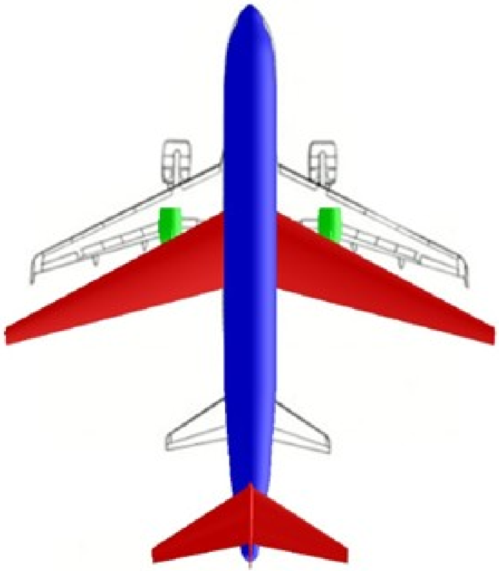
Aero

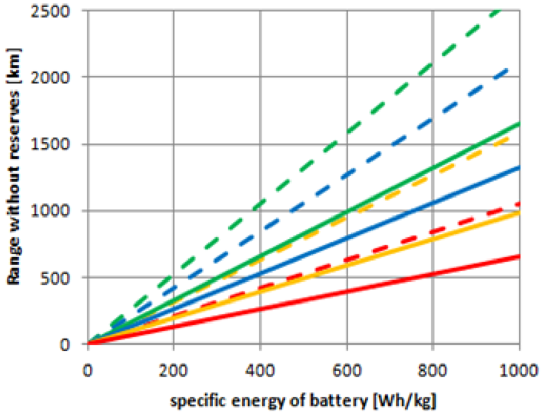
Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

Electric and Hybrid Aviation –
From Media Hype to Flight Physics

Dieter Scholz
Hamburg University of Applied Sciences





Hamburg Aerospace Lecture Series
DGLR, RAeS, VDI, ZAL, HAW Hamburg
Hamburg, 25th April, 2019
https://doi.org/10.5281/zenodo.3265211
(Presentation with Update from 2019-06-30)

Abstract

Purpose – This presentation takes a critical look at various electric air mobility concepts. With a clear focus on requirements and first principles applied to the technologies in question, it tries to bring inflated expectations down to earth. Economic, ecologic and social (noise) based well accepted evaluation principles are set against wishful thinking.

Design/methodology/approach – Aeronautical teaching basics are complemented with own thoughts and explanations. In addition, the results of past research projects are applied to the topic.

Findings – Electric air mobility may become useful in some areas of aviation. Small short-range general aviation aircraft may benefit from battery-electric or hybrid-electric propulsion. Urban air mobility in large cities will give time advantages to super-rich people, but mass transportation in cities will require a public urban transport system. Battery-electric passenger aircraft are neither economic nor ecologic. How overall advantages can be obtained from turbo-electric distributed propulsion (without batteries) is not clear. Maybe turbo-hydraulic propulsion has some weight advantages over the electric approach.

Research limitations/implications – Research findings are from basic considerations only. A detailed evaluation of system principles on a certain aircraft platform may lead to somewhat different results.

Practical implications – The discussion about electric air mobility concepts may get more factual. Investors may find some of the information provided easy to understand and helpful for their decision making.

Social implications – How to tackle challenges of resource depletion and environment pollution is a social question. Better knowledge of the problem enables the public to take a firm position in the discussion.

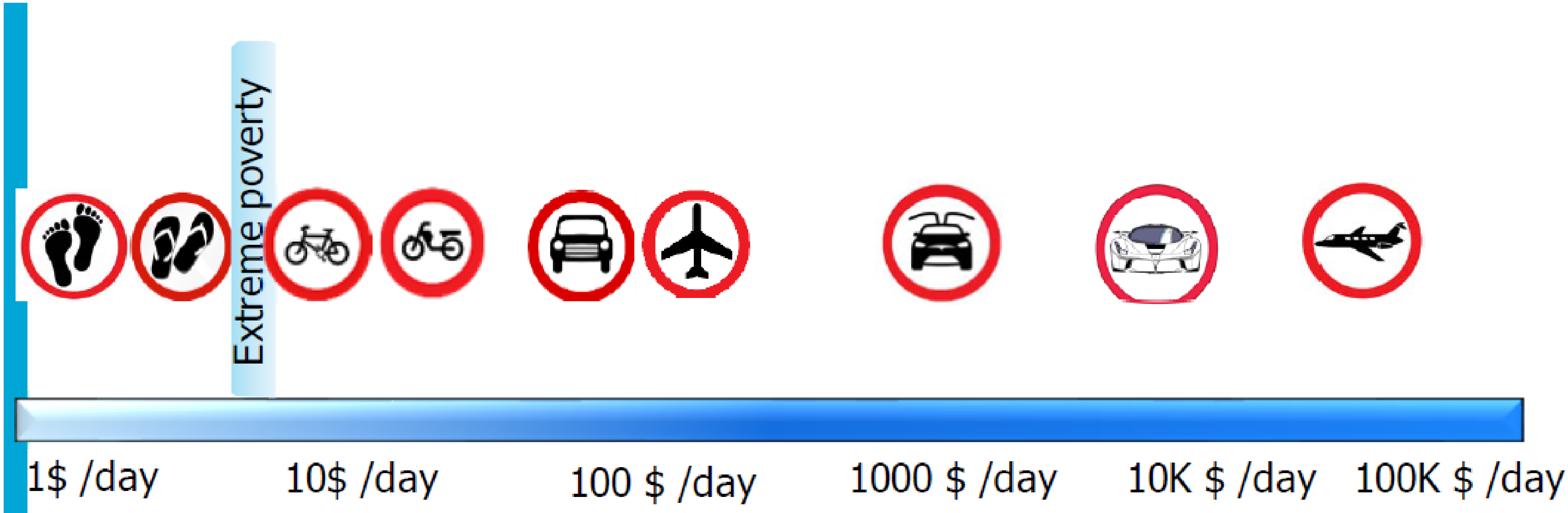
Originality/value – Holistic evaluation of electric air mobility has not much been applied yet. This presentation shows how to proceed.

Any further request may be directed to Prof. Dr.-Ing. Dieter Scholz, MSME
E-Mail see: http://www.ProfScholz.de

Initial Thoughts

Initial Thoughts

Modes of Transportation and Income



Av. Income / Day

www.gapminder.org

It is unfortunate that we have to use a logarithmic scale to depict disparity in incomes.
This is a shame on humanity.

Gangoli Rao 2018

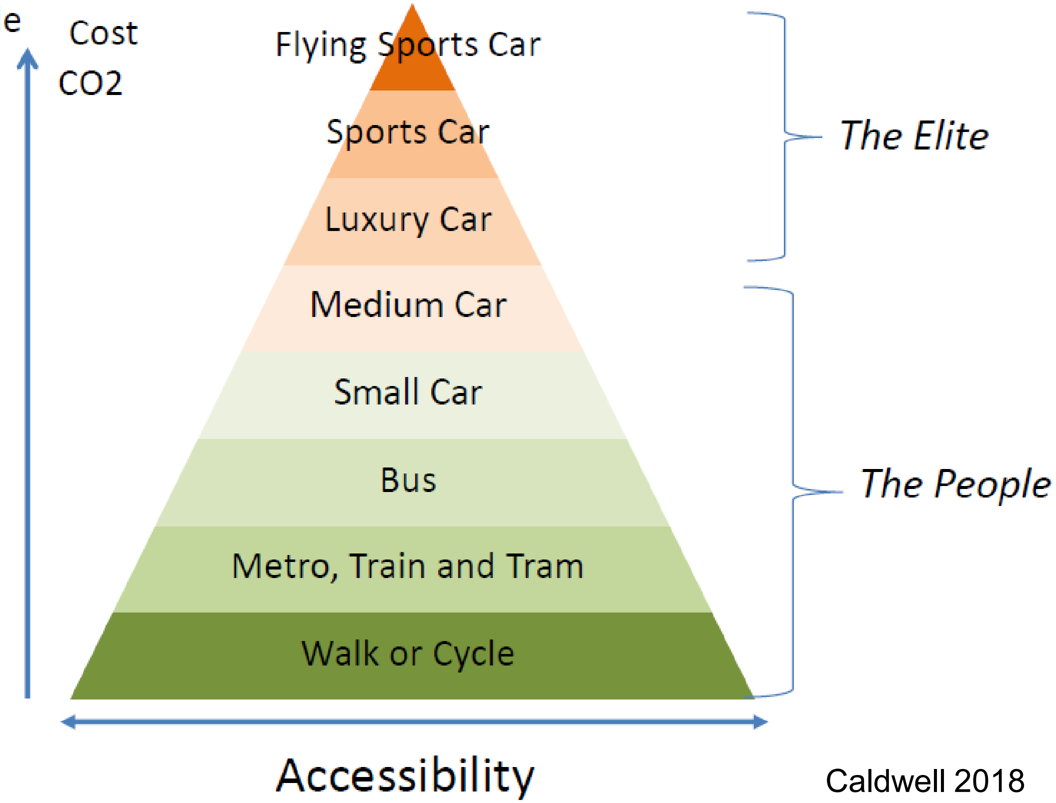
Modes of Transportation and Income

City Airbus, 4 passengers,
endurance: 15 min. (Airbus 2017a)

Max Pixel, CC0

Waiting for the City Airbus?

Speed Comfort
Convenience
Style Cost
CO2



- Flying Sports Car
- Sports Car
- Luxury Car
- Medium Car
- Small Car
- Bus
- Metro, Train and Tram
- Walk or Cycle

The Elite

The People

Accessibility

Caldwell 2018

Initial Thoughts

based on Caldwell 2018

Modes of Transportation and CO2

“Flying Taxi”? ……or “Flying Sports Car”?

Ehang184
Carbon fibre monocoque
360kg
106kW
=2.94kW/kg

CO2=1000g/km (in Dubai)

Lamborghini LP700
Carbon fibre monocoque
1575kg
515kW peak
=3.27kW/kg

CO2=370g/km

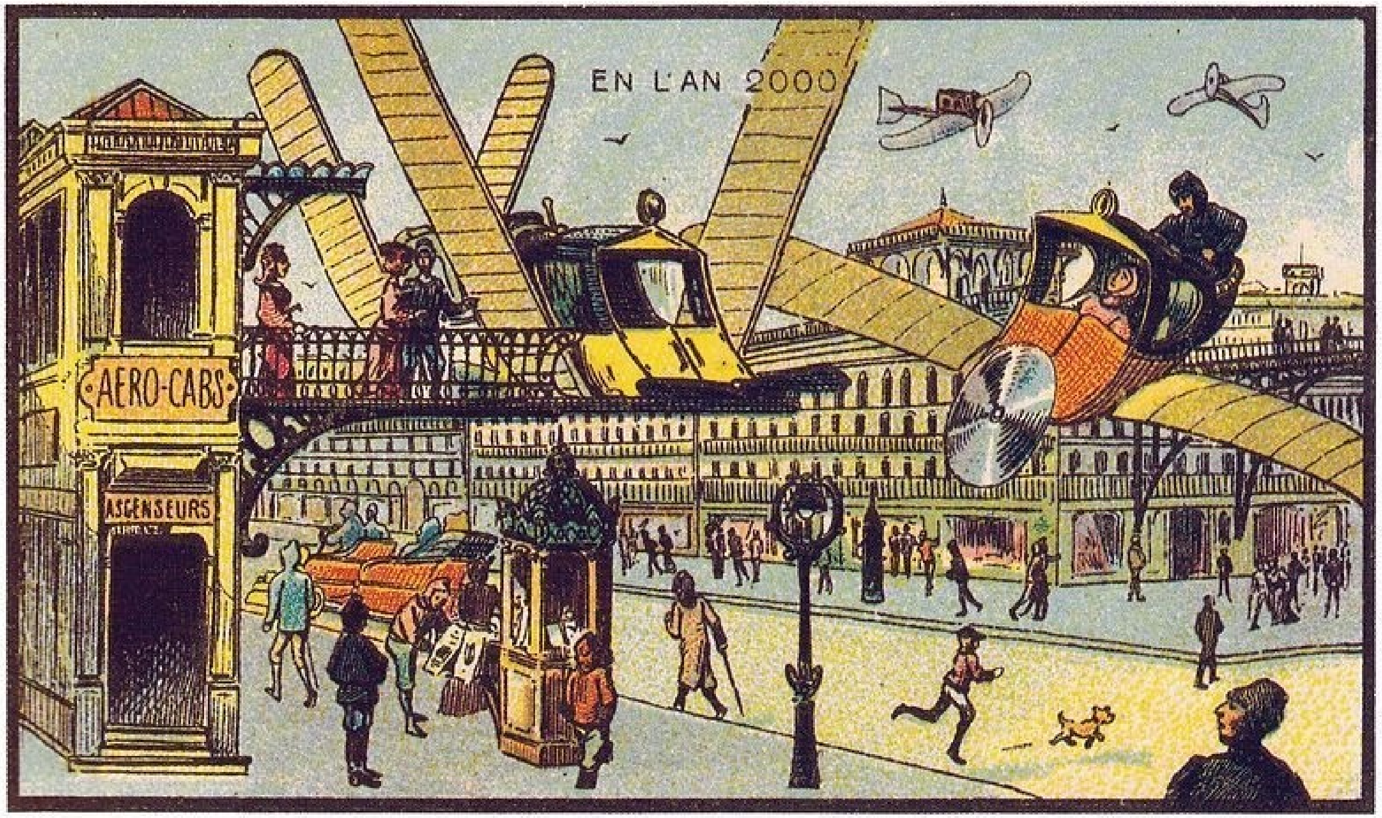
VW Golf TDI

4.2 l/100 km

CO2 = 106 g/km

Initial Thoughts

Predicting the Future



Aero-Cab Station

A french 1899 forecast of "AERO-CABS" in the year 2000 (courtesy of Prof. Zhuravlev)

Initial Thoughts

Media Hype or Media Circus and Greenwashing

Media Hype

Definition:
A news event for which the level of media coverage is perceived to be excessive or out of proportion to the event being covered.
(https://en.wikipedia.org/wiki/Media_circus)

Greenwashing

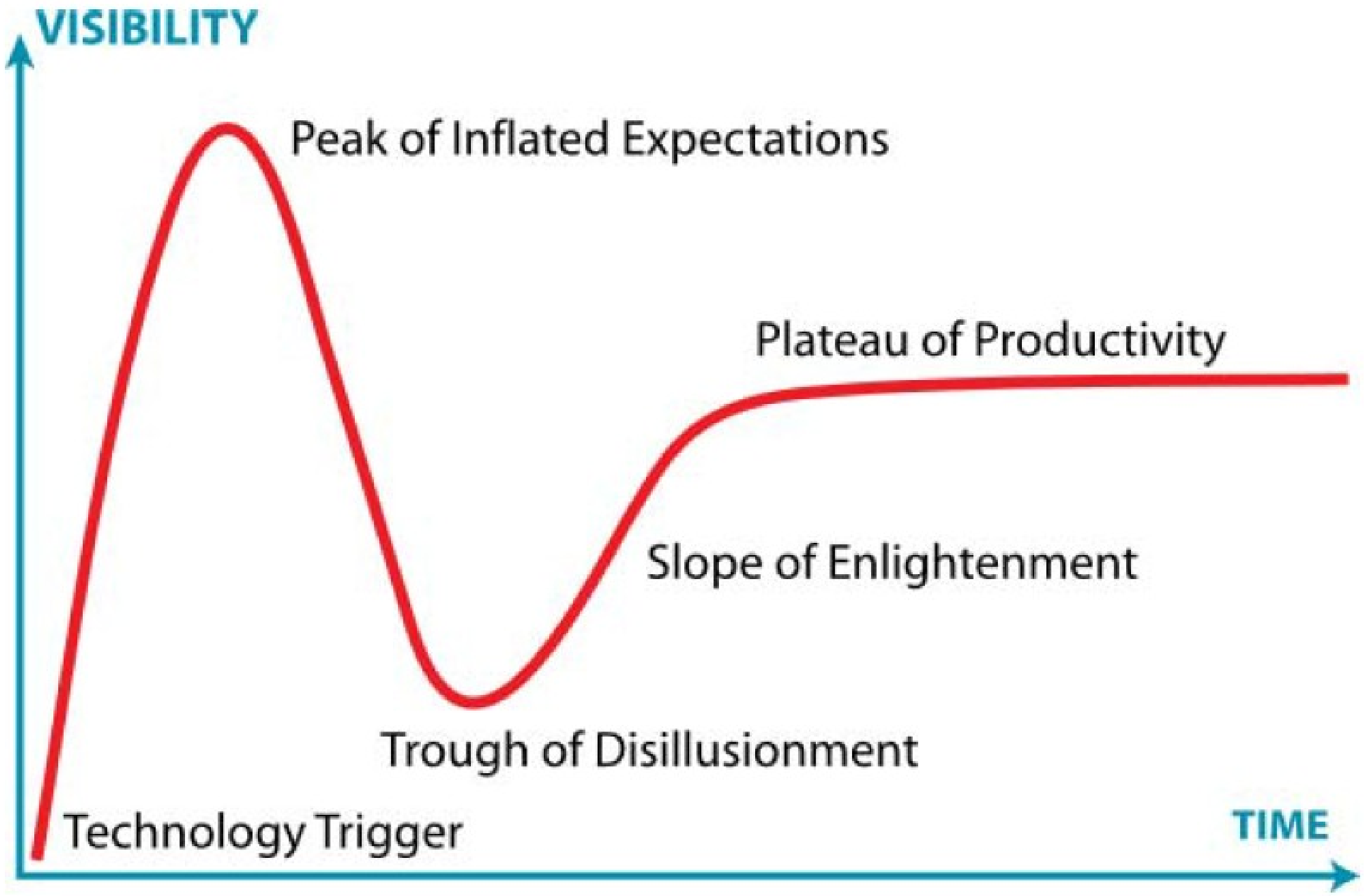
Definition:
A form of spin in which green PR or green marketing is deceptively used to promote the perception that an organization's products, aims or policies are environmentally friendly
(https://en.wikipedia.org/wiki/Greenwashing)

Criteria (translated):
Missing acts, borrowed plumes, hidden goal conflicts, lack of evidence, vague statements, wrong labels, irrelevant statements, lesser evil, untruths, Deep Greenwash
(https://de.wikipedia.org/wiki/Greenwashing)

Contents

Media Hype?

Hype Cycle (by information technology firm Gartner)

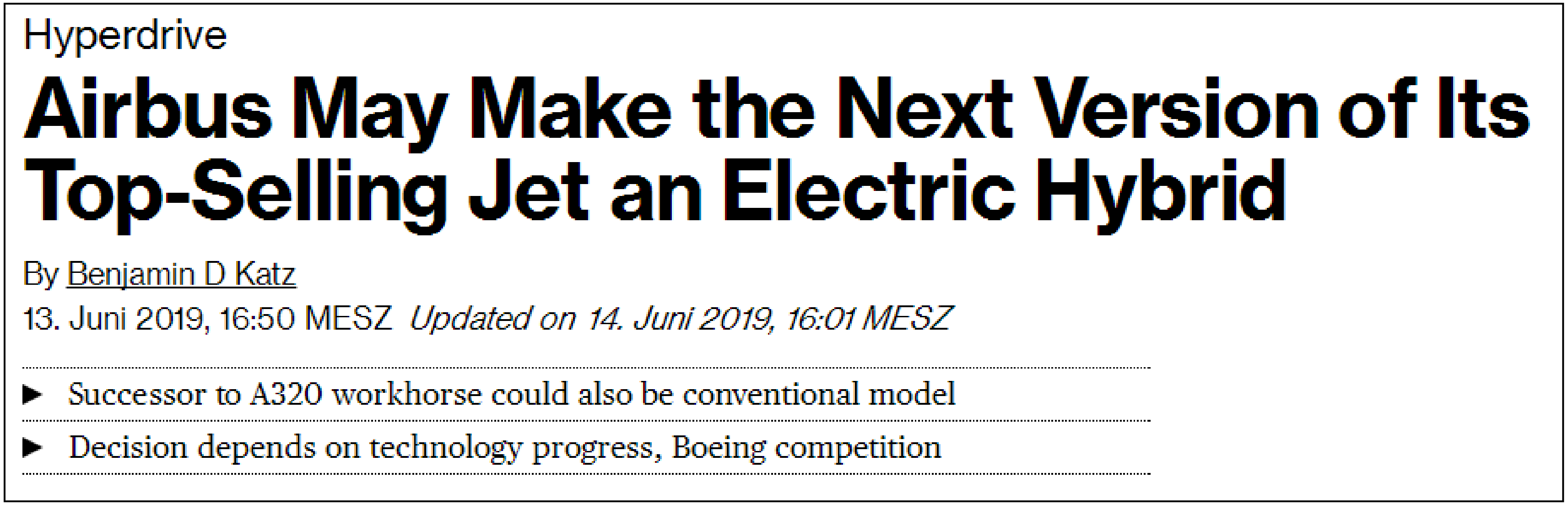


Kemp 2019

Media Hype?

A320 Successor ?

Bloomberg



Hyperdrive

Airbus May Make the Next Version of Its Top-Selling Jet an Electric Hybrid

By Benjamin D Katz

13. Juni 2019, 16:50 MESZ *Updated on 14. Juni 2019, 16:01 MESZ*

- Successor to A320 workhorse could also be conventional model
- Decision depends on technology progress, Boeing competition

Katz 2019

The launch of a hybrid model, while the biggest advance in the industry for decades, would bring its own challenges, not least convincing airlines to back technology that might initially offer only limited range and capacity. ?

! The aircraft would operate at slightly lower speeds, adding, for example, about 30 minutes to a typical flight within Europe.

Airbus is ultimately working toward a zero-emissions aircraft ?; though given the relative immaturity of the technology it's likely to have to develop a hybrid model first, head of engineering Jean-Brice Dumont said at the May briefing.

May 22 interview at the planemaker's headquarters in Toulouse, France.

Media Hype?

E-Fan X Hybrid-Electric Flight Demonstrator (based on Avro RJ100 / BAe 146)

Airbus 2018

Airbus 2018

The project was announced on 2017-11-28 (Airbus 2017b/c).

"Airbus will involve BAE Systems Regional Aircraft in the design of the modification ... to work together with the other partners to approve the modification and release the aircraft for flight under their Design Organisation Approval [DOA]." (E-Fan X project lead Olivier Maillard, Airbus 2018)

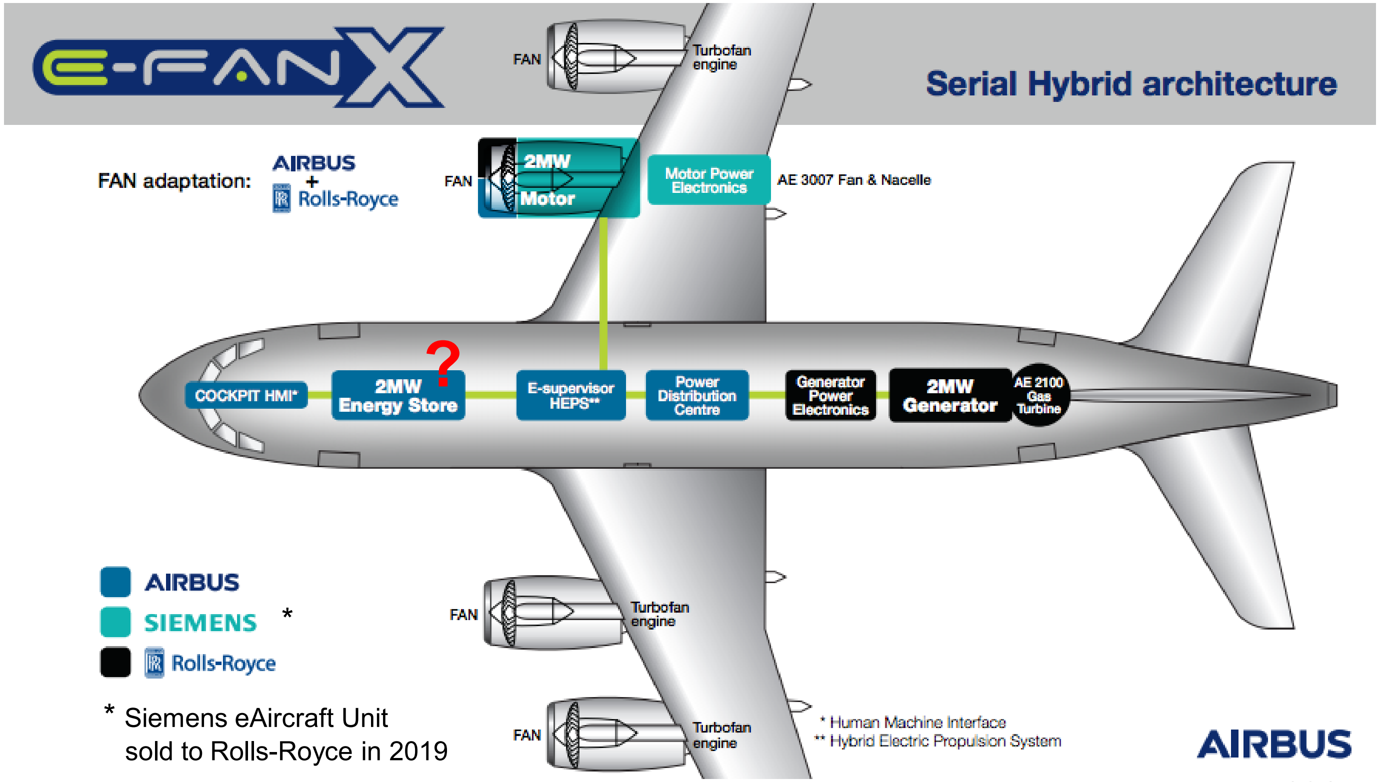
Note: Airbus as aircraft manufacturer only adds a few electronic componets to the project. Batteries are bought.

Airbus 2018

Media Hype?

E-Fan X Hybrid-Electric Flight Demonstrator

More at RAeS:
Robinson 2017



* Siemens eAircraft Unit
sold to Rolls-Royce in 2019

Rolls-Royce 2017

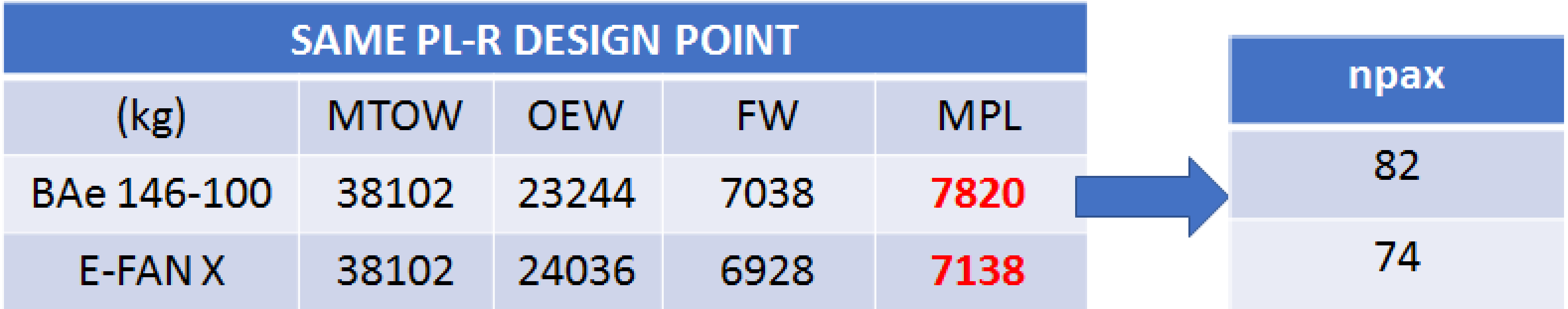
- Electric engines have at best the same mass as an aviation gas turbine.
- The new propulsion system (gas turbine, generator, electric motor) has at least 3 times the mass of the original propulsion system, which could do with only the gas turbine.

Media Hype?

E-Fan X Hybrid-Electric Flight Demonstrator

First insight:

- Given aircraft => Wing area, maximum loads, mass (MTOW, MZFW) relevant for certification is fixed!
- E-Fan X: Three Lycoming ALF 502 engines (old), one AE2100A turboshaft (new)
- New AE2100A gas turbine is slightly more efficient
- Take-off requires less than 2.5 MW => no batteries required (therefore eliminated here to improve design)
- Operating empty weight (OEW) increases => payload (MPL) decreases
  => number of passengers npax decreases to 74 (from 82)
- Direct Operating Costs (DOC) per passenger seat mile increase by about 9%



SAME PL-R DESIGN POINT				
(kg)	MTOW	OEW	FW	MPL
BAe 146-100	38102	23244	7038	**7820**
E-FAN X	38102	24036	6928	**7138**

npax
82
74

Preliminary caluclations by Diego Benegas Jayme.

Media Hype?

E-Fan X Hybrid-Electric Flight Demonstrator

Greenwashing

Airbus is giving false impression:

"Among the top challenges for today's aviation sector is to move towards a means of transport with improved environmental performance, that is more efficient and less reliant on fossil fuels. The partners are committed to meeting the EU technical environmental goals of the European Commission's Flightpath 2050 Vision for Aviation (reduction of CO2 by 75%, reduction of NOx by 90% and noise reduction by 65%). These cannot be achieved with the technologies existing today. Therefore, Airbus, Rolls-Royce and Siemens are investing in and focusing research work in different technology areas including electrification. Electric and hybrid-electric propulsion are seen today as among the most promising technologies for addressing these challenges."

Airbus 2017b

Translated from German: "The hybrid drive offers advantages above all with regard to noise emissions and consumption. Incidentally, the e-turbine, which draws its power from a fossil fueled generator rather than a battery, is expected to consume a good 25 percent less."

Focus 2017

Media Hype?

easyJet Full Electric Aircraft (9-seat demonstrator: 2019)

Greenwashing

Wright 2019

- Design for an easyJet-sized aircraft London - Amsterdam, Europe’s second busiest route, is seen as a strong contender for full electric flying in the future.
- easyJet ... confirmed progress ... towards its strategy to operate ... more sustainably and reduce noise from aviation.
- US start-up company, Wright Electric, has commenced work on an electric engine that will power a nine seater aircraft.
- Wright Electric partner Axter Aerospace already has a two seater aircraft flying, and the larger [nine seater] aircraft is expected to start flying in 2019.
- Work will commence on an easyJet-sized aircraft by aircraft designer Darold Cummings [Aerospace Consultant].

(EasyJet 2018)

More on Darold B. Cummings see under: CSULB 2016.

Media Hype?

easyJet Full Electric Aircraft (9-seat demonstrator: 2019)

Greenwashing

AXTER AEROSPACE *

Axter 2019

→ ? →

Seats:	2	9	> 100
Year:	2018 (2016)	2019	< 2038? **

Source: Easy Jet 2018

* Axter does not mention the EasyJet project on its website!

* Wright Electric's goal is for every short flight to be zero-emissions within 20 years (Wright 2019).

Media Hype?

Eviation Aircraft: Alice All-Electric Business and Commuter Aircraft

won't meet spec

- One main pusher propeller at the tail and two pusher propellers at the wingtips to improve efficiency
- 9 passengers (plus 2 pilots) up to 650 sm (1000 km) at a cruise speed of 240 kt
- Li-Ion battery: 900 kWh
- MTOW: 6350 kg

(https://www.eviation.co/alice as of 2019)

- Battery mass is 65% of total aircraft mass (without payload)
- Specific energy of battery is 400 Wh/kg [much too high]

(https://www.eviation.co/alice as of 2017)

EVIATION

Sarsfield 2019

- Service entry is expected in 2022
- Maximum payload: 1250 kg (including pilots). This is only 13.7% of MTOW (low due to batteries).
- 183 kg cargo (with assumed 97 kg per person)
- Direct Operating Costs (DOC): 200 USD per flight hour with 11 person at 240 kt

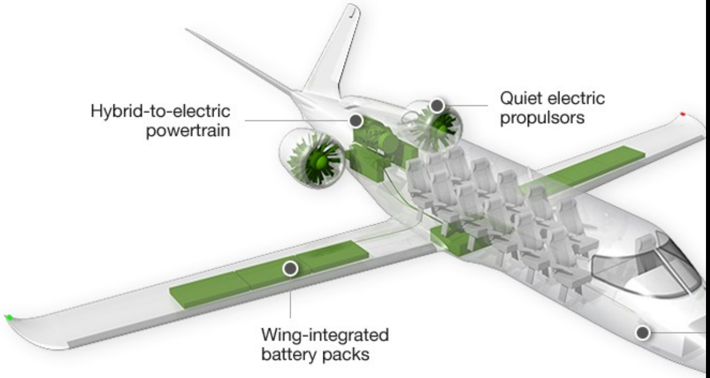
(Hemmerdinger 2019)

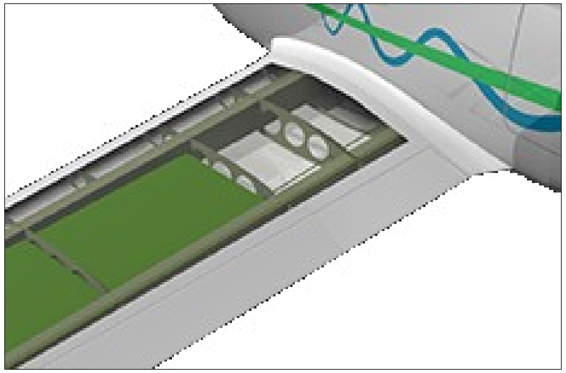
Own calculations based on given data:

- OEW: 2043 kg
- battery mass: 3434 kg
- OEW/MTOW = 0.32 (too low)
- Specific energy of battery calc.: 285 Wh/kg (high)
- L/D in cruise: 17.5 (based on 400 Wh/kg)
- L/D in cruise: 24.5 (based on 285 Wh/kg) (too high)

Media Hype?

ZUNUM Aero: Commuter Aircraft – Series Hybrid with Range Extender



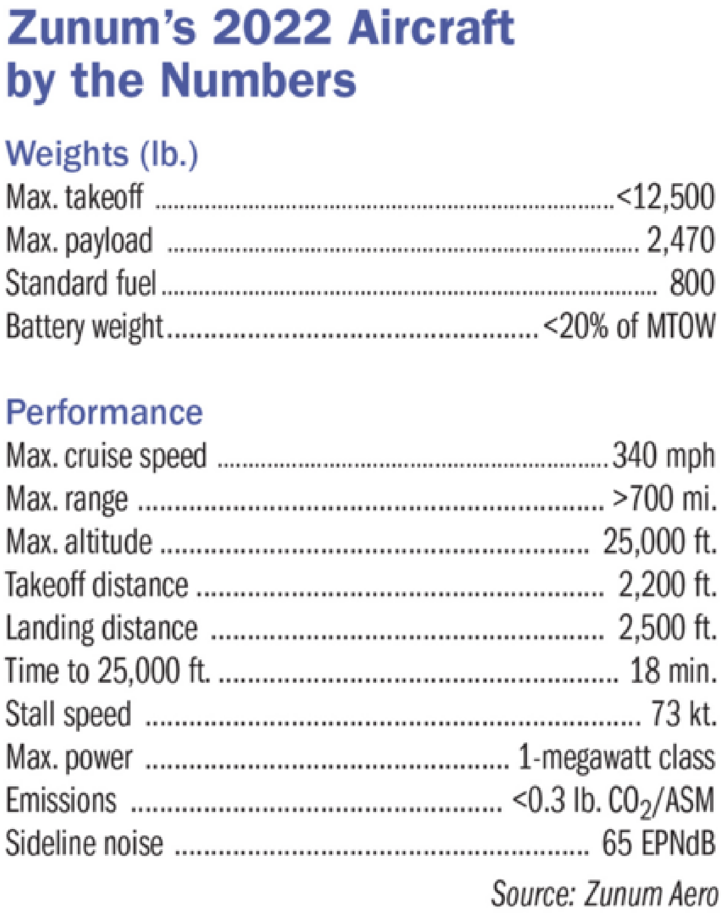


Zunum 2019

Media Hype?

ZUNUM Aero: Commuter Aircraft – Series Hybrid with Range Extender

Greenwashing



Zunum's 2022 Aircraft by the Numbers

Weights (lb.)

Max. takeoff	<12,500
Max. payload	2,470
Standard fuel	800
Battery weight	<20% of MTOW

Performance

Max. cruise speed	340 mph
Max. range	>700 mi.
Max. altitude	25,000 ft.
Takeoff distance	2,200 ft.
Landing distance	2,500 ft.
Time to 25,000 ft.	18 min.
Stall speed	73 kt.
Max. power	1-megawatt class
Emissions	<0.3 lb. CO_2/ASM
Sideline noise	65 EPNdB

Source: Zunum Aero

Warwick 2017

Zunum 2019: 11500 lbs = 5216 kg

Zunum 2019: 2500 lbs = 1134 kg

= 363 kg (will give range of about 1250 km = 780 SM as specified)

very low for battery electric flight

= 295 kt this gives *M* = 0,49 in 25000 ft

meant are 700 SM = 608 NM = 1126 km guaranteed by fuel !!!

Zunum 2019:

12 pax => 94.5 kg / pax (low)

battery mass (@ 20% MTOW): 2300 lbs = 1043 kg

OEW = 5900 lbs = 2676 kg

OEW/MTOW = 0,51 (realistic)

With 250 Wh/kg, L/D=18: battery range = 238 km = 148 SM

Aircraft flies only 21% of its range on batteries!

Media Hype?

Diamond Aircraft Multi-Engine Hybrid Electric Aircraft (based on DA40)

Diamond 2018

- First flight: 31st of October 2018 at Diamond Aircraft's headquarters in Wiener Neustadt, Austria.
- Two electric engines have been added on a forward canard, which combined can generate 150kW of take-off power.
- The diesel generator is located in the nose of the aircraft and can provide up to 110kW of power.
- Two batteries with 12 kWh each are mounted in the rear passenger compartment [taking two of the four seats!], and act as an energy storage buffer.
- Pure electric, the aircraft has an endurance of approximately 30 minutes. The hybrid system extends this to 5 hours.
- The objective of future flight tests will be to determine the exact efficiency increase achieved in comparison to similar non-electric aircraft.

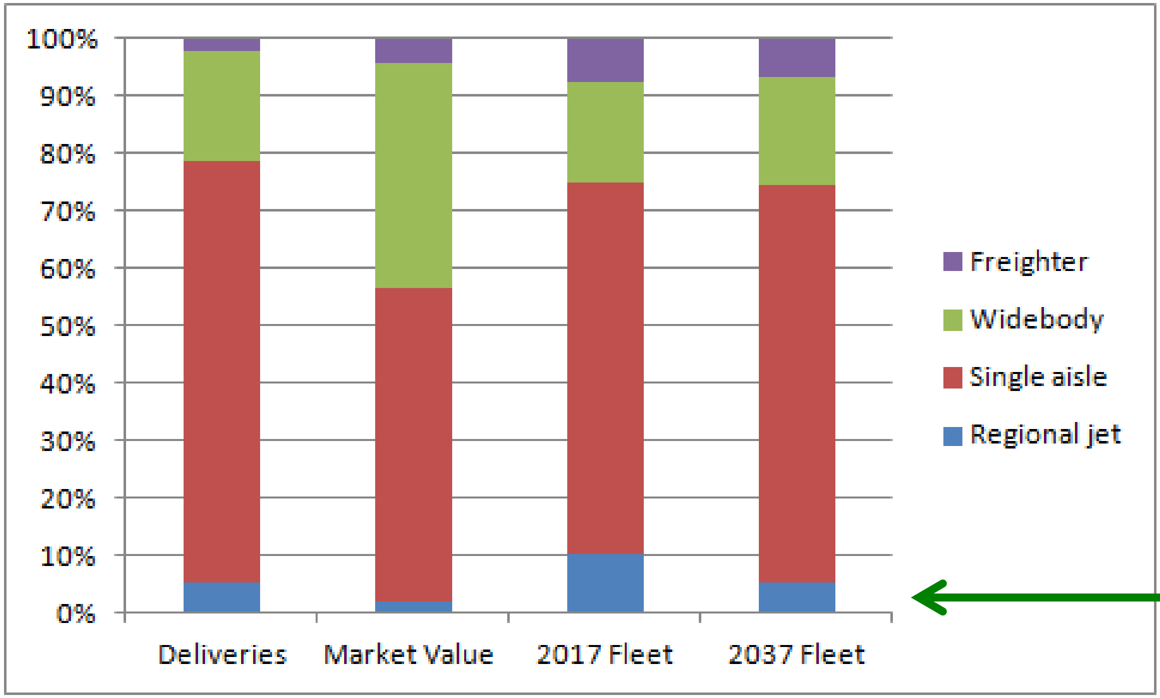
Remark: Direct Operating Costs (DOC) per passenger seat will roughly double with only 2 seats instead of 4!

Validation – Are we Doing the Right Thing?

Validation – Are we Doing the Right Thing?

Market Situation

Where is the market niche for short range, small passenger aircraft with (hybrid-) electric propulsion?



Data source: Boeing 2018

Boeing Commercial Market Outlook 2018-2037

(Hybrid-) electric propulsion with small short range passenger aircraft will be in **this niche market!**

Market value:
1.7% in next 20 years – declining.

Validation – Are we Doing the Right Thing?

Electric (Air) Mobility with/without Grid Connection?

"I am also much in favor of Electric Propulsion in aviation – once the problem with the Aerial Contact Line is solved!"

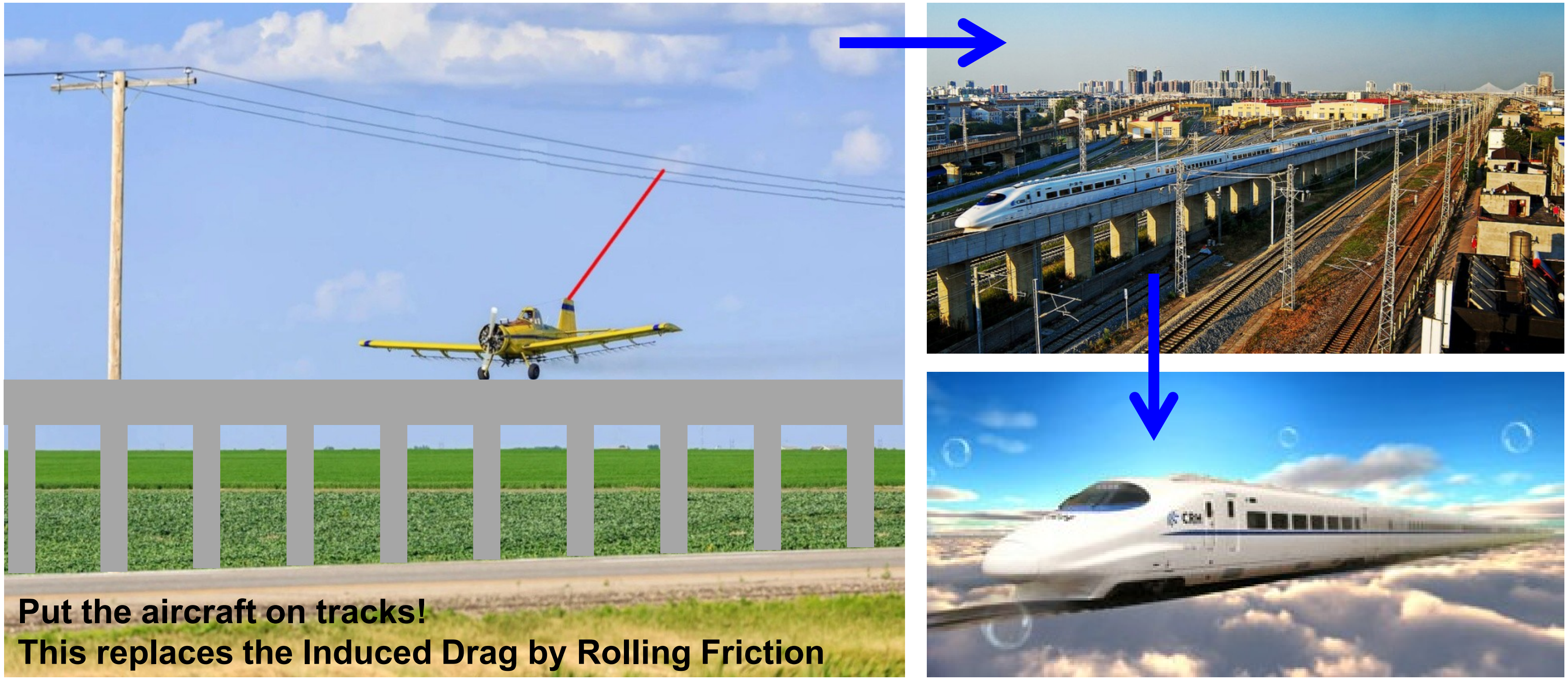
(one of my engineering friends)

We know:

- Electric propulsion suffers from large battery weight / low specific energy.
- Hybrid electric propulsion makes use of fuel with high specific energy, but leads to rather complicated, heavy and expensive systems.

Validation – Are we Doing the Right Thing?

Grid Connected Electric Mobility Operates Successfully on Tracks!

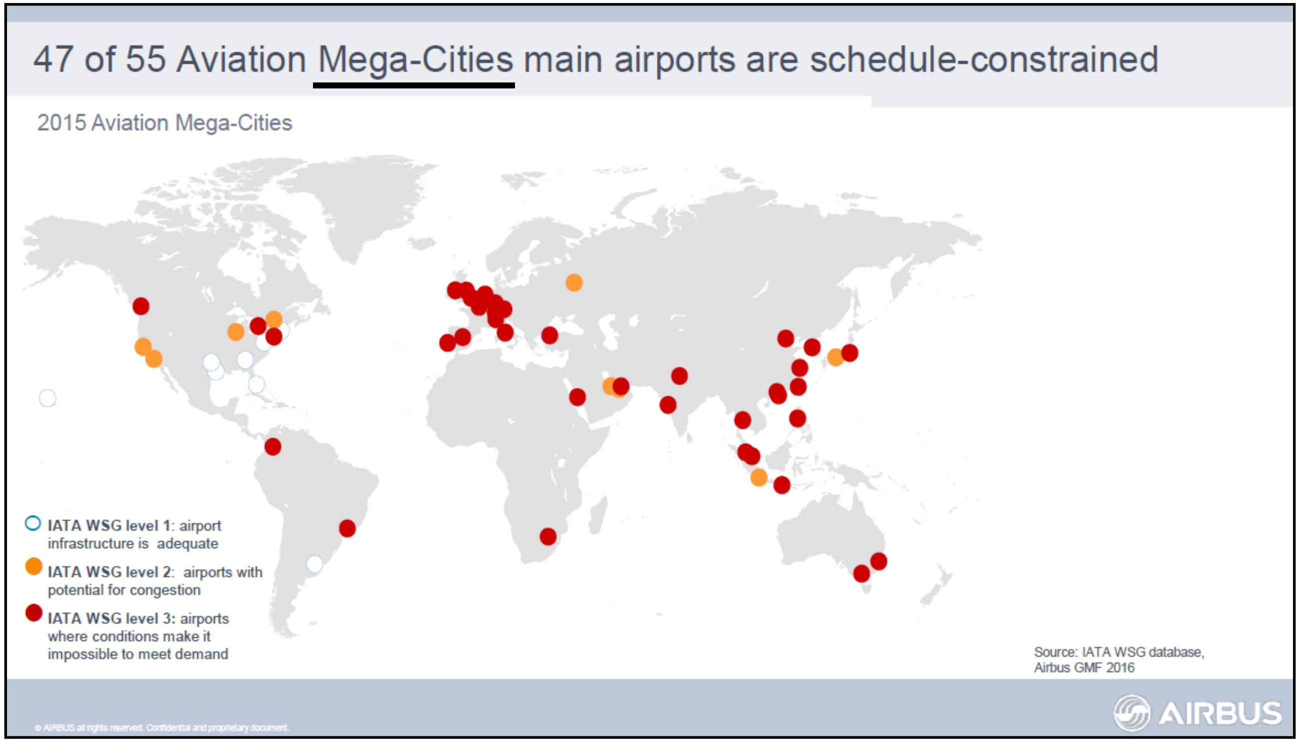


Put the aircraft on tracks!
This replaces the Induced Drag by Rolling Friction

- 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!

Validation – Are we Doing the Right Thing?

Mobility between Megacities – How?



47 of 55 Aviation Mega-Cities main airports are schedule-constrained

2015 Aviation Mega-Cities

○ **IATA WSG level 1**: airport infrastructure is adequate

● **IATA WSG level 2**: airports with potential for congestion

● **IATA WSG level 3**: airports where conditions make it impossible to meet demand

Source: IATA WSG database, Airbus GMF 2016

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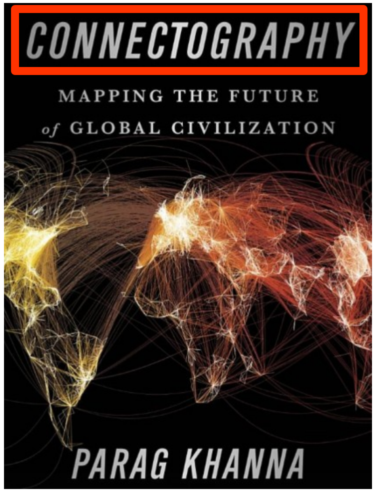
AIRBUS

Airbus 2016

- The world's population growth takes place in megacities.
- Airports at megacities are schedule-constrained already today – more so in the future.
- Adjacent megacities require mass capacity. Up to medium range => high speed trains needed!
- Megacities connect globally long range mostly over oceans => aircraft needed!

Validation – Are we Doing the Right Thing?

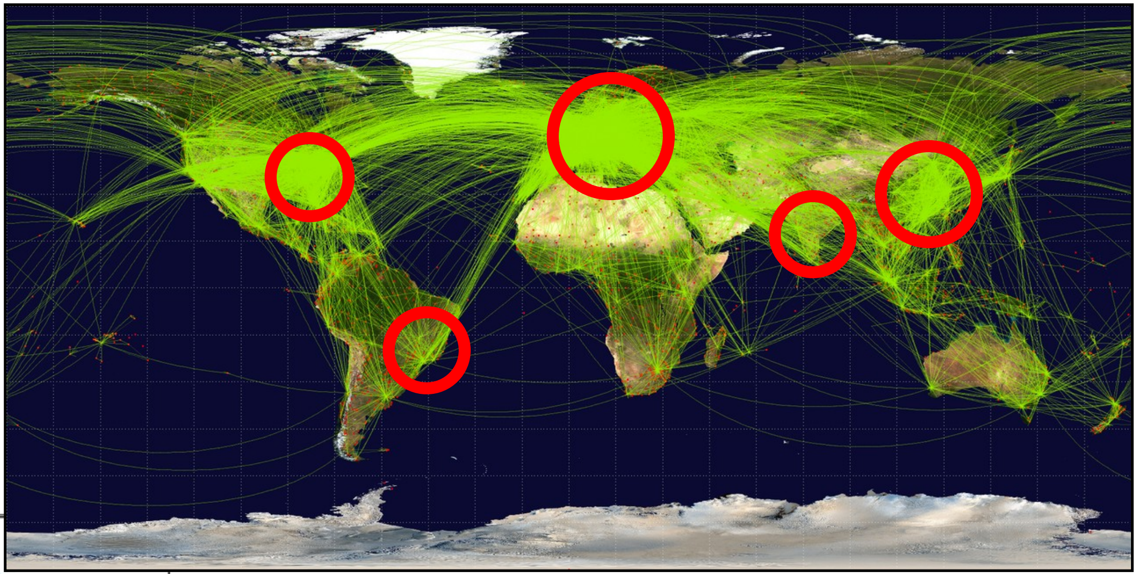


CONNECTOGRAPHY

MAPPING THE FUTURE of GLOBAL CIVILIZATION

PARAG KHANNA

Khanna 2016



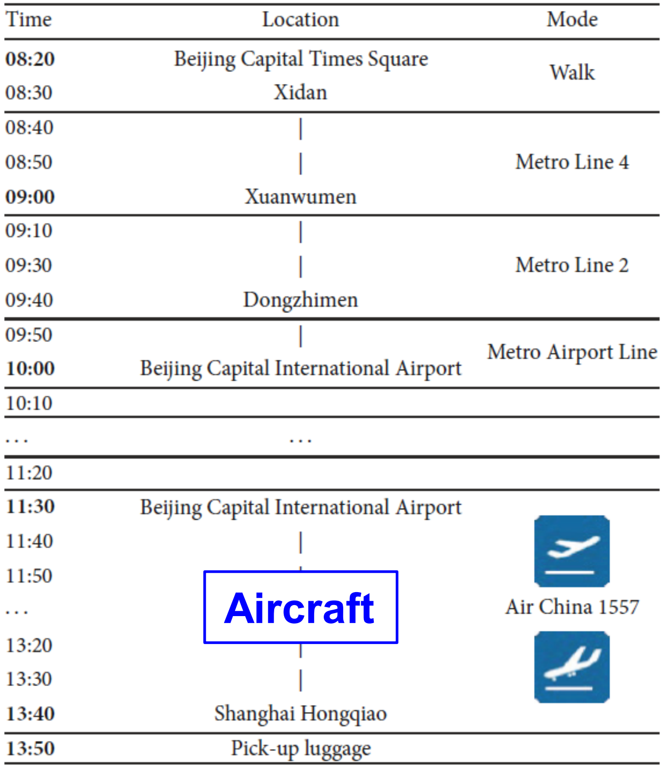
World Airline Routemap (Wikipedia 2009)

Maps of World 2018

○ Areas with adjacent megacities that will increasingly be *connected* by high speed trains.

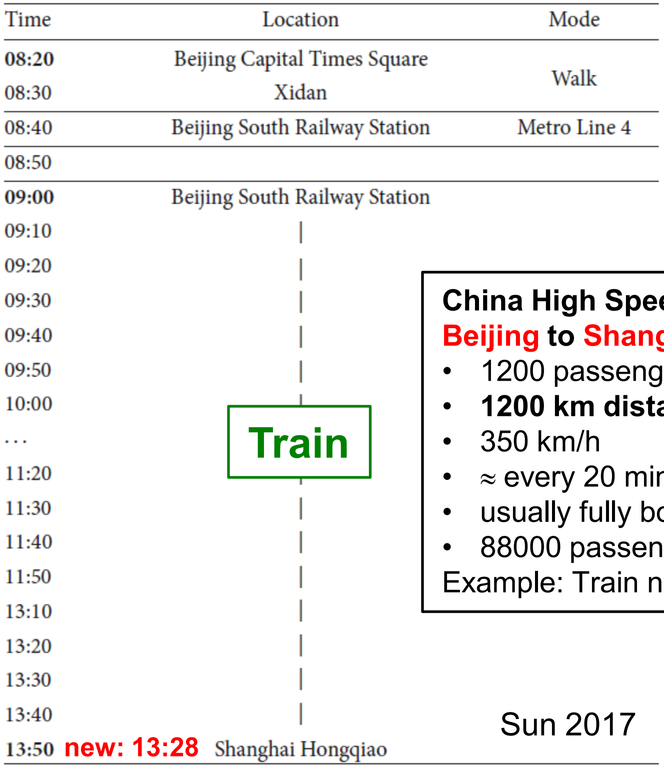
Validation – Are we Doing the Right Thing?

Connecting Adjacent Megacities – Beijing & Shanghai – Comparing Aircraft with 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	|	
. . .		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		
. . .		
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.

Validation – Are we Doing the Right Thing?

Increasing Political Pressure ...

... to **shift short range flights** from airports **to trains**!

(190 km)

Per Jet von Frankfurt nach Köln

Verlagerung der Kurzstreckenflüge auf die Bahn würde Mensch und Umwelt entlasten

Frankfurter Rundschau, 26.10.2018

DB Rail&Fly

Kleine Anfragen an die Bundes- und Landesregierungen und die Antworten:

08.10.2018(Q)	19/4784	Potenzial der Verlagerung von Inlandsflügen auf die Bahn am Flughafen **Frankfurt**
18.09.2017(A)	18/13587	Potenzial der **Verlagerung von Flügen auf die Bahn** an den **Berliner** Flughäfen
06.09.2017(A)	18/13510	Potenzial der Verlagerung von Flügen auf die Bahn am Flughafen **München**
17.06.2016(A)	19/3263(HE)	Potenzial der Verlagerung von Passagierflügen auf die Bahn am Flughafen **Frankfurt** a.M.
16.06.2016(A)	19/3264(HE)	Potenzial der Verlagerung von Frachtflügen auf die Bahn am Flughafen **Frankfurt** a. M.
28.08.2015(A)	18/5879	Potenzial der Verlagerung von Flügen auf die Bahn am Flughafen **München**
06.05.2014(A)	18/1324	Potenzial der Verlagerung von Flügen auf die Bahn am Flughafen **Frankfurt** am Main
05.08.2014(A)	19/542(HE)	Verlagerung Kurzstreckenflüge auf die Bahn
07.09.2012(A)	17/10615	Potenzial der Verlagerung von Flügen auf die Bahn am Flughafen **Hannover**
05.04.2012(A)	17/9274	Potenzial der Verlagerung von Flügen auf die Bahn am Flughafen **Frankfurt** am Main

...

http://dipbt.bundestag.de Q: Question; A: Answer; HE: Hessen

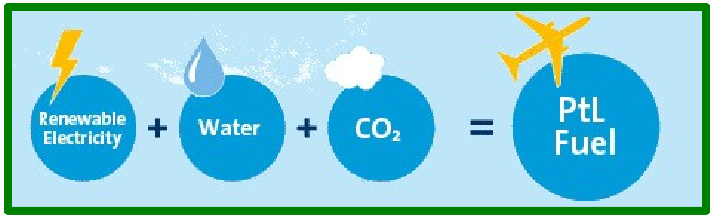
Validation – Are we Doing the Right Thing?

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
4.	regenerative electricity	=>	battery	=>	electric engine	**electric**: only for short range
5.	regenerative electricity	=>	LH2	=>	jet engine	new infrastructure & planes
6.	regenerative electricity	=>	LH2 => fuel cell	=>	electric engine	see 5.; trade-off !
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** , ???

PtL: Power to Liquid

GT: Gasturbine; **Gen.**: Generator



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

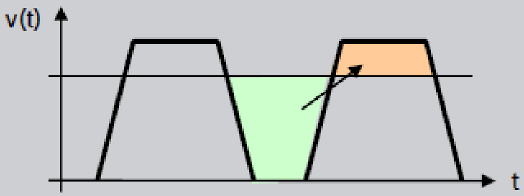
Validation – Are we Doing the Right Thing?

Electric versus Hydraulic Hybrid Propulsion

Geerling 2017

Electric Hybrid Technology

Unused(Diesel)Power charges electric storing device



Characteristics/ Advantages:

- Extension of reach
- reduction of peak loads
- Power peaks are balanced by batteries
- Additional electrical power
- Lower(Diesel)Power required

→Electric hybrid allows storage of high amounts of energy

Hydraulic Hybrid Technology

Recuperation of the kinetic / braking energy charges hydraulic accumulators

Characteristics/ Advantages:

- Vehicle inertia feeds accumulators
- Acceleration supported by stored hydraulic energy
- good recovery of kinetic energy
- Starting benefits from high power density
- High torque available, especially in the acceleration phase

→Hydraulic hybrid allows storage of high amounts of powers

In contrast to both of this: Aircraft have a very even load profile during most time of the operation!

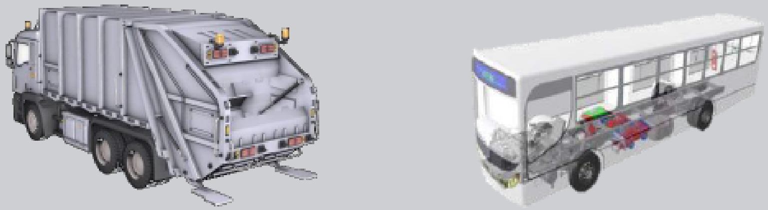
Validation – Are we Doing the Right Thing?

Electric versus Hydraulic Hybrid Propulsion

Geerling 2017

Possible Applications

→ Slow vehicles with multiple start and stop situations in normal operation, such as…
… busses, underground, tram
… garbage trucks
… construction vehicles
…



Customer Benefits HRB System (Hybrid Hydraulic)

- Fuel Savings by up to 15-30%
  - Equal Reduction of emission
- Reduction of brake wear and fine dust abrasion thanks to hydraulic braking
- Improved performance/ acceleration boost by hydraulic support (up to 10% increase)
- Easy integration in existing system (AddOn System)
- Low cost components (“from the shelf”)
- Functional safety according to ISO26262

Hydraulic Hybrid:	short time energy storing in short start-stop-cycles (high power density)
Electric Hybrid:	continuous storing of unused Power (high energy density)
HRB:	Hydrostatic Regenerative Breaking

In contrast to this: Aircraft have a very even load profile during most time of the operation!

Summing up the Considerations for Validation

- Physics favor trains over aircraft (*low drag due to weight*) => less energy, less CO2.
- PtL for jet engines is big competition for any electric flight bringing regenerative energy into aircraft.
- Hybrid propulsion has better applications than aircraft.
- Unpredictable political environment for short range flights.
- 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 better on **short range** (*less access time to station, less waiting time in station, ...*).
- Trains better to connect adjancent 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).

So, again:

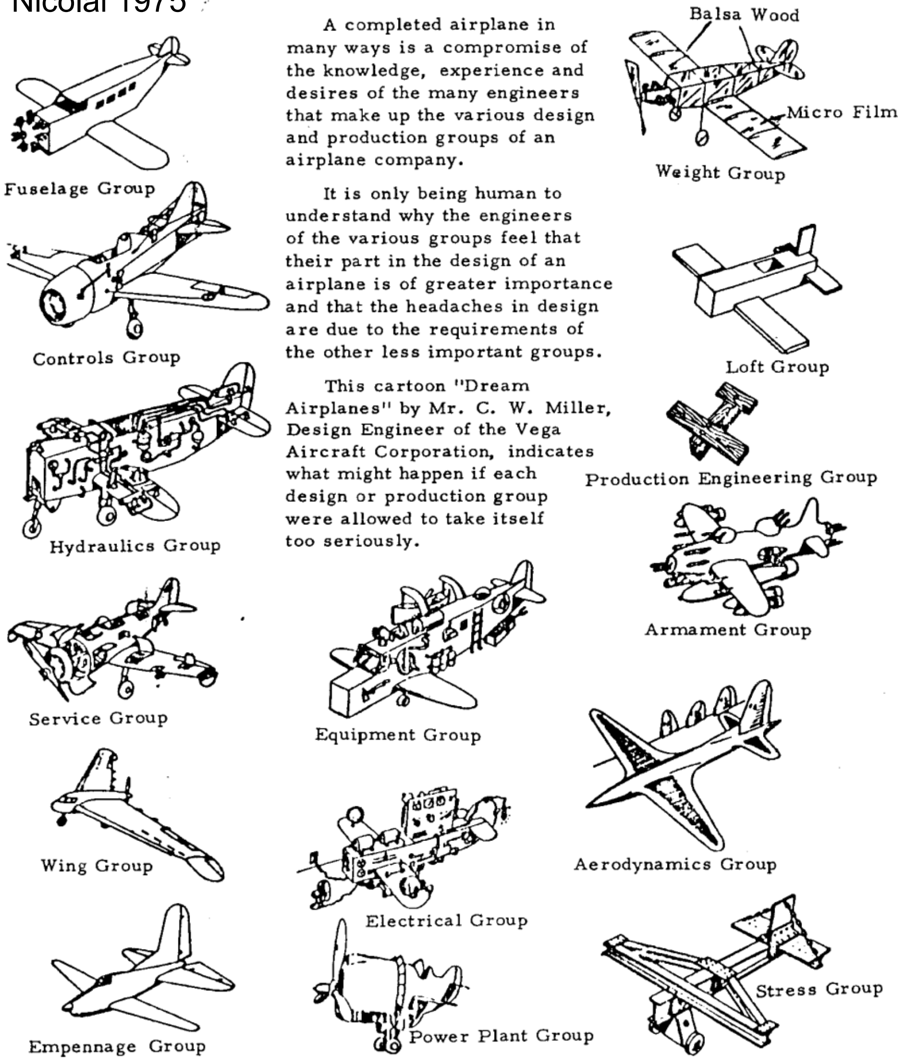
Where is the market niche for short range, small passenger aircraft with (hybrid-) electric propulsion?

Aircraft Design Basics

Aircraft Design Wisdom

- **No discipline should dominate** in Aircraft Design (see on right). Do not design your aircraft around your electric engine!
- Start from **Top Level Aircraft Requirements** (TLAR) that are based on market needs. Do not trim the TLARs such to make your design ideas shine.
- Start with a **wide variety of design principles** and narrow down based on trade studies / **evaluation**. Do not get locked in by one design idea (electric hybrid propulsion).
- **Engine integration** is an important part of Overall Aircraft Design (OAD) and effects many disciplines. Do not put your engines somewhere on the aircraft based just on one (good) idea.

Nicolai 1975



A completed airplane in many ways is a compromise of the knowledge, experience and desires of the many engineers that make up the various design and production groups of an airplane company.

It is only being human to understand why the engineers of the various groups feel that their part in the design of an airplane is of greater importance and that the headaches in design are due to the requirements of the other less important groups.

This cartoon "Dream Airplanes" by Mr. C. W. Miller, Design Engineer of the Vega Aircraft Corporation, indicates what might happen if each design or production group were allowed to take itself too seriously.

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.

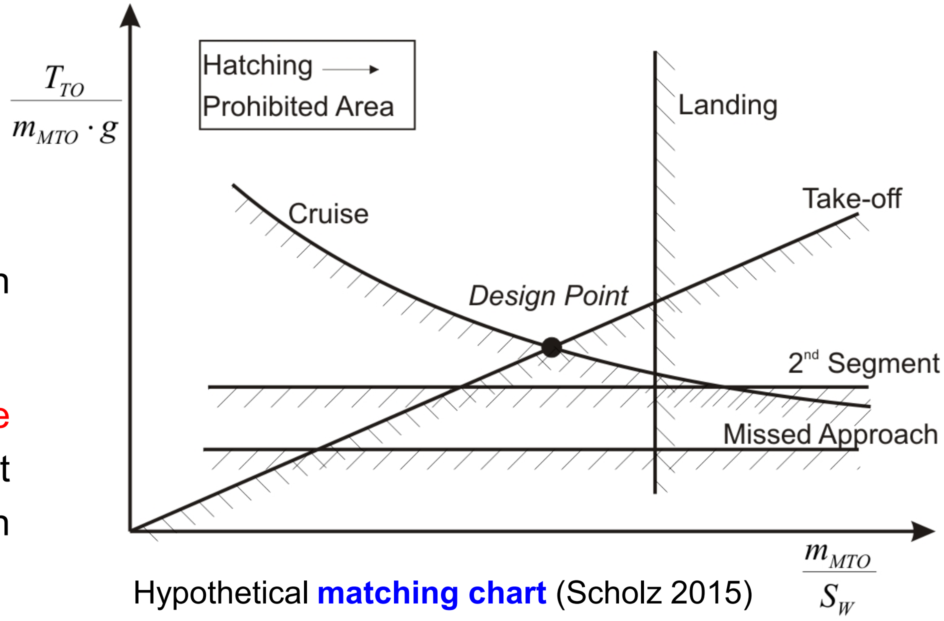
Maximum Take-Off mass is a surrogate parameter for cost !

Several Design Requirements Considered Simultaneously with the Matching Chart

- Requirements:
  - **Take-off** (engine failure)
  - **2nd Segment Climb** (engine failure)
  - (Time to Initial Cruise Altitude, not shown in chart)
  - **Cruise**
  - **Missed Approach** (engine failure)
  - **Landing**

- Heuristic for an optimum aircraft:
  - Lines from Take-Off, Landing and Cruise meet in one point
  - Move Cruise Line by selecting $1 \leq x_{opt} \leq 1.31$ for $V_{opt} = x_{opt} \cdot V_{md}$

- Thrust-to-Weight versus Wing Loading.
- Graphical Optimization to find the Design Point.
- Note: Some design features may not have an effect, if they influence a flight phase that has (in one particular design) no effect on the Design Point.



Hypothetical **matching chart** (Scholz 2015)

Find detailed information on

Aircraft Design

at

Hamburg Open Online University (HOOU)

http://hoou.ProfScholz.de

Scholz 2015

Aircraft Design for Electric Propulsion

First Law of Aircraft Design – Consequences for Electric Propulsion

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

- The "First Law of Aircraft Design" may have no solution.
- No solution, if m_{MTO} is infinity or negative.
- No solution if m_F / m_{MTO} is too large:
  - range is too high,
  - specific energy of fuel or batteries is too low,
  - propulsion is inefficient,
  - aerodynamics are inefficient.
- No solution, if m_{OE} / m_{MTO} is too large (typical value: m_{OE} / m_{MTO} = 0.5):
  - structure is too heavy
  - systems are too heavy
  - propulsion is too heavy

- Maximum take-off mass m_{MTO} is proportional to payload m_{PL} .
- Viability of electrical propulsion is not a matter of aircraft size.
  Very large electrical aircraft would be possible (if technology is ready)!

- Viability of electric propulsion is strongly a matter of
  - range and
  - specific energy.

Savings due to a Large Number of (Electric) Engines?

- Engine Maintenance Costs:
  - Knowledge: Maintenance costs increase with number of engines.
  - Apparent fact: Maintenance costs increase strongly with number of jet engines.
  - Assumed: Maintenance costs increase only moderately with number of electrical engines.
  - Hence: A large number of engines can be used with little detrimental effect on maintenance costs, if engines are electrical (and hence simple!?).
- A large number of engines reduces thrust requirements at engine failure (OEI) ...
  - during climb (if CS-25 interpretation is favorable – separate page)
  - during take-off (if CS-25 remains unchanged – separate page)
- A large number of engines (distributed propulsion along wing span) ...
  - does not help to increase maximum lift coefficient considerations, because lift needs to be achieved also with engines failed,
  - does help to reduces wing bending and hence reduces wing mass.

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

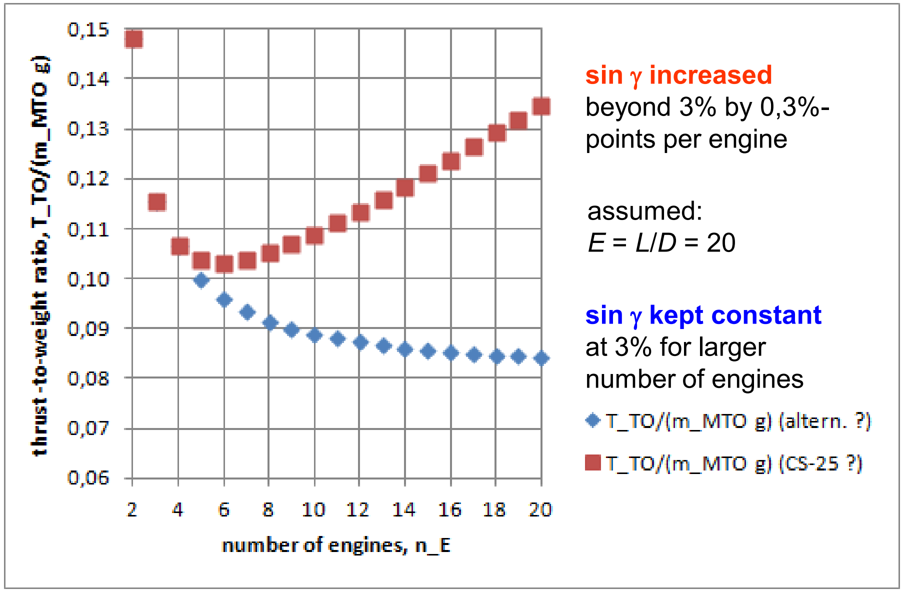
sin γ ↓

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

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



sin γ increased beyond 3% by 0,3%-points per engine

assumed:
E = *L*/*D* = 20

sin γ kept constant at 3% for larger number of engines

- 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?

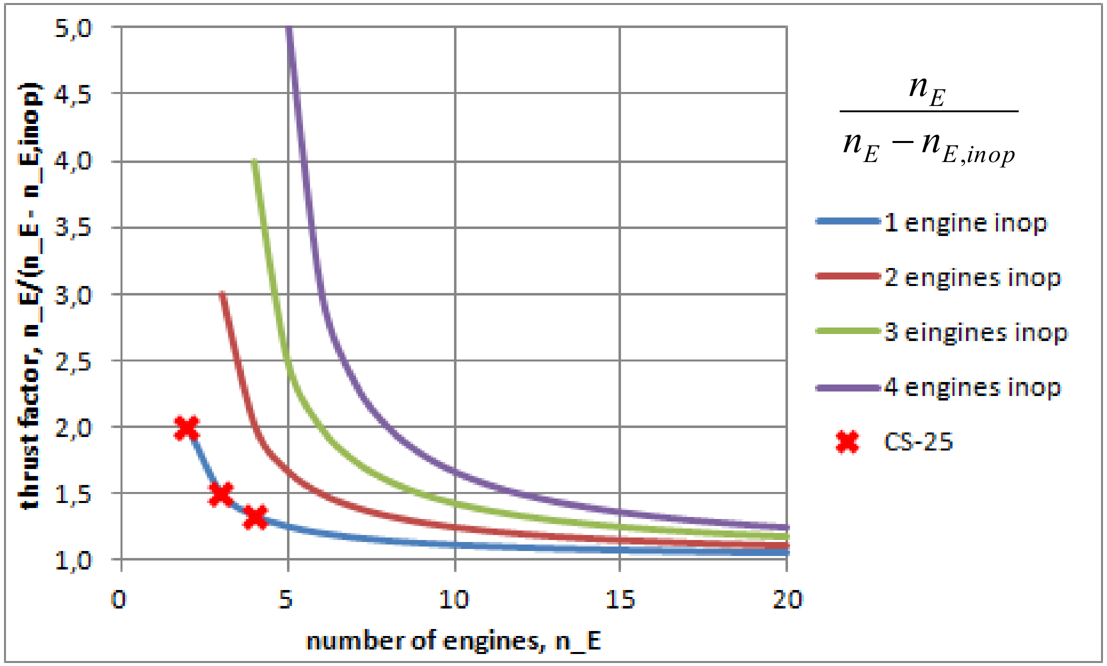
CS 25.107 Take-off speeds

(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



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

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.

Savings due to a Large Number of (Electric) Engines? – Propeller Efficiency

- A large number of engines can be used to reduce the propeller diameter, *D* at constant disk area, *A*. This would only reduce propeller tip speed and tip Mach number M_{tip} and result in higher propeller efficiency at constant RPM.

$$\lambda = U/V \qquad U = \omega D/2 = \pi n D$$

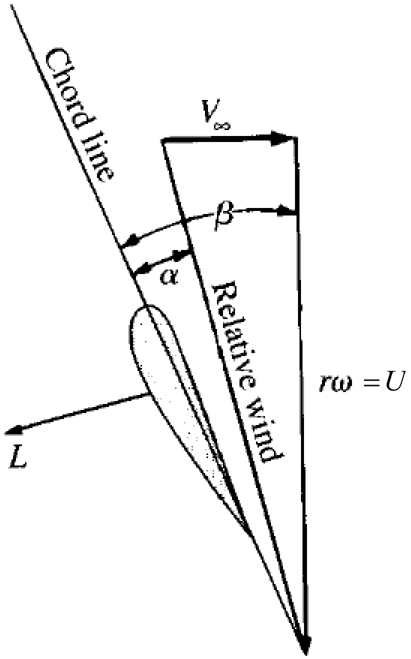
$$\lambda = \pi n D/V = \pi/J \qquad J = \frac{V}{n D} = \pi/\lambda \quad \text{advance ratio}$$

$$M = V/a \qquad M_{tip} = U/a \qquad U = \lambda V$$

$$M_{tip} = \frac{\lambda V}{a} = \frac{\pi n D}{a}$$

λ= *U*/*V*
follows from
required α

However, M_{tip} is independent of *D* and only proportional to *V*.
Smaller *D* requires larger RPM, *n*.



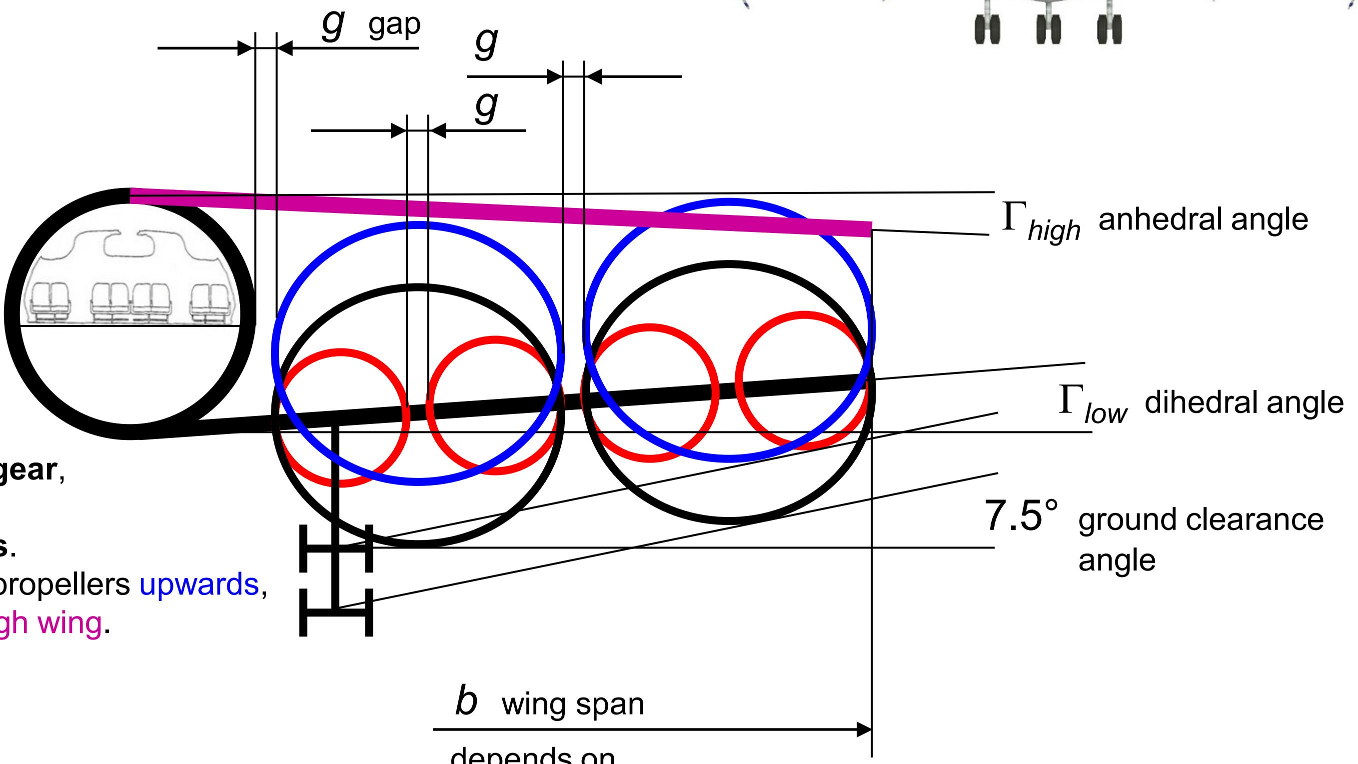
- A large number of engines can be used to increase total propeller disk area, *A* at constant propeller diameter, *D*. Propeller ground clearance is kept. This leads to lower disk loading and hence higher propeller efficiency.

$$\eta_{prop} \approx \frac{2 \cdot \left(1 - \lambda^2 \cdot \ln\left(1 + \frac{1}{\lambda^2}\right)\right)}{1 + \sqrt{1 + \frac{T}{q \cdot A}} - 2 \cdot \lambda^2 \cdot \ln\left(1 + \frac{1}{\lambda^2}\right)}$$

η_{prop} without wave drag (Truckenbrodt 1999)

Investigation of Propeller Area ...

... at least 2 times bigger with only 4 engines
instead of 8 engines!



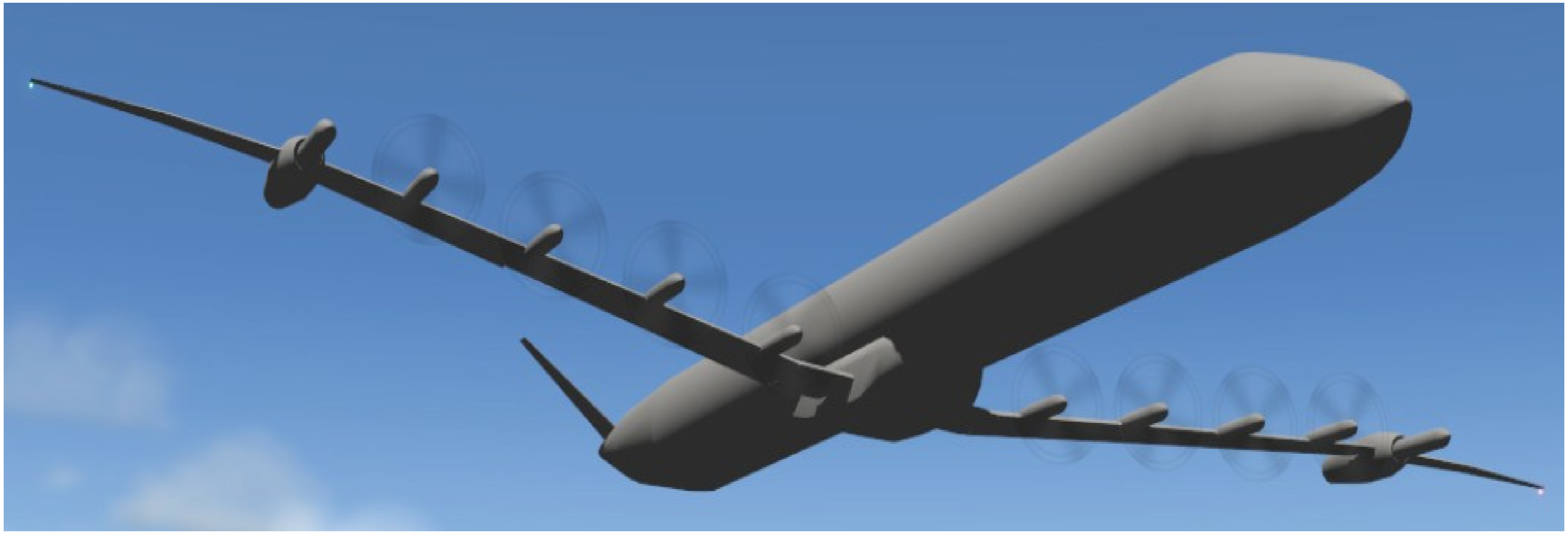
length of landing gear,
depends on
number of engines.
Alternatively: shift propellers upwards,
maybe mount on high wing.

depends on
ICAO aerodrome reference codes
24 m, 36 m, 52 m, 65 m, 80 m
=> propellers should not exceed wing tip!

... in Contrast Rolls-Royce thinks ...

Translated from German: "For Rolls Royce, for example, a gas turbine uses a generator to produce the electricity used for electric motors and on-board functions. The aim is to save up to 35 percent of the emissions of an aircraft in this way by changing the aircraft design with numerous small, electrically driven propellers, says Ulrich Wenger, head of technology at the engine manufacturer.

Rolls-Royce (NAS 2016)

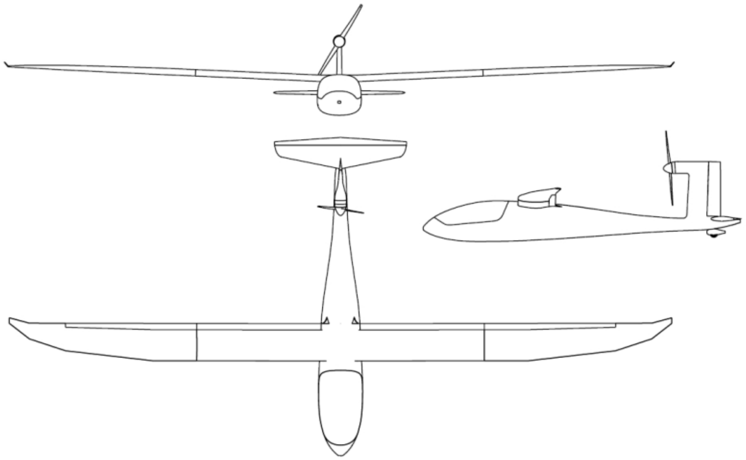


Rolls-Royce (NAS 2016)

Engine Integraton – Examples

e-Genius
Uni Stuttgart

- **Integration of the engine in the tail.** Particularly electrical motors with their compact configuration are suitable for this. Advantages:
  - Compared to conventional touring motor gliders a substantial larger propeller-diameter can be realized without a high and consequentially heavier undercarriage. This leads to an increased propeller-efficiency.
  - The front body part has the aerodynamic quality of a modern glider (no vorticities and local impact pressure peaks) and thus a very small drag.
  - The propeller is well protected from ground contact.



e-Genius 2018

Engine Integraton – Examples

E-Fan
Airbus

Airbus:

- **Two ducted**, variable pitch **fans** are spun by two electric motors.
- The ducting increases the thrust [compared to an unducted propeller with the same diameter] while reducing noise.
  (Szondy 2014)

- Ducted fans have lower propeller efficiency. For the same thrust they only need a smaller diameter and move less air mass at higher velocity. This results in a lower propulsive efficiency (despite reduced tip losses). Detrimental also: higher friction drag and added weight from the shroud and support structure.

- **Ducted fans** were chosen to make the aircraft **look good**.
  (Oral: Corporate Technical Office, Airbus Group, 2015)

Airbus' concept art: E-Fan 2.0 (Szondy 2014)

E-Fan (DGLR 2015)

Maximum Relative Battery Mass

m_{MTO} : Maximum Take–Off mass

m_{bat} : battery mass

m_{OE} : Operating Empty mass

m_{PL} : PayLoad

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

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

$$\frac{m_{OE}}{m_{MTO}} \approx 0.50$$ **technology parameter**

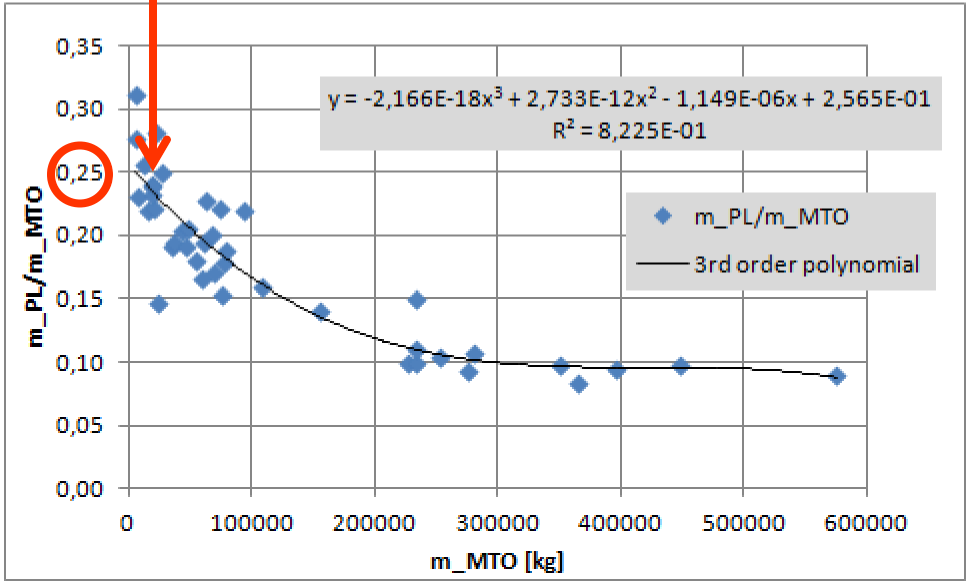
$$\frac{m_{PL}}{m_{MTO}} = 0.25 : \quad \frac{m_{bat}}{m_{MTO}} = 0.25$$

$$\frac{m_{PL}}{m_{MTO}} = 0.10 : \quad \frac{m_{bat}}{m_{MTO}} = 0.40$$

$$\boxed{0.25 \le \frac{m_{bat}}{m_{MTO}} \le 0.40}$$

this is equivalent to **revenue / expenses**

small A/C; short range



Payload, m_PL calculated from "typical number of seats" from manufacturers seat layout and 93 kg/seat. Data points represent passenger aircraft most frequently in use with 19 seats or more. Note: Although the regression is quite good, physically m_PL/m_MTO is a function of range.

Aircraft Design for Electric Propulsion

Maximum Range for Electrical Propulsion

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)

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

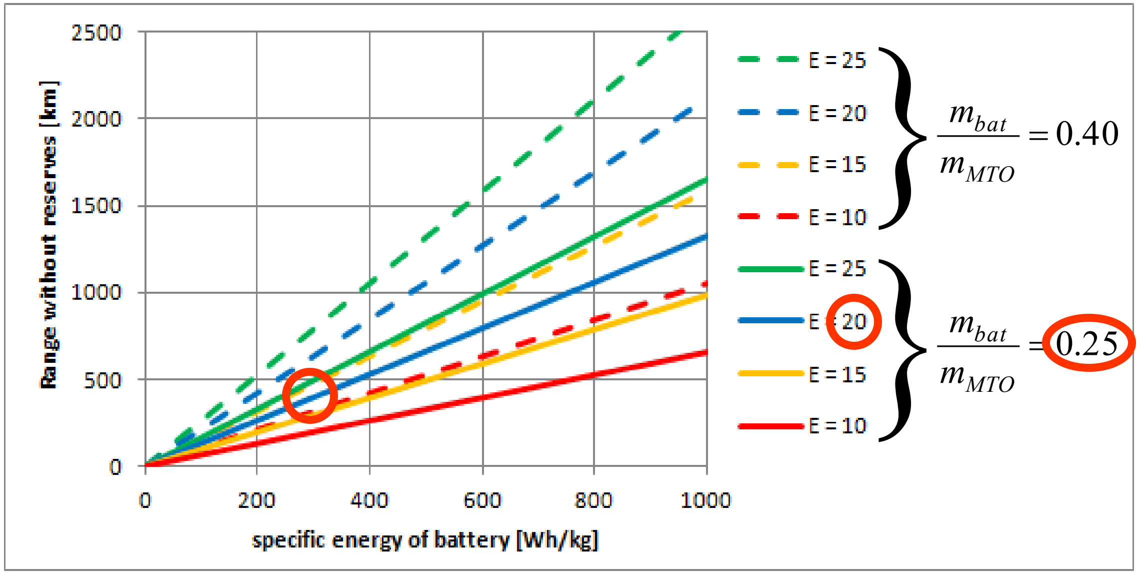
$$P_D = D V = \frac{m_{MTO}\, g}{E} V = P_T = P_{bat}\, \eta_{prop}\, \eta_{elec} \qquad V = \frac{R}{t}$$

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

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

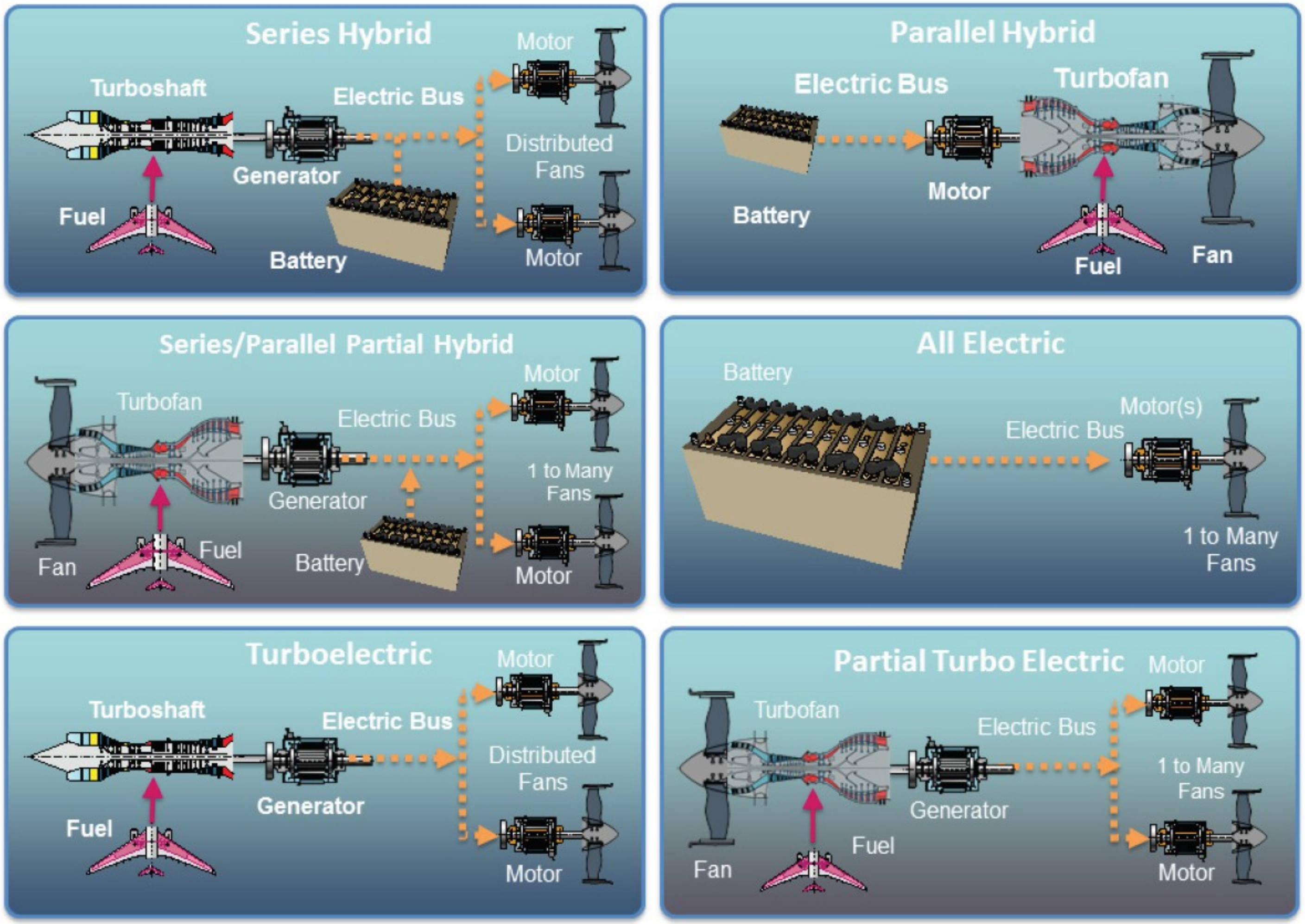
$$\boxed{R = \frac{m_{bat}}{m_{MTO}} \frac{1}{g} e_{bat}\, \eta_{elec}\, \eta_{prop}\, E}$$

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



○ : realistic parameters

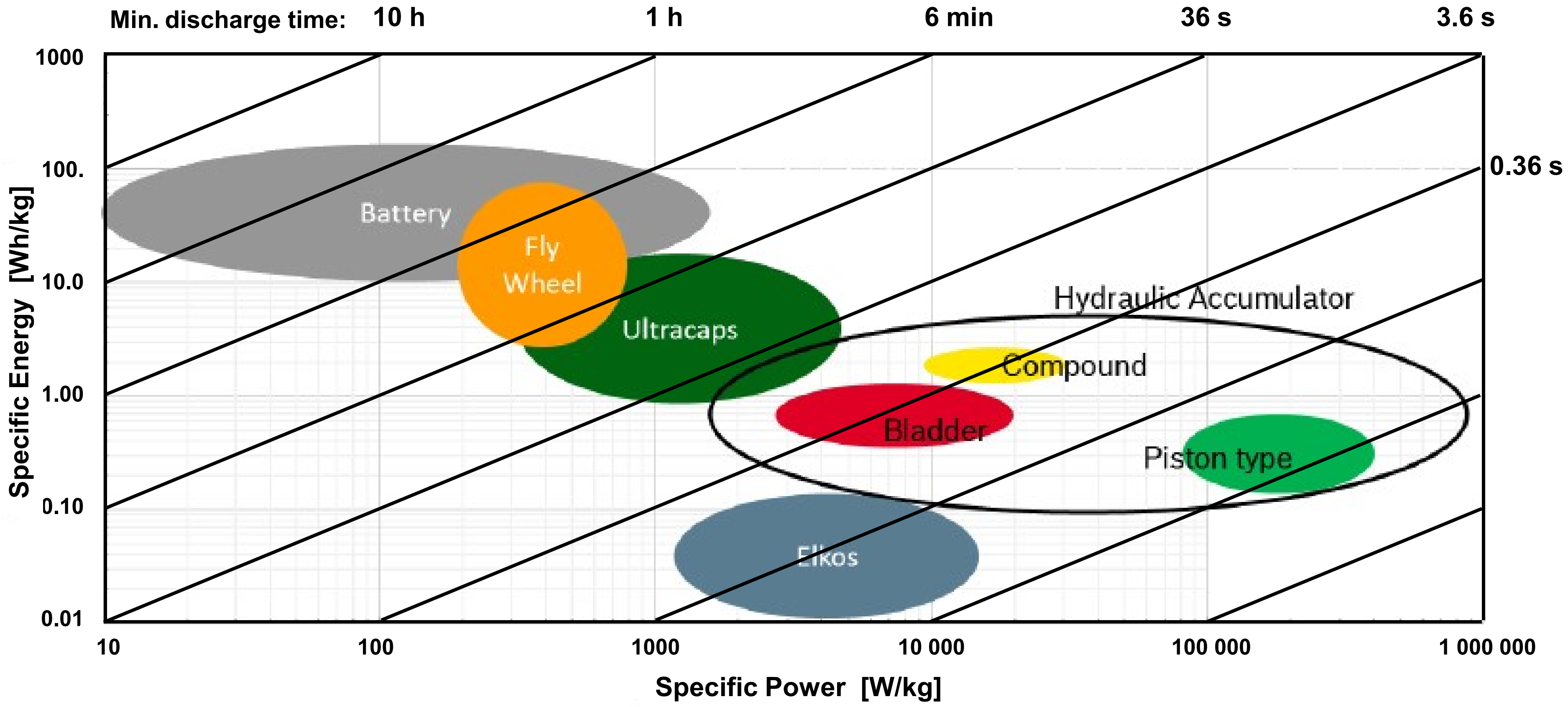
The Major 6 Turbo / Electric / Hybrid Architectures



NAS 2016

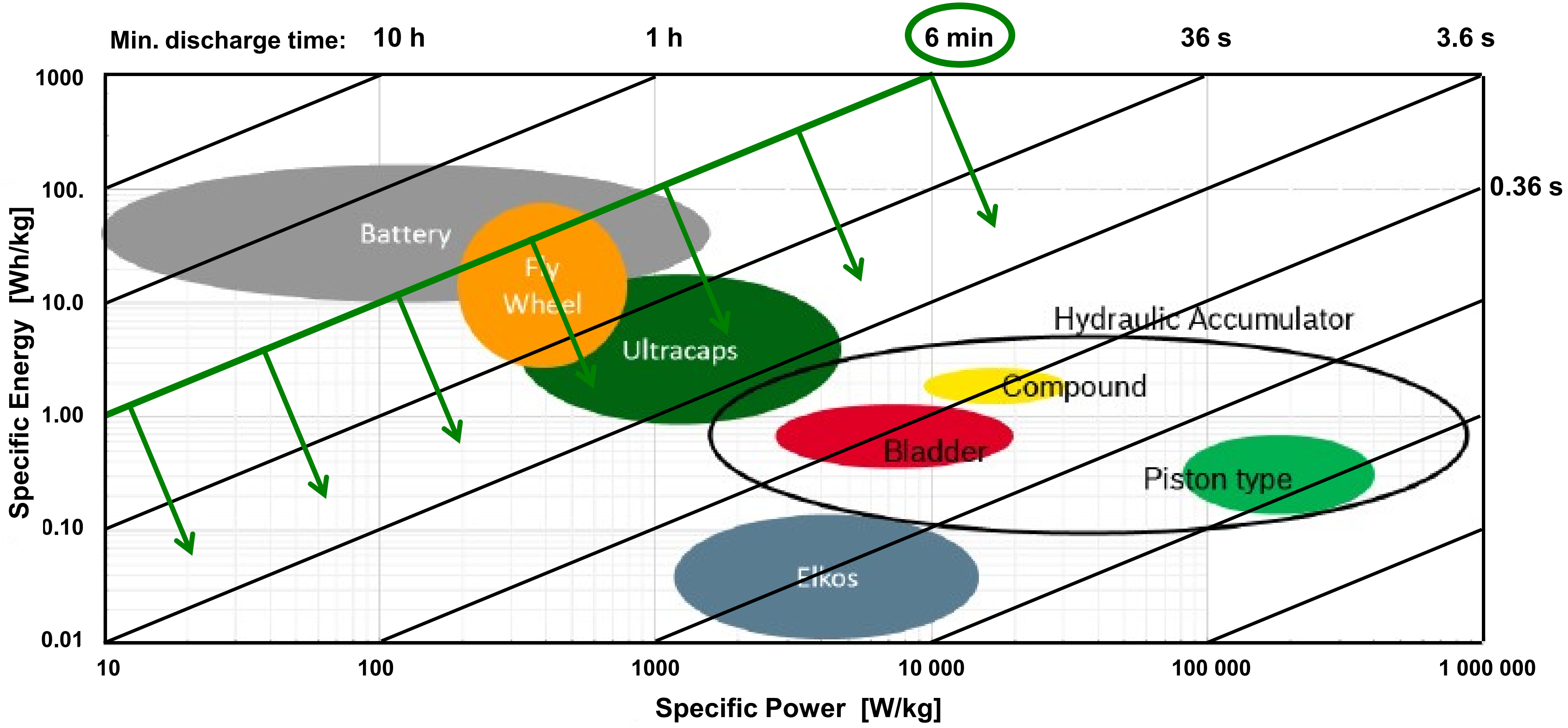
Aircraft Design for Electric Propulsion

Ragone Diagram for Energy Storage Devices



based on Geerling 2017

Energy Storage Suitable for Take-Off and Initial Climb



Collecting Aircraft Design Wisdom

- Thrust levels depend on flight phase. Decreasing thrust for: Take-Off → Climb → Cruise
- Cruise thrust is ≈20% of take-off thrust
- Climb thrust is ≈80% down to ≈20% of take-off thrust (≈50% on average)
- Take-off thrust required for only 5 min. (fuel ratio: 25 min / t_F)
- Operating Empty Mass ≈50% of Maximum Take-Off Mass
- Engine mass is ≈10% of Operating Empty Mass

Derivation of Exergy Density, *b*

$E = A + B$

$B = W$

$\eta = W / E = B / E$

$B = \eta E$

$E = m_F H_L$

$e = E / m_F = H_L$

$b = B / m_F = \eta E / m_F$

$\boxed{b = \eta H_L}$

E : energy

A : anergy

B : exergy

W : work

η : efficiency

m_F : fuel mass

H_L : lower heating value

e : specific energy

b : specific exergy

	Gas Turbine (GT)	Electric Motor (EM)	**Hydraulic Motor** (HM)
relative component mass, m_x/m_{GT}	1.0	1.0	**0.1**
efficiency, η	0.35	0.9 (with controller)	0.9 (with controller)

	kerosine (k)	battery (b)	accumulator (a)
energy density, *e*	43 MJ/kg = 11900 Wh/kg	300 Wh/kg	5.0 Wh/kg
specific **exergy**, $b = \eta\ e$	**4165 Wh/kg**	270 Wh/kg	4.5 Wh/kg
relative specific exergy, b_x/b_k	1.0	0.065	0.01

Aircraft Design for Electric Propulsion

Generic Evaluation of Turbo / Electric / Hydraulic Architectures

- Reference Configuration

  Kerosene feeds Gasturbine (turbofan)
- All Electric

  Component mass: ≈ unchanged

  Battery mass (exergy comparison): 15 times that of kerosene (with snowball effects even more)
- Turbo Electric: Gasturbine + Generator + Electric Motor

  Component mass: 3 times mass of Gasturbine

  Efficiency (from storage to propulsor): 0.9·0.9 = 81% that of reference i.e. 28%

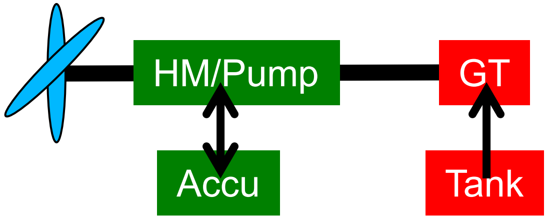
  Fuel mass: 1/0.81 = 1.2 that of reference
- Turbo Hydraulic: Gasturbine (GT) + Pump + Hydraulic Motor (HM)

  Component mass: now only 1.2 the mass of the gasturbine
- Parallel Hydraulic Hybrid – hydraulic used only during take-off (accumulator filled again for TOGA)

  Component mass: 0.8+0.2·0.1=> only 82% that of reference => OEW reduced by 1.8%

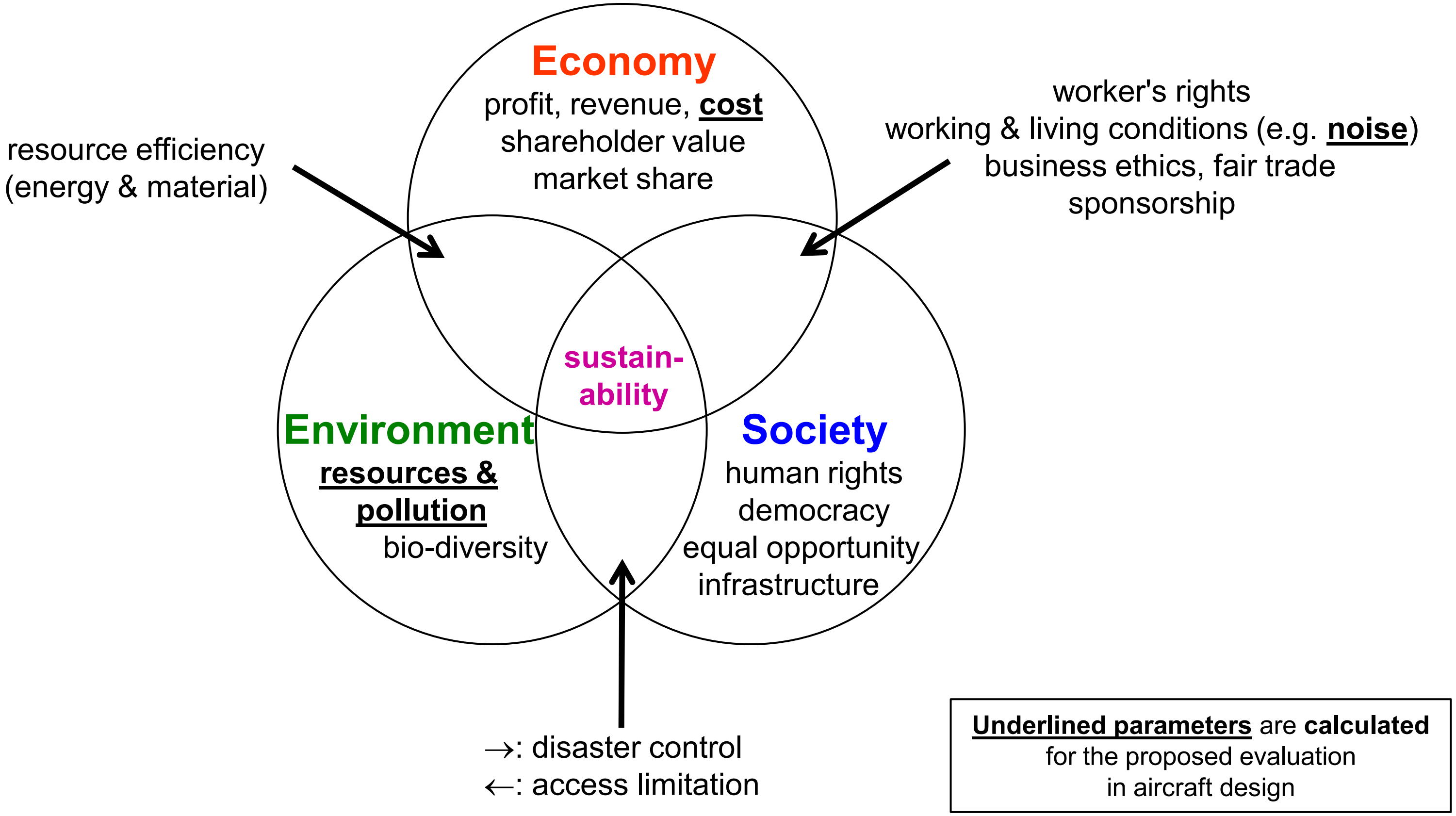
  Assume 5h flight => 5% of energy is in accumulator.

  Storage mass: 0.95 + 0.05/0.01= 5.95 that of reference => This idea does not work!



Evaluation in Aircraft Design

The 3 Dimensions of Sustainability



Underlined parameters are **calculated**
for the proposed evaluation
in aircraft design

Sustainability Venn Diagram

Evaluation in Aircraft Design

Evaluation: Purpose

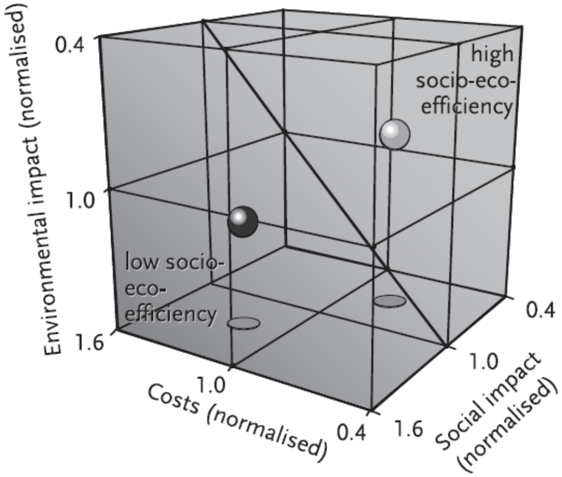
- evaluation of the aircraft for **optimum design** (definition of an objective function)
- **technology evaluation** (on an assumed aircraft platform)
- evaluation for **aircraft selection** (for aircraft purchase by an airline)

Evaluation in the 3 Dimensions of Sustainability: Measuring Socio-Eco-Efficiency

- Economic Evaluation
- Environmental Evaluation
- Social Evaluation

Economic + Environmental } Eco-Efficiency

Eco-Efficiency + Social } Socio-Eco-Efficiency (SEE)

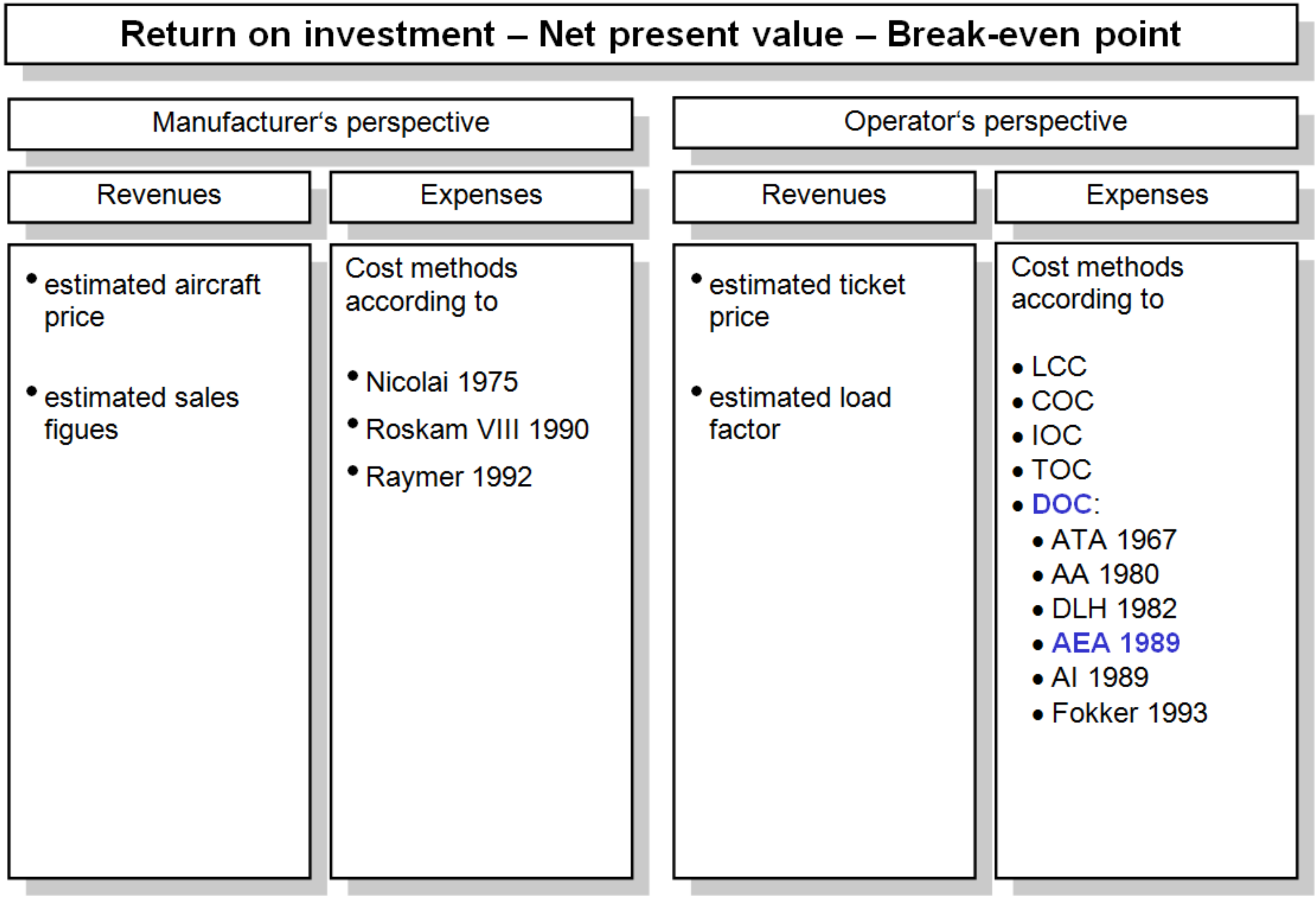


Type of Evaluation	Method
Economic	DOC
Environmental	LCA
Social	S-LCA

Schmidt 2004 (BASF SEE)

Economic Evaluation
(DOC)

Approaches to Economic Evaluation in Aircraft Design and Procurement



Return on investment – Net present value – Break-even point

Manufacturer's perspective

Revenues

- estimated aircraft price
- estimated sales figues

Expenses

Cost methods according to

- Nicolai 1975
- Roskam VIII 1990
- Raymer 1992

Operator's perspective

Revenues

- estimated ticket price
- estimated load factor

Expenses

Cost methods according to

- LCC
- COC
- IOC
- TOC
- DOC:
  - ATA 1967
  - AA 1980
  - DLH 1982
  - AEA 1989
  - AI 1989
  - Fokker 1993

Scholz 2015

Economic Evaluation

Overview of DOC Methods

Organization	Comment	Year of Publication	Source
Air Transport Association of America (ATA)	Predecessors to this method are from the year: 1944, 1949, 1955 and 1960.	1967	**ATA 1967**
American Airlines (AA)	The Method is based on Large Studies sponsored by NASA. See also: **NASA 1977**.	1980	**AA 1980**
Lufthansa	The Method was continuously developed further.	1982	**DLH 1982**
Association of European Airlines (AEA)	Method for Short- and Medium Range Aircraft	1989	**AEA 1989a**
Association of European Airlines (AEA)	Method for Long Range Aircraft (a modification of the method **AEA 1989a**)	1989	**AEA 1989b**
Airbus Industries (AI)	The Method was continuously developed further.	1989	**AI 1989**
Fokker	The Method was produced to evaluate aircraft design project.	1993	**Fokker 1993**
TU Berlin	Method developed by Prof. Thorbeck	2013	**Scholz 2013**

Scholz 2015

Scholz 2015

DOC Cost Elements

$$\boxed{C_{DOC} = C_{DEP} + C_{INT} + C_{INS} + C_F + C_M + C_C + C_{FEE}}$$

- depreciation C_{DEP}
- interest C_{INT}
- insurance C_{INS}
- fuel C_F
- maintenance C_M, consisting of the sum of
  - airframe maintenance $C_{M,AF}$
  - power plant maintenance $C_{M,PP}$
- crew C_C, consisting of the sum of
  - cockpit crew $C_{C,CO}$
  - cabin crew $C_{C,CA}$
- fees and charges C_{FEE}, consisting of the sum of
  - landing fees $C_{FEE,LD}$
  - ATC or navigation charges $C_{FEE,NAV}$
  - ground handling charges $C_{FEE,GND}$

Annual Costs:

$$C_{DOC} = C_{a/c,a}$$

Trip-Costs:

$$C_{a/c,t} = \frac{C_{a/c,a}}{n_{t,a}}$$

Mile-Costs:

$$C_{a/c,m} = \frac{C_{a/c,t}}{R} = \frac{C_{a/c,a}}{n_{t,a}\ R}$$

Seat-Mile-Costs:

$$C_{s,m} = \frac{C_{a/c,t}}{n_{pax}\ R} \text{ or } \frac{C_{a/c,a}}{n_s\ n_{t,a}\ R}$$

Utilization, annual, flight time: $U_{a,f} = t_f \dfrac{k_{U1}}{t_f + k_{U2}}$

number of trips, annual: $n_{t,a} = \dfrac{U_{a,f}}{t_f}$

Environmental Evaluation
(LCA)

Environmental Evaluation

Kerosene Versus Battery in Flight

Type of Comparison	Kerosene	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)	$m_{CO2,eq} = m_{CO2} (k_{RFI} + 0.1)$	$m_{CO2,eq} = m_{CO2}$

$H_L = 43 \text{ MJ/kg}$

$\eta_{charge} = 0.9$

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

Carnot Efficiency:

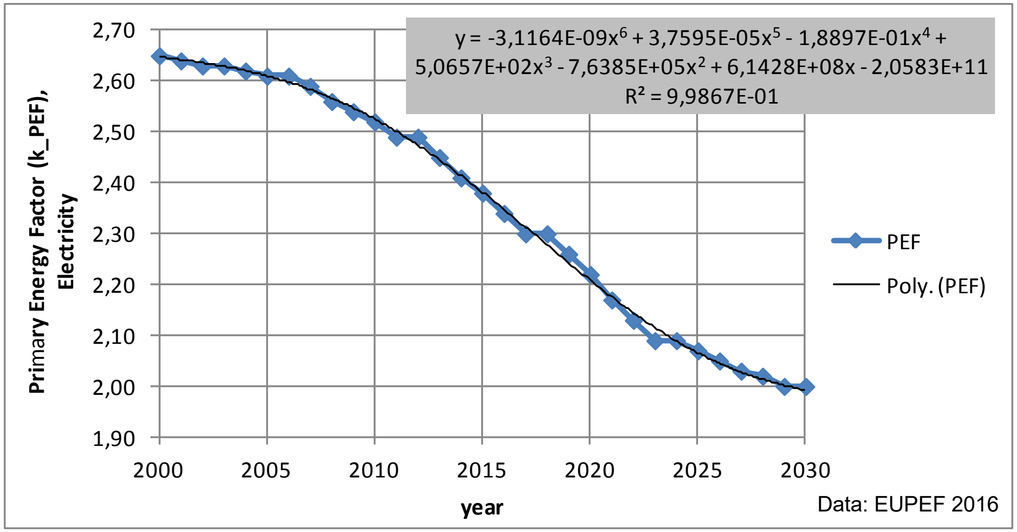
$\eta_C = 1 - T/(h) / T_{TET} = 1 - 216.65/1440 = 0.85$

Radiative Forcing Index:

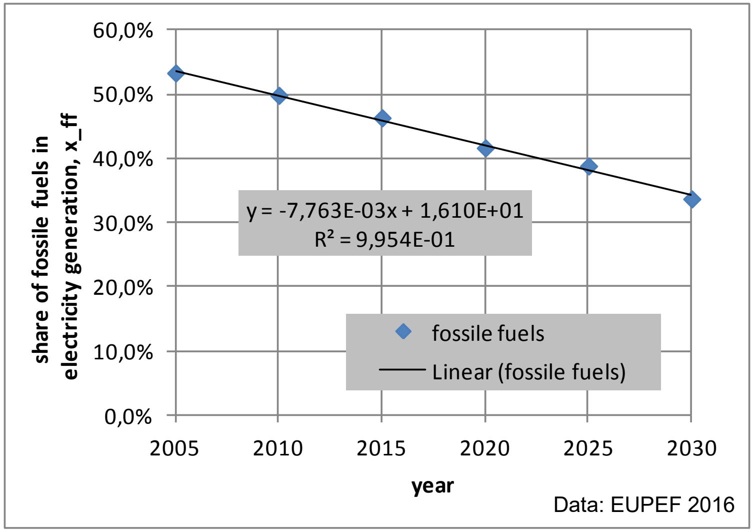
$k_{RFI} = 2.7 \quad (1.9 \ldots 4.7)$

Due to flight at altitude plus energy mix with renewables & nuclear power:

$m_{CO2,eq,kerosene} \approx 2.5 \cdot m_{CO2,eq,battery}$



Data: EUPEF 2016



Data: EUPEF 2016

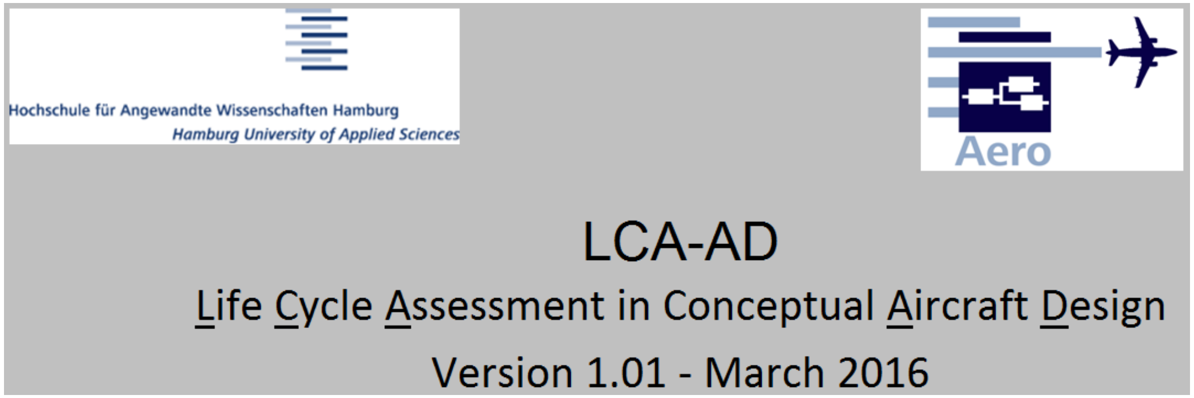
An Excel-Based Life Cycle Tool

29th Congress of the International Council
of the Aeronautical Sciences
St. Petersburg, Russia; September 7-12, 2014

CONCEPTUAL AIRCRAFT DESIGN BASED ON
LIFE CYCLE ASSESSMENT

Andreas Johanning, Dieter Scholz
Aircraft Design and Systems Group (AERO), Hamburg University of Applied Sciences,
Hamburg, Germany

Johanning 2014 http://Airport2030.ProfScholz.de

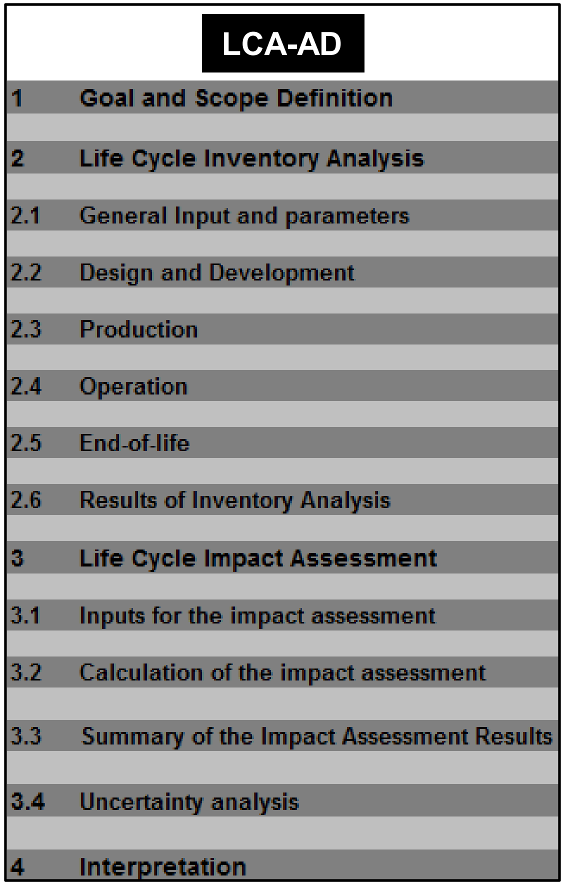


Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

Aero

LCA-AD
Life Cycle Assessment in Conceptual Aircraft Design
Version 1.01 - March 2016

Johanning 2016 http://doi.org/10.13140/RG.2.1.1531.0485
Johanning 2017



LCA-AD

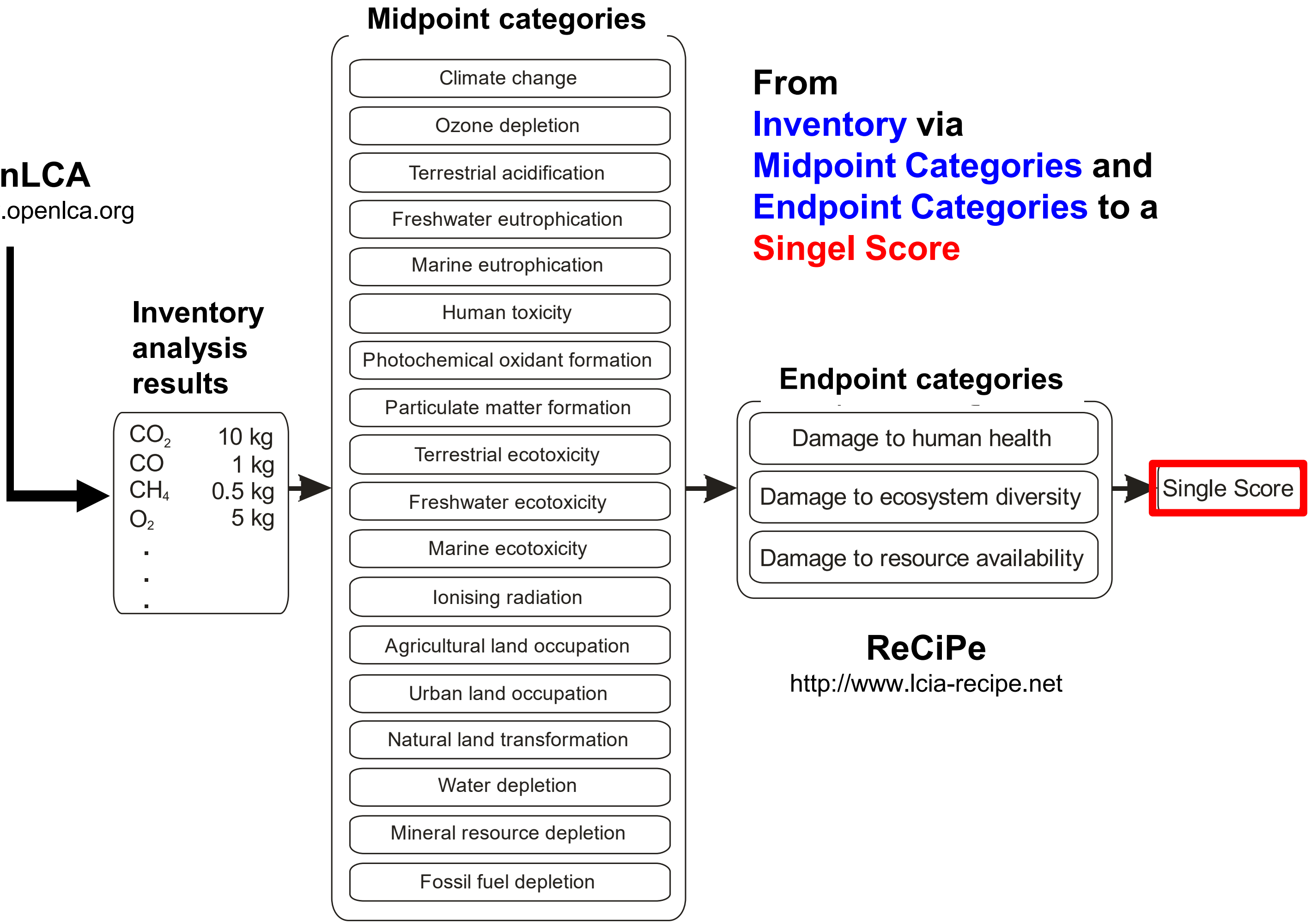
1	Goal and Scope Definition
2	Life Cycle Inventory Analysis
2.1	General Input and parameters
2.2	Design and Development
2.3	Production
2.4	Operation
2.5	End-of-life
2.6	Results of Inventory Analysis
3	Life Cycle Impact Assessment
3.1	Inputs for the impact assessment
3.2	Calculation of the impact assessment
3.3	Summary of the Impact Assessment Results
3.4	Uncertainty analysis
4	Interpretation

An Excel-Based Life Cycle Tool

Processes Considered in the Life Cycle Analysis – Cruise Flight Dominates the LCA

Design & Development	Electric energy due to computer use	Wind tunnel testing	Flight test campaign	
Production	Material production	Use of production facilities		
Operation	Maintenance Repair & Overhaul	**Cruise flight** LTO-cycle	Energy generation and consumption at airports Operation of ground handling vehicles	Kerosene production
End-of-life	Reuse	Landfill		

An Excel-Based Life Cycle Tool



OpenLCA
http://www.openlca.org

Inventory analysis results

CO_2	10 kg
CO	1 kg
CH_4	0.5 kg
O_2	5 kg
.	
.	
.	

Midpoint categories

- Climate change
- Ozone depletion
- Terrestrial acidification
- Freshwater eutrophication
- Marine eutrophication
- Human toxicity
- Photochemical oxidant formation
- Particulate matter formation
- Terrestrial ecotoxicity
- Freshwater ecotoxicity
- Marine ecotoxicity
- Ionising radiation
- Agricultural land occupation
- Urban land occupation
- Natural land transformation
- Water depletion
- Mineral resource depletion
- Fossil fuel depletion

Endpoint categories

- Damage to human health
- Damage to ecosystem diversity
- Damage to resource availability

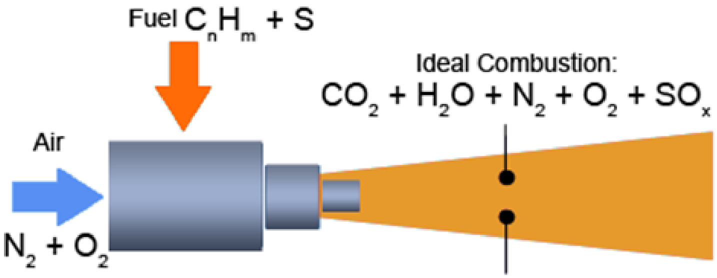
Single Score

ReCiPe
http://www.lcia-recipe.net

From
Inventory via
Midpoint Categories and
Endpoint Categories to a
Singel Score

Environmental Evaluation

Altitude Dependent Equivalent CO2



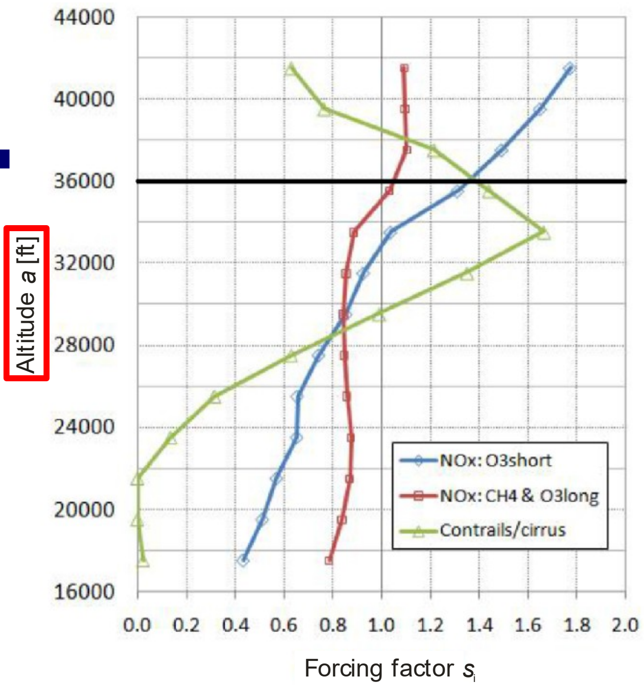
Real Combustion: $CO_2 + H_2O + N_2 + O_2 + SO_x + UHC + CO + C_{Soot} + \underbrace{NO + NO_2}_{NO_x}$

EI_{NOx}

m_F

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

Own Fuel Calculation



$$m_{CO2,eq} = \frac{EI_{CO2}}{SAR \cdot n_{seat}} \cdot 1 + \frac{EI_{NOx}}{SAR \cdot n_{seat}} \cdot CF_{midpoint,NOx} + \frac{L_{flight}}{L_{flight} \cdot n_{seat}} \cdot CF_{midpoint,clouds}$$

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

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

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

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	$SGTP_{i,100}$
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)	$2{,}54 \cdot 10^{-13}$
Cirrus (K/NM)	$7{,}63 \cdot 10^{-13}$

Environmental Evaluation

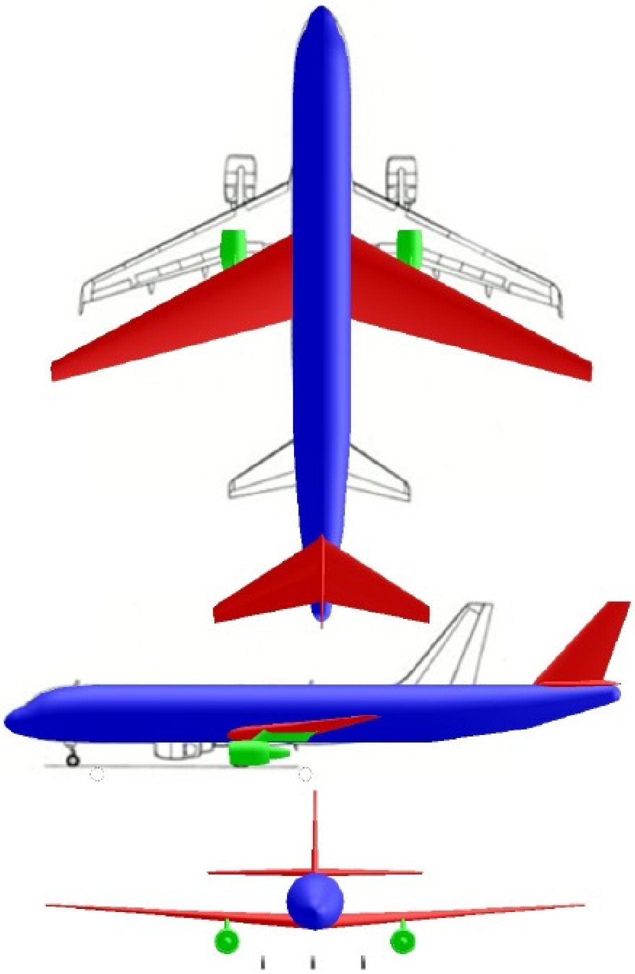
Battery Powered A320

- Only design solution with Range reduced by 50%
  => not a fair trade-off <=

- Specific Energy: 1.87 kWh/kg
- Energy density: 938 kWh/m³
- Batteries in LD3-45 container
- 2 container in cargo compartment
- 13 container forward and aft of cabin
- Fuselage streched by 9 m to house batteries

- MTOW plus 38%
- Battery mass plus 79% (compared with fuel mass)
- On study mission (294 NM) environmental burden (SS) down by 45% (EU electrical power mix)

Parameter	Value	Deviation from A320
Requirements		
m_{MPL}	19256 kg	0%
R_{MPL}	755 NM	-50%
M_{CR}	0.76	0%
max(s_{TOFL} , s_{LFL})	1770 m	0%
n_{PAX} (1-cl HD)	180	0%
m_{PAX}	93 kg	0%
SP	29 in	0%
Main aircraft parameters		
m_{MTO}	95600 kg	30%
m_{OE}	54300 kg	32%
m_F	22100 kg	70%
S_W	159 m²	30%
$b_{W,geo}$	36.0 m	6%
$A_{W,eff}$	9.50	0%
E_{max}	18.20	≈ + 3%
T_TO	200 kN	38%
BPR	6.0	0%
h_{ICA}	41000 ft	4%
s_{TOFL}	1770 m	0%
s_{LFL}	1450 m	0%
Mission requirements		
R_{Mi}	294 NM	-50%
$m_{PL,Mi}$	13057 kg	0%
Results		
$m_{F,trip}$	7800 kg	72%
SS	0.0095	-45%



Environmental Evaluation

Battery Powered A320

A320 Reference Aircraft

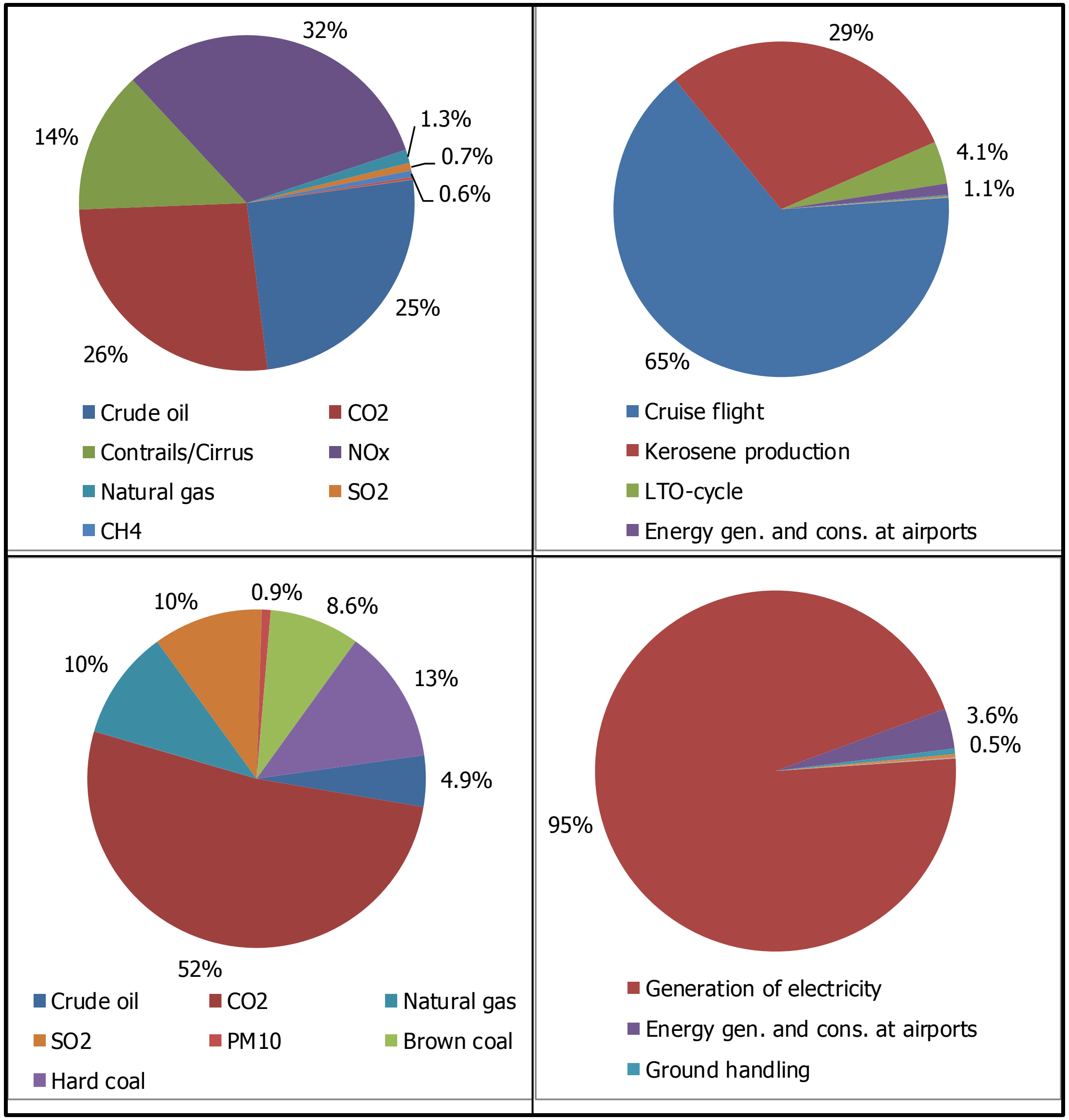
- Contributions of In- and Outputs on Single Score (SS) (left)
- Considered Processes (right)
- SS = 0.0173 points
- CO2 = 0.0045 points in SS

Battery Powered Aircraft

- Contributions of In- and Outputs on Single Score (SS) (left)
- Considered Processes (right)
- SS = 0.0095 points
- CO2 = 0.0049 points in SS

⇒The battery powered aircraft does not save CO2

⇒Generation of electricity dominates SS. With regenerative electricity: SS = 0.0008 points



Social Evaluation
(S-LCA, Noise)

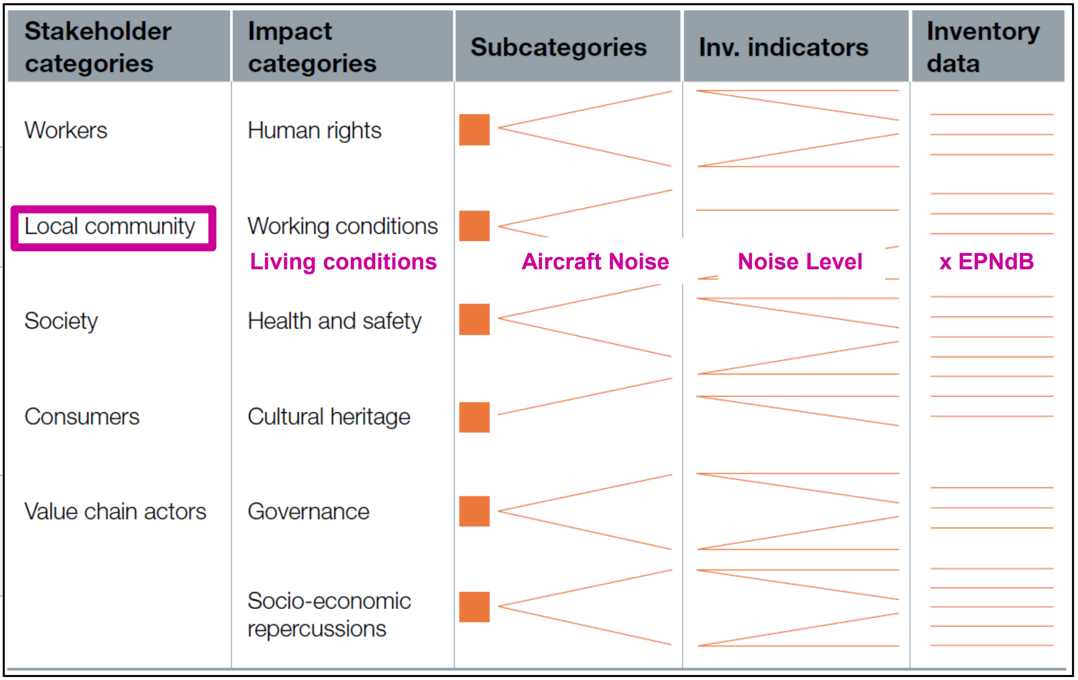
Social Evaluation

Social Life Cycle Assessment (S-LCA)

S-LCAs follow the ISO 14044 framework. They assess **social** and socio-economic **impacts** found along the life cycle (supply chain, use phase and disposal) of products and services. Aspects assessed are those **that** may directly or indirectly **affect stakeholders** positively or negatively. These aspects may be linked to the behaviors of socio-economic processes around enterprises, government, ... (UNEP 2009)

Stakeholder categories	Subcategories
Stakeholder "worker"	Freedom of Association and Collective Bargaining Child Labour Fair Salary Working Hours Forced Labour Equal opportunities/Discrimination Health and Safety Social Benefits/Social Security
Stakeholder "consumer"	Health & Safety Feedback Mechanism Consumer Privacy Transparency End of life responsibility
Stakeholder "local community"	Access to material resources Access to immaterial resources Delocalization and Migration Cultural Heritage Safe & healthy living conditions Respect of indigenous rights Community engagement Local employment Secure living conditions
Stakeholder "society"	Public commitments to sustainability issues Contribution to economic development Prevention & mitigation of armed conflicts Technology development Corruption
Value chain actors* not including consumers	Fair competition Promoting social responsibility Supplier relationships Respect of intellectual property rights

Noise: Only <u>one of many</u> possible indicators in an S-LCA



Stakeholder categories	Impact categories	Subcategories	Inv. indicators	Inventory data
Workers	Human rights			
Local community	Working conditions			
	Living conditions	**Aircraft Noise**	**Noise Level**	**x EPNdB**
Society	Health and safety			
Consumers	Cultural heritage			
Value chain actors	Governance			
	Socio-economic repercussions			

Aircraft Noise

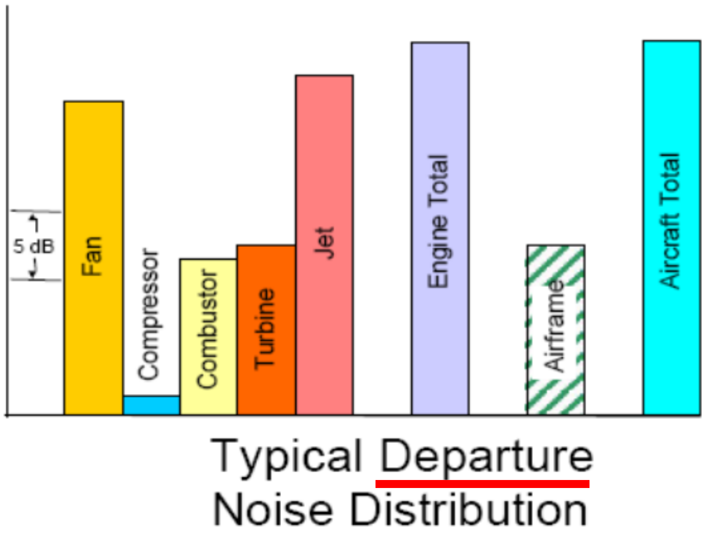
Aircraft noise is external noise and internal noise (cabin noise). Considered here: is only external noise:

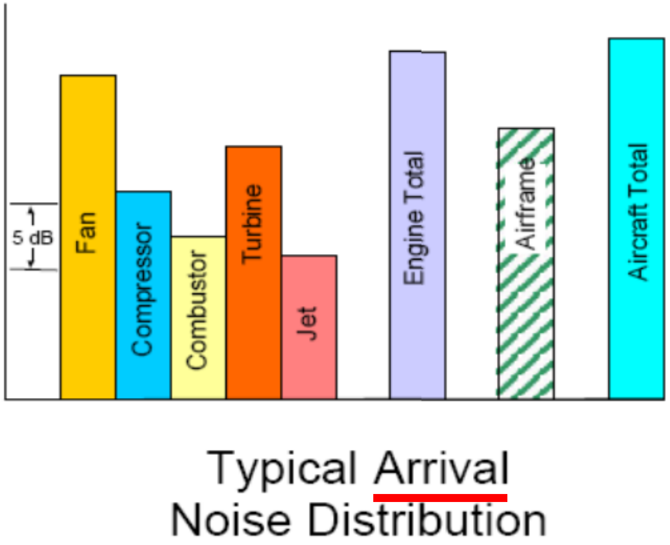
- Mechanical noise
  - engine (turbo jet, turbo fan, turbo prop, piston prop)
    - jet noise (exhaust) of jet aircraft – dominant for jets on take-off
    - fan blades (*buzzsaw noise* when tips reach supersonic speeds)
    - noise from compressor, combustion chamber, turbine, after burner, reverse thrust
    - propeller noise (tips reach supersonic speeds) – dominant for turbo props
    - combustion engine (and propeller noise) – dominant for piston props
- Aerodynamic noise
  - airframe noise from flow around the surfaces of the aircraft (flying low at high speeds)
    - wing
      - high lift devices (flaps, slats) – dominant for jets on approach
    - tails with control surfaces
    - fuselage
    - landing gear – dominant for jets on approach
  - sonic boom
- Noise from aircraft systems
  - Auxiliary Power Unit, APU (important only at the airport)

Understand which noise source is dominant.
Substancial overall noise reduction can only be achieved, if the dominat noise source is made less noisy.

Social Evaluation

Aircraft Noise on Departure versus Arrival



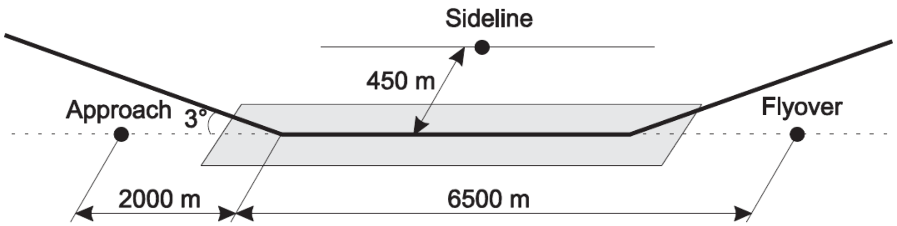


Dickson 2013

Noise Data (A321neo)

Noise Certification Database

http://noisedb.stac.aviation-civile.gouv.fr



Noise Certification Reference Points

Example Data from Database:
Manufacturer AIRBUS
Type A321 Version 272NX (neo)
Engine Type PW1130G-JM
Maximum Take-Off Mass: 80000 kg

For newly developed aircraft use own measurements!

NOISE CERTIFICATION STANDARD
Noise Regulation ICAO Annex 16, Volume I
Chapter or Stage 4

	Lateral/Full-Power	Approach	Flyover
Noise Level (EPNdB)	88	94.6	81.9
Noise Limit (EPNdB)	97.1	100.8	91.9
Margin (EPNdB)	9.1	6.2	10

Cumulative Margin (EPNdB)	25.30

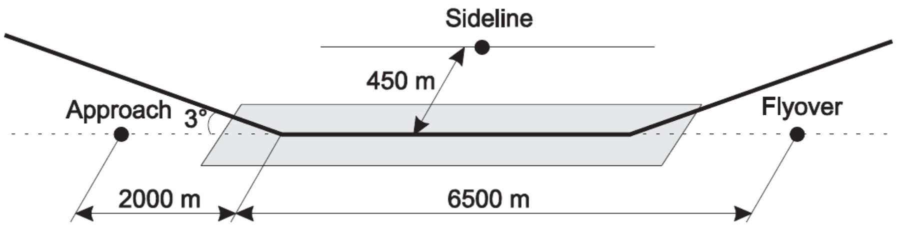
1.) read
Cumulative Margin: $\Sigma(\Delta n_i)$

2.) determine
Minimum Margin: $\min(\Delta n_i)$

Noise Data (TU 154)

Noise Certification Database

http://noisedb.stac.aviation-civile.gouv.fr



Example Data from Database:
Manufacturer TUPULEV
Type TU 154 M/D01
Engine Type D-30KU-154
Maximum Take-Off Mass: 92000 kg

For newly developed aircraft use own measurements!

NOISE CERTIFICATION STANDARD
Noise Regulation ICAO Annex 16, Volume I
Chapter or Stage 3

	Lateral/Full-Power	Approach	Flyover
Noise Level (EPNdB)	99.5	101.5	91.5
Noise Limit (EPNdB)	97.6	101.2	95.7
Margin (EPNdB)	-1.9	-0.3	4.2

Cumulative Margin (EPNdB)	2.00

1.) read
Cumulative Margin: $\Sigma(\Delta n_i)$

2.) determine
Minimum Margin: $\min(\Delta n_i)$

Noise Emission Fees (NEF)

EVALUATION OF WORLDWIDE NOISE AND POLLUTANT EMISSION COSTS FOR INTEGRATION INTO DIRECT OPERATING COST METHODS

A. Johanning, D. Scholz
Hamburg University of Applied Sciences

Johanning 2012 has created a method to calculate globally the **average noise charges per flight $c_{n,f}$** in a given year n_y (e.g. 2018) based on data from 2011, taking into account inflation with p_{INF} = 2% per year :

$$c_{n,f} = \left(1 + \frac{n_y - 2011}{41}\right) \cdot \frac{m_{MTO}\,(1 + p_{INF})^{n_y - 2011}}{143.5\,(2 + \Sigma(\Delta n_i) + \min(\Delta n_i)\,)}$$

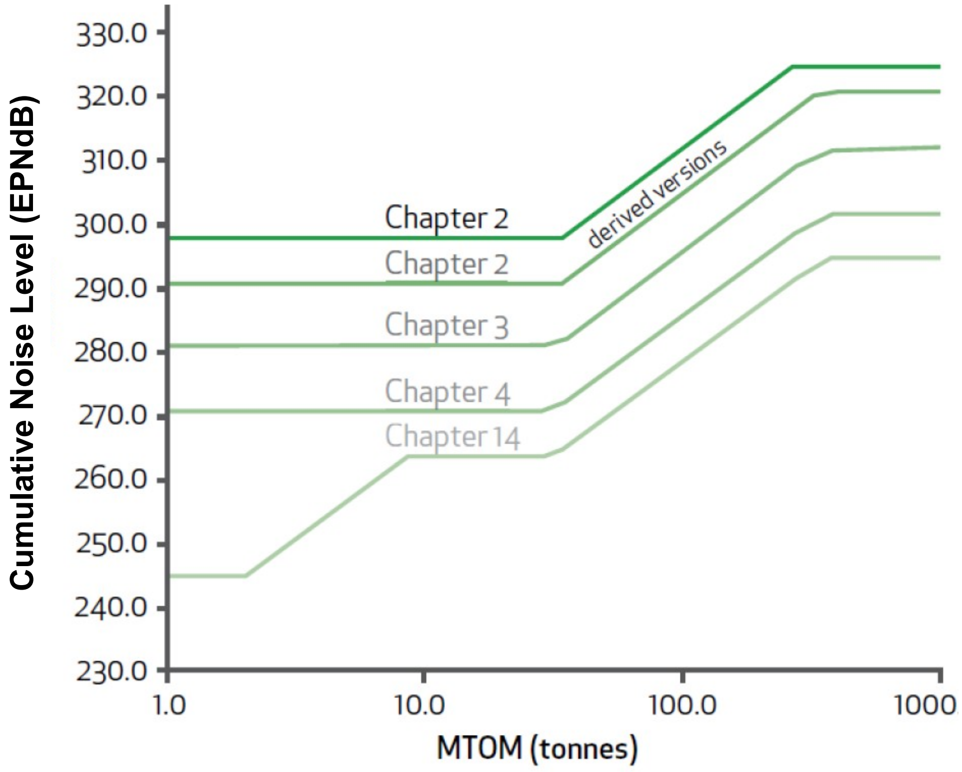
With example data from database of **A321neo**:

$$c_{n,f} = \left(1 + \frac{2018 - 2011}{41}\right) \cdot \frac{80000(1.02)^{2018-2011}}{143.5\,(2 + 25.3 + 6.2\,)} = \underline{\underline{22.3\ \mathrm{USD}}} \qquad (\mathrm{TU154:\ 410.6\ USD})$$

- These costs can be added to the Direct Operating Costs (DOC) of an aircraft.
- These costs can also represent the social noise impact of an aircraft relative to another aircraft. Alternatively use the Cumulative Noise Level (sum of the 3 levels in EPNdB).

Social Evaluation

Margins of the Cumulative Noise Level



Dickson 2013

Indicated are the

Cumulative Noise Limits according to the ICAO Noise Chapters as a function of Maximum Take-Off Mass

"Cumulative" means the sum of the 3 noise levels/limits in EPNdB from

- Approach
- Sideline
- Flyover

Chapter	Applicable Year
2	1972
3	1978
4	2006

Combined Evaluation

Combined Evaluation

Multiple-Criteria Decision Analysis (MCDA)

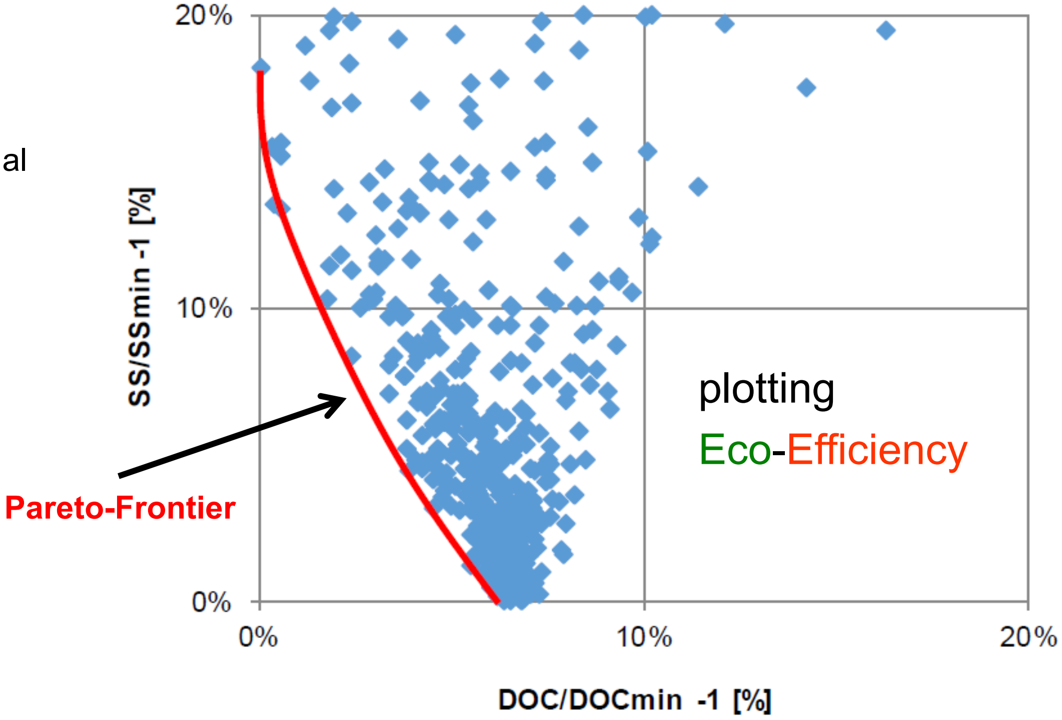
- **Many techniques** exist => Literature
- **Weighted Sums Analysis**: $SS_{total} = k_{DOC}\ DOC + k_{SS,LTA}\ SS_{LTA} + k_{SS,S-LTA}\ SS_{S-LTA}$
- **Pareto-Optimum**:

Pareto optimality is a state of allocation of resources from which it is impossible to reallocate so as to make any one individual or preference criterion better off without making at least one individual or preference criterion worse off.

Usualy Pareto-Frontiers are show from **two variables only**.

Here **three plots** could be used to overcome the limitations:

- *DOC* – SS_{LTA}
- *DOC* – $SS_{S\text{-}LTA}$
- SS_{LTA} – $SS_{S\text{-}LAT}$

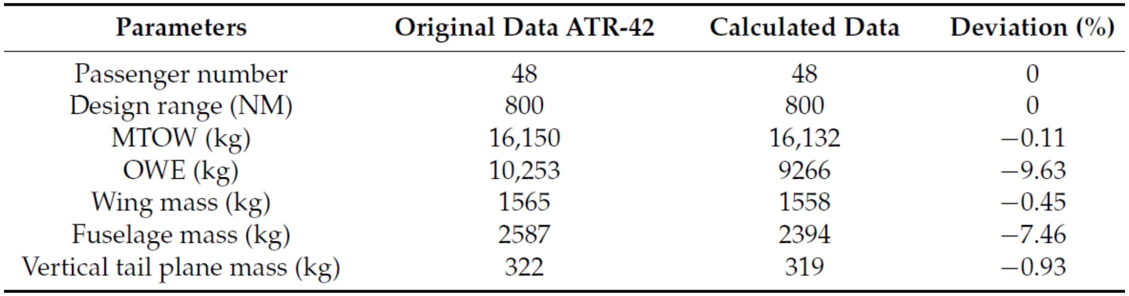


Johanning 2017

Example

Example

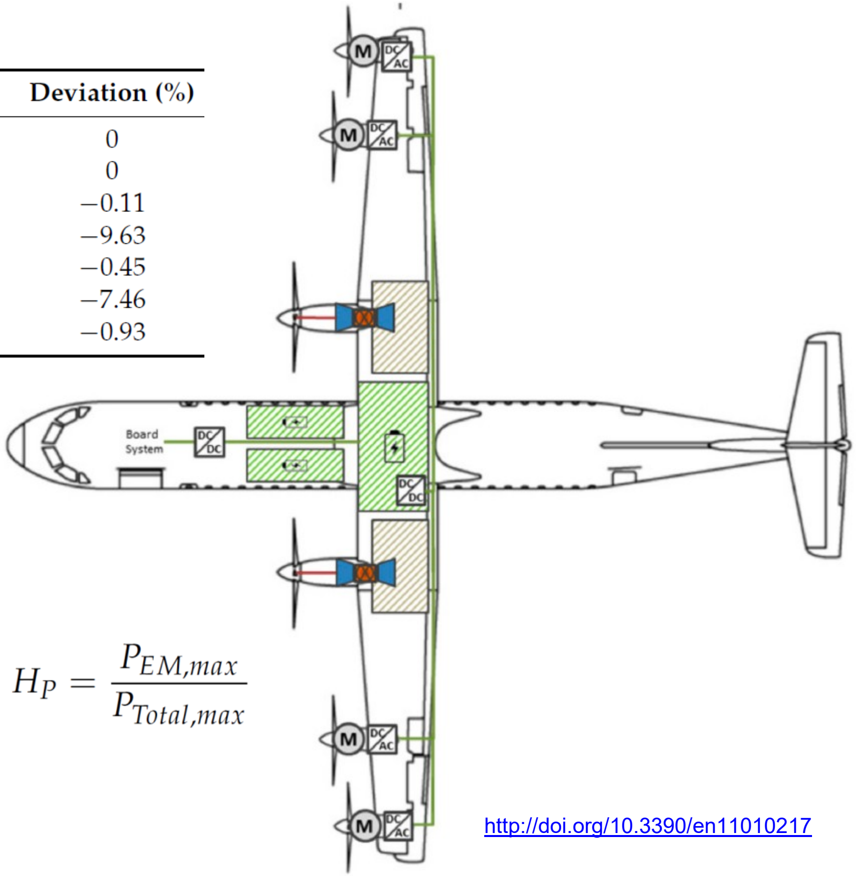
Hybrid-Electric ATR-42



Parameters	Original Data ATR-42	Calculated Data	Deviation (%)
Passenger number	48	48	0
Design range (NM)	800	800	0
MTOW (kg)	16,150	16,132	−0.11
OWE (kg)	10,253	9266	−9.63
Wing mass (kg)	1565	1558	−0.45
Fuselage mass (kg)	2587	2394	−7.46
Vertical tail plane mass (kg)	322	319	−0.93

Battery strategies:
1.) Minimum battery sizing to provide energy for maximum power peak shaving of the gas turbine power rating. H_P determines the peak shaving possibility.
2.) Maximize the battery utilization. Hence, the battery supplies maximum mission energy in every mission segment depending on its maximum power rating and the maximum required power.

The **battery usage** is described with the battery strategy parameter λ_{Bat} ranging from 0 to 1. Maximum power peak shaving strategy (1.) is reached with $\lambda_{Bat} = 0$.



$$H_P = \frac{P_{EM,max}}{P_{Total,max}}$$

http://doi.org/10.3390/en11010217

Hoelzen 2018

Conceptual Design of Operation Strategies for Hybrid Electric Aircraft

Julian Hoelzen [1], Yaolong Liu [2,*], Boris Bensmann [1,*], Christopher Winnefeld [1], Ali Elham [3], Jens Friedrichs [4] and Richard Hanke-Rauschenbach [1]

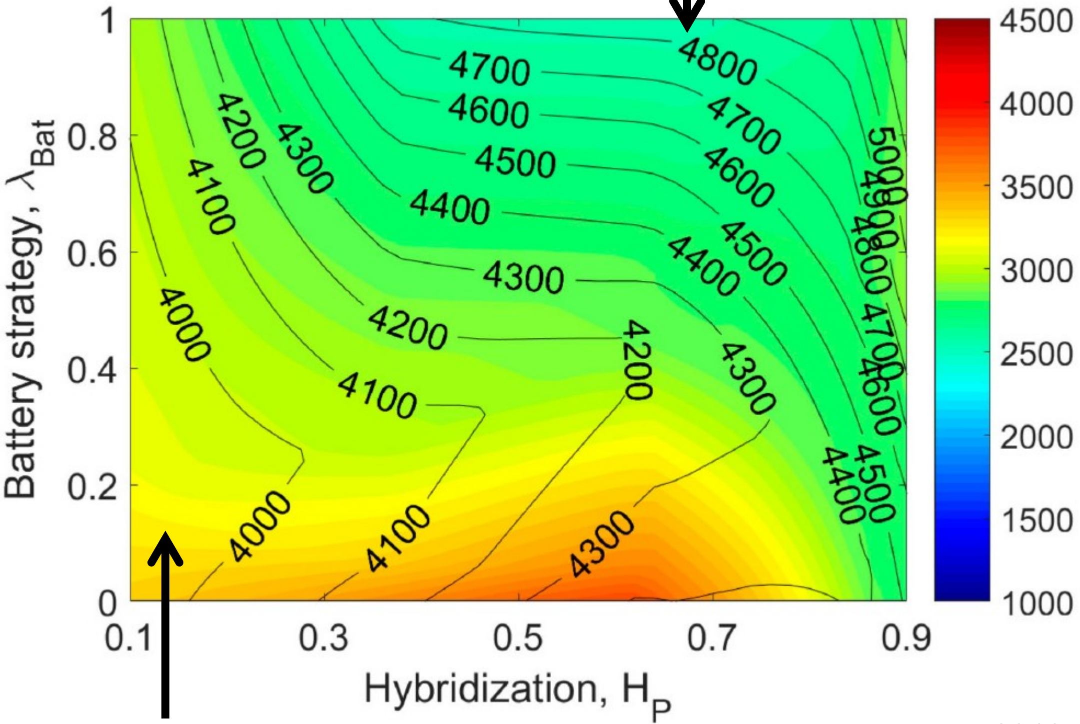
Example

Hybrid-Electric ATR-42

- The figure shows the total CO2 emissions (heat map) and Direct Operating Costs, DOC (contour lines) in dependence of hybridization H_P and battery strategy parameter λ_{Bat}.
- CO2 emissions decrease with larger battery strategy parameters and reach an optimum at a degree of Hybridization of around 0.66.
- Points of min. DOC and min. CO2 do not fall together!
- Cost competitive HEA configurations do not promise the targeted CO2 emission savings.

  (electricity production from OECD mix; 0.42 kg CO2 per kWh)

minmum CO2



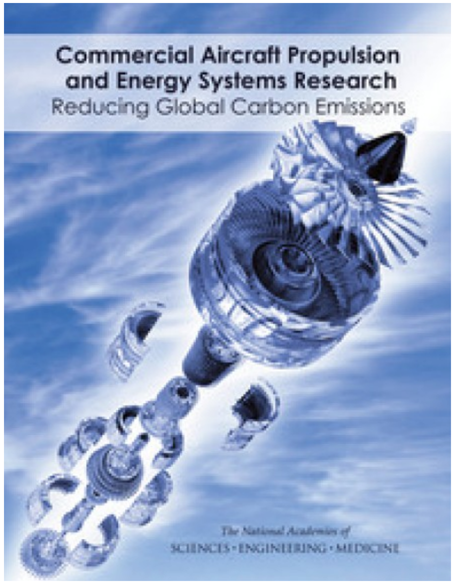
minmum DOC

Hoelzen 2018

Summary

Summary Compiled from National Academies of Sciences (USA)

- The most important parameters are specific energy (Wh/kg) for energy storage and specific power (kW/kg).
- Jet fuel is an excellent way to store energy, with approximately 13000 Wh/kg.
- State of the art: 200-250 Wh/kg (2016).
- The committee's projection of how far the state of the art will advance during the next 20 years: 400-600 Wh/kg.
- All-electric regional and single-aisle aircraft would be suitable only for short-range operations, and even then they would require a battery system specific energy of 1800 Wh/kg.
- CO2 emissions from the source of electricity used to charge the batteries.
- Cost of new infrastructure at airports to charge aircraft batteries, new power transmission lines to airports and, potentially, new generating (power plant) capacity.
- **No** electric propulsion concept will mature to the point to meet the needs of **twin-aisle aircraft within the next 30 years**.



Commercial Aircraft Propulsion and Energy Systems Research
Reducing Global Carbon Emissions

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NAS 2016

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Recommendation of Related Video (in German)

https://www.3sat.de/wissen/nano

SENDUNG: MONTAG, 24. JUNI 2019, 18:30

Wissen -
Wie wird das Fliegen grün?

Schmalrumpf-Flugzeuge, Elektro- und Hybridantrieb, Kerosin aus Sonnenenergie – die Flugbranche will nachhaltiger werden. Welche Technik ist am vielversprechendsten?

Video (6 min.) verfügbar bis 24.06.2024, danach auf YouTube(?)**:**
https://www.zdf.de/wissen/nano/nachhaltiges-fliegen-100.html
https://www.3sat.de/wissen/nano/nachhaltiges-fliegen-100.html