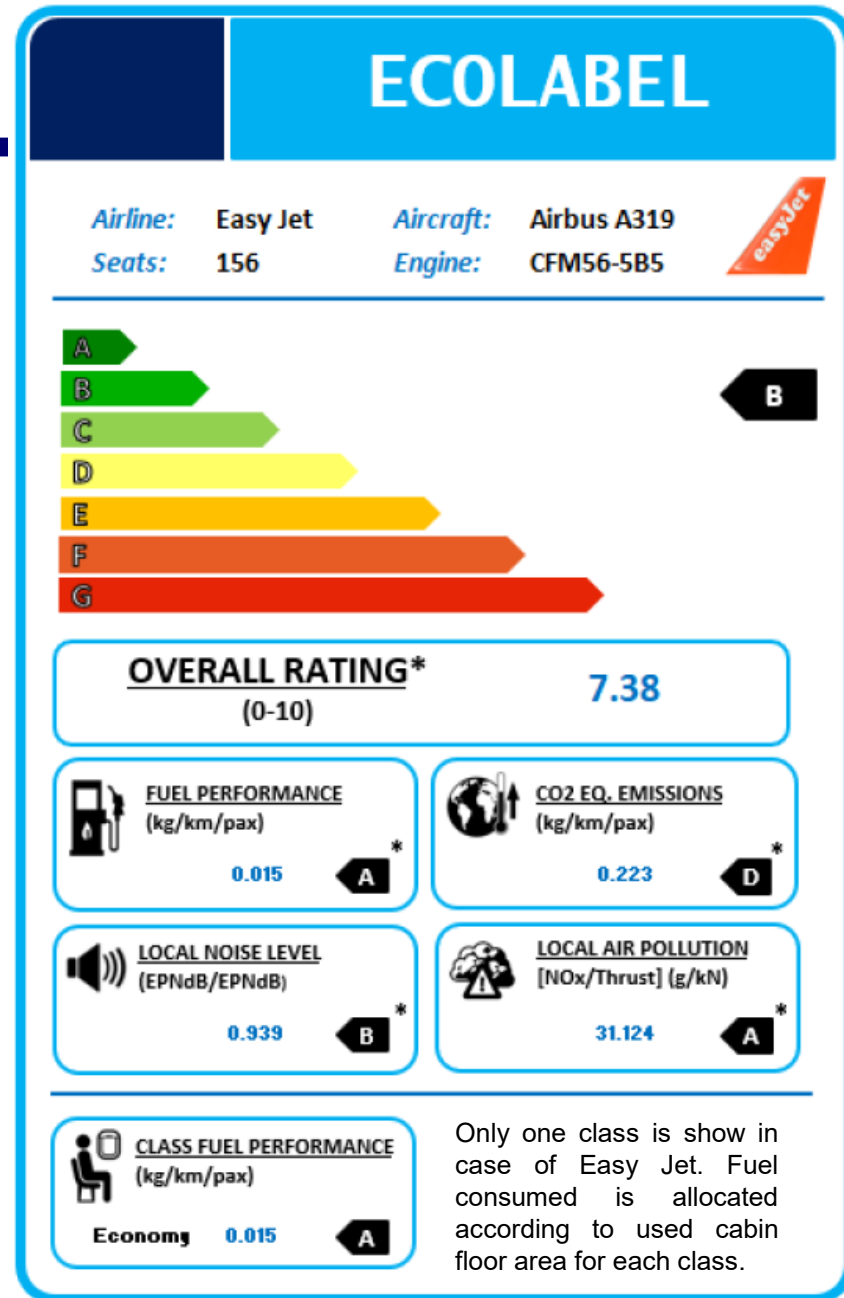
<https://youtu.be/jzl2zpoCuz0>

<https://perma.cc/AV2V-P7Q2>

Von der Ökobilanz zum Ökolabel

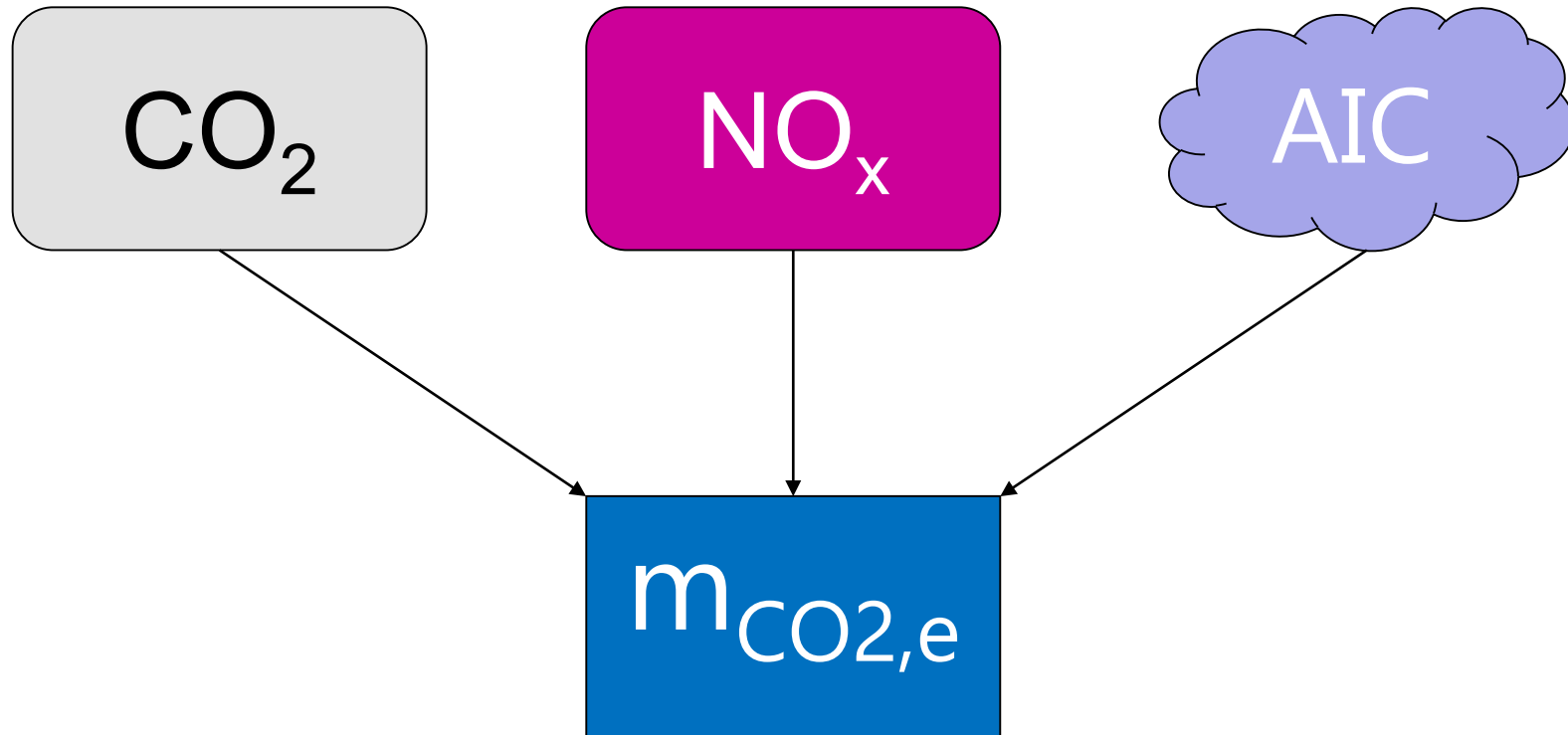
Jedes Flugzeug einer Flugesellschaft erhält ein Ökolabel

Vergleich
aller Passagierflugzeuge
untereinander (A bis G)



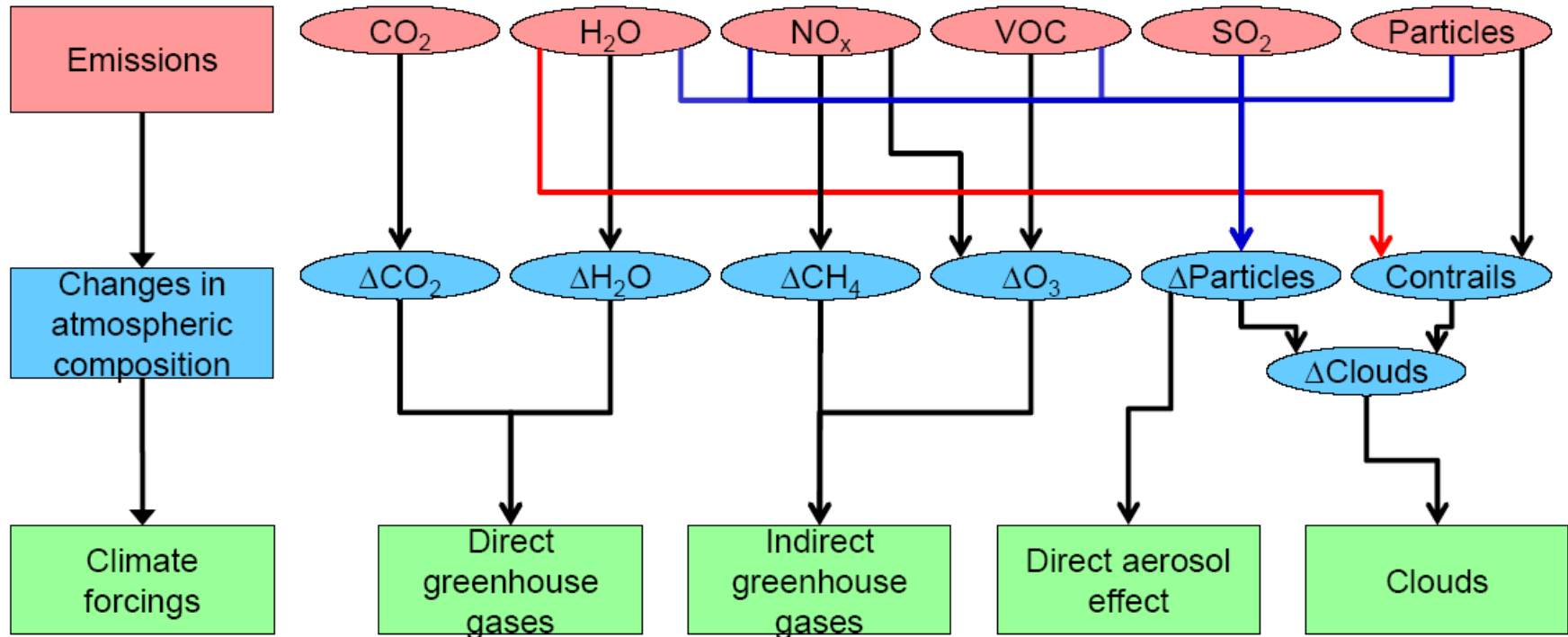
SCHOLZ, Dieter, 2017. *An Ecolabel for Aircraft*. German Aerospace Congress 2017 (DLRK 2017), Munich, Germany, 05.-07.09.2017. Available from: <https://doi.org/10.5281/zenodo.4072826>

CO₂ – Äquivalente



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>

Luffahrt Emissionen und der Klimawandel



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

Billigflieger Pro & Contra – Wer hat Recht?

**EUROPE'S NO. 1 AIRLINE
FOR CARBON
EFFICIENCY**




RYANAIR MONTHLY
CO₂ EMISSIONS REPORT

March

69g

Ryanair reported an average of 69g
CO₂ per passenger /km in March 2020.



ASA Ruling on Ryanair Ltd t/a
Ryanair Ltd Advertising Standards Authority, 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>

Positive Umweltwirkung: Tiefer fliegen!

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

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

Clear altitude boundary from $m_{CO_2,eq}$ visible

Fuel consumption shape visible

Fly low and slow

Units: normalized value between 0 and 1

Positive Umweltwirkung: Tiefer fliegen!

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.

Wasserstoff (LH2)

Airbus: "Zero-Emission" Hybrid – Wasserstoff Passagierflugzeug



"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).

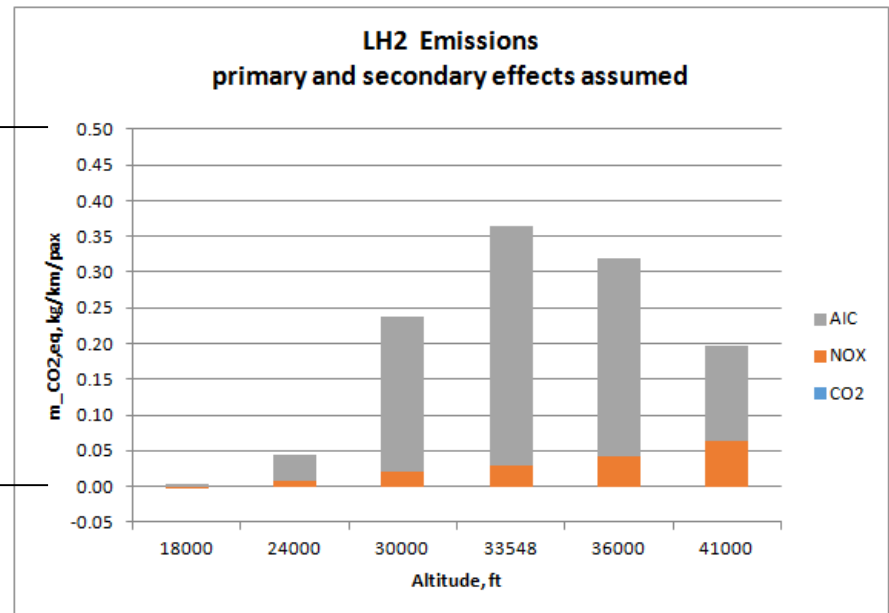
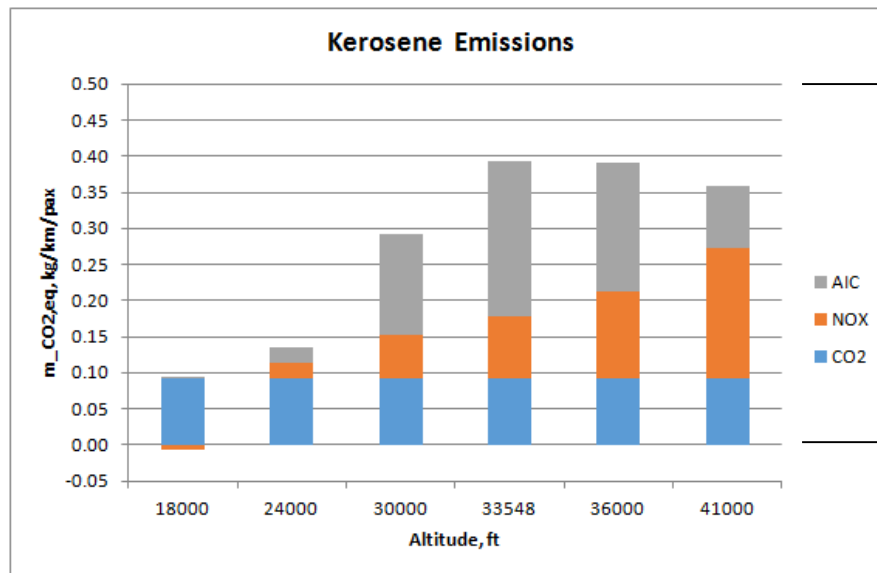
For details: SCHOLZ, Dieter, 2020. [Design of Hydrogen Passenger Aircraft – How much 'Zero-Emission' is Possible?](#)

Berechnung der Emission von Kerosin- und Wasserstoffflugzeugen –Ein Vergleich

Here **secondary effects** are applied on top of the primary effect for **contrails** due to larger ice crystals (factor 0.77) and for visible contrails (factor 0.77 assumed) leading all together to a **reduction factor** of $0.77^2 = 0.6$. 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 in the order of that for kerosene propulsion**. See Excel table:
<https://doi.org/10.7910/DVN/DLJUUK>

LH2 versus kerosene aircraft as function of altitude. **LH2 aircraft benefit at high or low altitudes** compared to kerosene aircraft.

Altitude [ft]	rel. to kero
18000	1%
24000	32%
30000	81%
33548	93%
36000	82%
41000	55%



EU-Study, May 2020



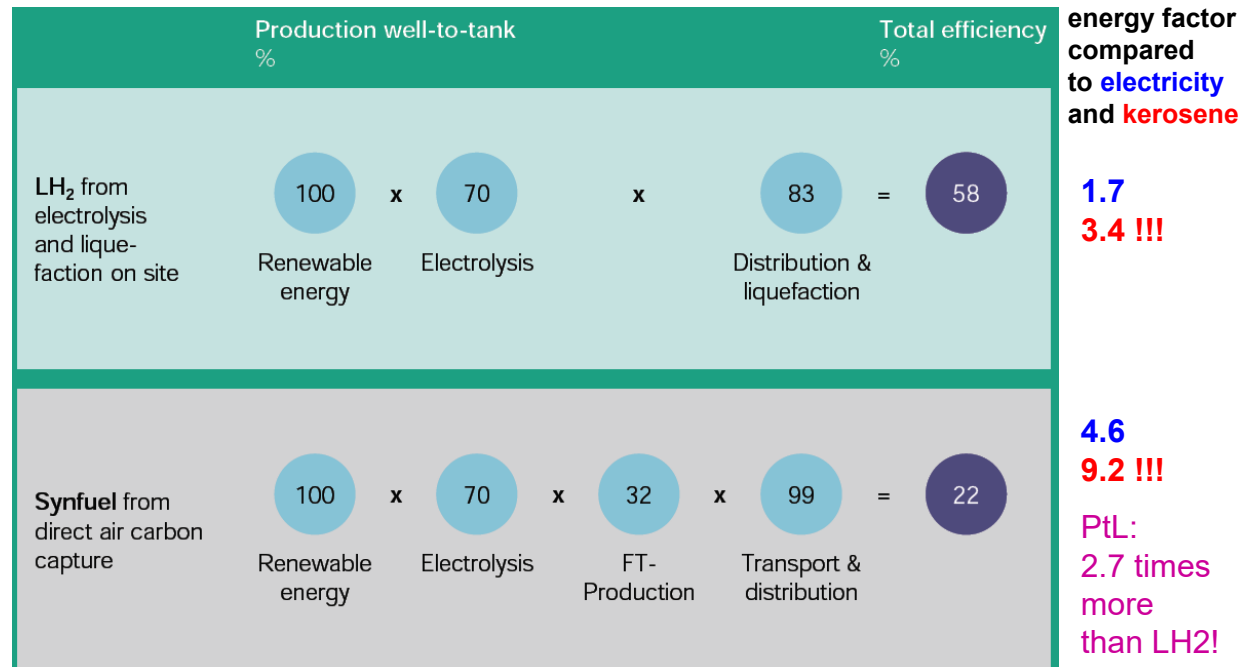
<https://doi.org/10.2843/471510>
 Archived at: <https://perma.cc/BJJ6-5L74>

AIRBUS and many others

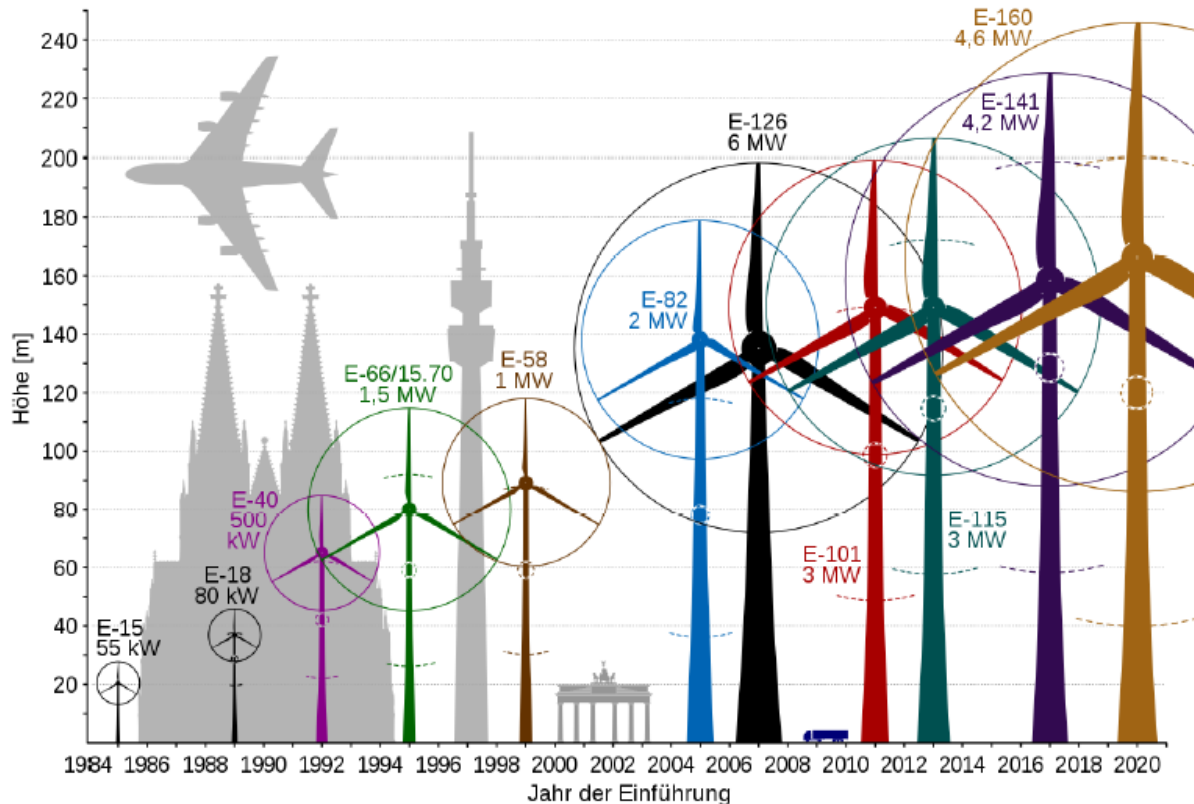
Emissions

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

Energy / Primary Energy



**Betankung eines A350 einmal pro Tag
kann mit 52 großen Windrädern (je 4.6 MW) erreicht werden**



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

Elektrisches Fliegen ?

Berechnung der maximalen Reichweite beim batterie – elektrischen Fliegen

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

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

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

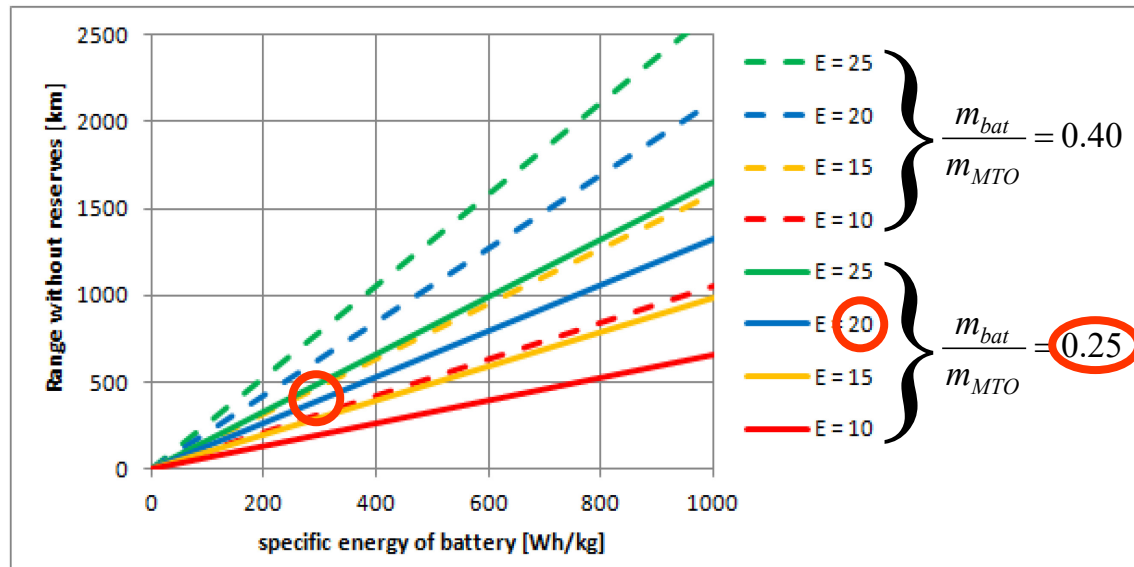
$$m_{bat} e_{bat} \frac{V}{R} \eta_{elec} \eta_{prop} = \frac{m_{MTO} g}{E} V$$

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

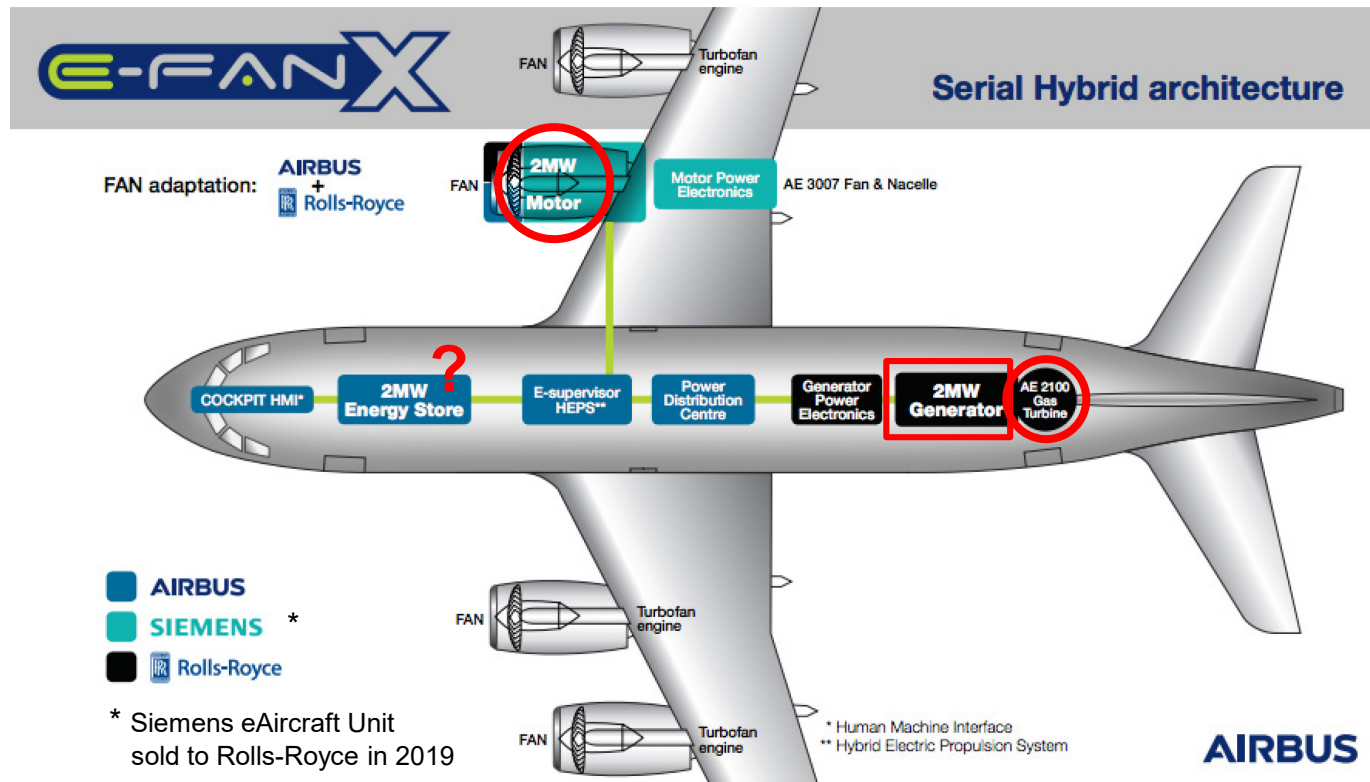
$$\eta_{elec} = 0.9; \quad \eta_{prop} = 0.8$$

○ : realistic parameters

- 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)



Airbus / Rolls-Royce: E-Fan X: hybrid – elektrisches Fliegen



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

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

Airbus / Rolls-Royce: E-Fan X: hybrid – elektrisches Fliegen



<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>

Weniger Fliegen !



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>

Größte Reduktion der Emissionen in der Luftfahrtgeschichte durch die Corona-Pandemie



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



Traffic reduction is more efficient than technology



<https://stay-grounded.org>

It's about more than just CO2

Aviation must reduce its total impact on climate

Digitalisierung

Digitalisierung

- **Automatischer Flug:** Autopilot & Flight Management System
- **Schutzfunktionen:** Flight Envelope Protection
- **Autonomer Flug:** VFR => IFR => Autonomous Flight Rules (AFR)
- **Flugzeugsysteme / Avionik:** Integrated Modular Avionics (IMA)
- **Wartung:** Health and Usage Monitoring Systems (HUMS),
Predictive Maintenance
- **Airlines:** Big Data (Flugzeug- und Passagierdaten),
Flight Performance Optimization, Multimodaler Verkehr
- **Flugzeugentwurf:** MDO, FEM, CFD, Virtual Reality (VR), ...
- **Flugzeugbau:** Industrie 4.0, Vernetzte Lieferketten,
- Automatisierung in der **Fertigung**, kollaborierender Roboter
- **Weiterbildung:** Digitales Lernen

Zusammenfassung

- **Urban Air Mobility** ist für die Reichen. Kein Umweltvorteil, Staus bleiben.
- **Kurzstrecke auf die Bahn.**
- **Mittelstrecke zwischen Megacities auf die Bahn.**
- Für die Mittelstrecke ansonst **Propellerflugzeuge in intelligenter Auslegung**, evtl. mit **Wasserstoff**.
- Langstrecke: **Drop-In Kraftstoffe** aus erneuerbaren Energien (SAF, E-Fuel), aber: **hoher Primärenergieverbrauch.**
- Wir brauchen eine **Verbrauchsangabe** für Flugzeuge und eine Beachtung vorhandener **Ökolabel**.
- Beurteilung von Vorschlägen anhand von Ökobilanzen.
- Wir haben **in der Luftfahrt** weniger ein CO₂-Problem als mehr ein **Wasserproblem** (AIC).
- Jedoch: **CO₂** setzt sich **auf lange Zeiten** durch.
- **Tiefer fliegen** bringt deutliche Vorteile.
- **Batterie-elektrisches Fliegen** geht nur auf Kurzstrecke, wo es nicht benötigt wird.
- **Hybrid-elektrisches Fliegen** hat keine technischen Vorteile für Passagierflugzeuge.
- **Wasserstoff** hat den gleichen Strahlungsantrieb, **vermeidet** aber **die Ansammlung von CO₂**.
- Die Luftfahrt wie sie heute (2019) existiert(e) kann mit regenerativen Energien nicht versorgt werden: **Weniger fliegen.**
- Die **Digitalisierung** ist in der Luftfahrt genauso wichtig wie in anderen Bereichen.

Grüner Fachworkshop zum Thema Luftverkehr

Kontakt

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<http://www.ProfScholz.de>

<http://AERO.ProfScholz.de>

So kann das Dokument zitiert werden:

SCHOLZ, Dieter, 2020. *Luftverkehr: Energie, Klima, Technik*. Grüner Fachworkshop zum Thema Luftverkehr, Online, 05.12.2020. Available from: <https://doi.org/10.5281/zenodo.4312988>

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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>

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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>

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Backup / Ergänzungen

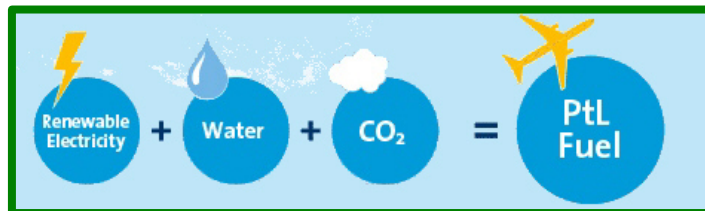
Many Possible Energy Paths for Aviation

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

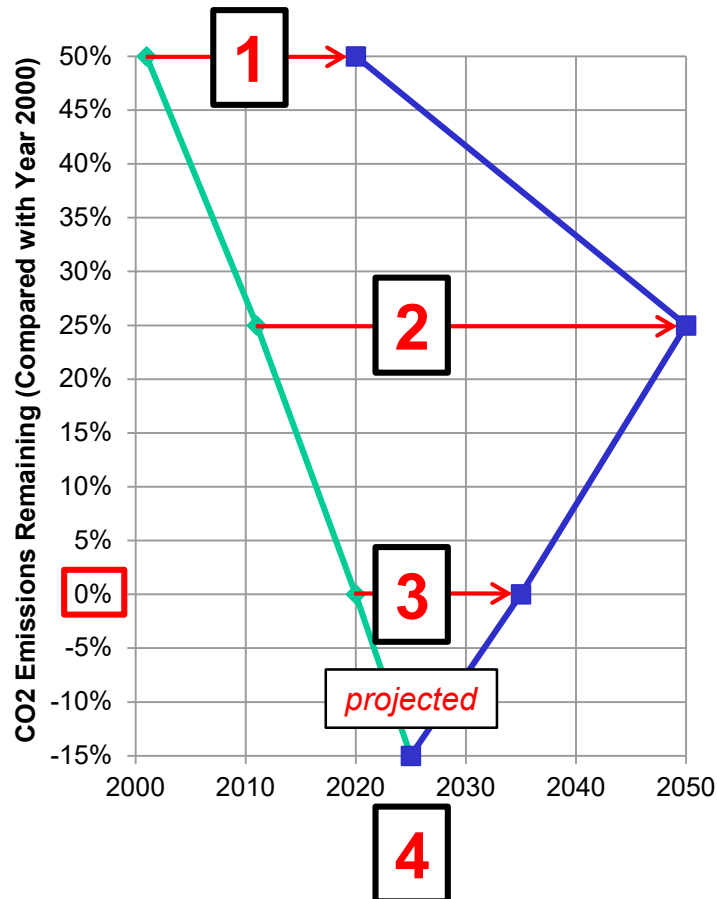


Additional conversions & major aircraft parts: **Solutions 6** (one more component) **and 8/9** (two more comp.)

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 infrastructure 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, deserts, polar regions).

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.

Further reading:

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>

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

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

<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: Minimum 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.

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	$\frac{1}{\text{Specific Air Range}} = \frac{1}{\text{SAR}}$				
Two-parameter metric	$\frac{1}{\text{SAR} \cdot \text{Payload}}$	$\frac{1}{\text{SAR} \cdot \text{Useful Load}}$	$\frac{1}{\text{SAR} \cdot \text{MTOW}}$	$\frac{1}{\text{SAR} \cdot \text{Floor Area}}$	$\frac{1}{\text{SAR} \cdot \text{Av. Seats}}$
Three-parameter metric	$\frac{1}{\text{SAR} \cdot \text{Payload} \cdot \text{Speed}}$	$\frac{1}{\text{SAR} \cdot \text{Useful Load} \cdot \text{Speed}}$	$\frac{1}{\text{SAR} \cdot \text{MTOW} \cdot \text{Speed}}$	$\frac{1}{\text{SAR} \cdot \text{Floor Area} \cdot \text{Speed}}$	$\frac{1}{\text{SAR} \cdot \text{Av. Seats} \cdot \text{Speed}}$

Note: R = Range

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



Selecting a Fuel Metric:

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

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

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

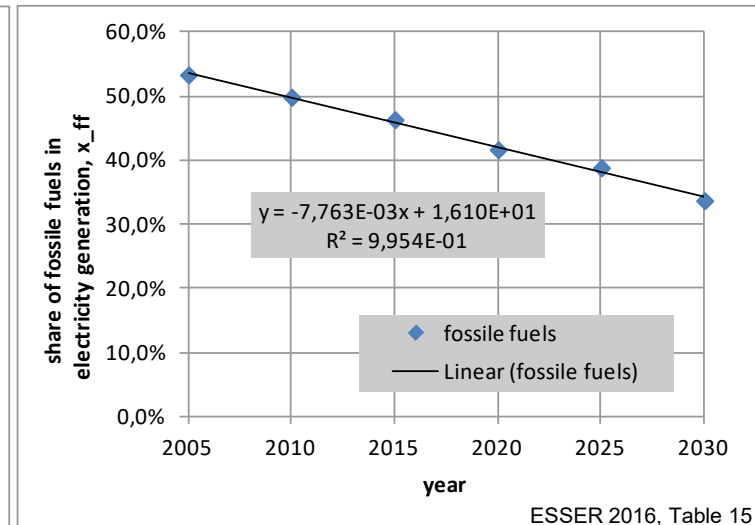
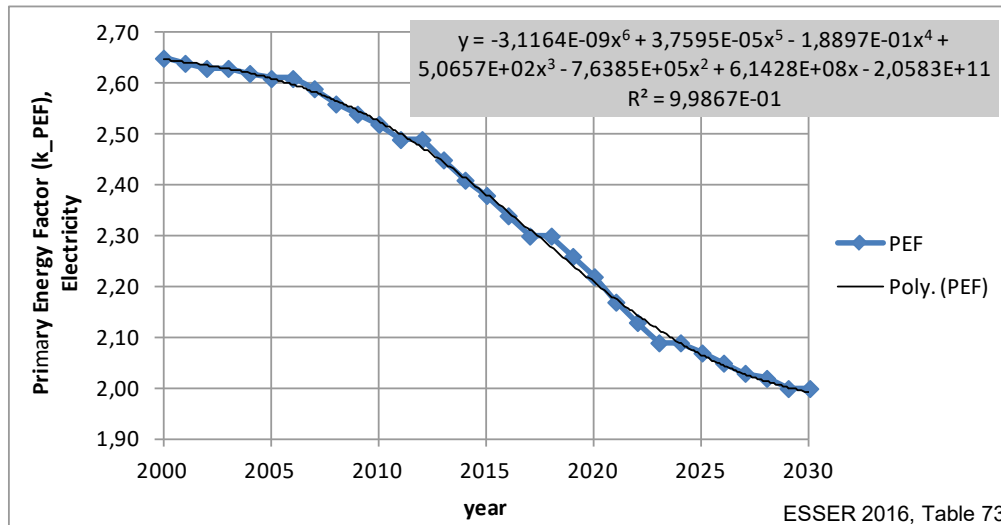
- aircraft mass, m
- aerodynamic efficiency, L/D
- specific fuel consumption, SFC
- aircraft speed, V

or extracted from published **Payload Range Diagrams**

From Energy to Approximate Emission Comparison

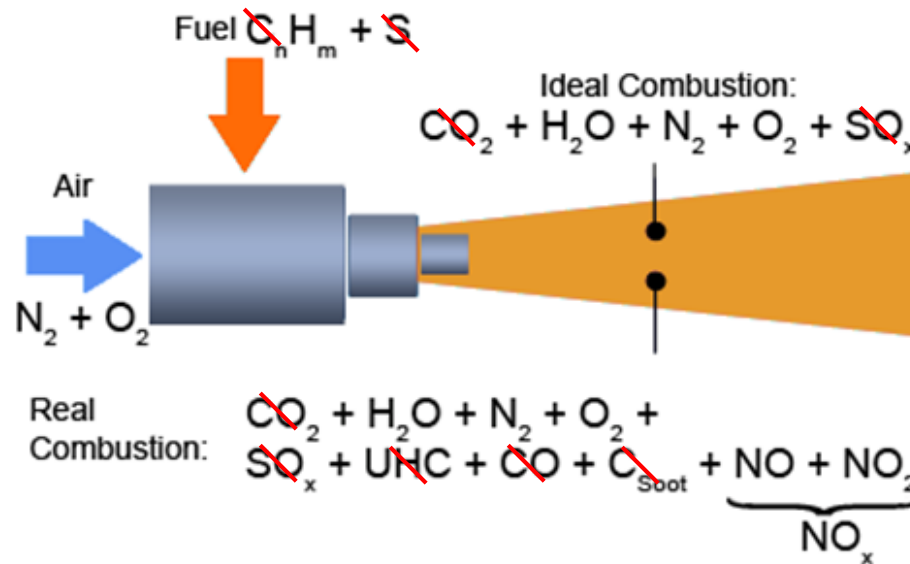
Type of Comparison	Kerosene	Electricity / Battery
Energy (wrong)	$E = m_F H_L$	$E = E_{bat} / \eta_{charge}$
Max. Exergy (not good)	$B_{max} = \eta_C H_L m_F$	$B_{max} = E$
Exergy (ok)	$B = \eta_{GT} H_L m_F$	$B = \eta_{EM} E$
Primary Energy (better)	$E_{prim} = 1.1 H_L m_F$	$E_{prim} = k_{PEF} E$
CO2 (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)	$m_{CO2,eq} = m_{CO2} (k_{RFI} + 0.1)$	$m_{CO2,eq} = m_{CO2}$

$H_L = 43 \text{ MJ/kg}$ $\eta_{charge} = 0.9$
 Carnot Efficiency:
 $\eta_C = 1 - T/(h) / T_{TET} =$
 $= 1 - 216.65 / 1440 = 0.85$
 $\eta_{GT} = 0.35$ $\eta_{EM} = 0.9$
 Radiative Forcing Index:
 $k_{RFI} = 2.7$ (1.9 ... 4.7)



ESSER, Anke, SENFUSS, 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>

Kerosene and LH2 Combustion



/ not included in LH2 combustion

EI_{NOx} ↑
EMEP/EEA Guidebook
<https://www.eea.europa.eu>
 m_F ↑
Own Fuel Calculation

Altitude-Dependent Equivalent CO2 Mass

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

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

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

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

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

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

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

Cirrus/Contrails = 3.0

water vapor not considered

AIC aviation-induced cloudiness

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

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

Altitude-Dependent Equivalent CO2 Mass

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

↓ units only

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

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

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

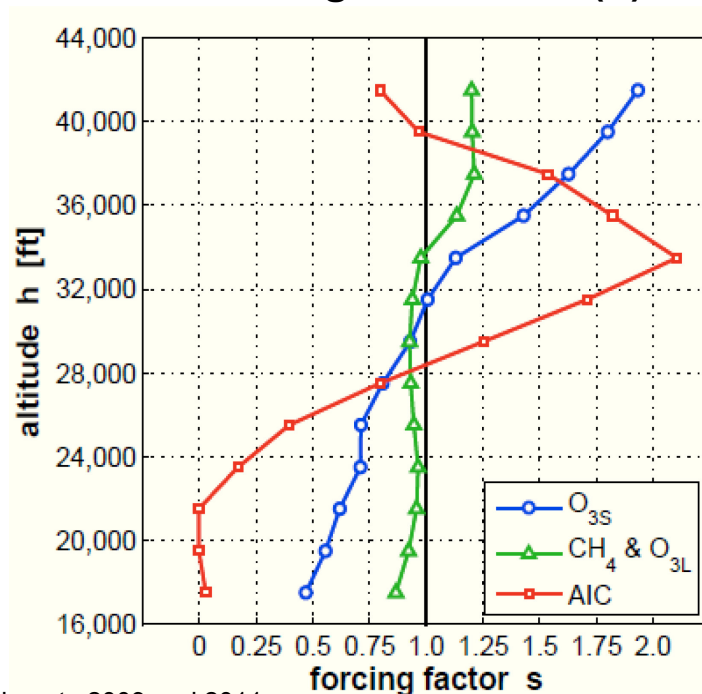
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Altitude-Dependent Equivalent CO2 Mass

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

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

Forcing Factor $s = f(h)$



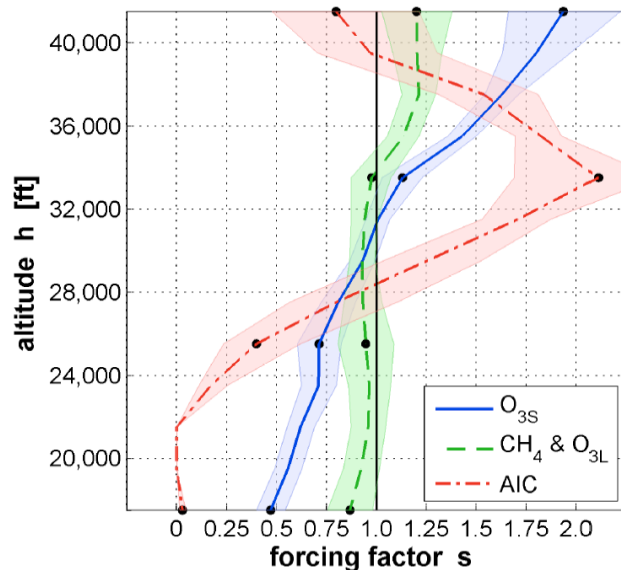
Schwartz 2009 and 2011

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

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

Altitude-Dependent Equivalent CO2 Mass

Forcing Factor $s = f(h)$



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

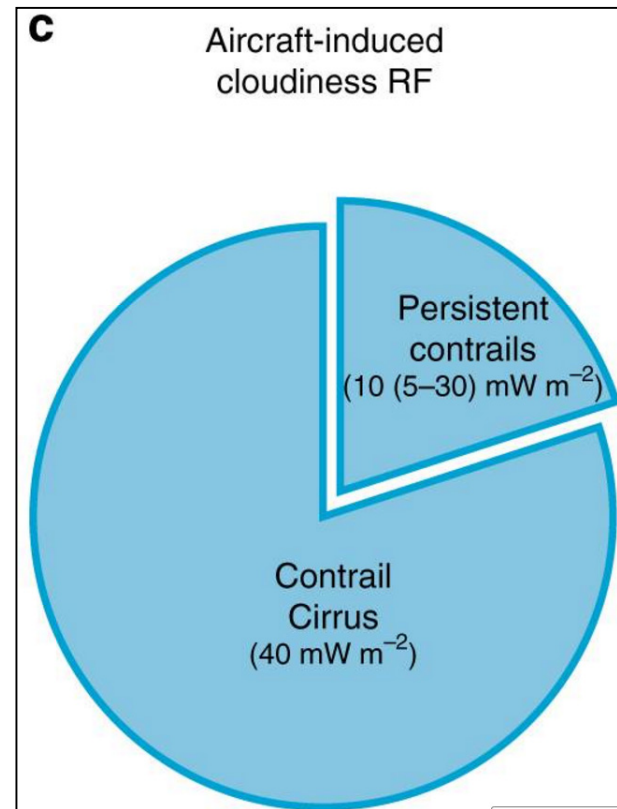
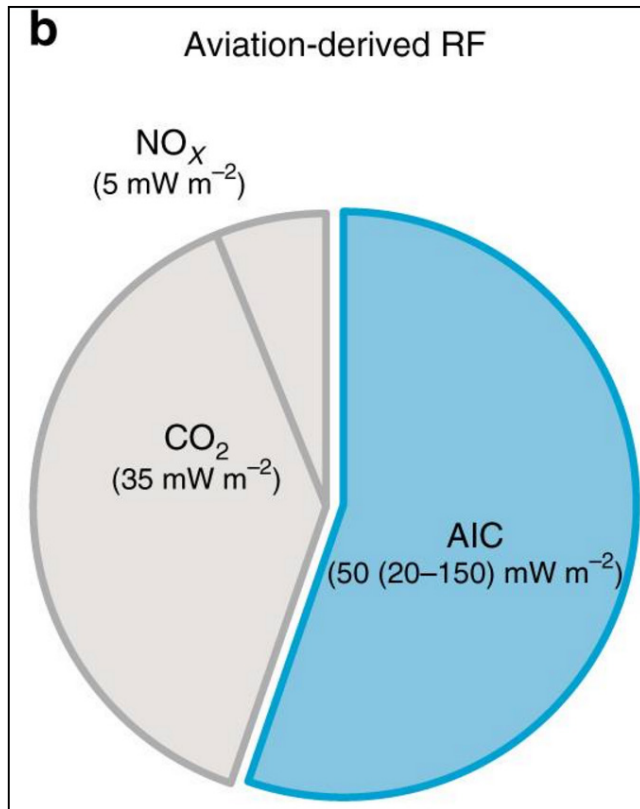
Based on KÖHLER 2008 and RÄDEL 2008.

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

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

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

Aviation-Induced Cloudiness: Contrail Cirrus & Persistent Contrails



Cirrus/Contrails = 4.0

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

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

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)

