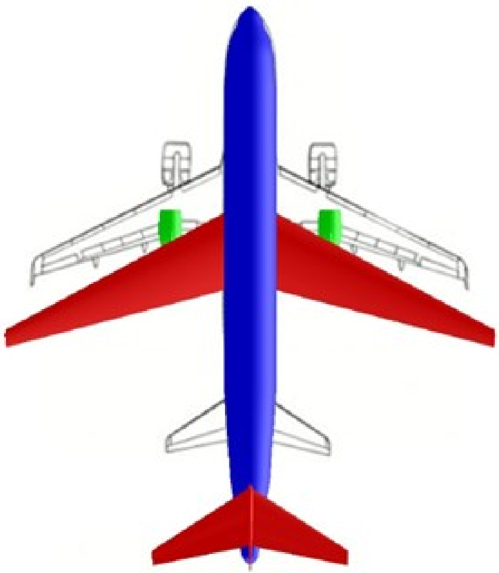
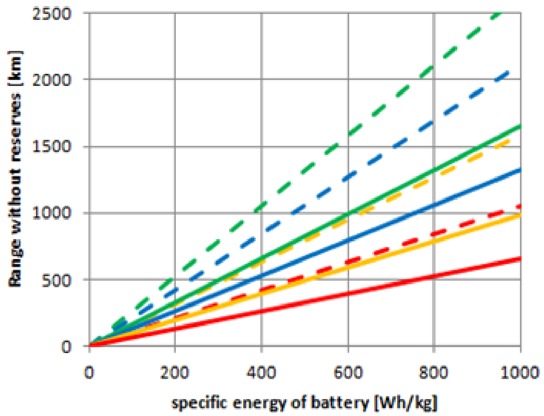
Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

Evaluating Aircraft
with Electric and Hybrid Propulsion

Dieter Scholz Hamburg University of Applied Sciences





Electric & Hybrid Aerospace Technology Symposium 2018

Cologne, Germany, 08.-09.11.2018

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

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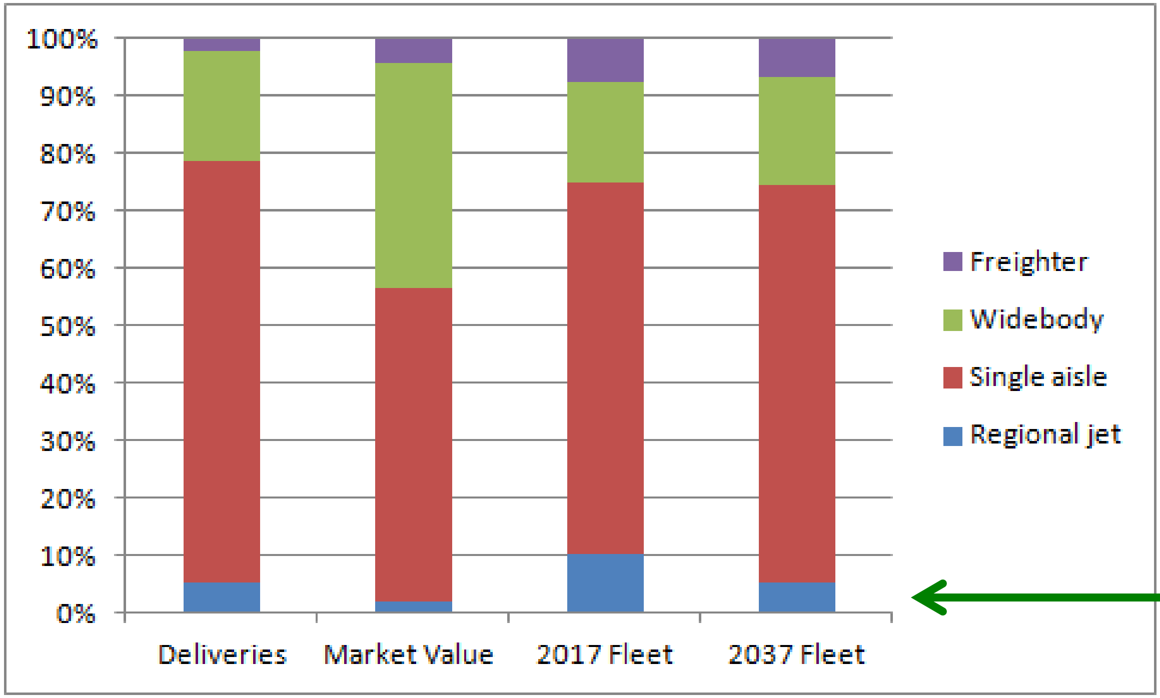
Validation – Are we Doing the Right Thing?

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.

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.

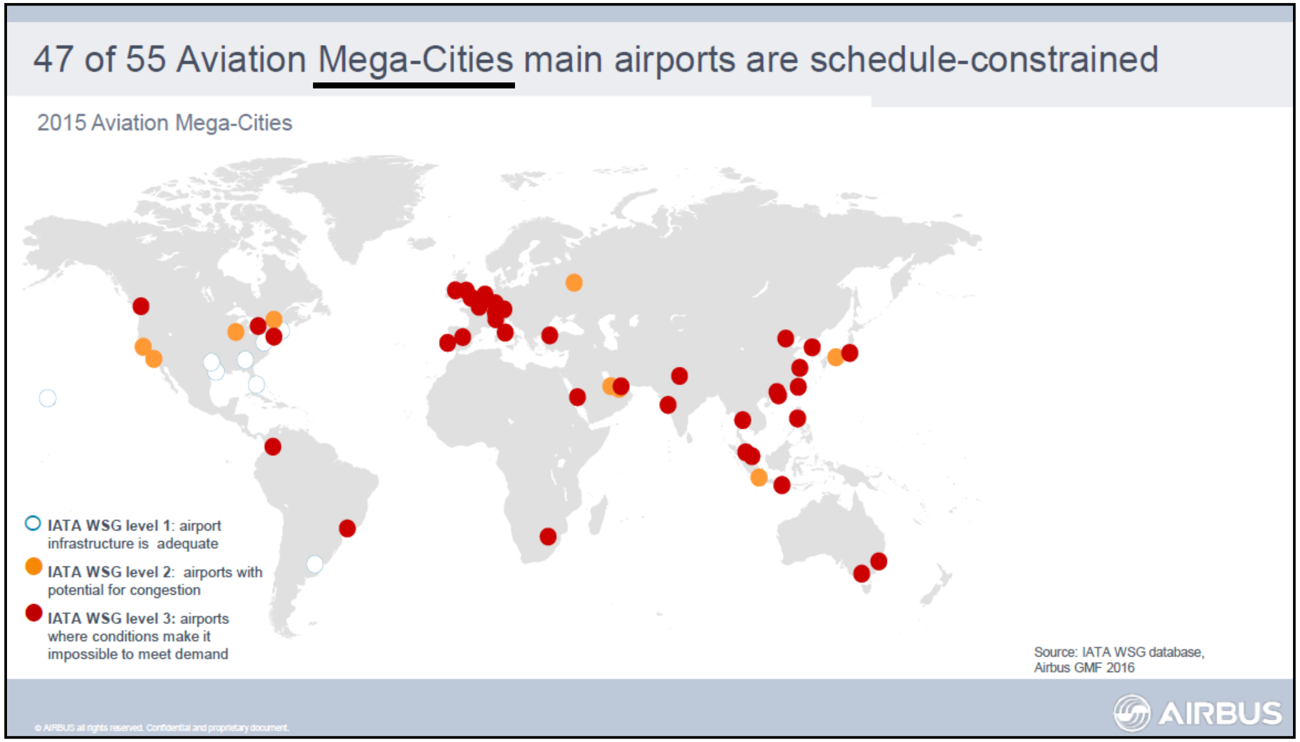
Validation – Are we Doing the Right Thing?

Grid Connected Electric Mobility Operates Successfully on Tracks!

- 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?

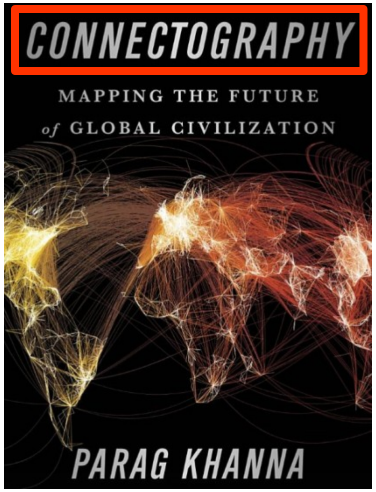
Mobility between Megacities – How?



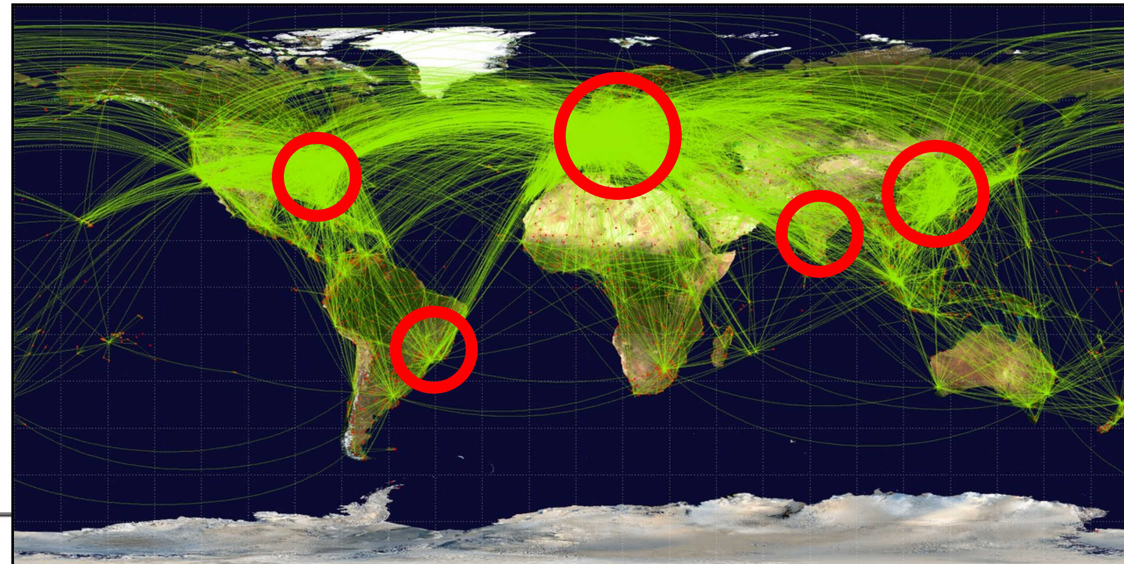
Airbus 2016

- 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?



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		
...	**Aircraft**	Air China 1557
13:20		
13:30		
13:40	Shanghai Hongqiao	
13:50	Pick-up luggage	

(a) Travel mode: metro + aircraft

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

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

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

Example: Train number G1

Sun 2017

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

Validation – Are we Doing the Right Thing?

Increasing Political Pressure ...

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


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

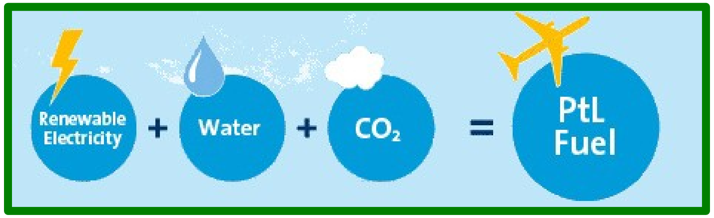
Validation – Are we Doing the Right Thing?

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.)

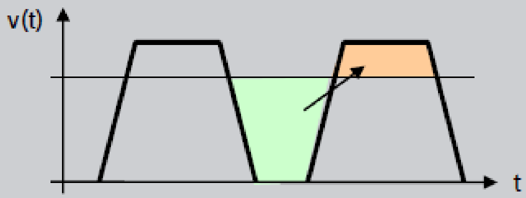
Validation – Are we Doing the Right Thing?

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

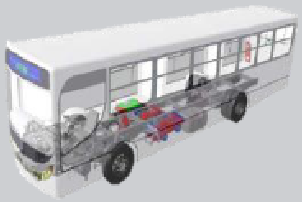
In contrast to both of this: Aircraft have a very even load profile during most time of the operation!

Validation – Are we Doing the Right Thing?

Electric versus Hydraulic Hybrid Propulsion

Geerling 2017

Possible Applications	Customer Benefits HRB System (Hybrid Hydraulic)
→ Slow vehicles with multiple start and stop situations in normal operation, such as… … busses, underground, tram … garbage trucks … construction vehicles …	• 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:

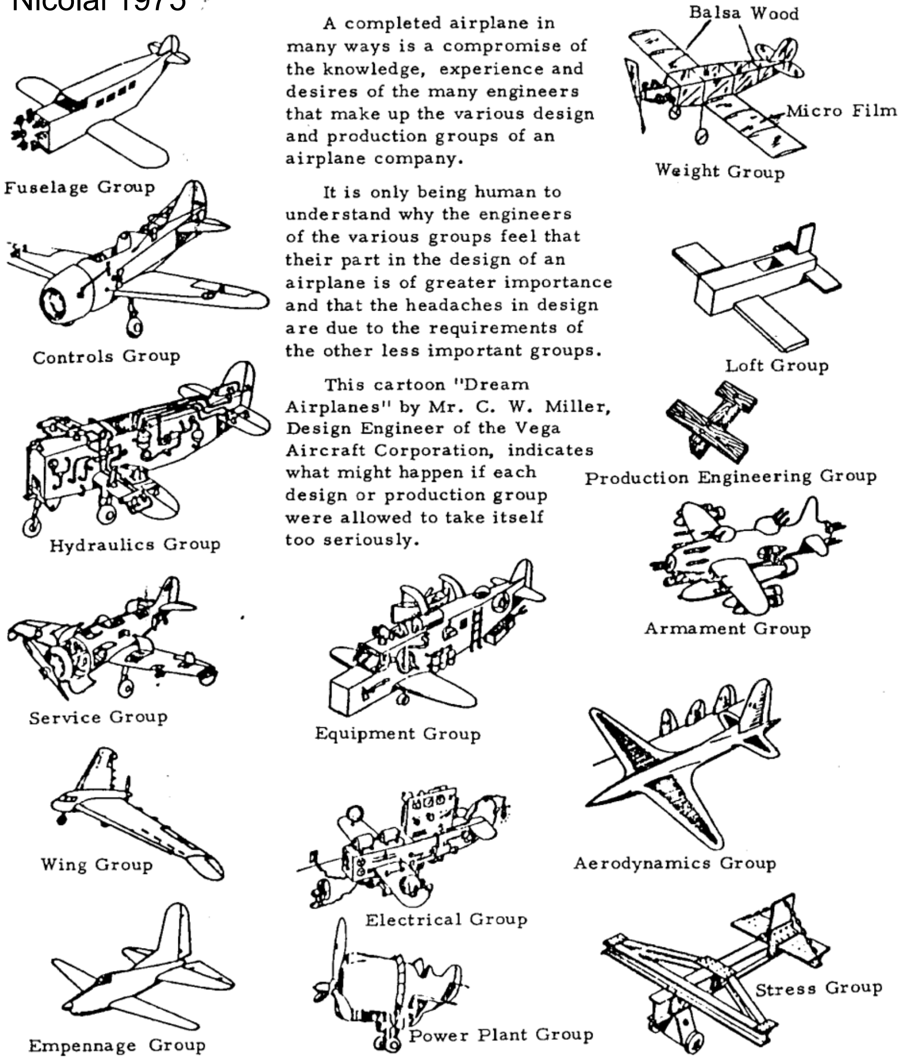
Where is the market niche for short range, small passenger aircraft with (hybrid-) electric propulsion?

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



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.

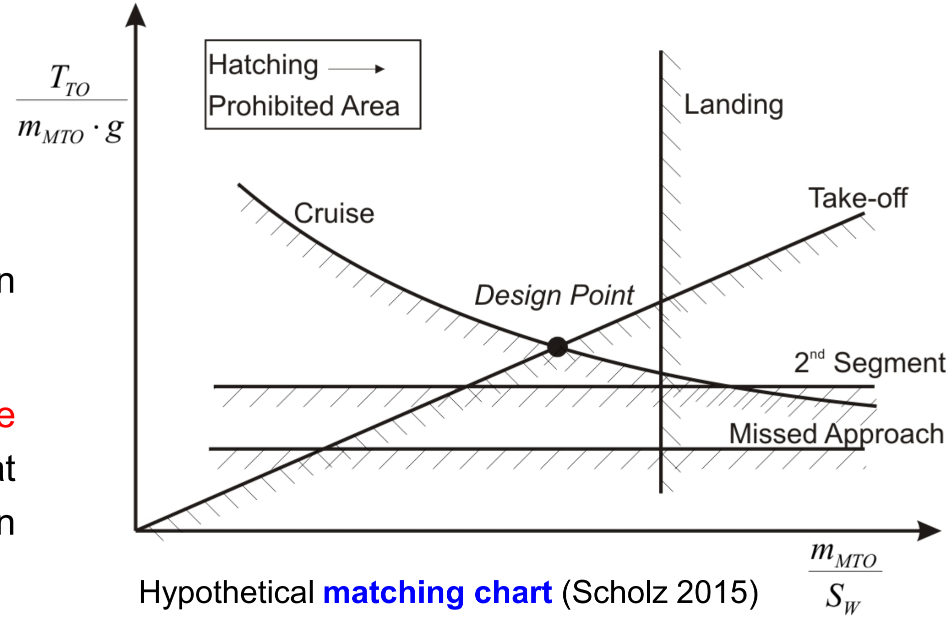
Maximum Take-Off mass is a surrogate parameter for cost !

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

- 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

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

- 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**

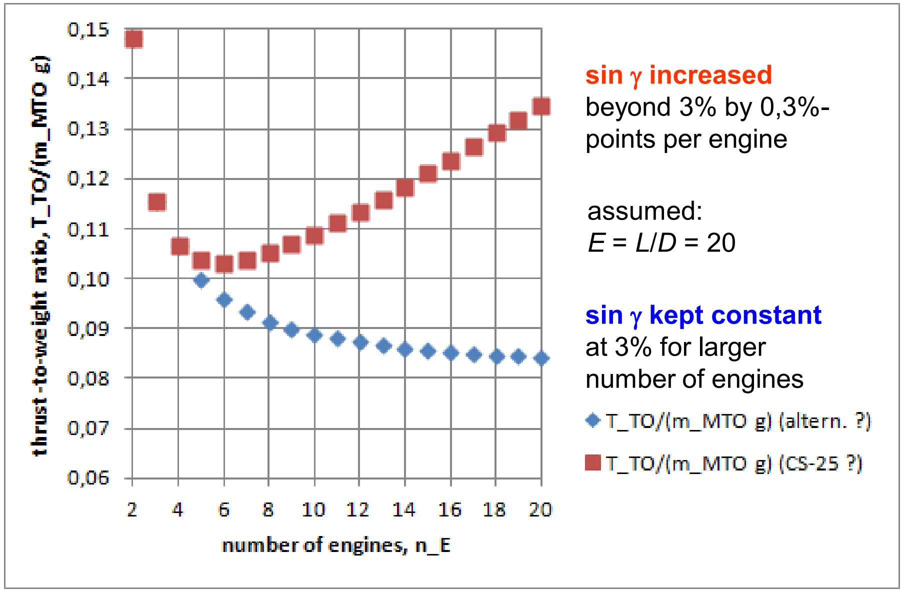
sin γ ↓

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

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



- 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 γ : climb gradient

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

CS 25.107 Take-off speeds

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

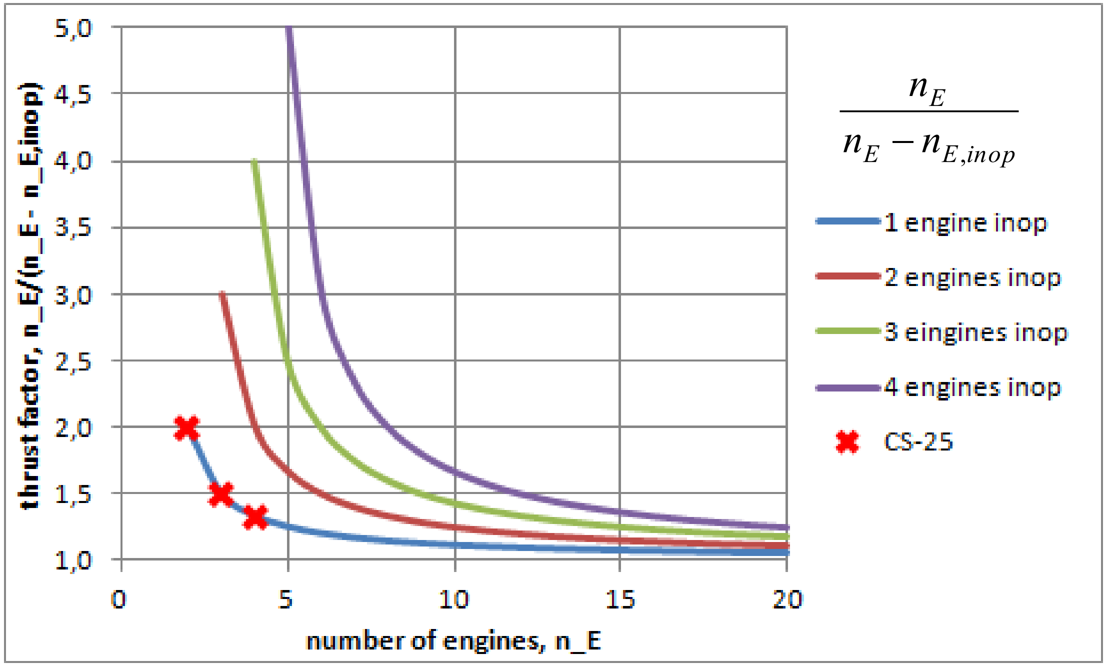
CS 25.109 Accelerate-stop distance

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

CS 25.121 Climb: one-engine-inoperative

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

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



- 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.

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

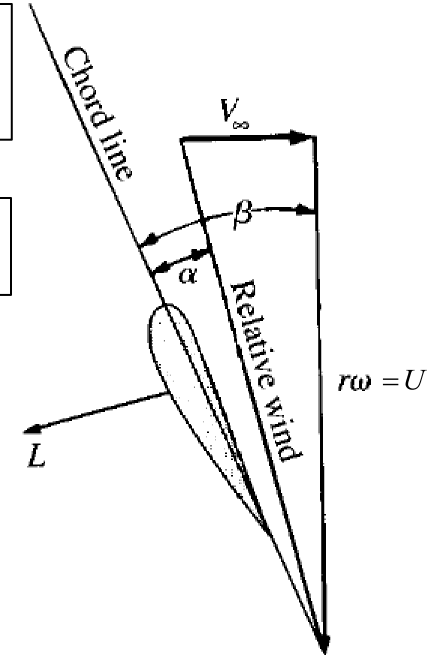
$$\lambda = \pi n D/V = \pi/J \qquad J = \frac{V}{nD} = \pi/\lambda \quad \text{advance ratio}$$

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

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

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.

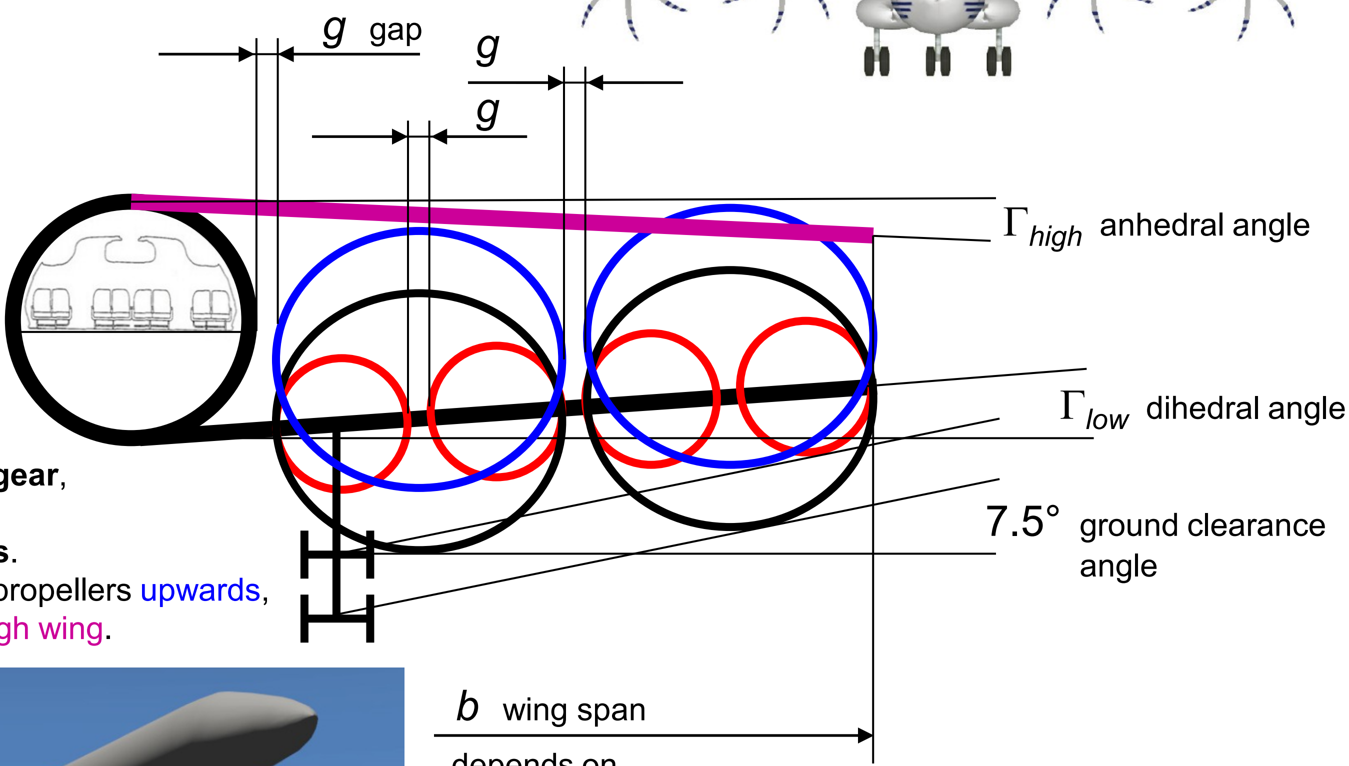
$$\eta_{prop} \approx \frac{2 \cdot \left(1 - \lambda^2 \cdot \ln\left(1 + \frac{1}{\lambda^2}\right)\right)}{1 + \sqrt{1 + \frac{T}{q \cdot A} - 2 \cdot \lambda^2 \cdot \ln\left(1 + \frac{1}{\lambda^2}\right)}}$$

η_{prop} without wave drag (Truckenbrodt 1999)

Aircraft Design for Electric Propulsion

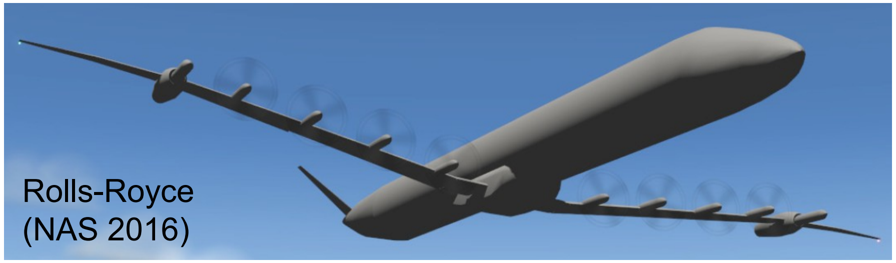
Investigation of Propeller Area ...

... 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!

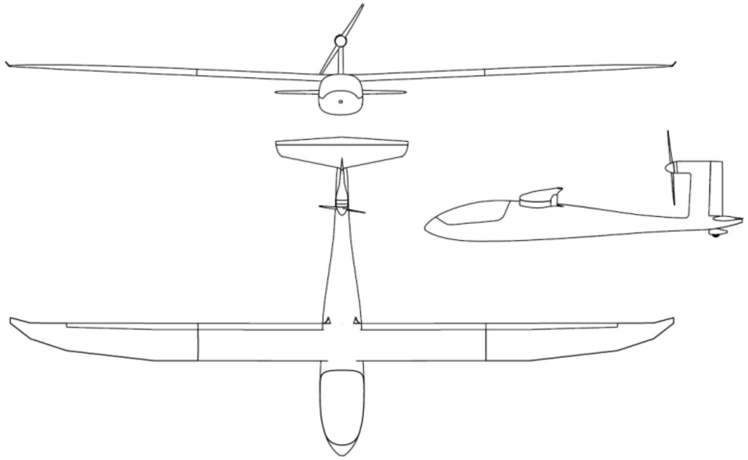

Rolls-Royce
(NAS 2016)

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



Aircraft Design for Electric Propulsion

Engine Integraton – Examples

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)

E-Fan
Airbus

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

E-Fan (DGLR 2015)

Maximum Relative Battery Mass

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

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

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

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

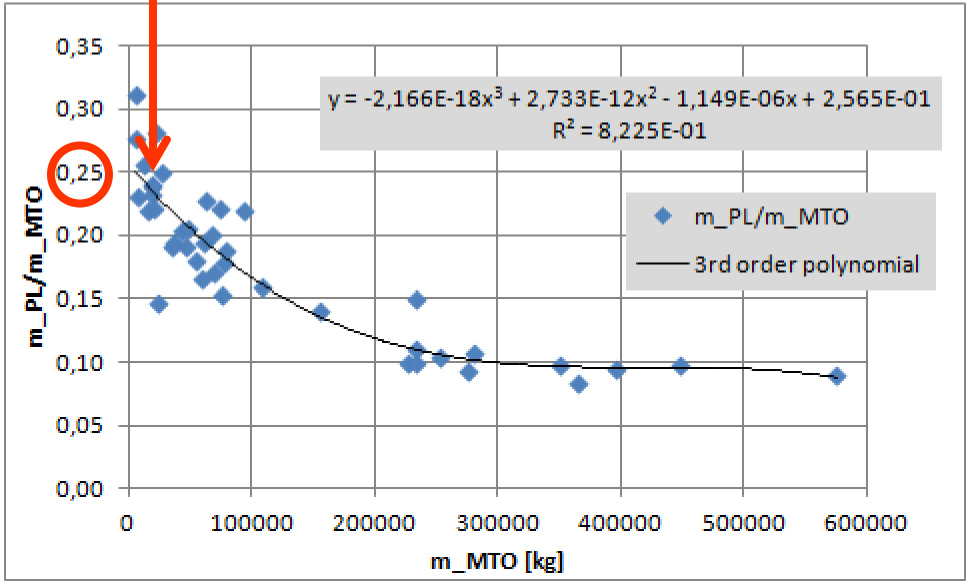
$$\frac{m_{PL}}{m_{MTO}} = 0.10 : \quad \frac{m_{bat}}{m_{MTO}} = 0.40$$

$$0.25 \leq \frac{m_{bat}}{m_{MTO}} \leq 0.40$$

this is equivalent to **revenue / expenses**

m_{MTO} : Maximum Take–Off mass
m_{bat} : battery mass
m_{OE} : Operating Empty mass
m_{PL} : PayLoad

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

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

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

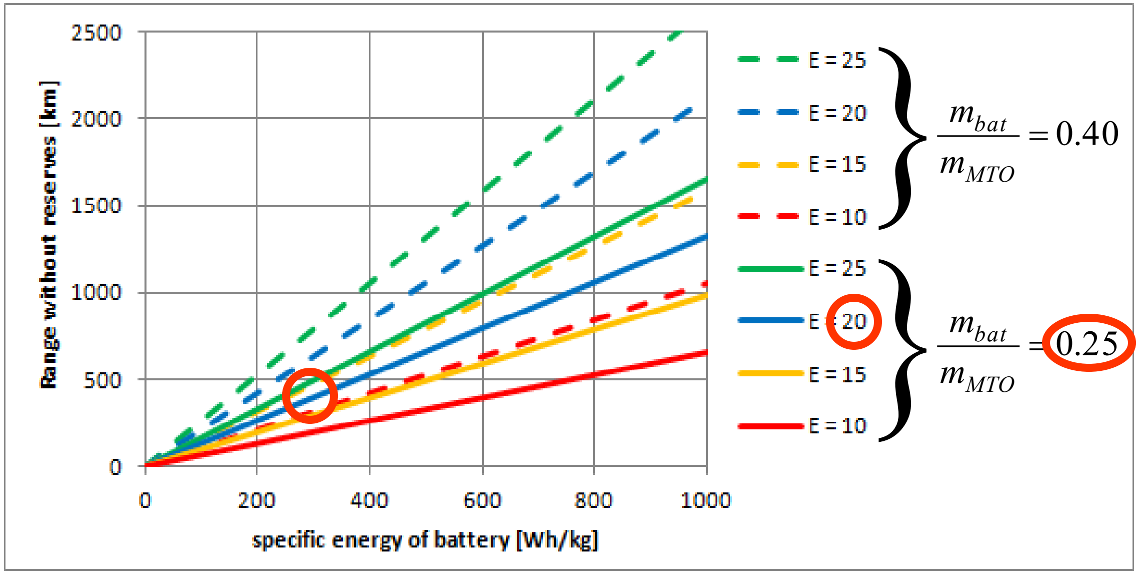
$$P_{bat} = \frac{E_{bat}}{t} = m_{bat}\, e_{bat} \frac{V}{R}$$

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

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

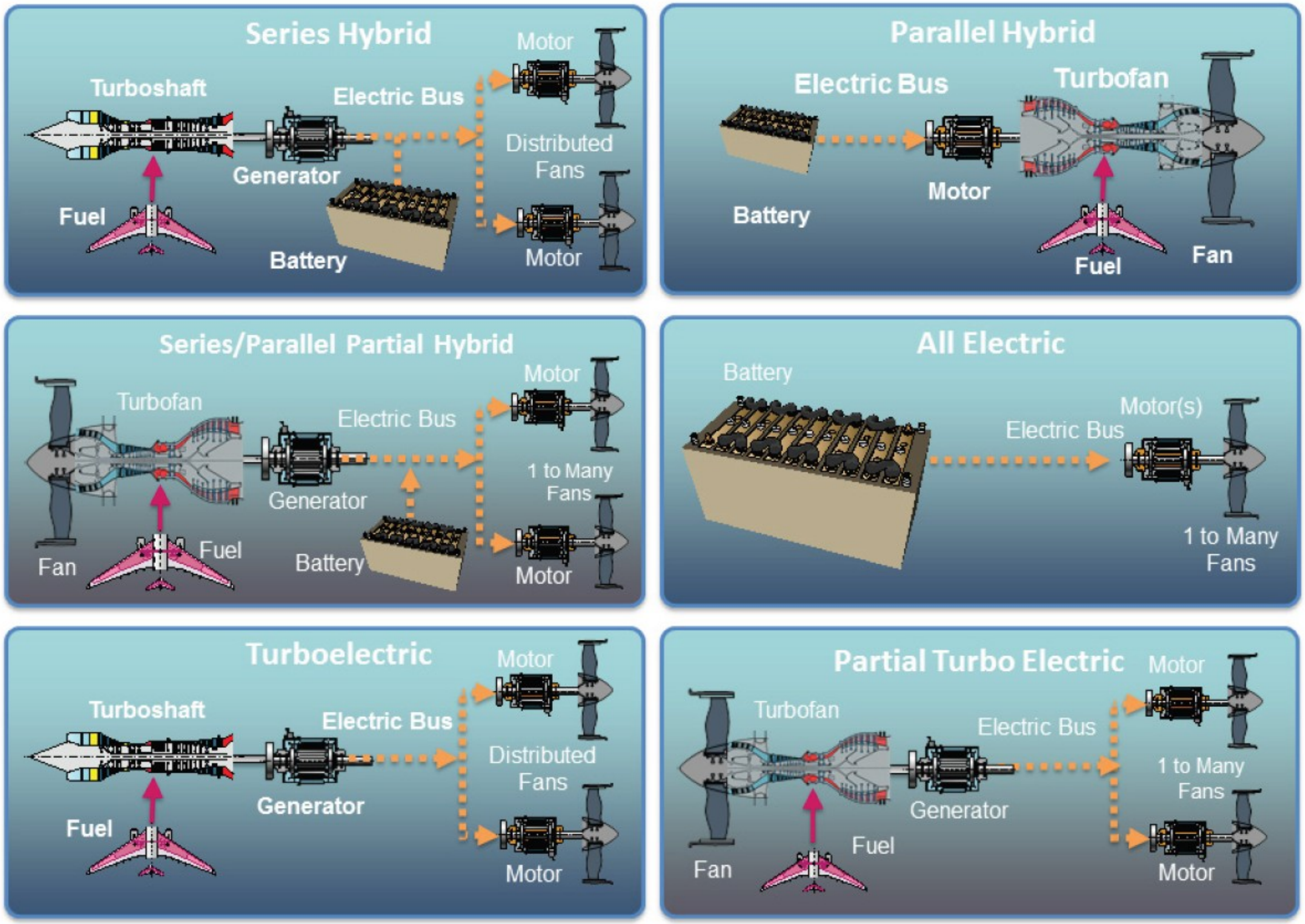
$$\eta_{elec} = 0.9; \qquad \eta_{prop} = 0.8$$

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



○ : realistic parameters

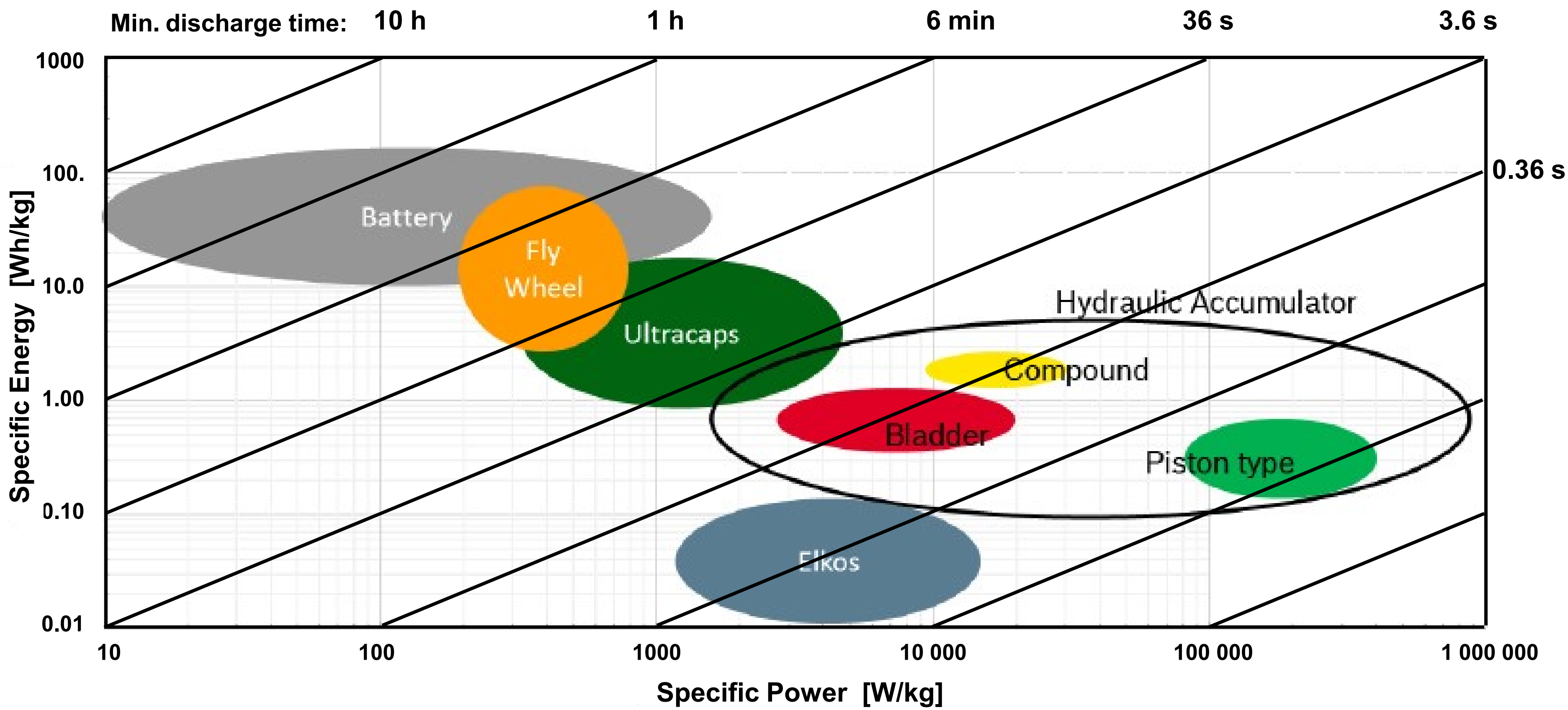
The Major 6 Turbo / Electric / Hybrid Architectures



NAS 2016

Aircraft Design for Electric Propulsion

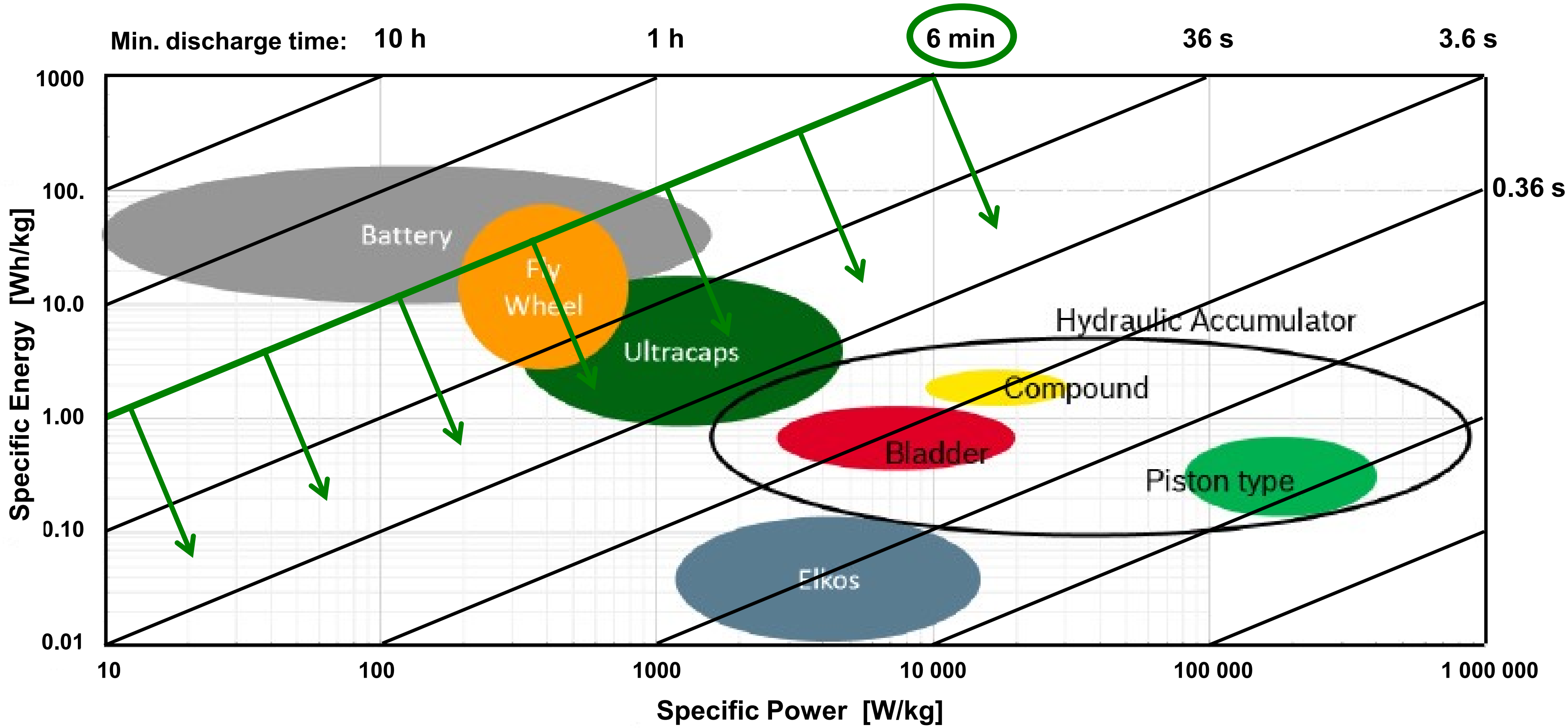
Ragone Diagram for Energy Storage Devices



based on Geerling 2017

Aircraft Design for Electric Propulsion

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*

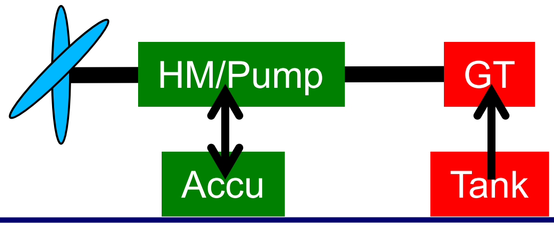
$E = A + B$	E: energy
$B = W$	A: anergy
$\eta = W / E = B / E$	B: exergy
$B = \eta E$	W: work
$E = m_F H_L$	η: efficiency
$e = E / m_F = H_L$	m_F: fuel mass
$b = B / m_F = \eta E / m_F$	H_L: lower heating value
$b = \eta H_L$	e: specific energy
	b: specific exergy

	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

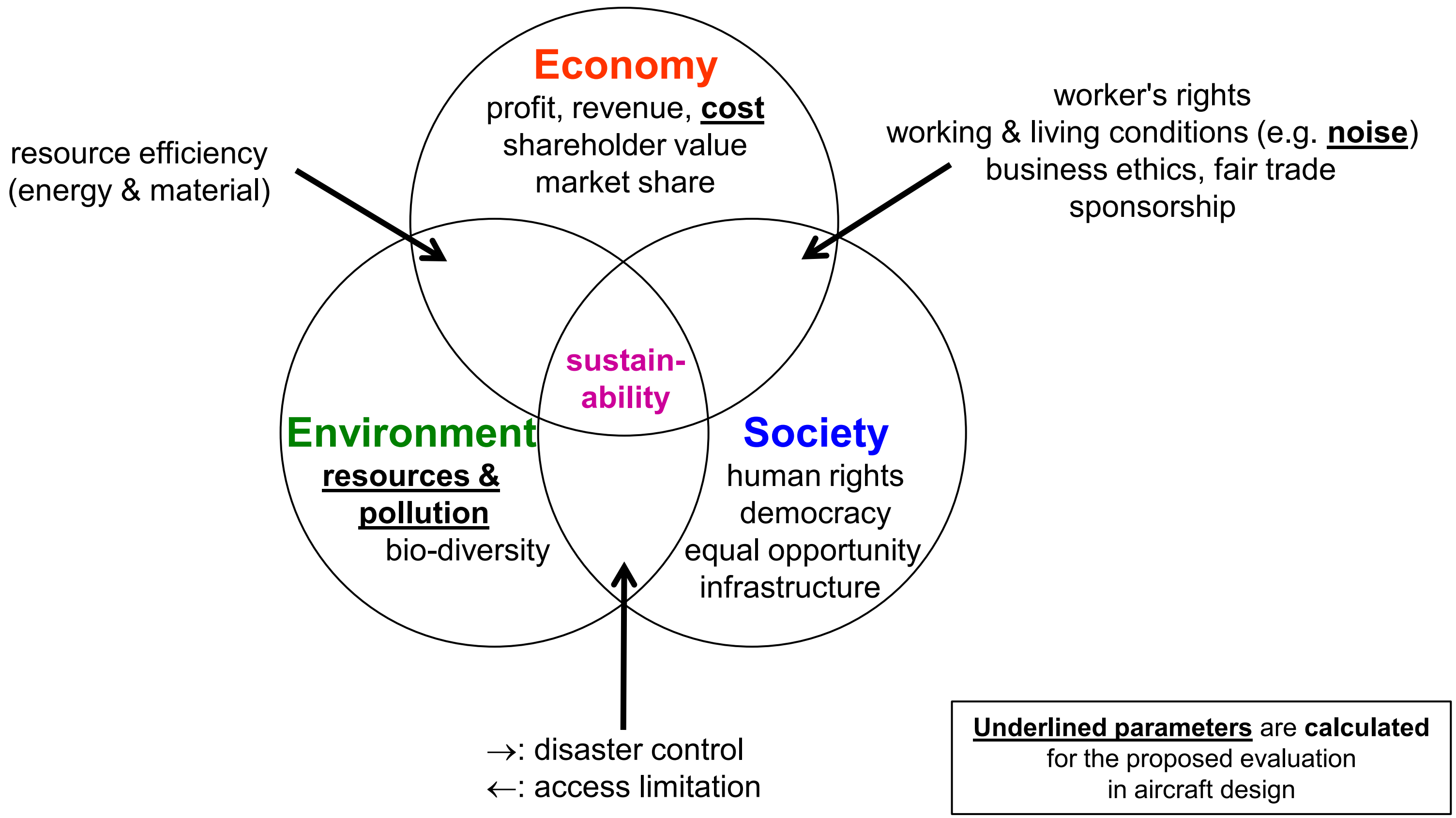
Generic Evaluation of Turbo / Electric / Hydraulic Architectures

- 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



Sustainability Venn Diagram

Evaluation: Purpose

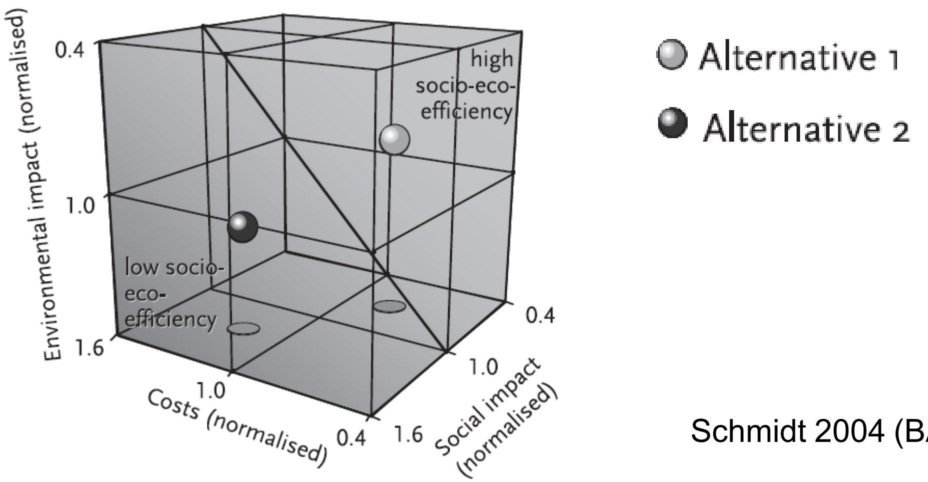
- evaluation of the aircraft for **optimum design** (definition of an objective function)
- **technology evaluation** (on an assumed aircraft platform)
- evaluation for **aircraft selection** (for aircraft purchase by an airline)

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 devel-oped 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 mo-dification of the method **AEA 1989a**)	1989	**AEA 1989b**
Airbus Industries (AI)	The Method was continuously devel-oped 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

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

- 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)

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

$H_L = 43$ MJ/kg

$\eta_{charge} = 0.9$

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

Carnot Efficiency:

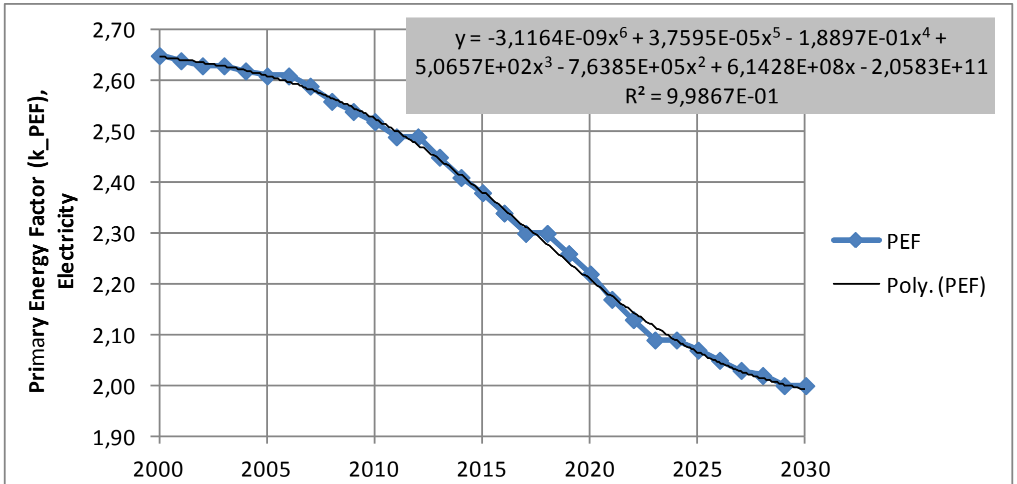
$\eta_C = 1 - T(h) / T_{TET} = 1 - 216.65/1440 = 0.85$

Radiative Forcing Index:

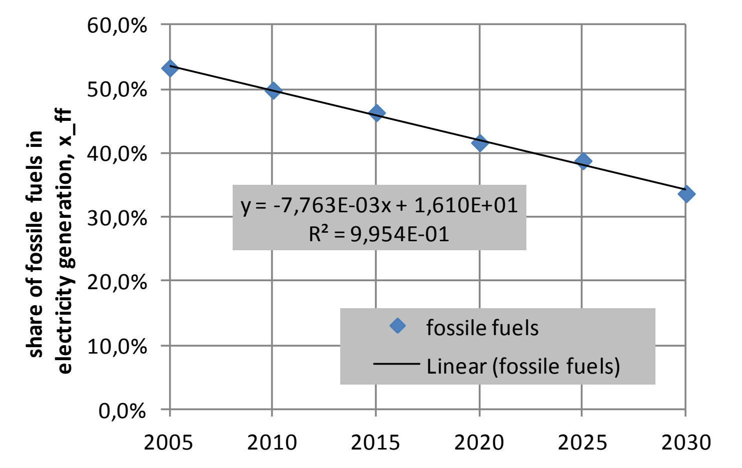
$k_{RFI} = 2.7 \quad (1.9 \ldots 4.7)$

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

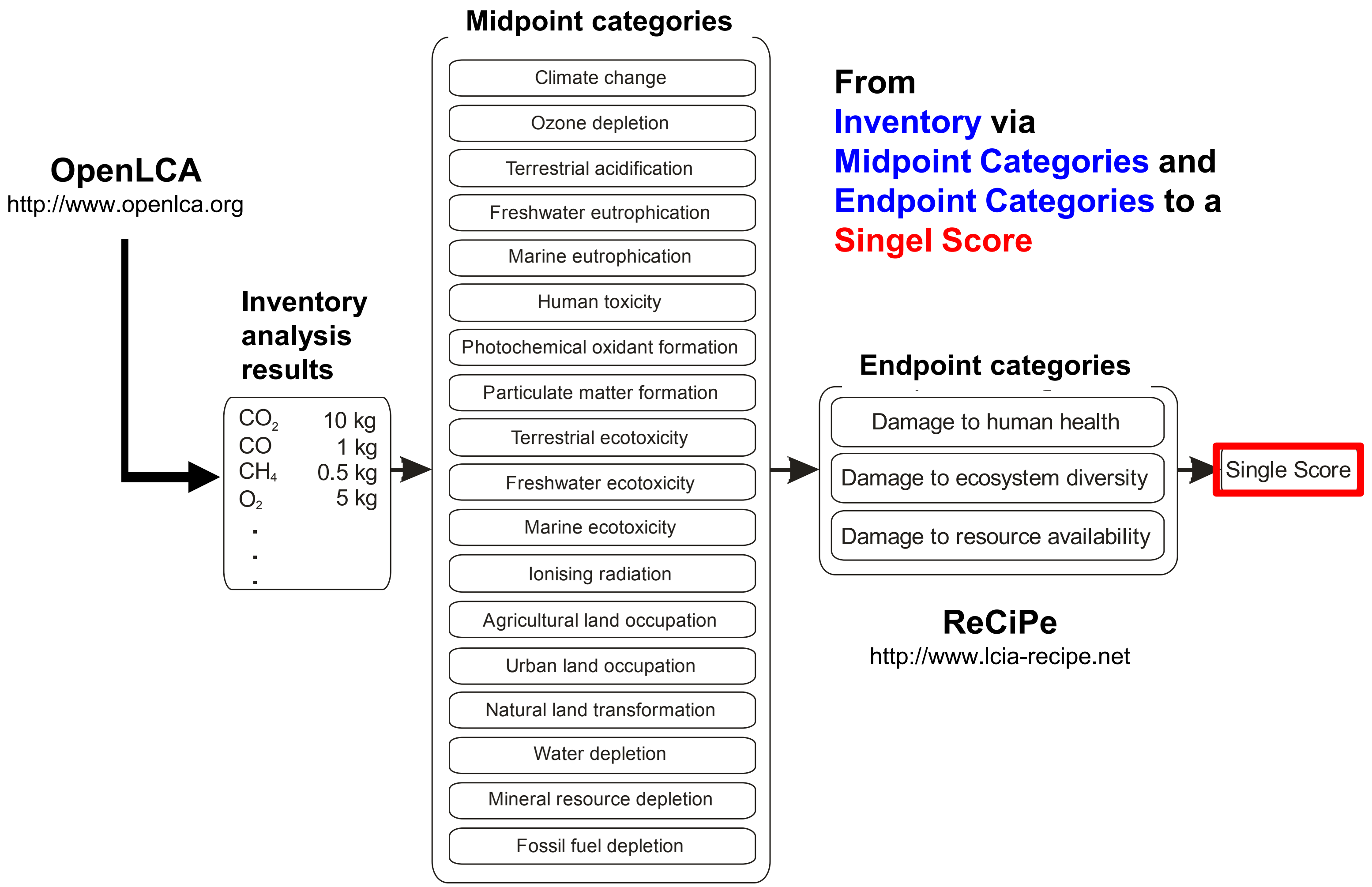
Environmental Evaluation

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		

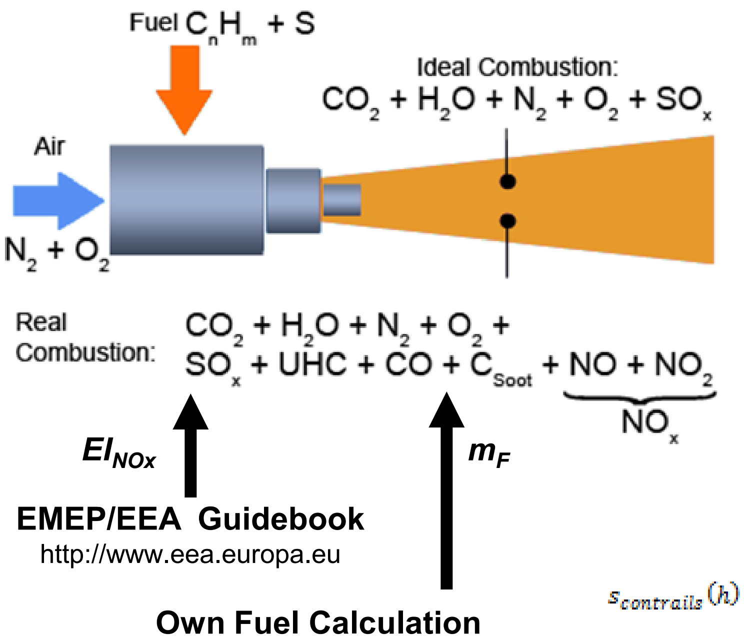
An Excel-Based Life Cycle Tool

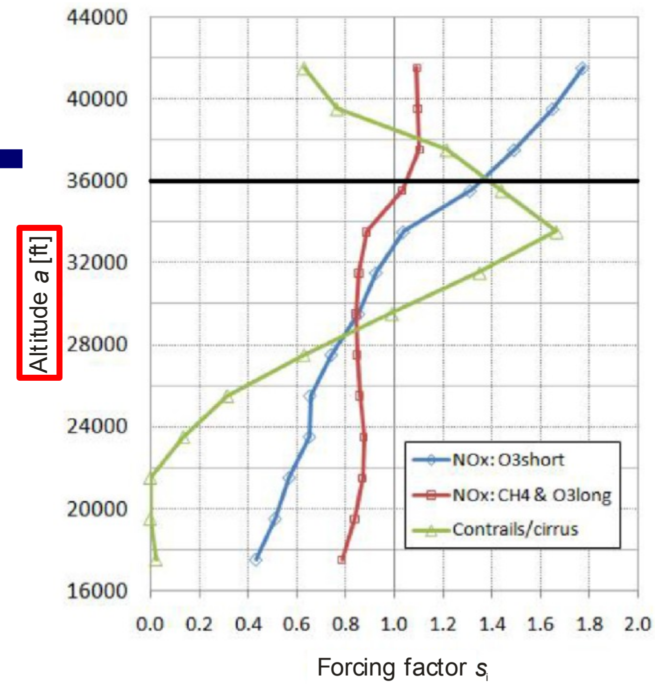


From
Inventory via
Midpoint Categories and
Endpoint Categories to a
Singel Score

Environmental Evaluation

Altitude Dependent Equivalent CO2





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

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

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

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

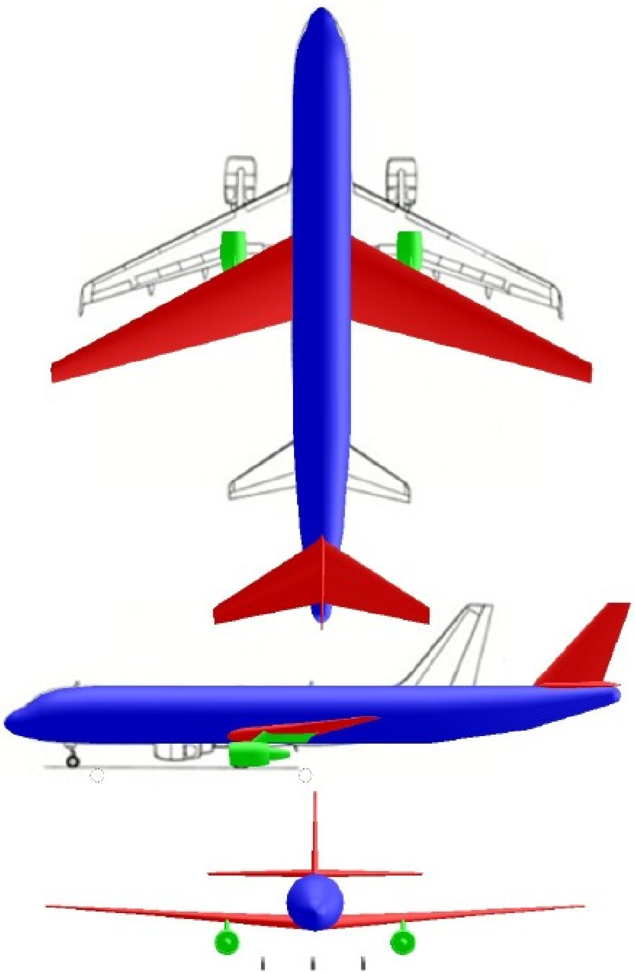
Battery Powered A320

- 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

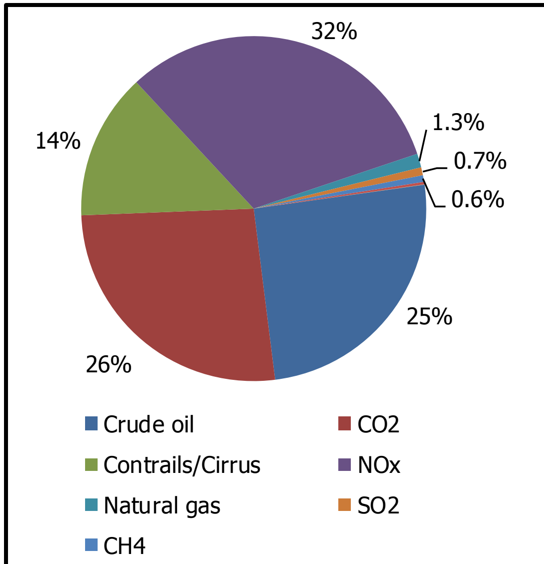
- Contributions of In- and Outputs on Single Score (SS) (left)
- Considered Processes (right)
- SS = 0.0173 points
- CO_2 = 0.0045 points in SS

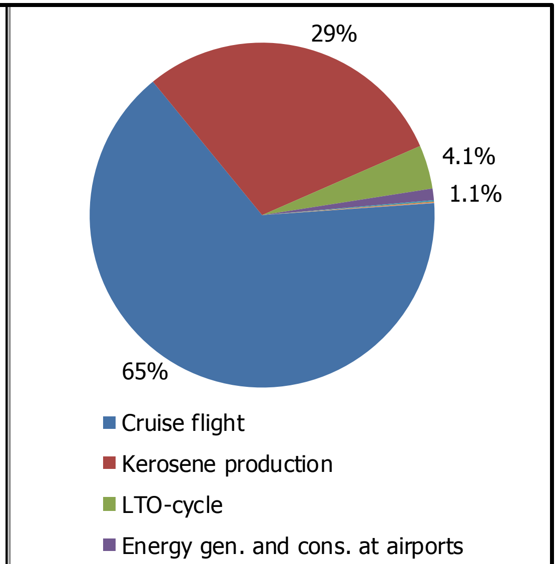
Battery Powered Aircraft

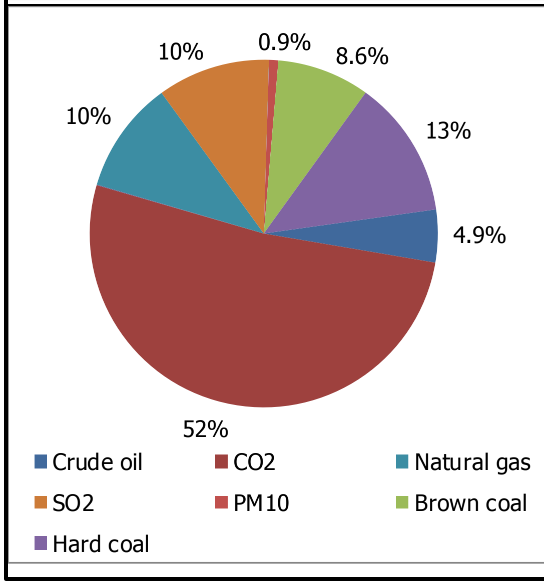
- Contributions of In- and Outputs on Single Score (SS) (left)
- Considered Processes (right)
- SS = 0.0095 points
- CO_2 = 0.0049 points in SS

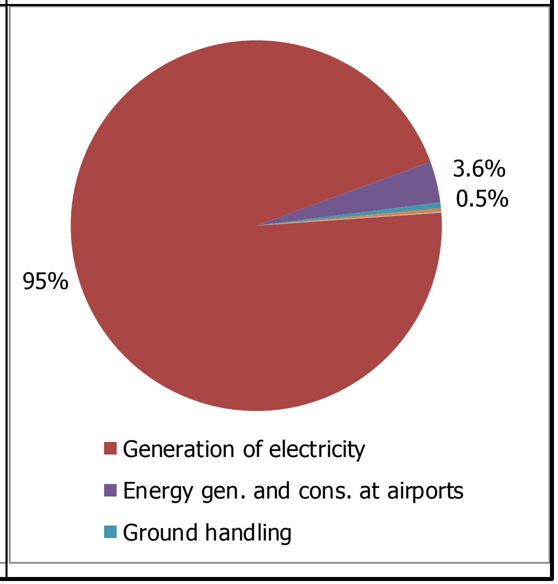
⇒The battery powered aircraft does not save CO_2

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









Social Evaluation (S-LCA, Noise)

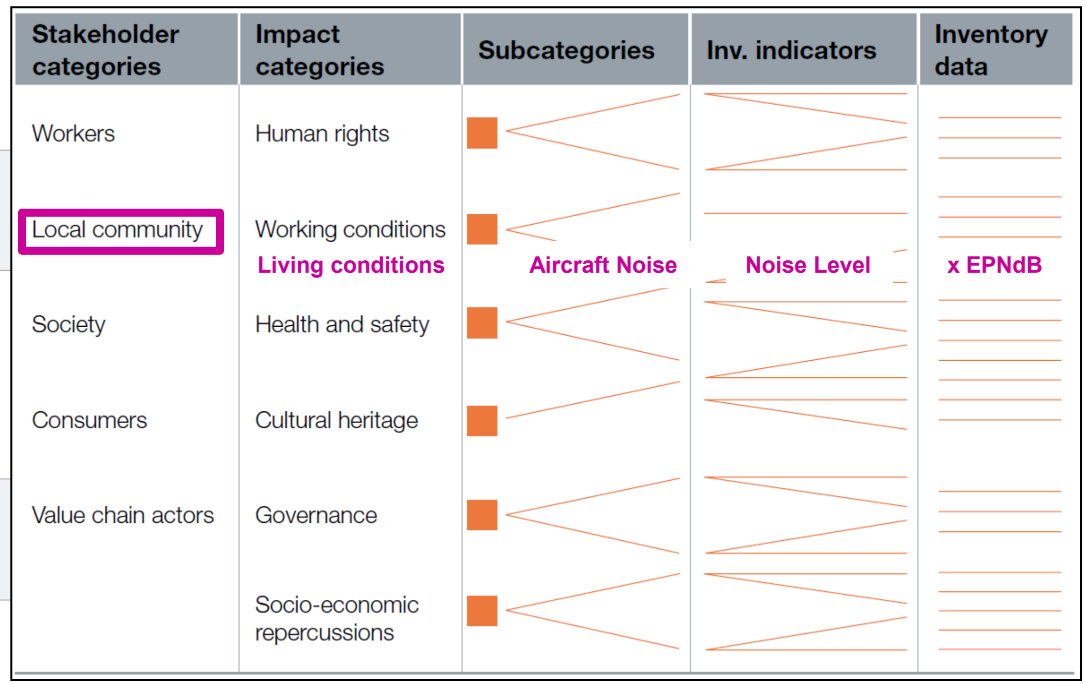
Social Evaluation

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 one of many possible indicators in an S-LCA



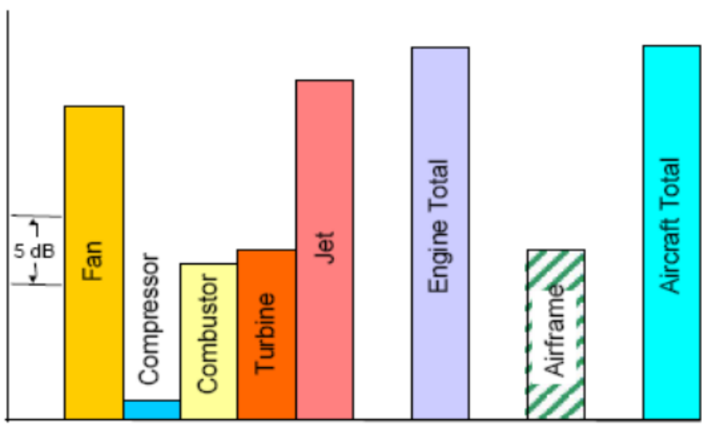
Aircraft Noise

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

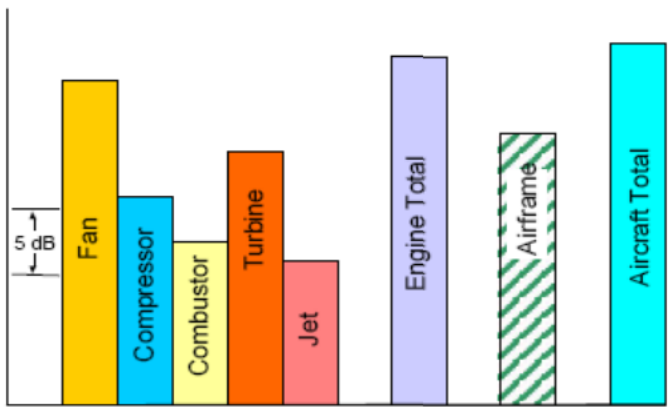
- Mechanical noise
  - engine (turbo jet, turbo fan, turbo prop, piston prop)
    - jet noise (exhaust) of jet aircraft – dominant for jets on take-off
    - fan blades (*buzzsaw noise* when tips reach supersonic speeds)
    - noise from compressor, combustion chamber, turbine, after burner, reverse 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.

Aircraft Noise on Departure versus Arrival



Typical Departure Noise Distribution



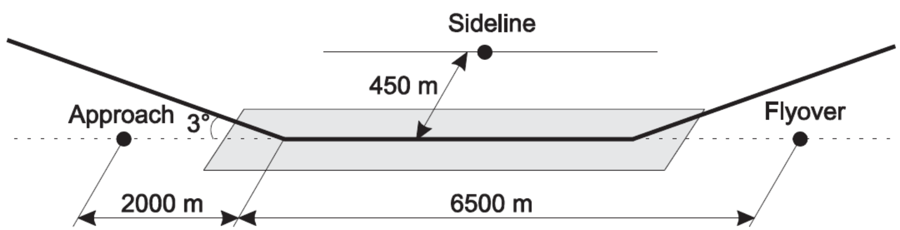
Typical Arrival Noise Distribution

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	

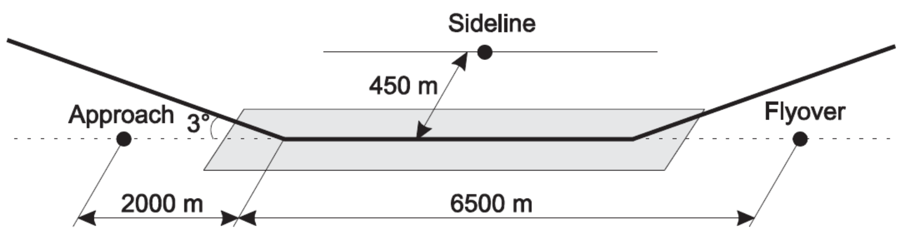
1.) read
Cumulative Margin: $\Sigma(\Delta n_i)$

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 :

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

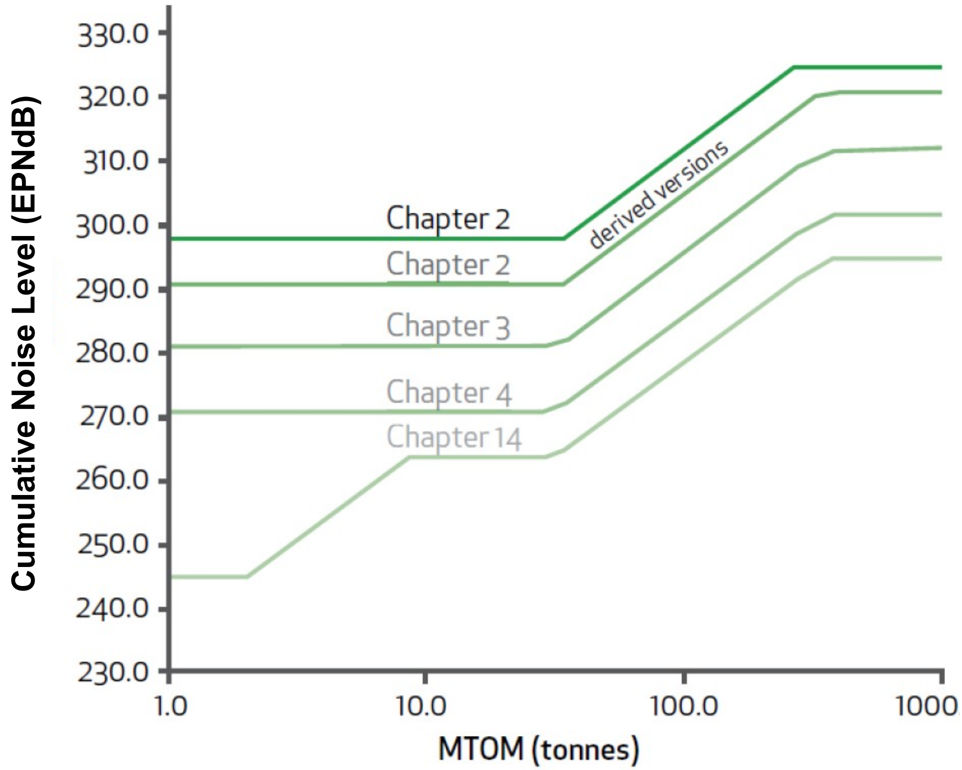
With example data from database of **A321neo**:

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

- 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)

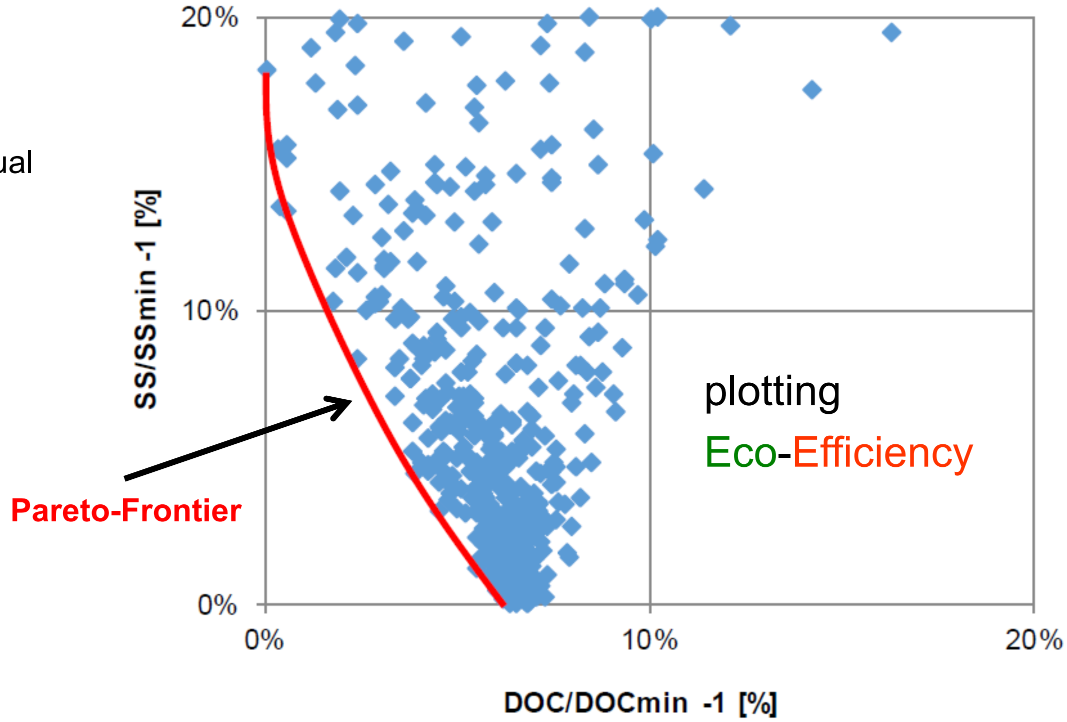
- **Many techniques** exist => Literature
- **Weighted Sums Analysis**: $SS_{total} = k_{DOC}\ DOC + k_{SS,LTA}\ SS_{LTA} + k_{SS,S-LTA}\ SS_{S-LTA}$
- **Pareto-Optimum**:

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} – $SS_{S\text{-}LAT}$



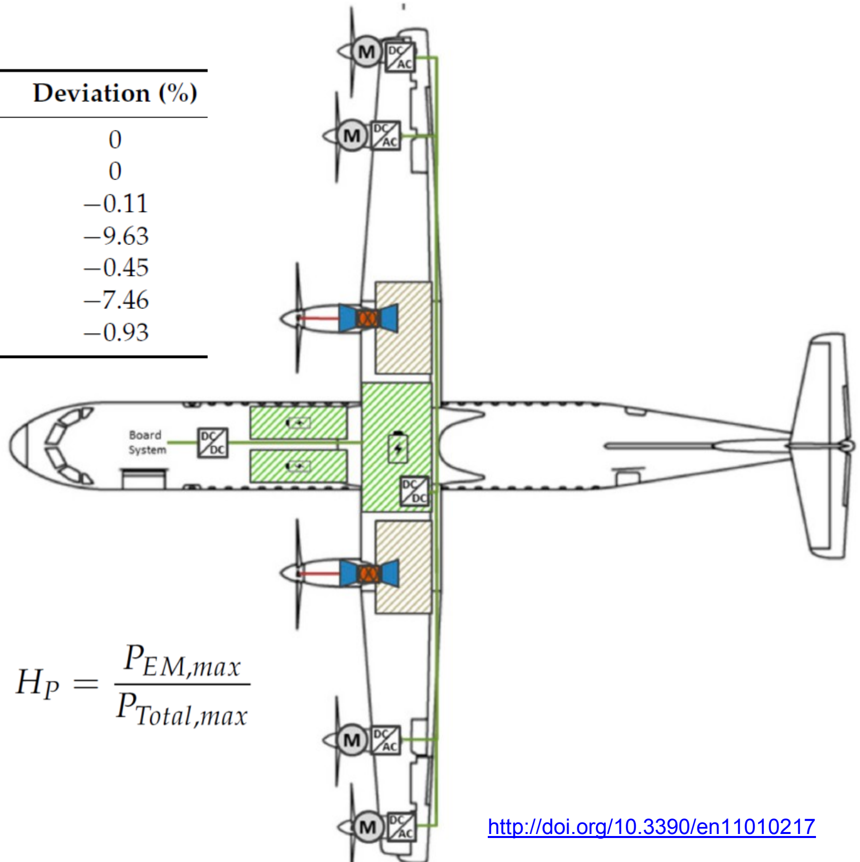
Johanning 2017

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.

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

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 $\lambda_{Bat} = 0$.

http://doi.org/10.3390/en11010217

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]

Hoelzen 2018

Example

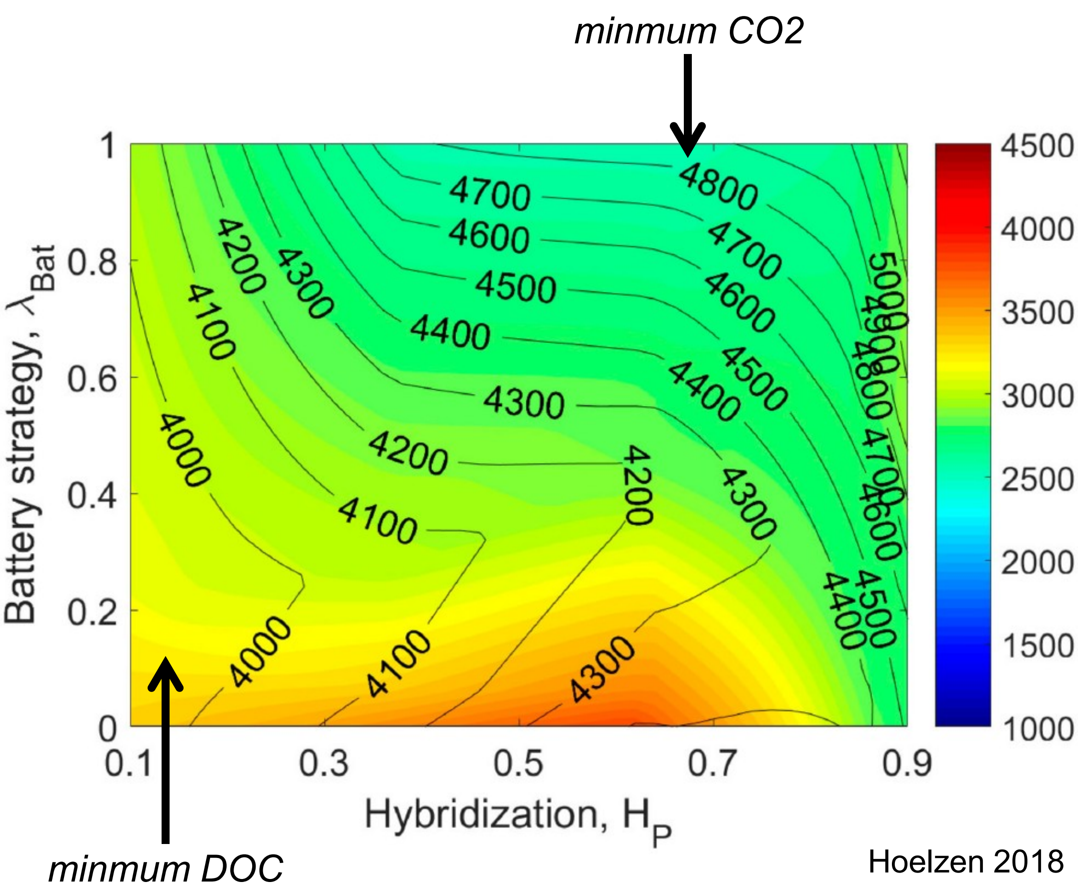
Hybrid-Electric ATR-42

- The figure shows the total CO_2 emissions (heat map) and Direct Operating Costs, DOC (contour lines) in dependence of hybridization H_P and battery strategy parameter λ_{Bat}.
- CO_2 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. CO_2 do not fall together!

- Cost competitive HEA configurations do not promise the targeted CO_2 emission savings.

  (electricity production from OECD mix; 0.42 kg CO_2 per kWh)

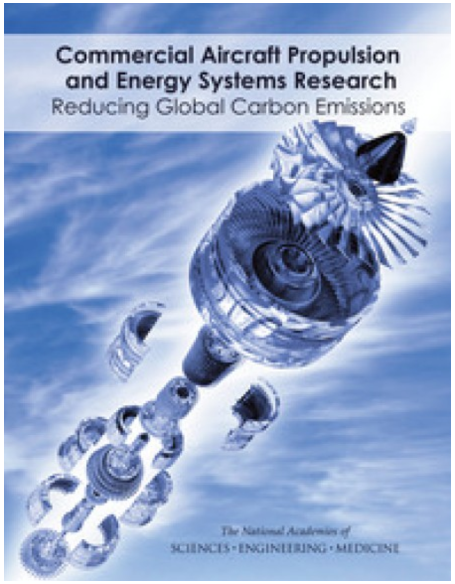


Hoelzen 2018

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.
- CO_2 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**.



The National Academies of
SCIENCES · ENGINEERING · MEDICINE

NAS 2016

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