HAW Lecture by DLR Institute of System Architectures in Aeronautics

Electric Air Travel Potential for Improved Sustainability

Georgi Atanasov – DLR - System Architectures in Aeronautics
23.06.2025

Today‘s Session

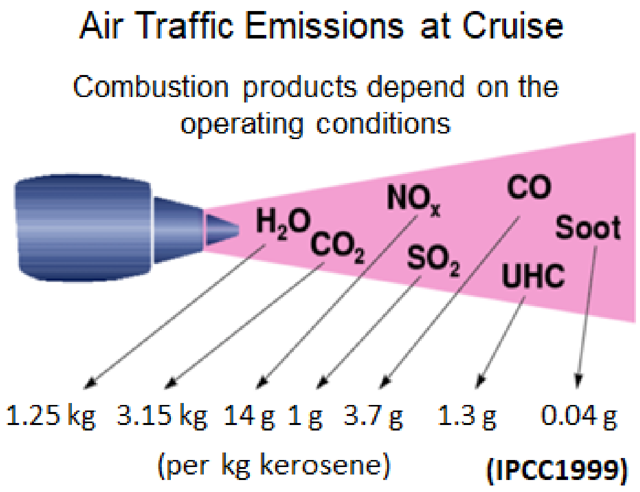
- Introduction of the Challenges of Aviation Sustainability
- What Types of Aircraft Can be Operated in a Sustainable Way
- Battery-Electric Aircraft Extensive Overview → Theory, Challenges, and Potential Solutions
- DLR Project Experience with Battery-Electric Aircraft Concepts

Aviation Climate Impact

Aviation global CO_2 contribution (2018) ~2%

Aviation global temperature impact contribution (2018) ~5%

A Key DLR Research Topic: Sustainability of Aviation.

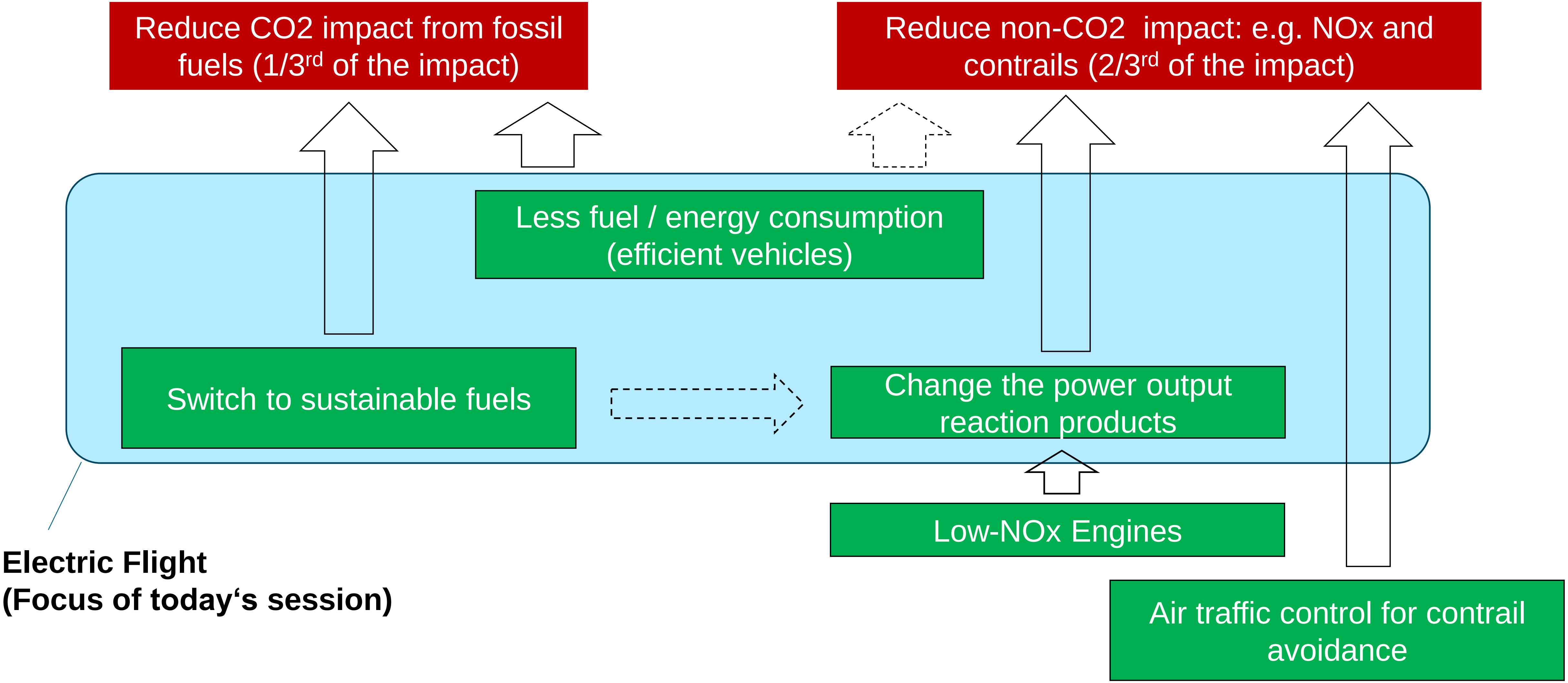


Main problems to solve:

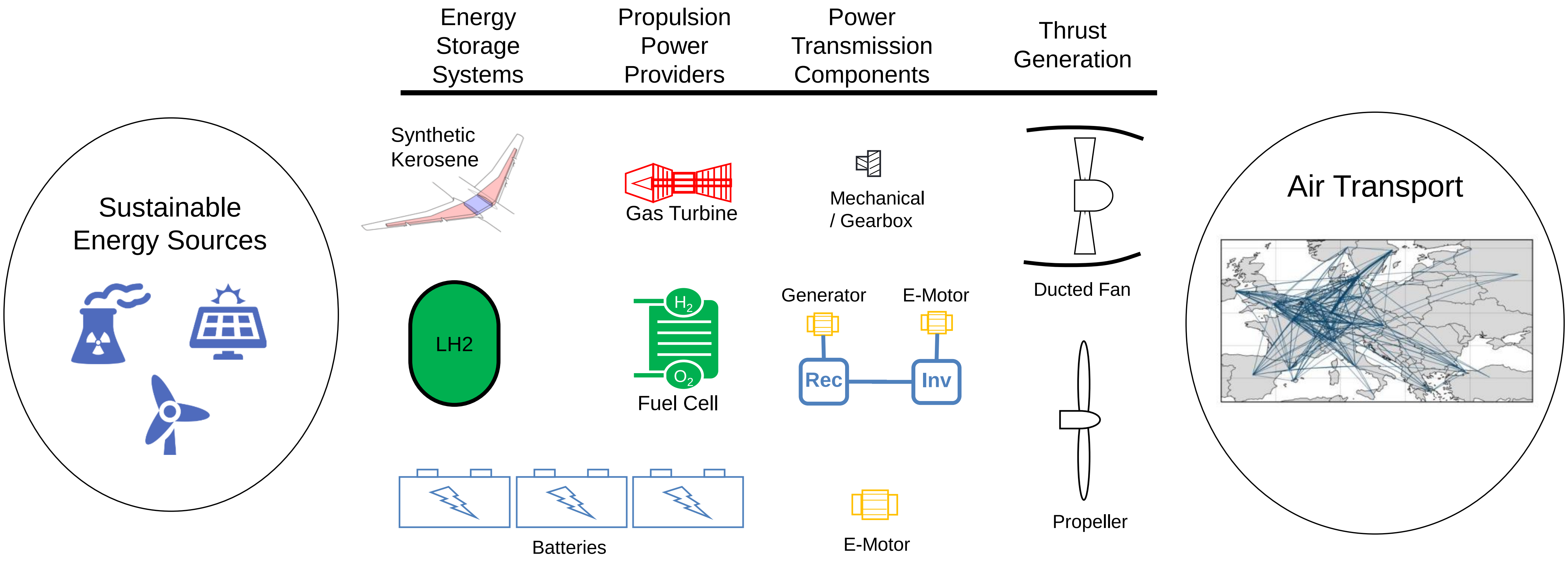
- **CO2 impact from fossil fuels (1/3rd of the impact)**
- **Non-CO2 impact from NOx and contrails (2/3rd of the impact)**

• CO_2	~1/3 impact
• NO_x • Contrails • H_20	~2/3 impact Source: **Grewe et al (2019)**

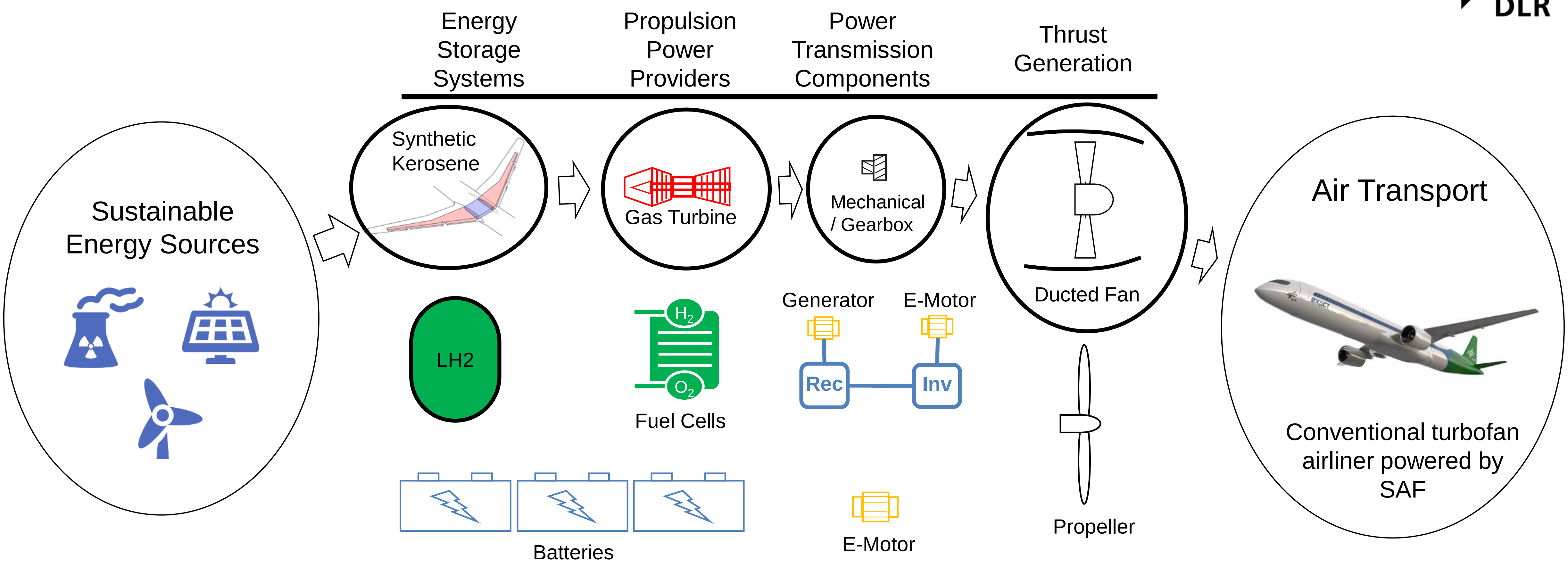
Reducing Climate Impact



Some Possible Means for Electric Flight



Some Possible Means for Electric Flight



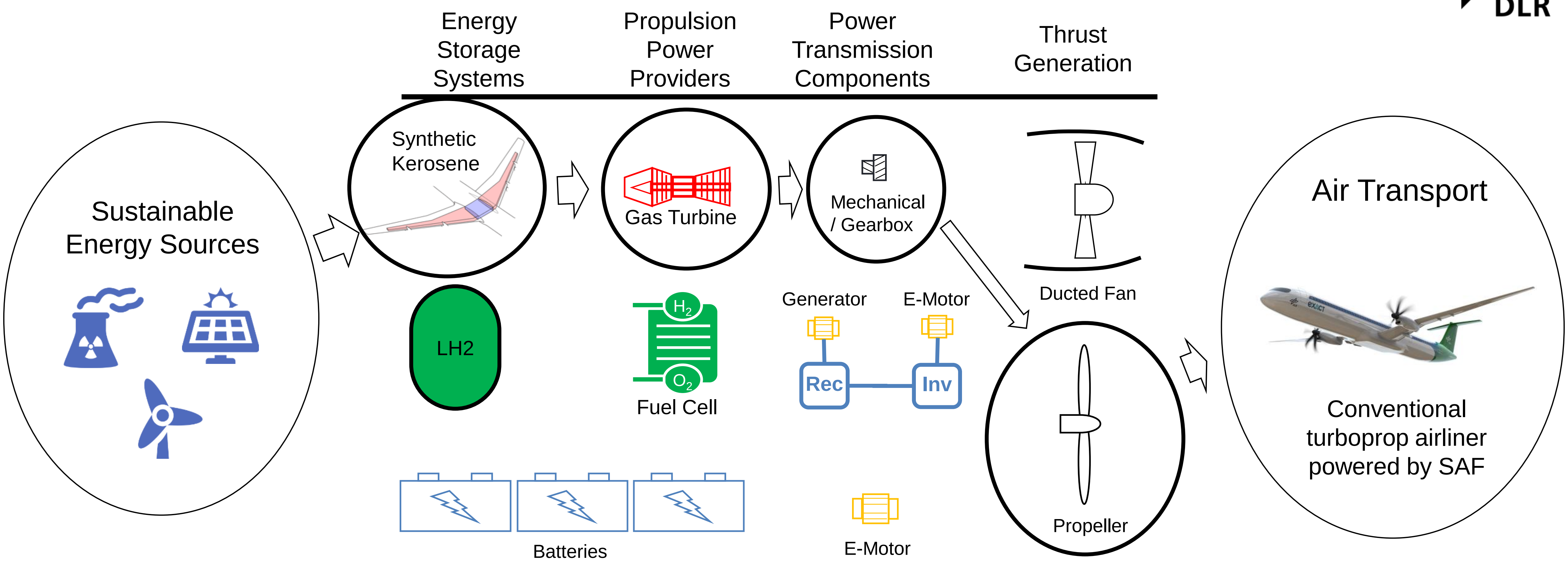
Benefits

- Minimal change in airport infrastructure and aircraft manufacturing.

Draw-backs:

- Expensive fuel production.
- Needs low-NOx gas turbines & specialized air traffic control to solve non CO2 impact

Some Possible Means for Electric Flight



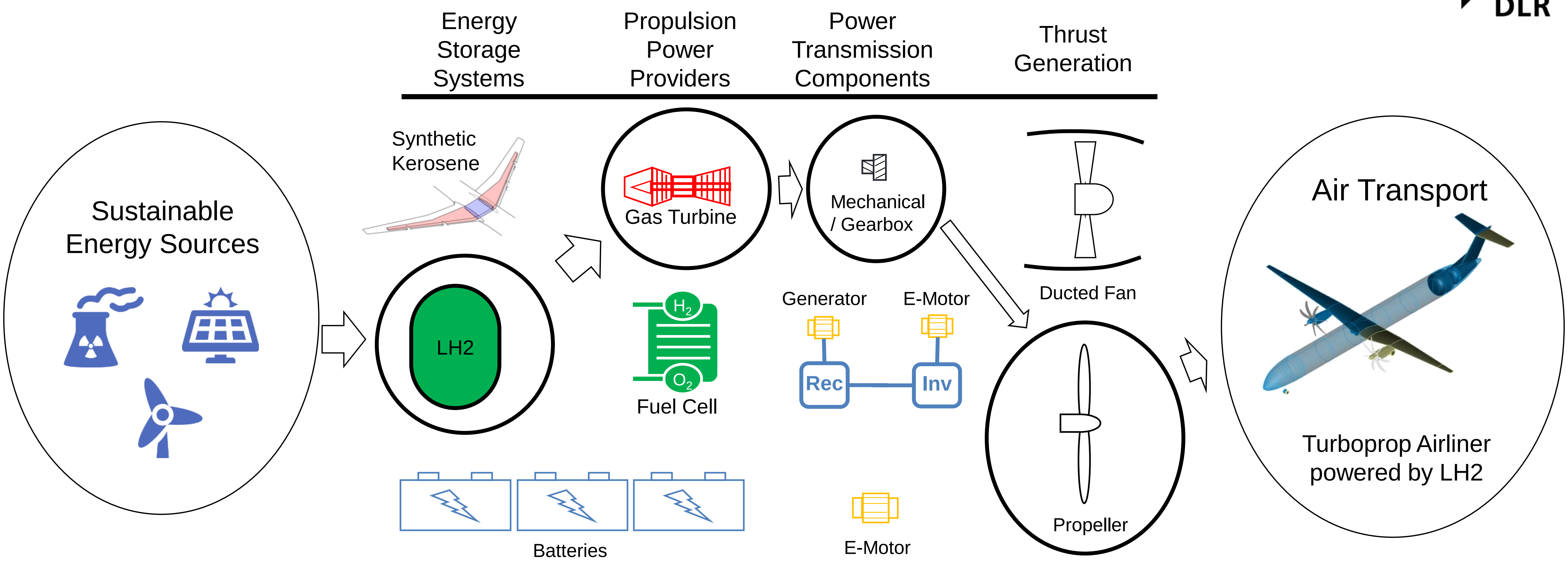
Benefits

- Increased fuel efficiency (vs turbofan)
- Typically lower cruise alitude → reduced non-CO2 impact

Draw-backs:

- Speeds only up to Mach 0.7
- Or extremely noisy counter rotating propellers (or open propeller-stator combination) for higher speeds (~Ma0.8).

Some Possible Means for Electric Flight



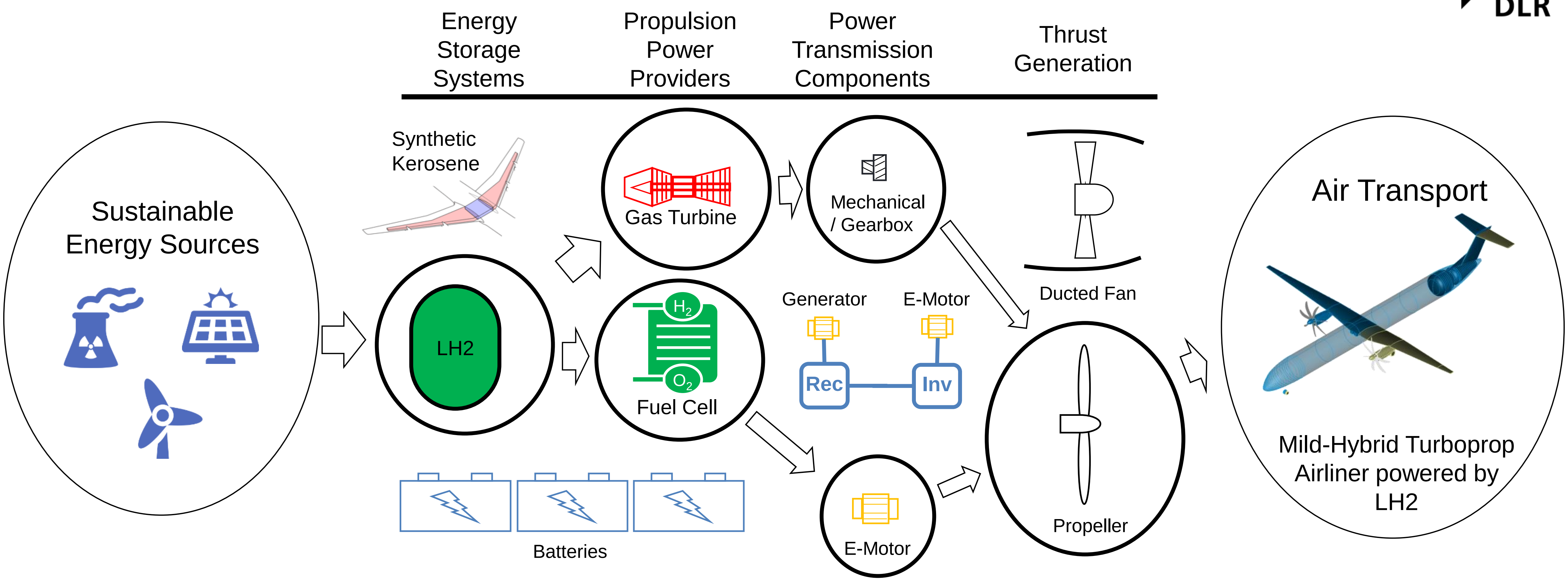
Benefits

- More efficiency and potentially cheaper production of energy storage
- Poentially less NOx emissions

Draw-backs:

- Cryogenic storage
- Larger integration volume
- More complex energy storage system

Some Possible Means for Electric Flight



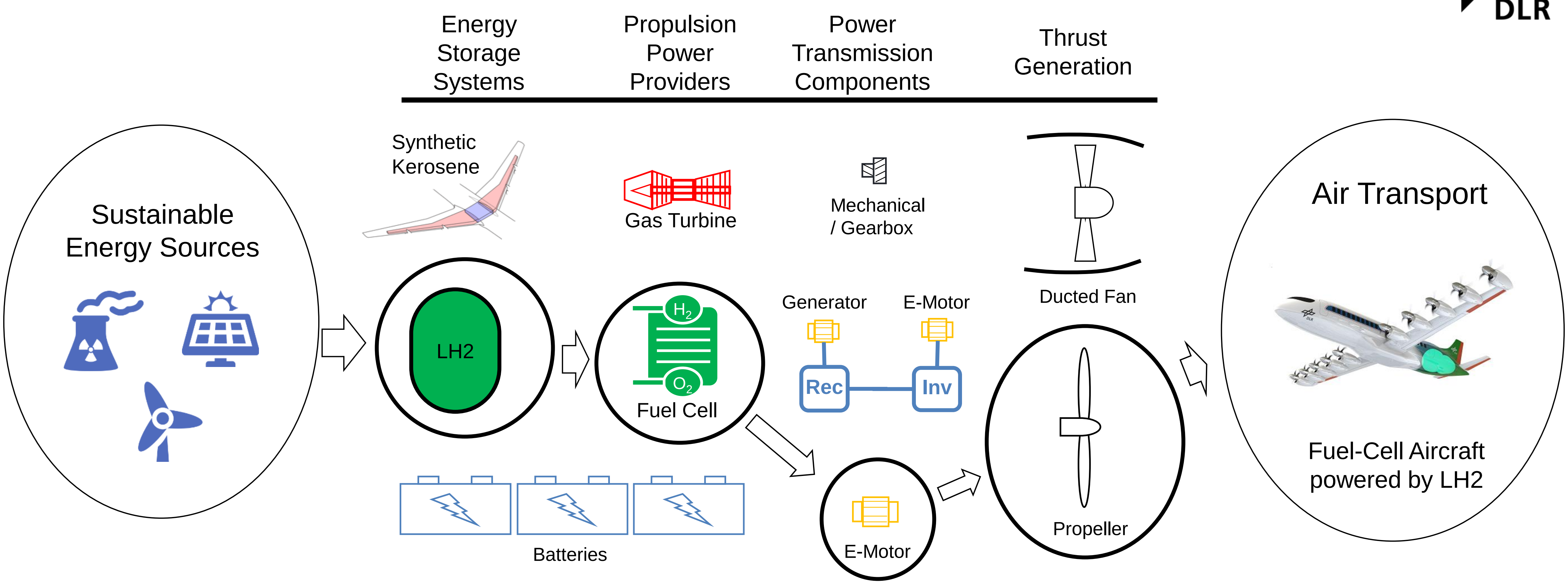
Benefits

- Reduced fuel consumption in off-design operation (e.g. taxi on the runway, descent, landing)

Draw-backs:

- A more complex (i.e. expensive) propulsion chain

Some Possible Means for Electric Flight



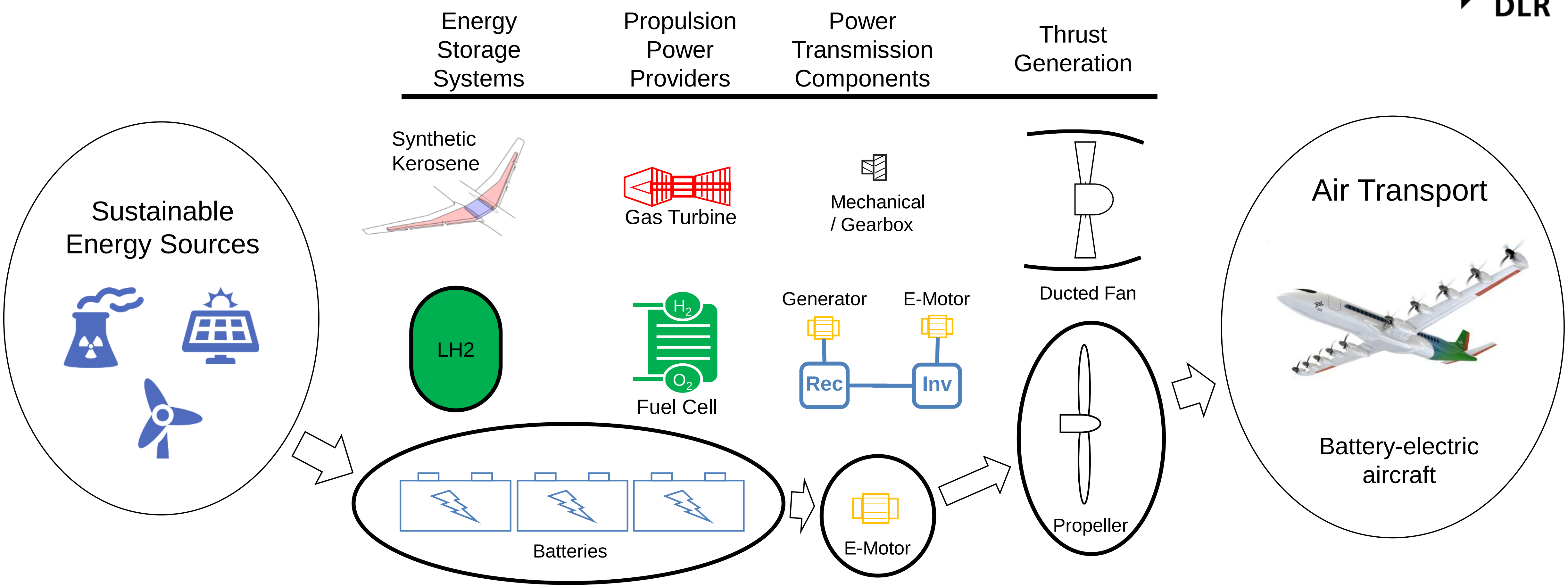
Benefits

- Minimal non-CO2 impact
- Higher fuel efficiency than gas turbines but mostly for smaller aircraft (small gas turbines are not very efficient)

Draw-backs:

- Heavy power provider → tendency towards even slower flight (Ma<0.5)
- Thermal management of low-temperature fuel cells is very challenging

Some Possible Means for Electric Flight



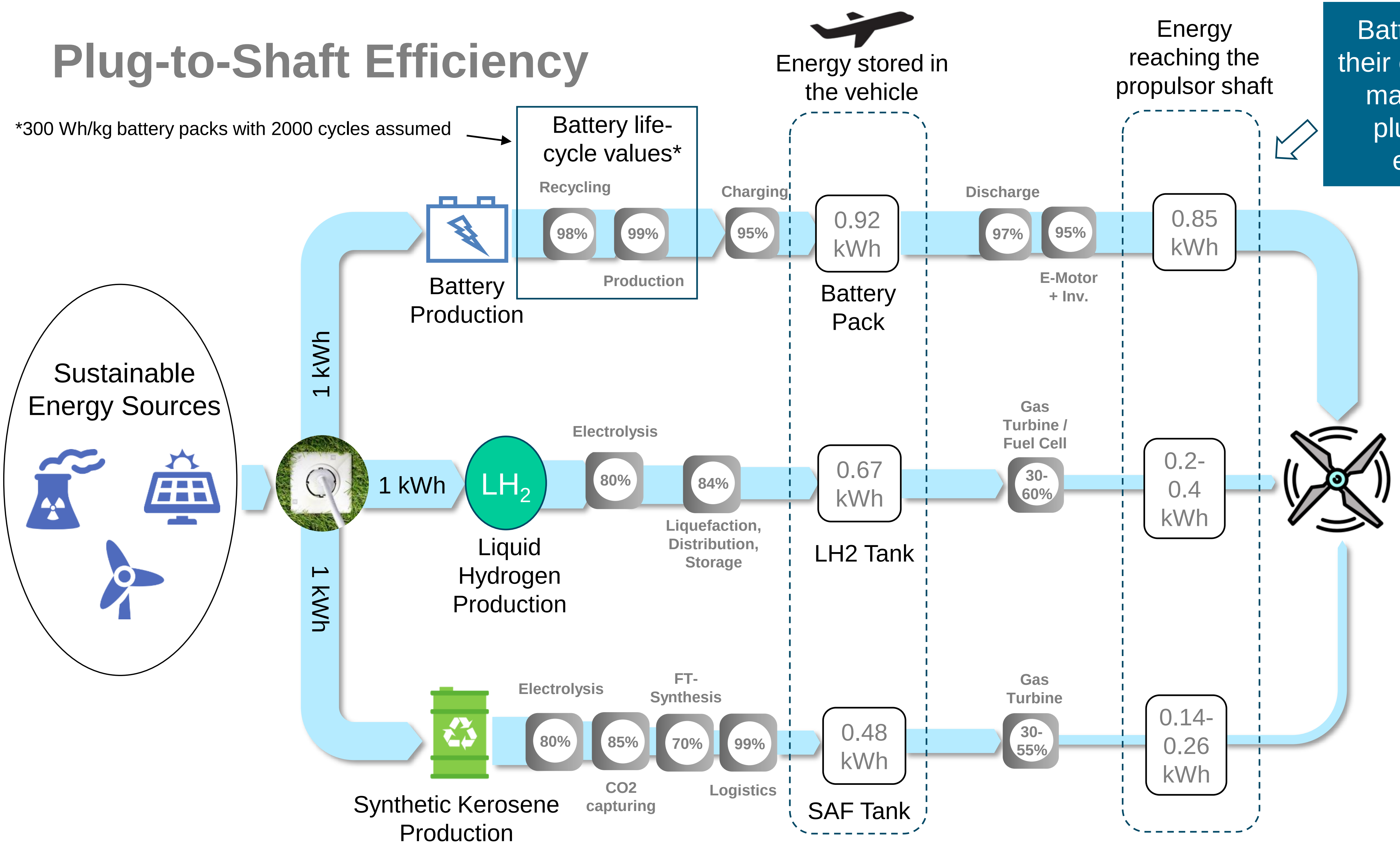
Benefits

- Most direct utilization of the sustainable energy
- Highest efficiency during flight
- Zero non-CO2 impact and zero flight emissions

Draw-backs:

- Heavy aircraft due to the heavy battery
- Limited to short distances

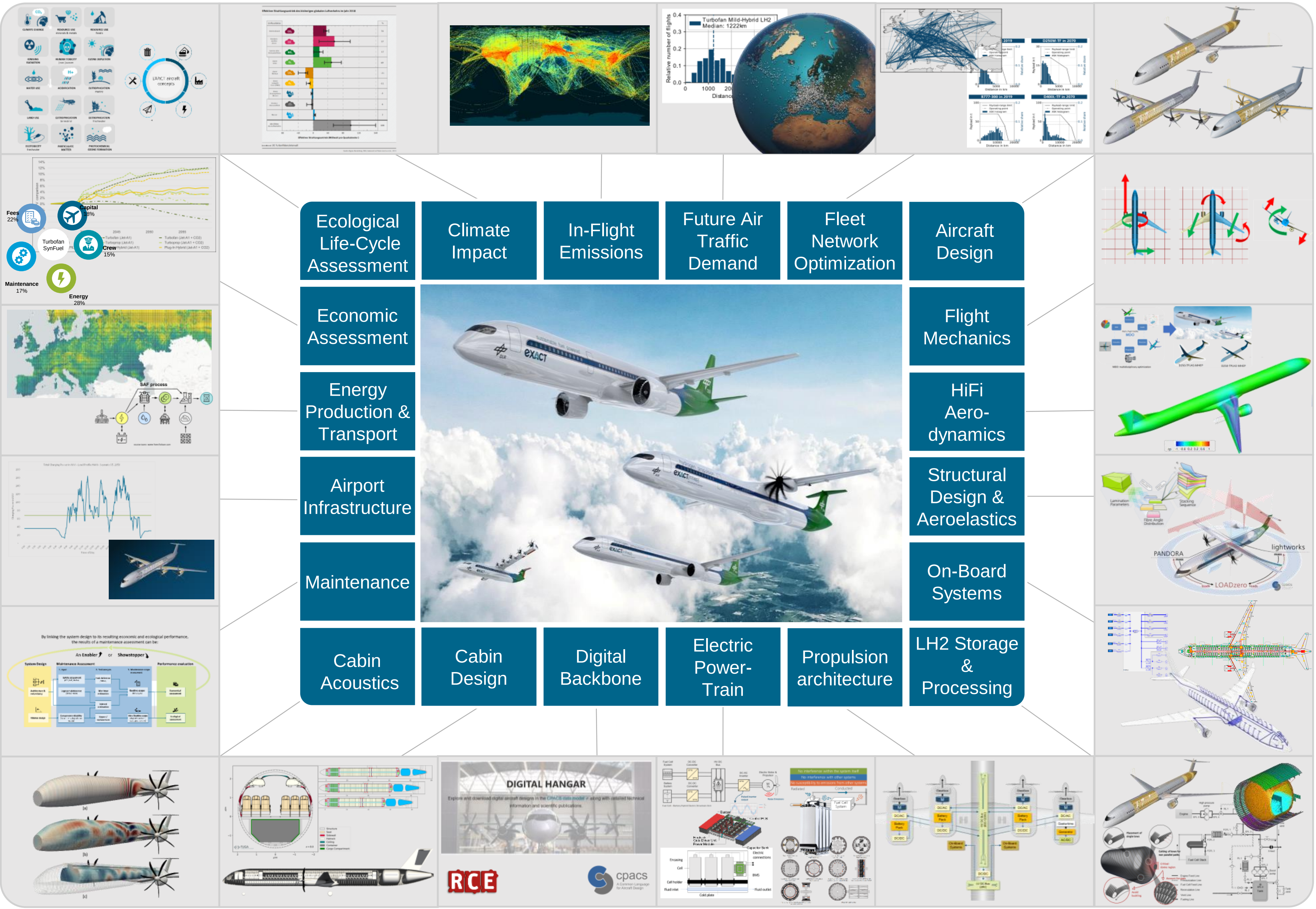
Plug-to-Shaft Efficiency



Batteries are in their own order-of-magnitude for plug-to-shaft efficiency

DLR EXACT PROJECT - Sustainable Aircraft Results Overview

Which aircraft concepts have the potential to
drastically reduce aviation’s climate impact
while being
economically competitive
considering operational, total energy lifecycle, infrastructural boundary conditions?



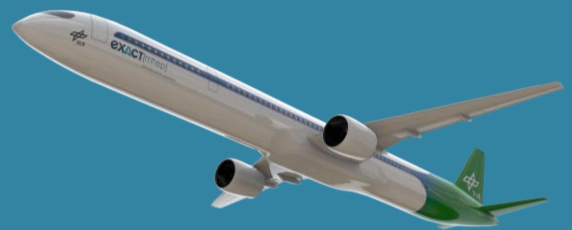
eXACT®

Digitally integrating competencies

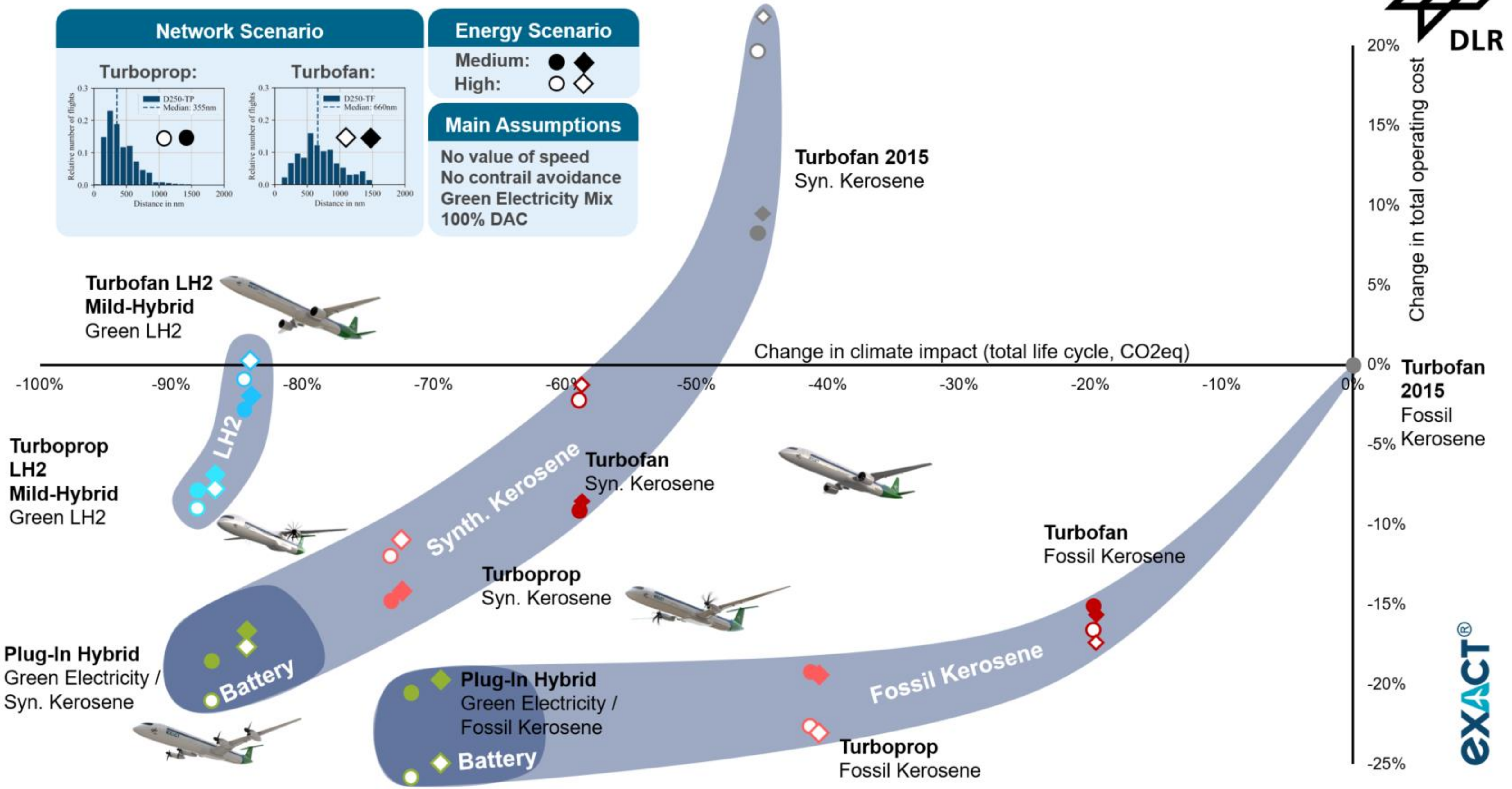
- > 100 scientists from 20 institutes involved
- considering short- to long-range future aircraft concepts

EXACT Short-Range Concepts

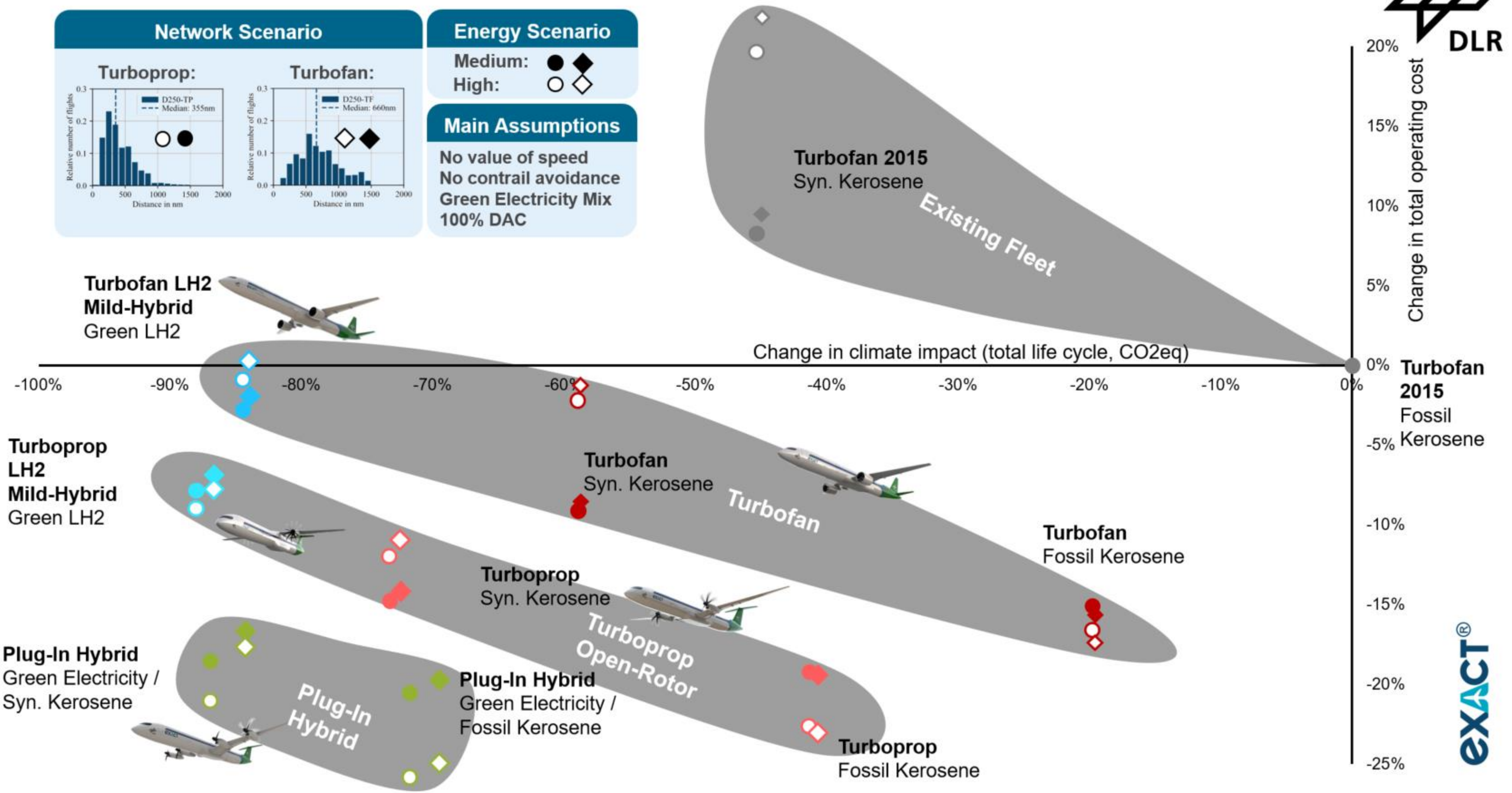
DLR

Turbofan Cruise Mach: 0.78	**Propeller** Cruise Mach: 0.66 – 0.72	
 **Conventional Turbofan**	 **Conventional Tuboprop**	**Synthetic Kerosene**
 **Turbofan / Fuel-Cell Mild-Hybrid Propulsion**	 **Turboprop / Fuel-Cell Mild-Hybrid Propulsion**	**LH_2**
Most Promising Short-Range Concepts Design Range: 1500 NM Design PAX: 250 Airport ICAO Code: C Entry Into Service: 2040	 **Plug-In Hybrid Electric Propulsion**	**Battery & Synthetic Kerosene**

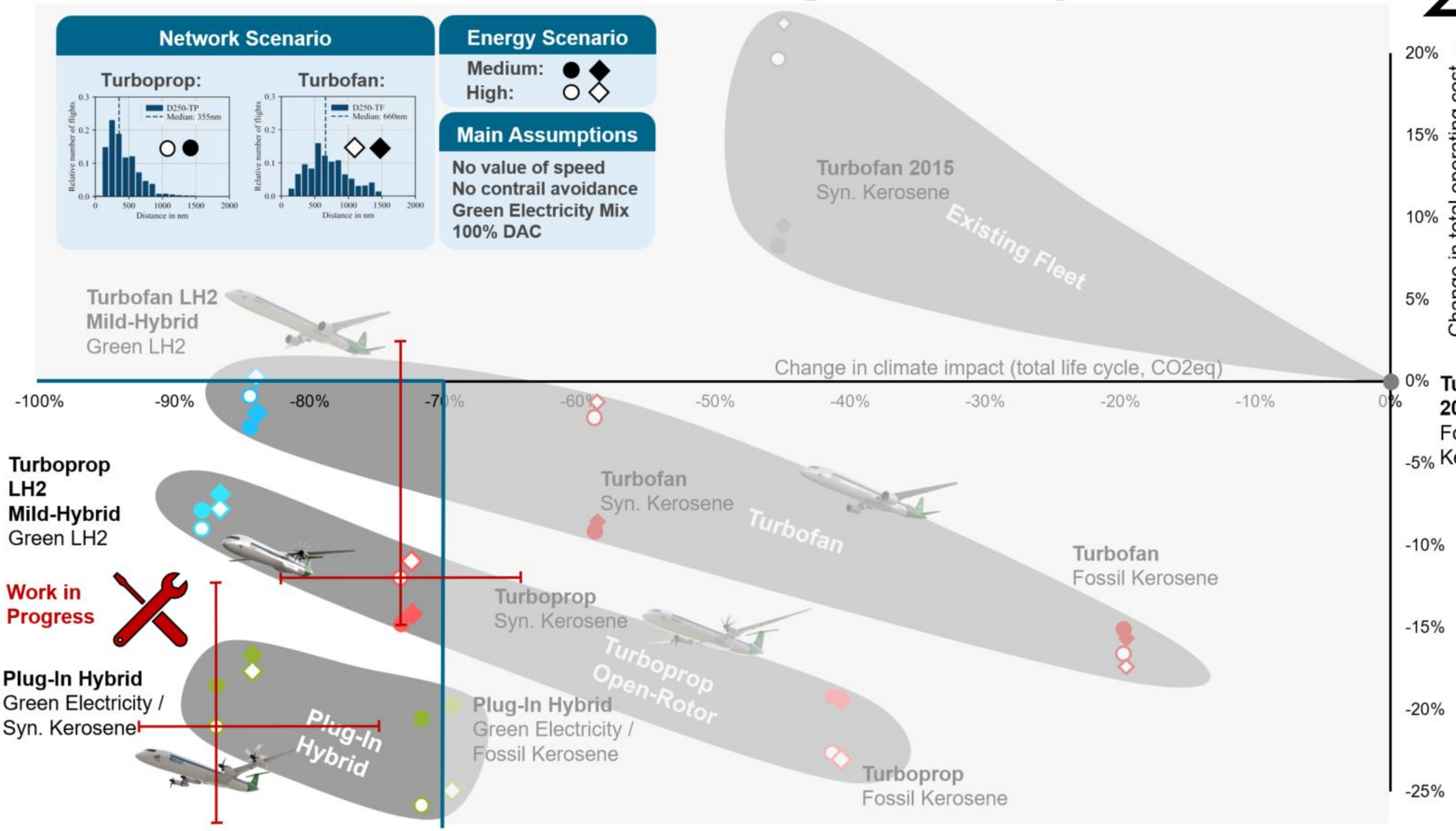
The Overall Economic and Ecological Life-Cycle Results



The Overall Economic and Ecological Life-Cycle Results



The Overall Economic and Ecological Life-Cycle Results



Conclusions from the EXACT Project

- Hydrogen and syn. fuel can be viable sustainable fuels for aviation

Syn. Fuel Powered

vs

Hydrogen Powered

→ Hydrogen can be economically better if hydrogen costs are ~20-30% lower than syn. fuel costs.

- Flying ~10-15% slower with a turboprop (730 km/h instead of 830 km/h) significantly decreases climate impact and is economically better when fuel costs are high.

Turbofan Propulsion

vs

Turboprop Propulsion

→ Even with fossil fuel, today‘s climate impact of modern similar class aircraft can be reduced by ~50% only by switching to a slower flying turboprop

- Battery-powered aircraft with a range-extender (plug-in hybrid) achieved the best results in terms of climate impact and operating costs for intra-continental operation:

250-seater
Plug-In Hybrid
Aircraft Concept

Shown EXACT results for:

- 500 Wh/kg battery cells (400Wh/kg battery packs)
- 100 €/kWh battery costs & 3000 discharge cycles
- Average fleet operation ranges of ~1000-1500 km

Battery-Electric Flight in Aviation?

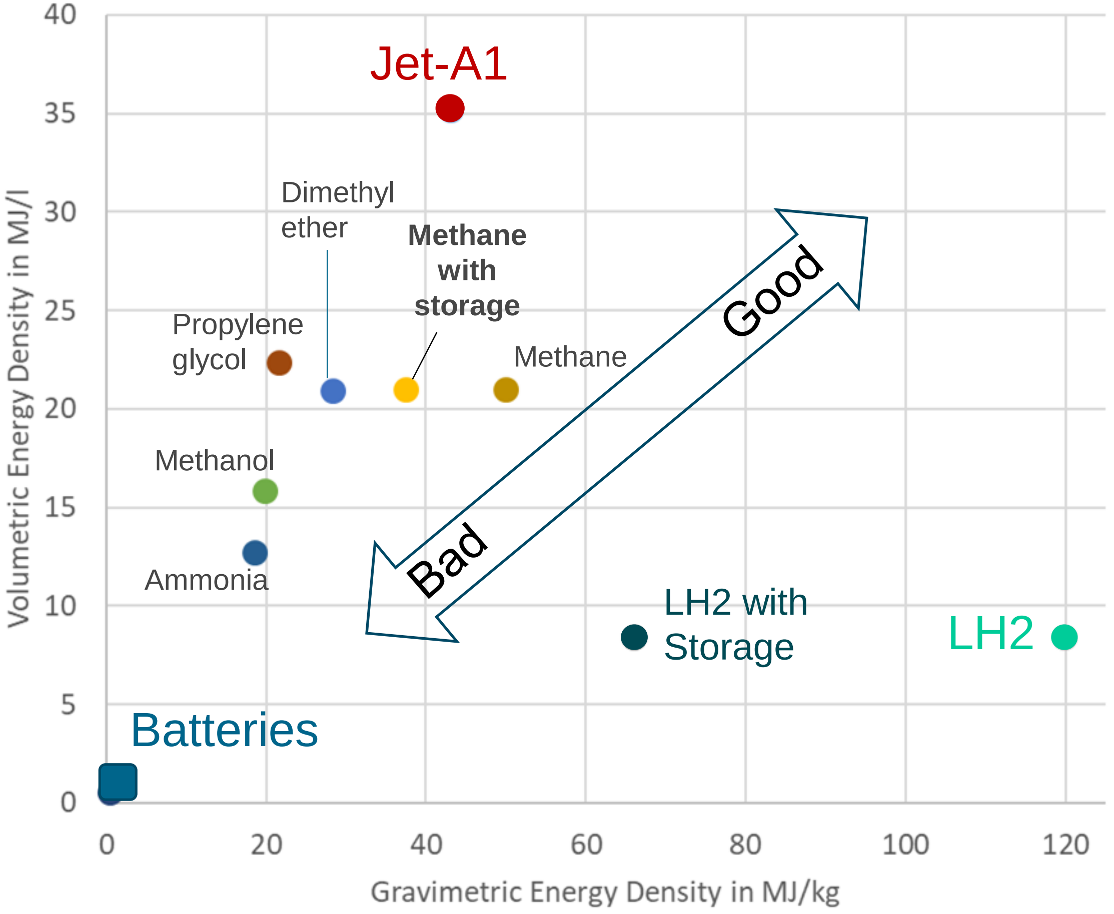
Battery-Electric Flight – High Potential?

From the conclusions of the EXACT Project:

→ BATTERY-POWERED AIRCRAFT can be a SUSTAINABLE and AFFORDBLE concept for intra-continental travel

HOW?

Main Limitation of Batteries – The Energy Density



Batteries are two orders of magnitude worse than chemical energy storage in terms of energy density

The main impact of this property is a highly constrained achievable range of a battery-driven vehicle!

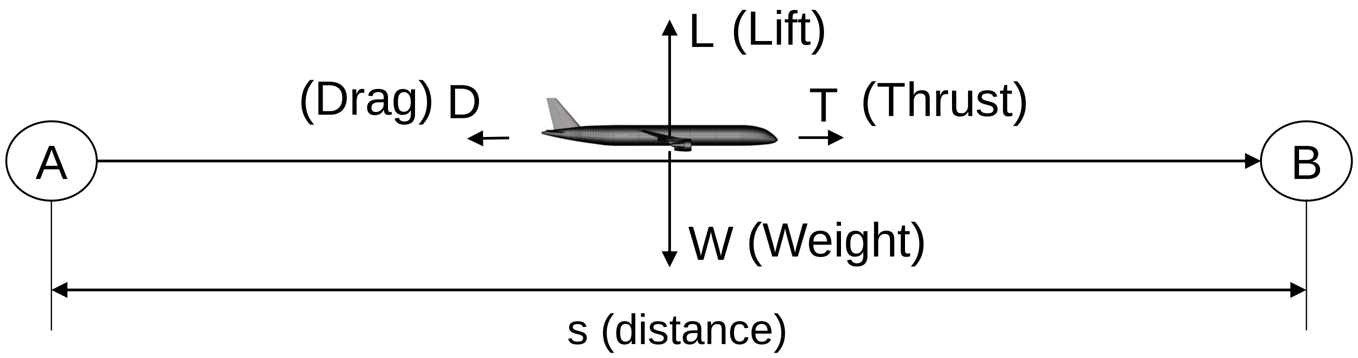
How Low Energy Density Can be Tackled?

➔ The next sections will describe:

- How to estimate conventional aircraft range?
- How to estimate <u>electric</u> aircraft range?
- How to design a good battery-powered aircraft?

Aircraft Transport Energy Estimation

Energy Needed for Transportation



In Cruise:

$$L = W = mass \cdot g$$

$$T = D = \frac{W}{L/D}$$

L/D – lift over drag (aerodynamic efficiency)

E_{AB} → Engine work (energy) output

$$E_{AB} = T \cdot s = \frac{W}{L/D} \cdot s$$

(distance-averaged expression)

Output Work

E_{AB}

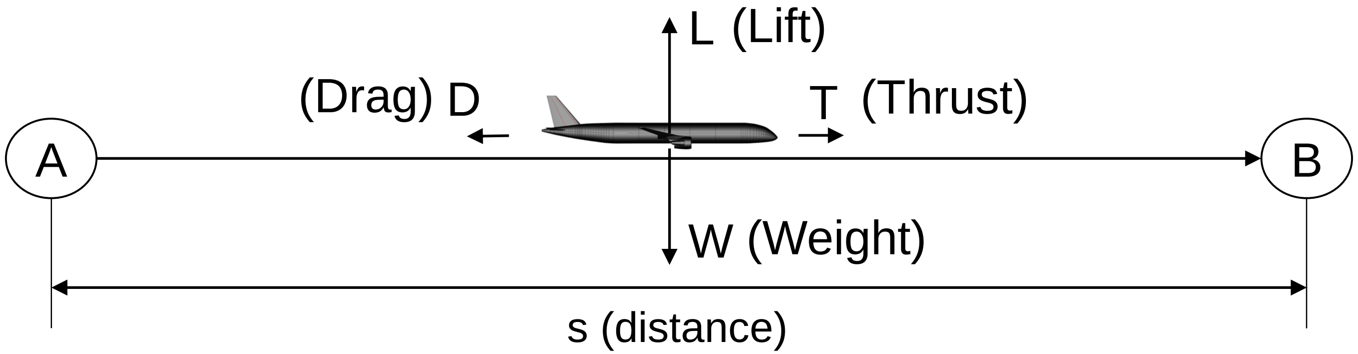
$$Engine\ Efficiency = \frac{Engine\ Work\ Output}{Fuel\ Energy\ Consumed}$$

Fuel: Stored Energy ($E_{Fuel,AB}$)

Fuel Energy Required:

$$E_{Fuel,AB} = \frac{E_{AB}}{Engine\ Efficiency}$$

Energy Needed for Transportation - Summary



Note: This is the base for the famous Breguet-Equation, which considers fuel burn (aircraft mass reduction during flight), where an integration of this equation over the distance (AB) is needed.

Required fuel energy is proportional to the mass of the aircraft

$$E_{Fuel} = \frac{m_{Aircraft} \cdot g}{L/D \cdot \eta_{Eng}} \cdot s$$

Increasing the aerodynamic efficiecy (L/D) proportionally reduces the required energy.

More efficient engines reduce the fuel energy proportionally.

Transport Energy Calculation

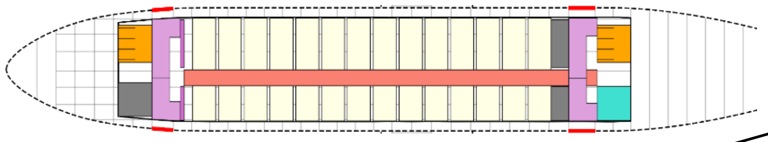
1. Estimating an Aircraft Mass

Aircraft Characteristics – Power Provider Efficiency

Payload Mass

$m_{Payload\_Max}$ is a Requirement

Payload accommodation structure, i.e. fuselage & systems



$m_{accommodation} \approx 1.0 * m_{Payload\_Max}$

Regional & short-range aircraft statistics* (±10%)

Energy Storage (Fuel)

$\mathbf{m_{Energy}}$ depends on Range

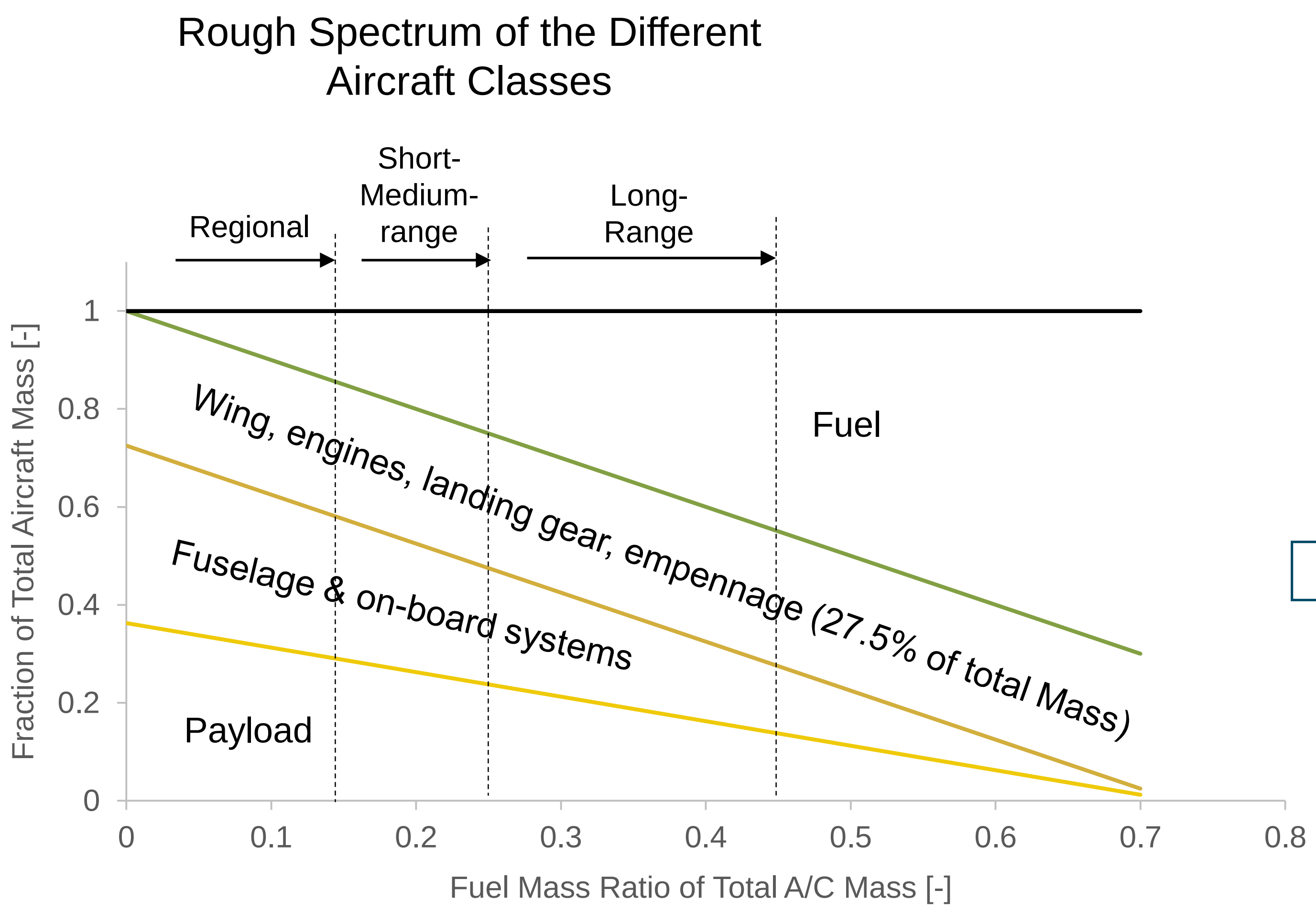
Aircraft Mission Components (i.e. propulsion, wing, stability, landing gear)

$m_{utiliites} \approx 0.275 * m_{Aircraft}$

All CS25 aircraft statistics* (±10%)

*Statistics from internal data

Aircraft Characteristics – Max. Energy Storage Mass



Aircraft Type	Payload-to-Total-Aircraft-Mass Ratio
Regional	0.30 - 0.33
Short-Medium-Range	0.25 - 0.30
Long-Range	0.15 - 0.20

Longer-range aircraft can need more fuel => can have less payload with respect to the total aircraft mass

Aircraft Mass Characteristics of Different Classes

EXAMPLE 1:
Design an aircraft with a aircraft mass of 100 t

→ Explore the Mass-Breakdown of the different aircraft classes

Aircraft Mass
= 100 tons

Needed for Range

Can be Used for Payload

Aircraft Type	Fuel Mass Ratio	Payload Mass Ratio
Regional	0.1	0.31
Short-Medium-Range	0.2	0.26
Long-Range	0.4	0.16

Design Fuel Mass	Design Payload Mass	Fuselage and Systems	Wing, Engines Landing Gear, and Empennage	Total Aircraft Mass
10 t	**31 t**	31 t	28 t	100 t
20 t	**26 t**	26 t	28 t	100 t
40 t	**16 t**	16 t	28 t	100 t

Longer-range aircraft must have a smaller fuselage and less passengers to be able to carry more fuel

Aircraft Mass Characteristics of Different Classes

EXAMPLE 2:
Design an aircraft that can carry 10 tons of payload

→ Explore the Mass-Breakdown of the different aircraft classes

Payload = 10 tons

Needed for Range → Fuel Mass Ratio

Can be Used for Payload → Payload Mass Ratio

Aircraft Type	Fuel Mass Ratio	Payload Mass Ratio
Regional	0.1	0.31
Short-Medium-Range	0.2	0.26
Long-Range	0.4	0.16

Design Fuel Mass	Design Payload Mass	Fuselage and Systems	Wing, Engines Landing Gear, and Empennage	Total Aircraft Mass
3.2 t	10 t	10 t	8.8 t	**32 t**
7.6 t	10 t	10 t	10.5 t	**38.1**
24.6 t	10 t	10 t	16.9 t	**61.5**

Longer-range aircraft get exponentially heavier because of the rapidly decreasing payload-to-total mass ratio.

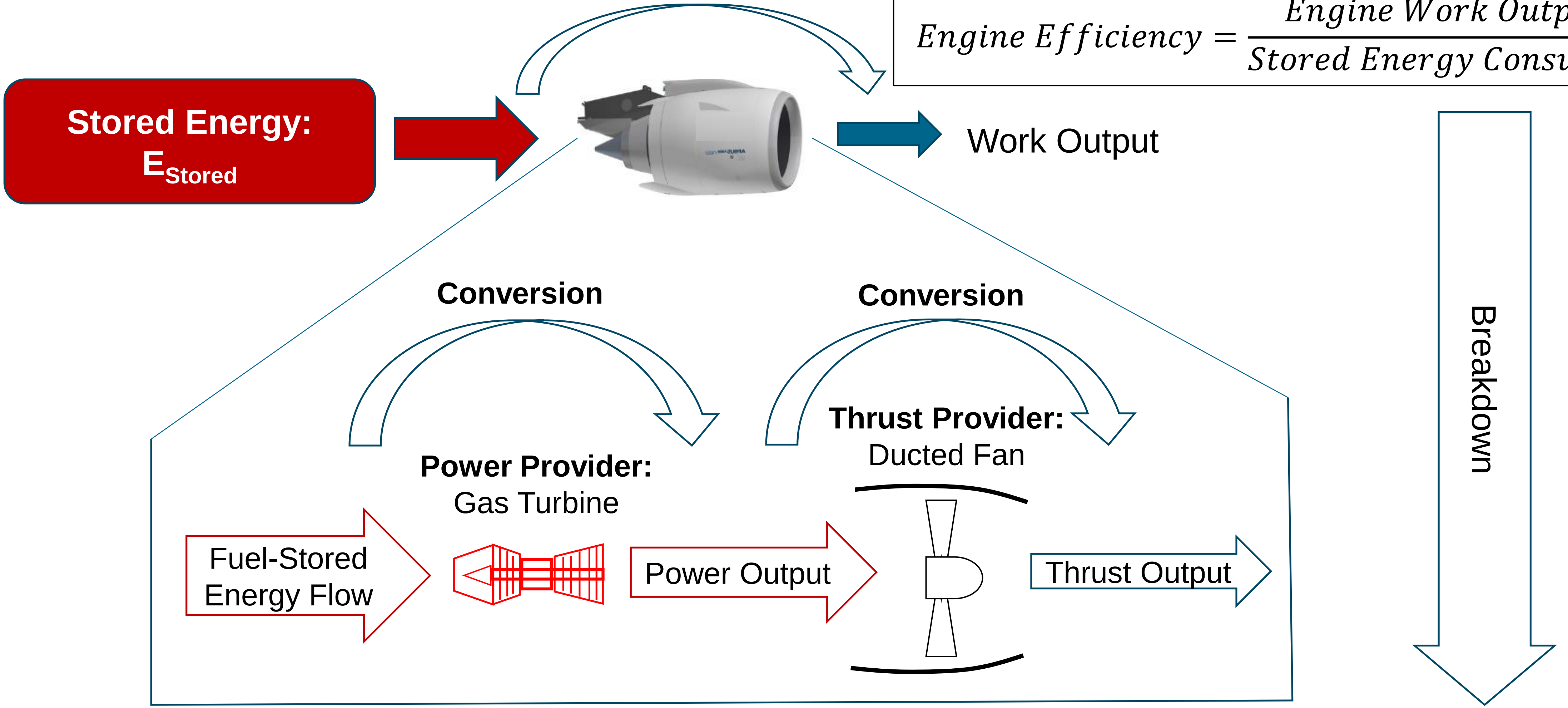
Transport Energy Calculation

2. Estimating an Aircraft Propulsive Efficiency

Engine Efficiency Breakdown

Top-level relationship

$$Engine\ Efficiency = \frac{Engine\ Work\ Output}{Stored\ Energy\ Consumed}$$

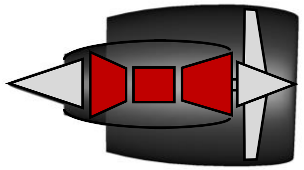


$$(Power\ Provider\ Efficiency) * (Thrust\ Provider\ Efficiency) = Engine\ Efficiency$$

Different Types of Propulsion Systems

Turbofan

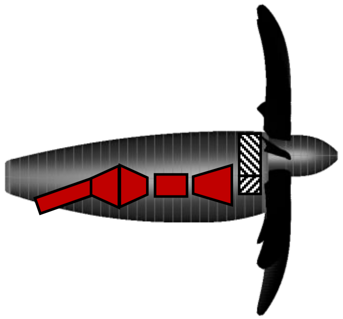
Power Provider:
Gas Turbine



Thrust Provider:
Ducted Fan

Turboprop

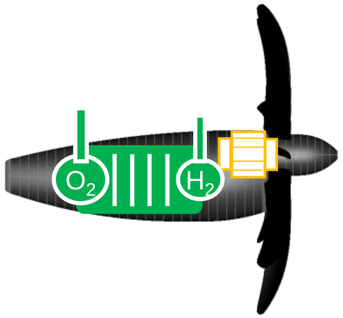
Power Provider:
Gas Turbine



Thrust Provider:
Open Propeller

Fuel-Cell-Powered Electric Propeller

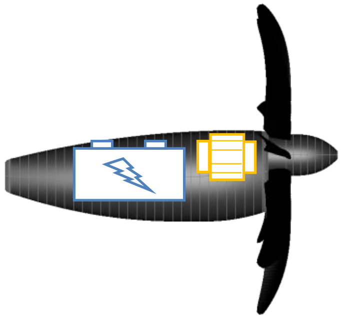
Power Provider:
Fuel Cells + E-Motor



Thrust Provider:
Open Propeller

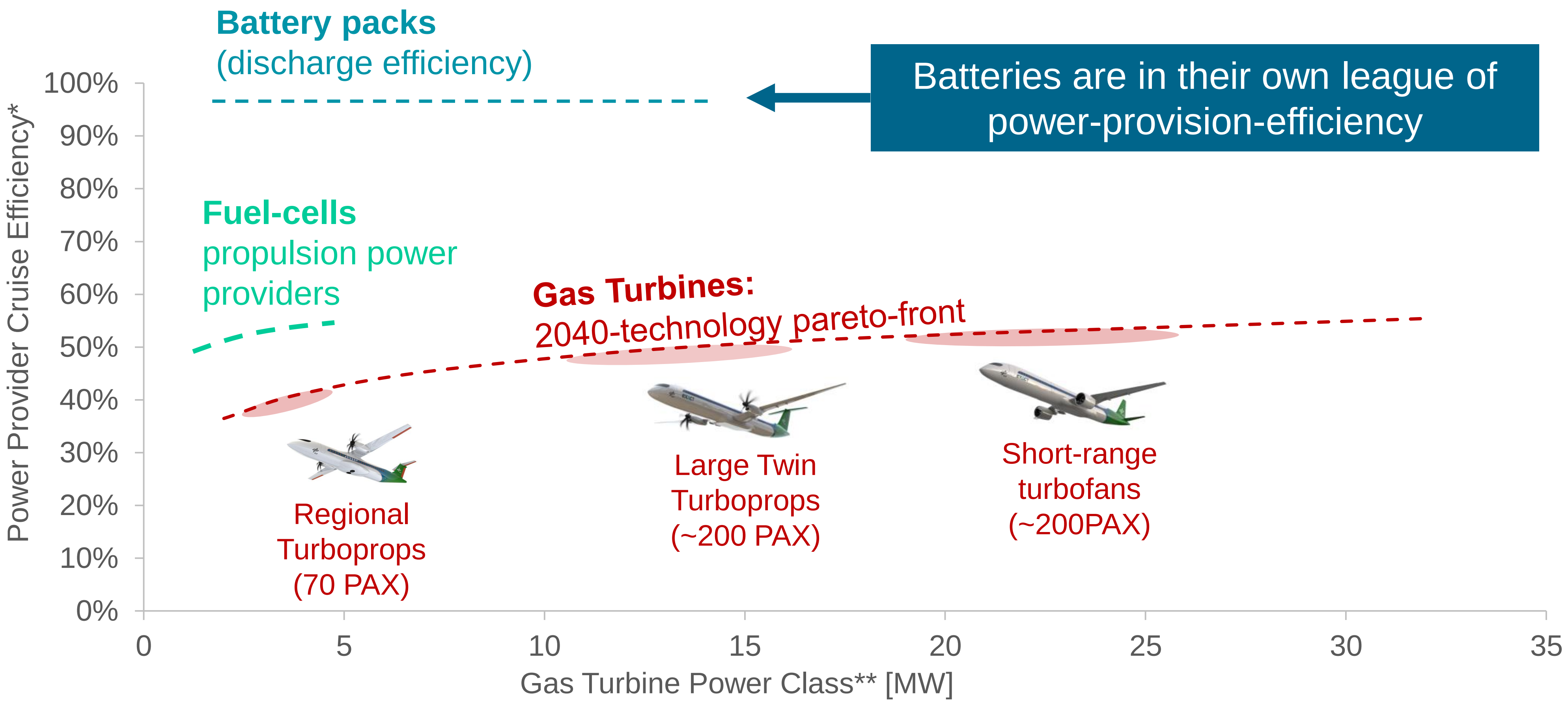
Battery-Powered Electric Propeller

Power Provider:
Battery + E-Motor



Thrust Provider:
Open Propeller

Power Provider Efficiency (from the EXACT Project)



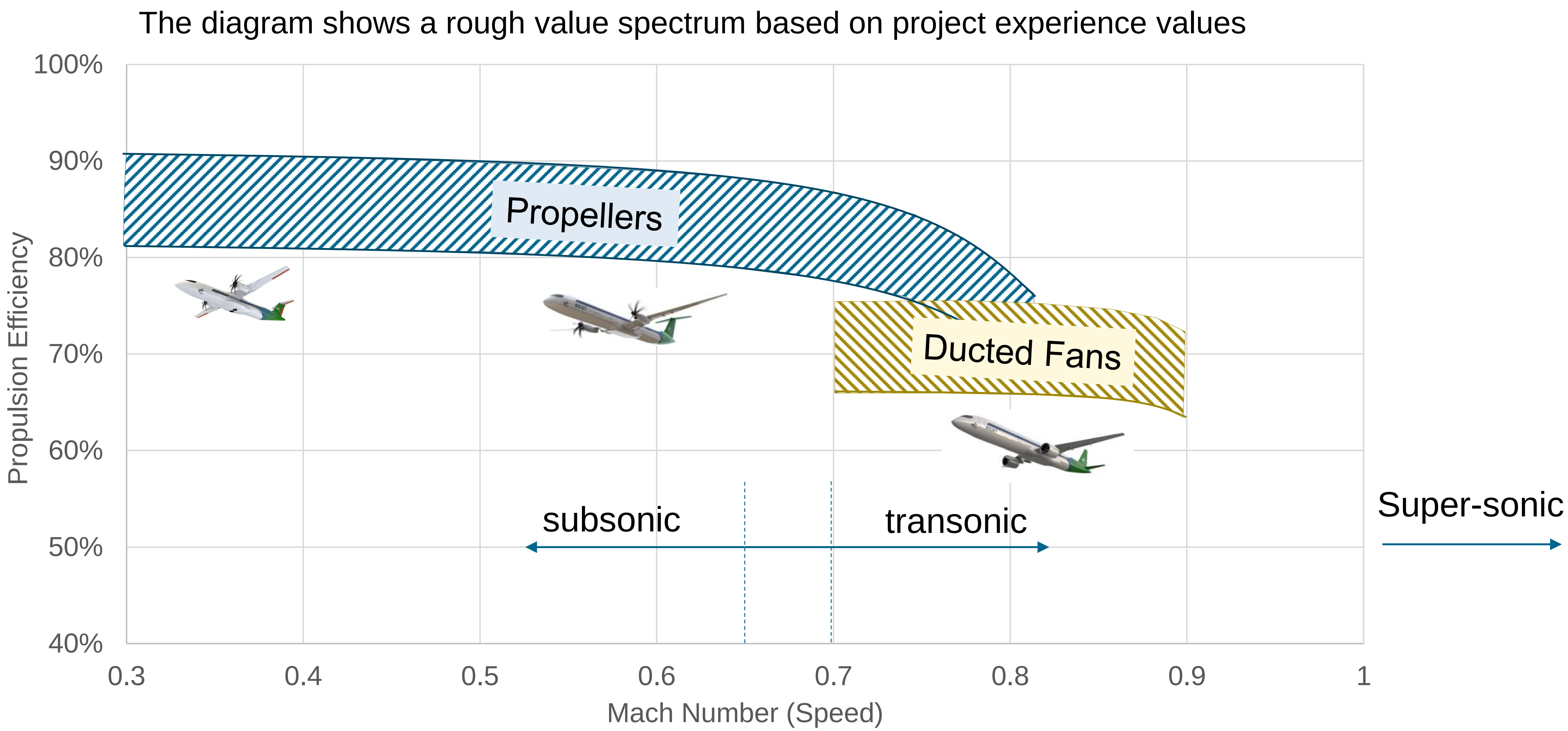
*Gas turbine cruise efficiency:

$etaGT = \frac{P_{eq}}{\dot{m}_{Fuel} \cdot LHV}$; LHV Low heating value;

P_{eq} Equivalent power; $\dot{m}_{Fuel}$ Fuel flow

**Power class:
Achievable power at sea-level static ISA conditions & TET limit without any mechanical power limitations or flat rating.

Aircraft Characteristics – Thrust Efficiency

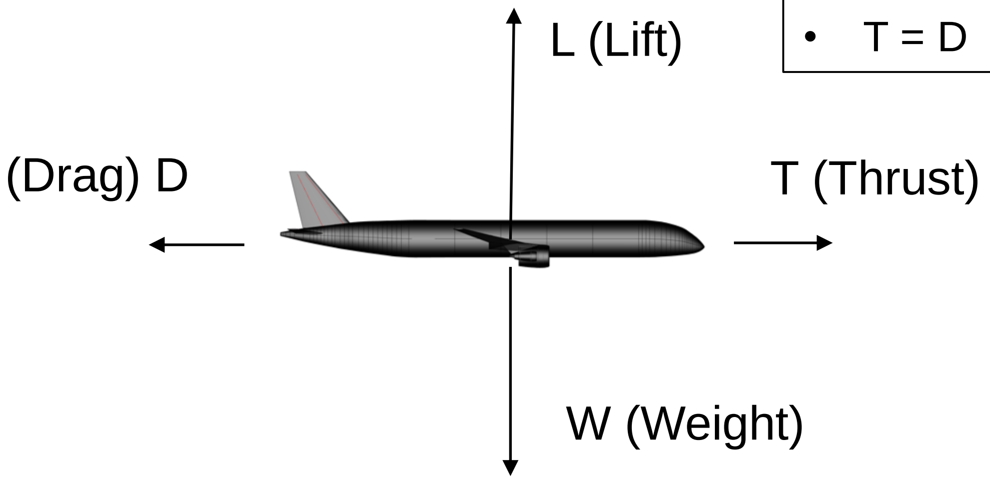


Transport Energy Calculation

3. Estimating an Aircraft Aerodynamic Efficiency (L/D - Lift over Drag)

Aerodynamic Efficiency – L/D

Level flight aircraft forces
- L = W
- T = D

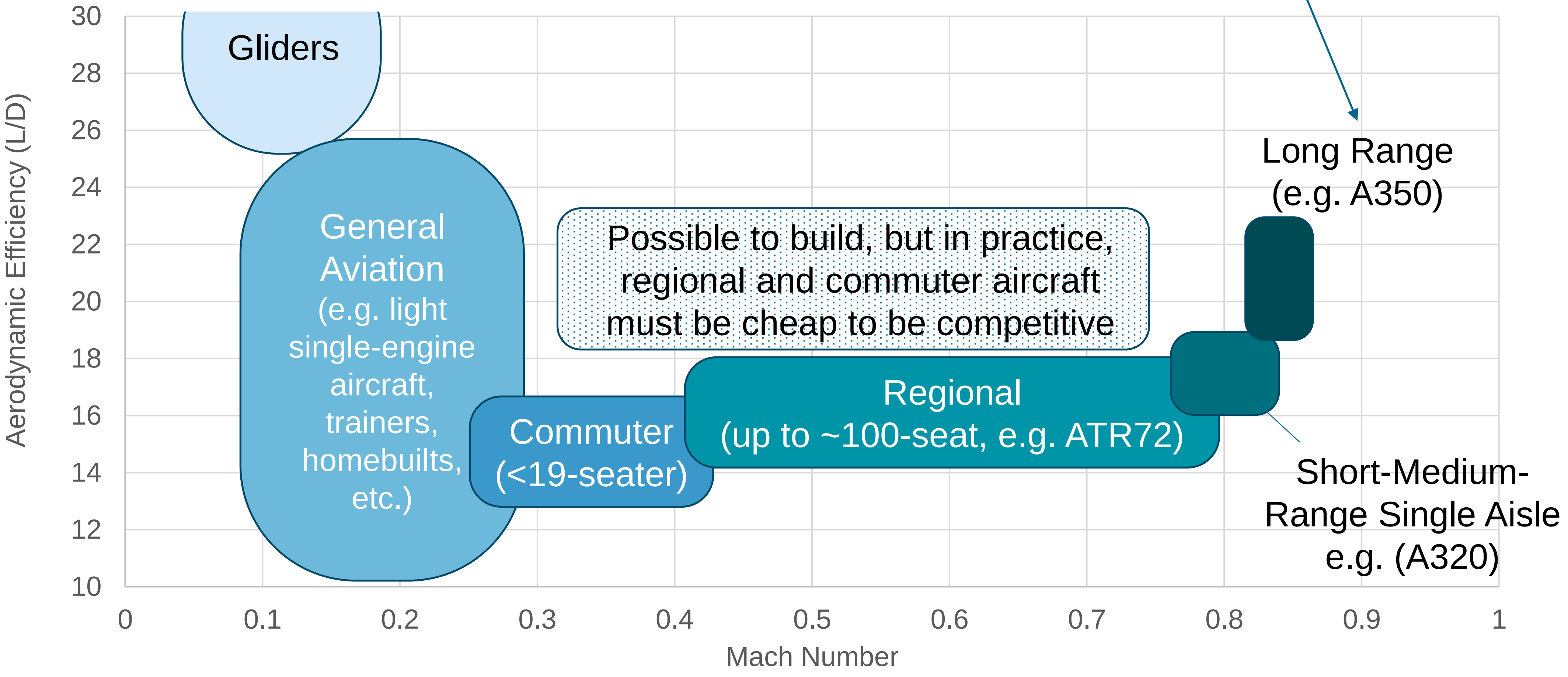


- The aerodynamic efficiency of aircraft is often described as **Lift-to-Drag Ratio (L/D)**
- Higher L/D means a more aerodynamically efficient aircraft
- Higher L/D → less drag → less thrust required for level flight
- A gliding aircraft with L/D of 10 → Will move 10 meters forward when dropped from 1 meter hight

Aircraft Characteristics - Aerodynamics

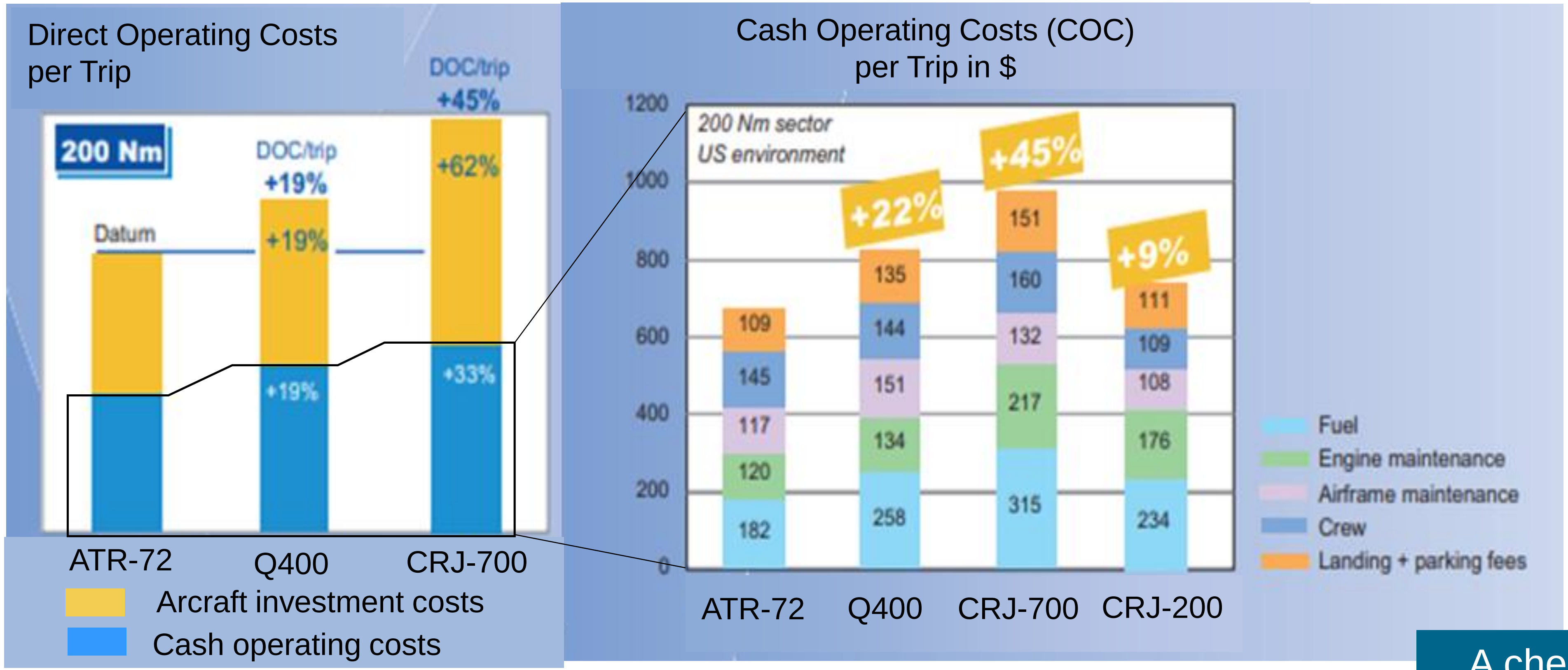
High-end technology due to challenging range requirements

The diagram shows a rough spectrum based on project experience values



Why not the Best Aerodynamics for Regional Aircraft?

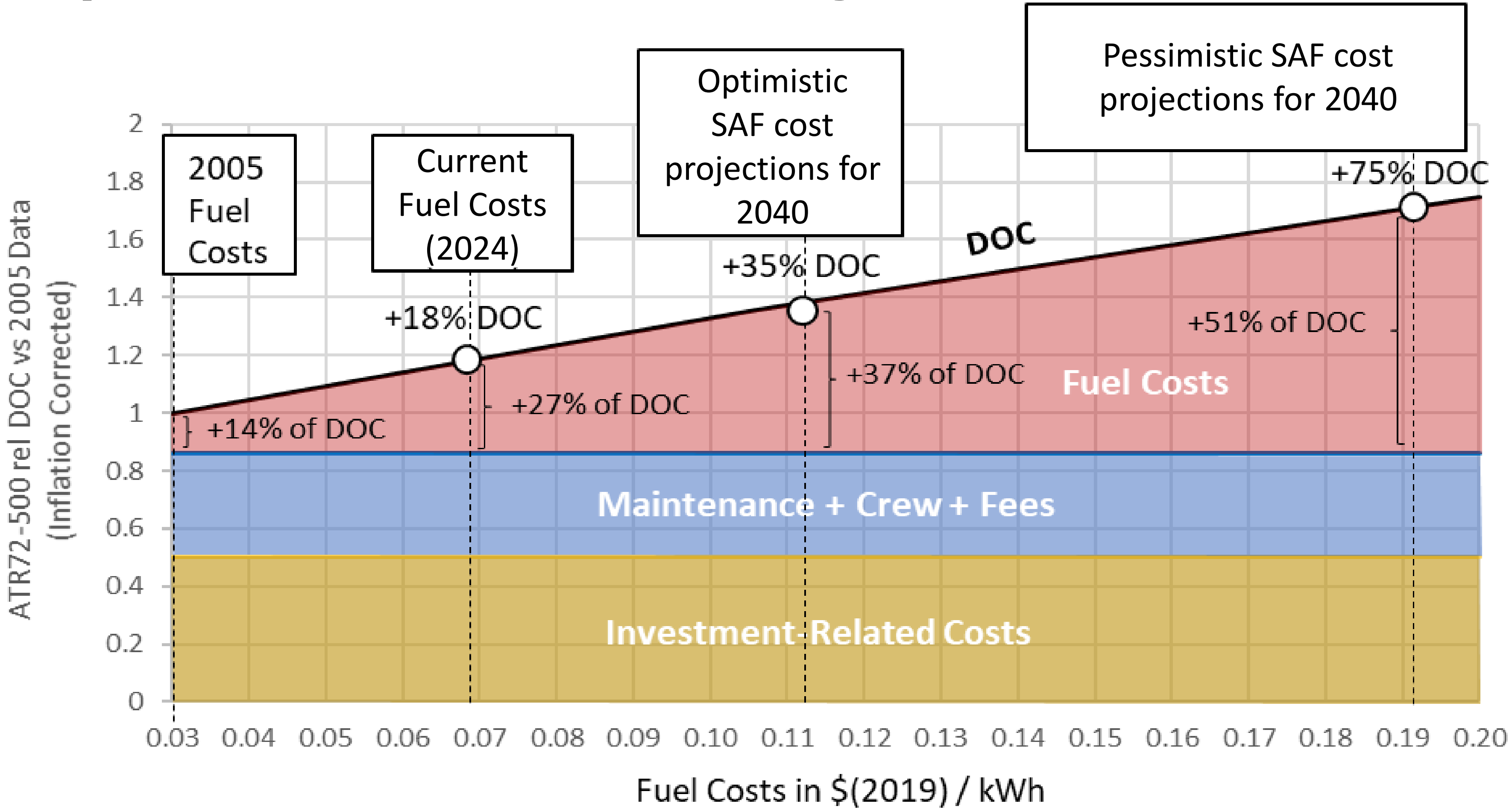
"ATR72-500 The Ultra Efficient Standard", ATR72 Brochure 2005



In 2005:
- Fuel costs were only ~15% of total aircraft cost of regional aircraft
- Aircraft purchase costs ~50% of the total costs

A cheap aircraft is more competitive than an efficient modern aircraft on the regional aircraft class market!

Cost Impact on Aircraft Efficiency



Increasing fuel costs can increase the competitiveness of efficient aircraft.

→ Designing an aerodynamically efficient electric aircraft is becoming more interesting with increasing energy costs.

Transport Energy Calculation

4. Breguett-Range Examples

Breguet-Range Calculation Examples

Aerodynamic Efficiency

Engine Efficiency

Fuel Mass Fraction

Low Heating Value
(Energy Density)
Kerosene → 43MJ/kg

Breguet Equation:

$$s = \frac{L/D \cdot \eta_{Eng}}{g} \cdot \left(-\ln\left(1 - \frac{m_{Fuel}}{m_{Aircraft}}\right)\right) \cdot LHV$$

A regional aircraft:

- **L/D ≈ 15**
  (small, cheap and robust airframe)
- **Turboprop Efficiency ≈ 0.25**
  (small, 1980s gas-turbines)
- **Fuel Mass Fraction ≈ 0.1**

s* ≈ 1700 km (900nm)

A short-medium-range aircraft:

- **L/D ≈ 17**
  (performance-driven airframe)
- **Turbofan Efficiency ≈ 0.35**
  (high-end engines)
- **Fuel Mass Fraction ≈ 0.2**

s* ≈ 5800 km (3100nm)

A long-range aircraft:

- **L/D ≈ 20**
  (large, high-end airframe)
- **Turbofan Efficiency ≈ 0.4**
  (large, high-end engines)
- **Fuel Mass Fraction ≈ 0.4**

s* ≈ 18000 km (10000nm)

*The result is total achievable distance, which is usually broken down into main mission and reserves.

How to Design a Feasible Battery-Driven Aircraft?

Breguett Equation for Electric Aircraft?

Kerosene-fueled Aircraft Range:

Energy Density of Kerosene

$$s = \frac{L/D \cdot \eta_{Eng}}{g} \cdot \left(-\ln\left(1 - \frac{m_{Fuel}}{m_{Aircraft}}\right) \right) \cdot 43 * 10^6 \; J/kg$$

The Breguet equation

→ **Necessary** for kerosene

(The aircraft becomes lighter during flight)

Battery-powered Aircraft Range:

Energy Density of Batteries

$$s = \frac{L/D \cdot \eta_{Eng}}{g} \cdot \frac{m_{Batteries}}{m_{Aircraft}} \cdot \varepsilon_B$$

Battery Mass Fraction

The Breguett Equation

→ **Simplified** for batteries

(the aircraft mass remains constant during flight)

Retrofit Solution?

Regional aircraft retrofit

Kerosene-Driven (Reference)

- **L/D ≈ 15**
  (cheap and robust airframe)
- **Fuel Mass Fraction ≈ 0.1**

Aircraft Parameter Remain Constant

Battery-Driven (Retrofit)

- **L/D ≈ 15**
  (cheap and robust airframe)
- **Battery Mass Fraction ≈ 0.1**

- **Turboprop Efficiency ≈ 0.25**
  (small, 1980s gas-turbines)
- **Energy Density Kerosene ≈ 43 MJ/kg**

Propulsion Parameter Change

- **Battery & propeller Efficiency ≈ 0.75**
- **Energy Density of Batteries ≈ 0.6 MJ/kg**
  (2015 electric cars data)

Breguet Equation

s ≈ 1700 km (900nm)

Energy density of 2015 batteries: 80x worse than kerosene!

Battery-Range Equation

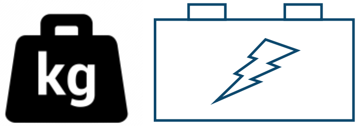
s ≈ 65 km (35 nm)

A retrofit is not practically possible for regional and commuter airliners!

How to Design a Feasible Battery-Driven Aircraft?

Low energy densigy of batteries:
→ **Limited range**

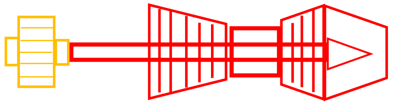
Design Measures for Increased Range



1. High battery mass to aircraft mass ratio

2. Higher Aero-Propulsive Efficiency & Lighter Components

Range-Extender for Hybridization



3. Range-Extender for operational flexibility

Enablers

Better Aerodynamics:
→ Higher aspect-ratio wings & clean airframe design

Slower Flight Speeds
→ Match cruise speed with best aerodynamic performance
→ Avoid transonic designs

Distributed Propulsion
→ For reduced take-off power (lighter engines)

How to Design a Feasible Battery-Driven Aircraft?

1. Optimal Battery Mass to Aircraft Mass Ratio?

Optimal Ration of Battery Mass to Aircraft Mass

EXAMPLE:

Design a battery-driven aircraft that can carry 10 tons of payload.

10 ton Payload

From project experience:

Conventional aircraft mass-breakdown empirics apply well to battery aircraft designs

→ Explore Different Battery-to-Aircraft Mass Ratios

Empirical Estimation

Battery-to-Aircraft Mass Ratio	Battery Mass	Design Payload Mass	Fuselage and Systems	Wing, Engines Landing Gear, and Empennage	Total Aircraft Mass
0.2	7.6 t	10 t	10 t	10.5 t	**38.1**
0.3	14.2 t	10 t	10 t	12.9 t	**47.1**
0.4	24.6 t	10 t	10 t	16.9 t	**61.5**

Increasing Electric Range

Project experience shows that battery mass fractions between 0.25 and 0.3 are usually a good compromise between electric range, energy efficiency and costs.

Increasing Energy Consumption and Costs!

Higher Battery Mass Fraction Effect on Range

Regional Aircraft with 10t payload (90 PAX)

Kerosene-Driven (Reference)		Battery-Driven (Resized)
• **L/D ≈ 15** (cheap and robust airframe)	→ Aerodynamics not optimized yet!	• **L/D ≈ 15** (cheap and robust airframe)
• **Fuel Mass Fraction ≈ 0.1** • **Turboprop Efficiency ≈ 0.25** (small, 1980s gas-turbines) • **Energy Density Kerosene ≈ 43 MJ/kg**	→ Airframe and Engines are redezigned	• **Battery Mass Fraction ≈ 0.3** • **Battery+Prop efficiency ≈ 0.75** • **Energy Density Battery ≈ 0.6 MJ/kg** (2015 electric cars data)
Aircraft Mass ≈ 32 t **Estimated range ≈ 1700 km**	Top-level parameters → estimation	**Aircraft Mass ≈ 47 t** **Estimated range ≈ 200 km**

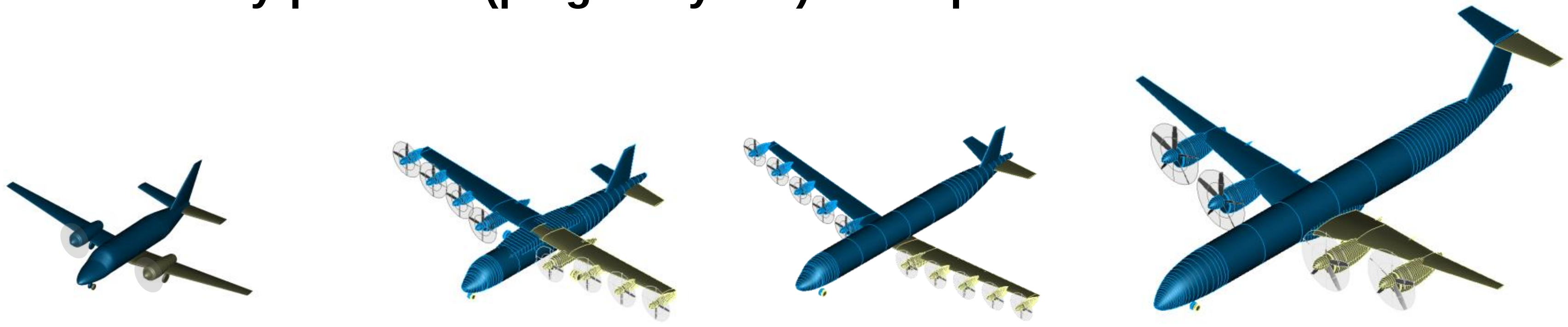
200km range is still not sufficient for airliners → more changes are needed!

How to Design a Feasible Battery-Driven Aircraft?

2. Aero-Propulsive Efficiency

What is Possible but Realistic Aerodynamic and Propulsion Efficiency Estimate?

DLR project aircraft models: Battery-powered (plug-in-hybrid) concepts



Class	19-Seater	40-Seater	70-Seater	250-Seater
L/D (cruise)	19	19	21	22
Battery + Propeller Efficiency*	75%	80%	80%	80%
Battery Mass Fraction	0.2	0.3	0.25	0.25
Cruise Mach	0.25	0.4	0.55	0.67

*System off-takes included

Effect of Design from Scratch

Regional Aircraft with Kerosene

L/D (cruise)	15
Turboprop Efficiency	25%
Fuel Mass Fraction	0.1
Range Estimate	1700 km

Regional Aircraft with Batteries 2015-car-technology-level

	Retrofit	**Re-sized**	**New design**
L/D (cruise)	15	15	21
Battery + Prop Eff.	75%	75%	80%
Battery Mass Fraction	0.1	0.3	0.3
Range Estimate	**65 km**	**200 km**	**300 km**

Design from scratch can shift the range by a factor of 5 over a retrofit!

How to Design a Feasible Battery-Driven Aircraft?

Effect of battery technology imrovement?

Electric Range vs Battery Energy

Electric range is directly proportional to battery energy density!

- Studies in 2015-2020 assumed battery packs with 160 Wh/kg (0.5 MJ/kg) to 200 Wh/kg (0.7 MJ/kg)
- Currently, TRL 6 is ~300 Wh/kg (1.1 MJ/kg) on pack level.
- Next generation roadmaps expect 500 Wh/kg (1.8 MJ/kg) on pack-level

Next generation batteries are expected to be 3x better than 2015 studies assumed!

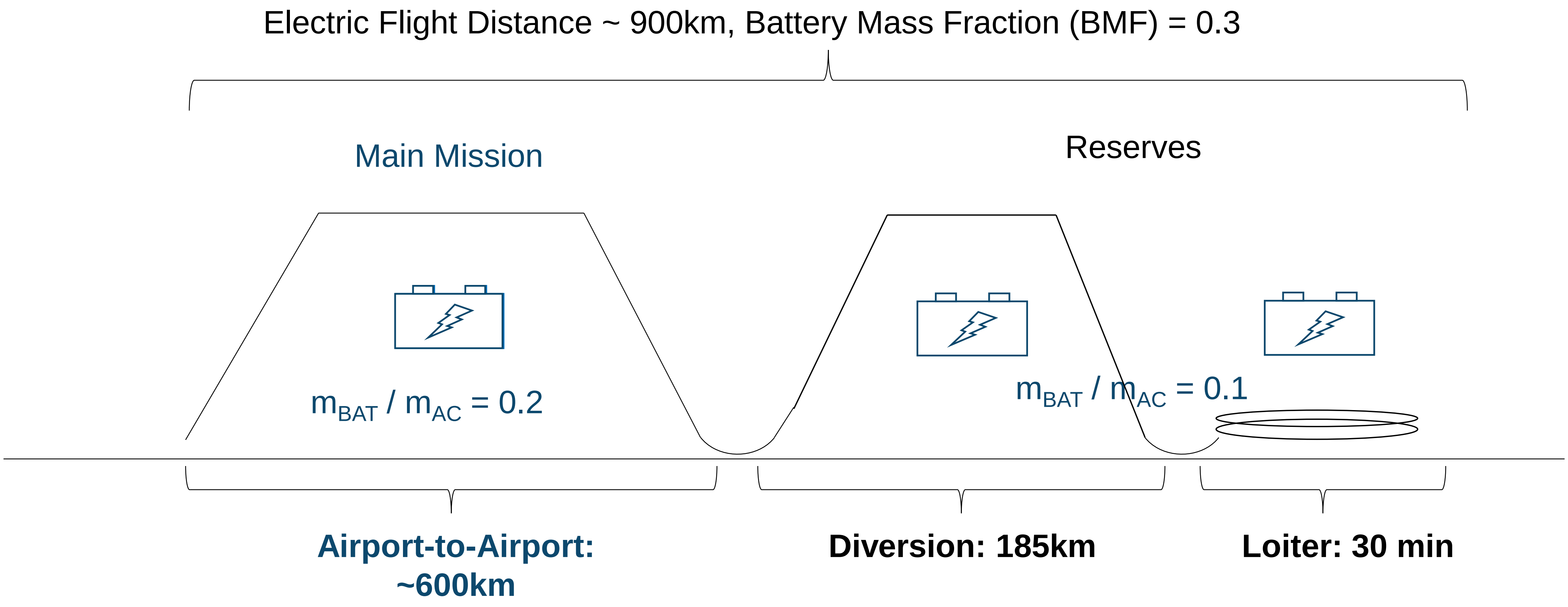
Regional aircraft designed with 2015 batteries:
300 km range

2040 batteries →

900 km range!

Note – this is the total range possible, not the practical range!

Practical Range

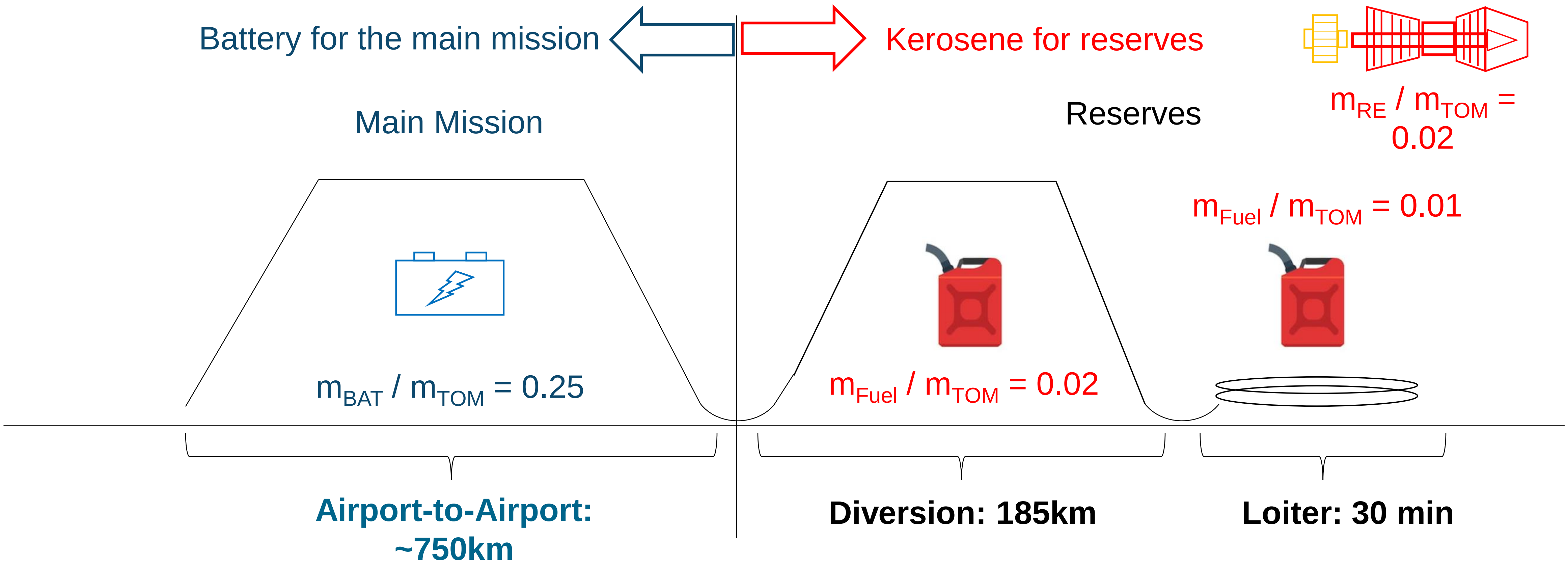


Airliner reserves requirements significantly reduce the effective range.

Why Plug-In Hybrid Propulsion (PHEP)?

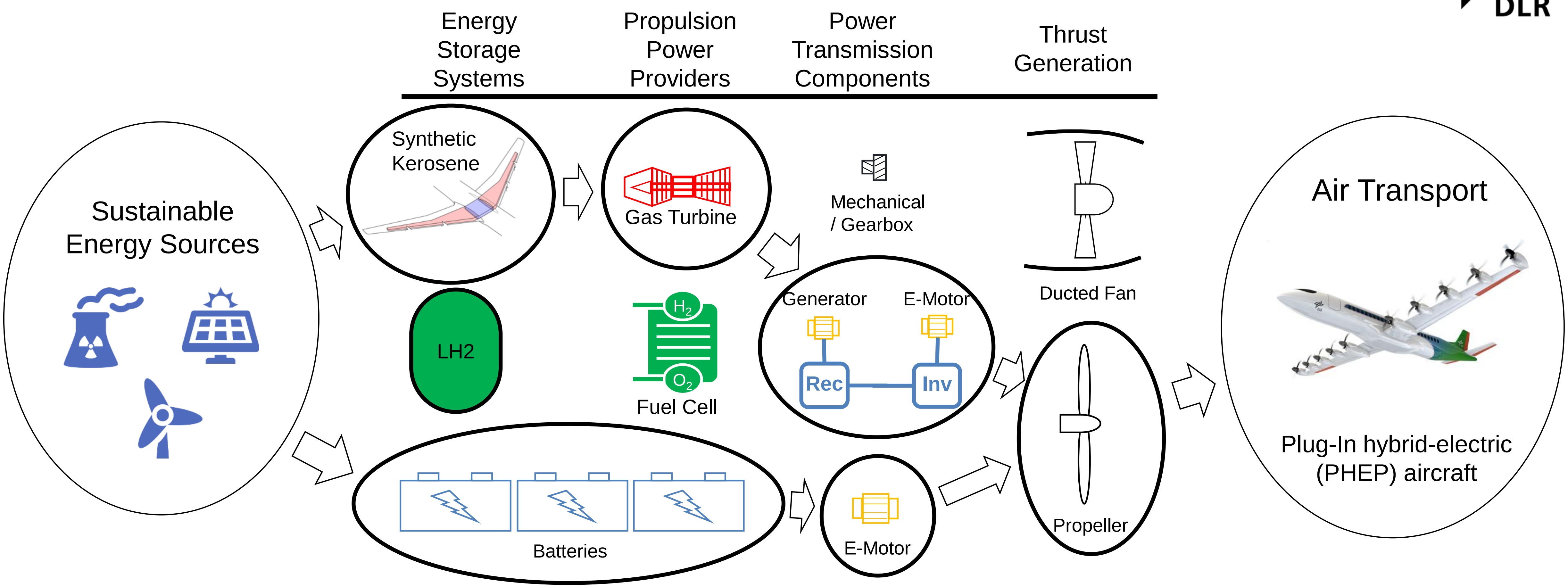
Range Extender for Increased Electric Range

Plug-In-Hybrid Mass Fraction = 0.3 (Battery + Range-Extender + Fuel)



A plug-in hybrid architecture can push the achievable electric range even further!

Plug-In-Hybrid-Electric Propulsion Archtecture (PHEP)



Benefits

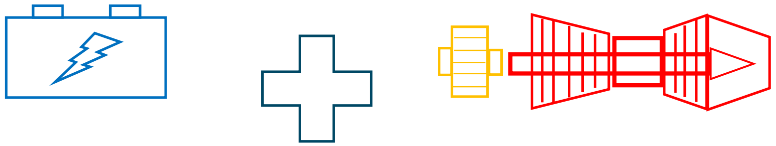
- All electric flight on short routes – efficiency on par with all-electric aircraft
- Range flexibility on par with conventional aircraft due to range-extender

Draw-backs:

- Heavy aircraft due to the heavy battery
- Overall efficiency is relatively low on long distances.

Additional Benefits of a Plug-In Hybrid Architecture

PHEP Propulsion:



Battery

Range-Extender

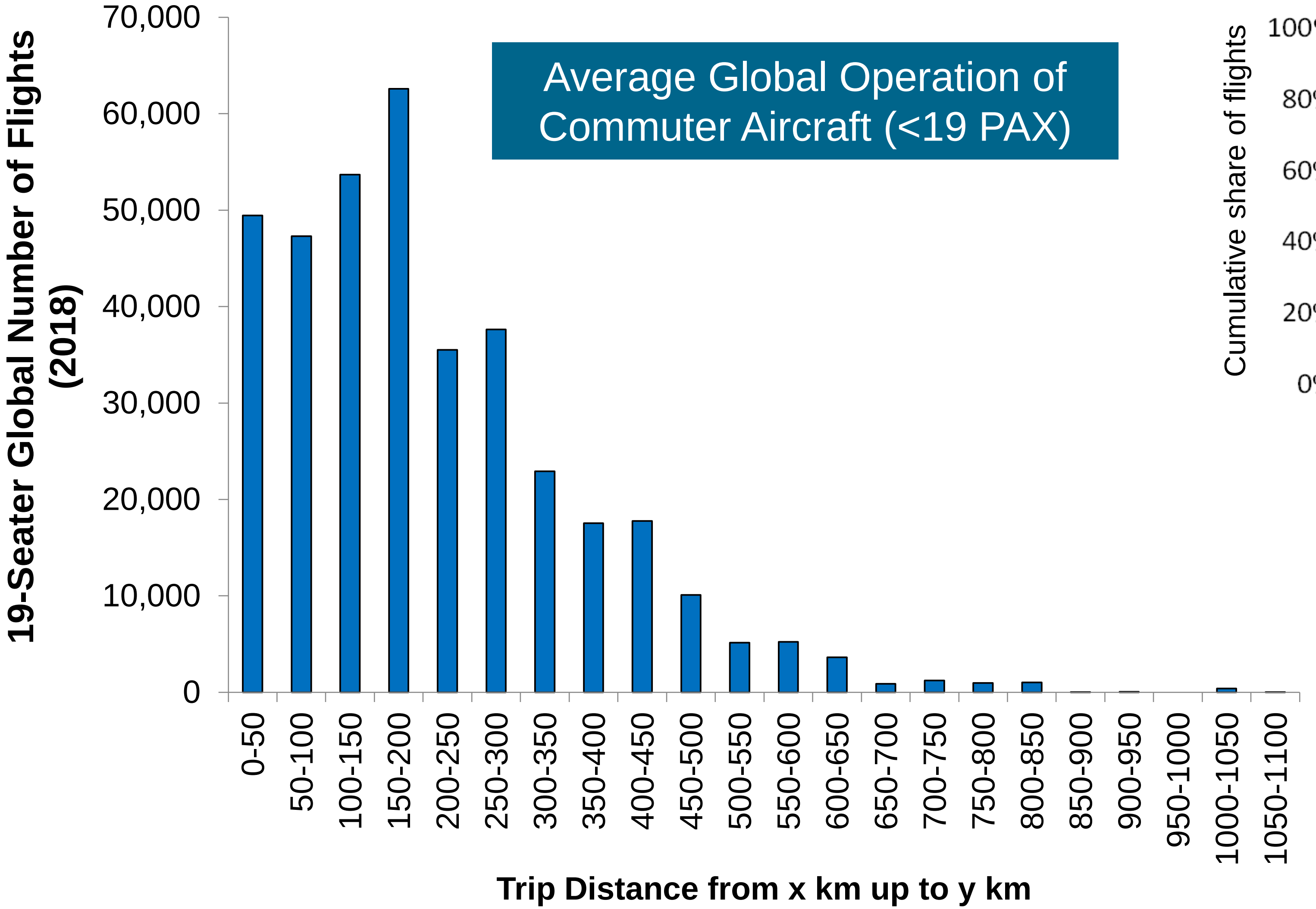
- Range-Flexibility → ranges of 1000s kilometers are enabled with a range-extender

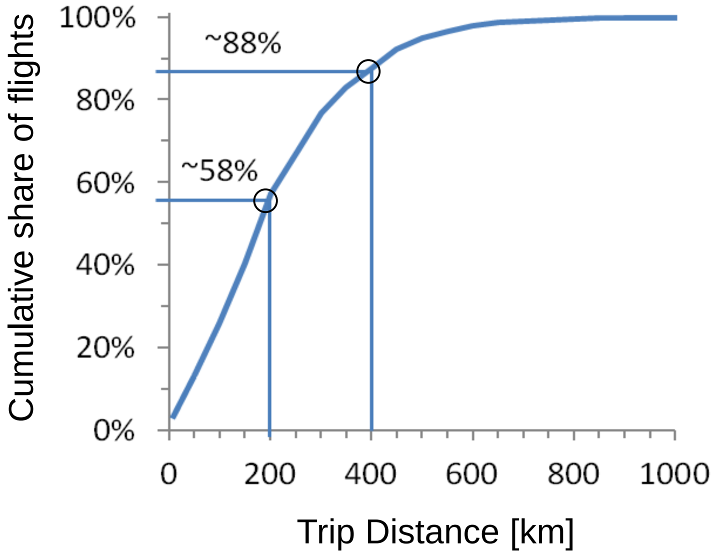
- The range flexibility can allow a lighter battery (less necessary electric range)
  → a lighter aircraft than only battery electric

- All-electric operation (e.g. up to 750km) are highly efficient
  Additionally → shorter-hybrid missions (e.g. up to 1000km) are mostly electric → also highly efficient

What are required ranges for a PHEP aircraft to make a difference?

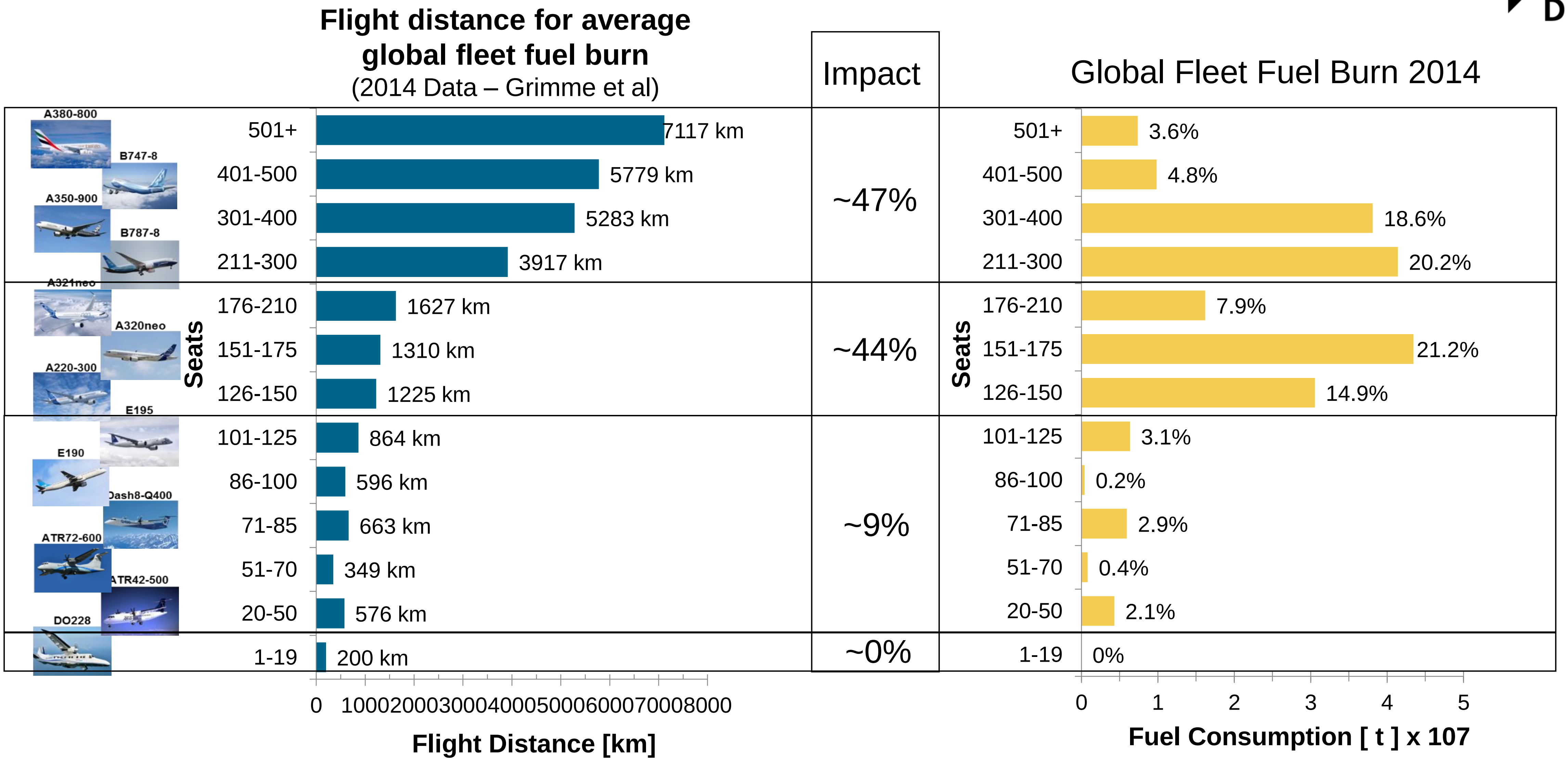
Design Goals of the CoCoRe Project (2019)





Most commuter aircraft fleet serve ultra-short distances, suitable for fully-electric operation.

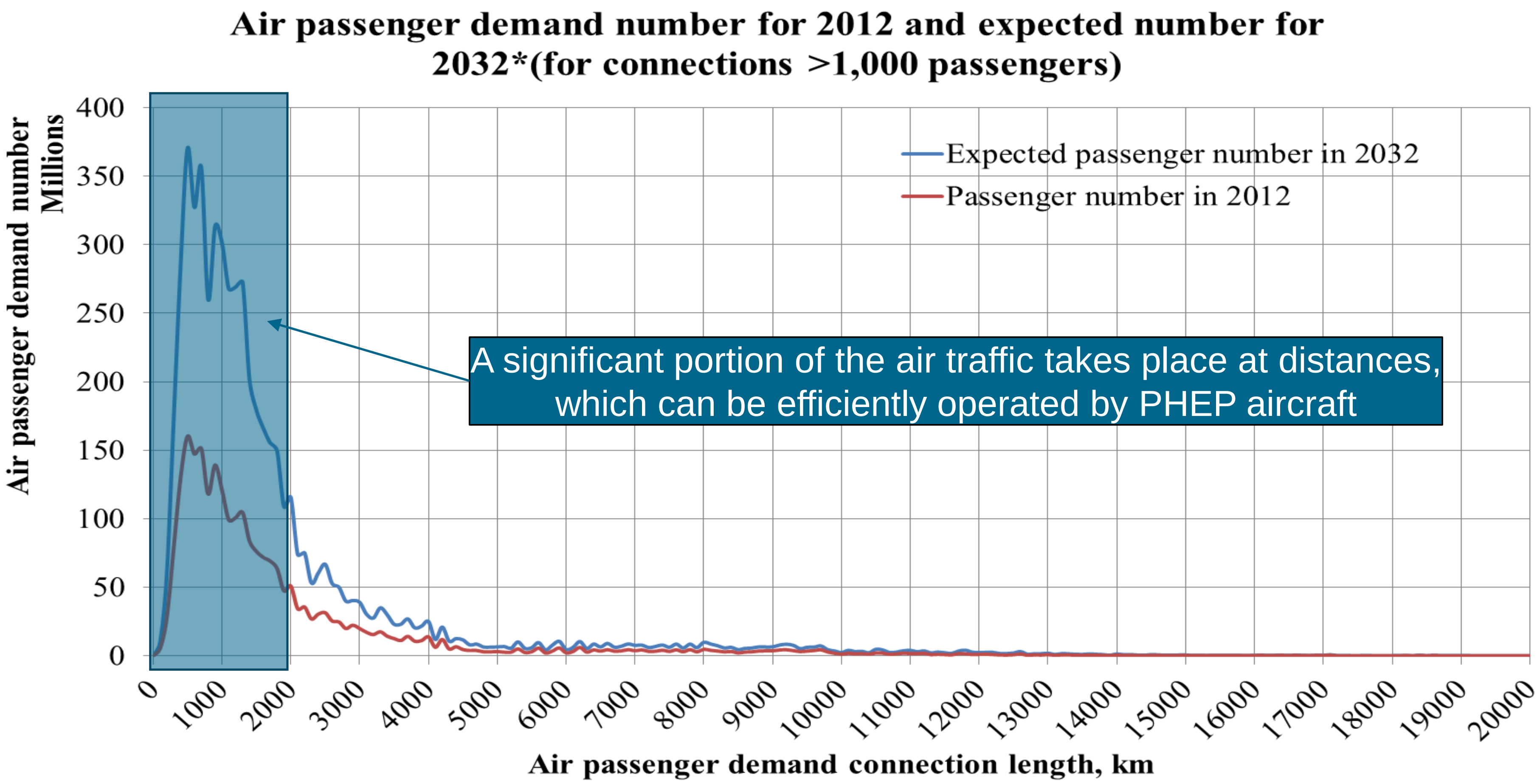
Aircraft Class Impact Breakdown



From a global perspective, aircraft of 100-seater+ classes have the most impact.

Global Travel Demand

* Based on the UN GEO-4 socio-economic scenario Sustainability First. Expected APD number is obtained from the APD forecasting model on city level – *D-Cast*.



DLR Project Experience of Overall Aircraft Design with Electric Propulsion

PHEP Concepts Explored in Multiple Projects

CoCoRe (2018-2019)

Commuter Class
19-seater

Small bi-lateral collaboration project:

DLR & Bauhaus Luftfahrt

Light, conceptual study, focusing on commuter fleet operation and efficiency

IMOTHEP(2020-2024)

Regional Class
40-seater

Large Horizon 2020 Project

Research: DLR, AIT, ONERA, ILOT
Unis: Nottingham, Florence, Strathclyde
Industry: Leonardo, SAFRAN, GE
Authorities: EASA, EUROCONTROL

TELEM (2021-2024)

Regional Class
70-seater

LuFo Project:

DLR, MTU, Rolls Royce Electric

Focus on Detailed Propulsion Component Design, Integration and Certification Aspects

EXACT (2020-2024)

Short-Range Class
250-seater

Large DLR-internal project

→ 20 DLR Institutes
→ over 100 people involved

Global fleet simulation
→ Operating costs
→ Climate impact
Comparison to other aircraft concepts

Conclusions

Battery-powered aircraft concepts (with range extender) were rigorously explored in the DLR, confirming:

- ✓ Viability of the technology for aircraft classes up to 250-seaters
- ✓ No direct show stoppers for primarily battery-powered propulsion integration into the airframe
- ✓ Highly interesting technology for intra-continental air travel, offering both sustainability and affordability

Outlook

Current and future activities with regard to Plug-In Hybrid Propulsion:

- Application of on a people-mover concept (400+ passengers)
- Combination with laminar-flow technologies & strut-braced wing
- Innovative retrofit solutions

DLR Project EXACT

250-seater PHEP Aircraft Concept Results

EXACT Short Range Class

Reference A/C:

A321neo interpretation (EIS2016)

D239

Top-Level-Aircraft Requirements (TLARs)

Design Range	[nm]	2500
Design PAX (single class)	[-]	239
Max. Payload	[kg]	25000
Cruise Mach Number	[-]	0.78
TOFL (ISA +0K SL)	[m]	2200
Approach Speed (CAS)	[kt]	136
Wing span limit	[m]	<=36

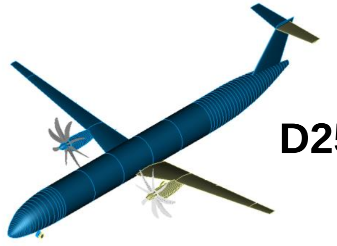
Redesign for EIS2040:

- **TLARS:**
  - Range 1500nm
  - TOFL (ISA +0K SL) 1900m
  - 250 PAX; Design Payload 23750kg
  - Approach speed <140kts
- **Technology factors:**
  - Gas turbine +5% efficiency
  - Fuselage mass -5%
  - Empennage Mass: -8%
  - CFRP Wing with foldable wing tips
  - Bleedless systems architecture

EXACT Turbofan Baseline

D250-TF

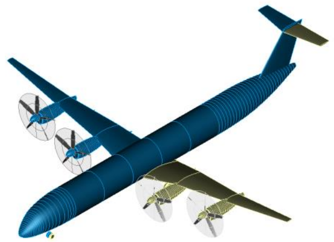
EXACT Turboprop Baseline



D250-TP

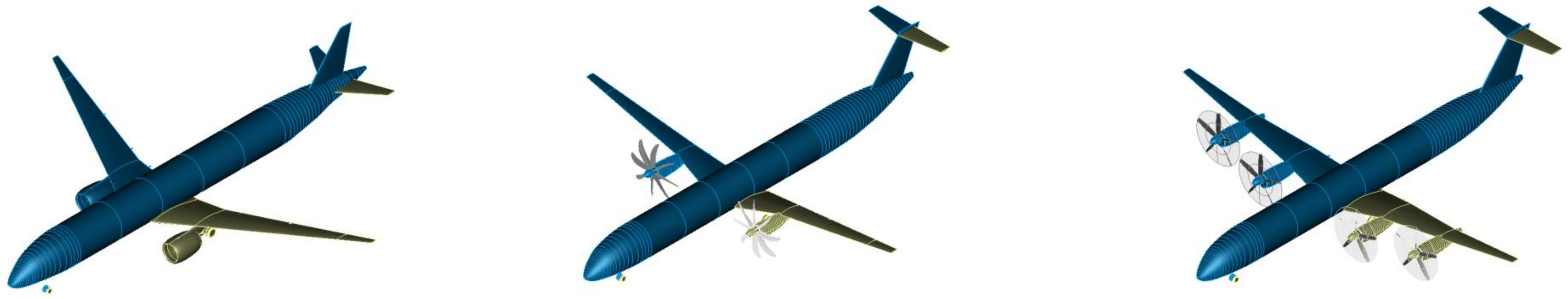
Design specific → Mach 0.67

D250-PHEP (Plug-In Hybrid-Electric Propulsion)



- Mach = 0.67
- Battery size optimized for cost in the sort-range operational network
- Fully electric flight capability

Modelling Consistency



D250-TF

D250-TP

D250-PHEP

All three concepts:

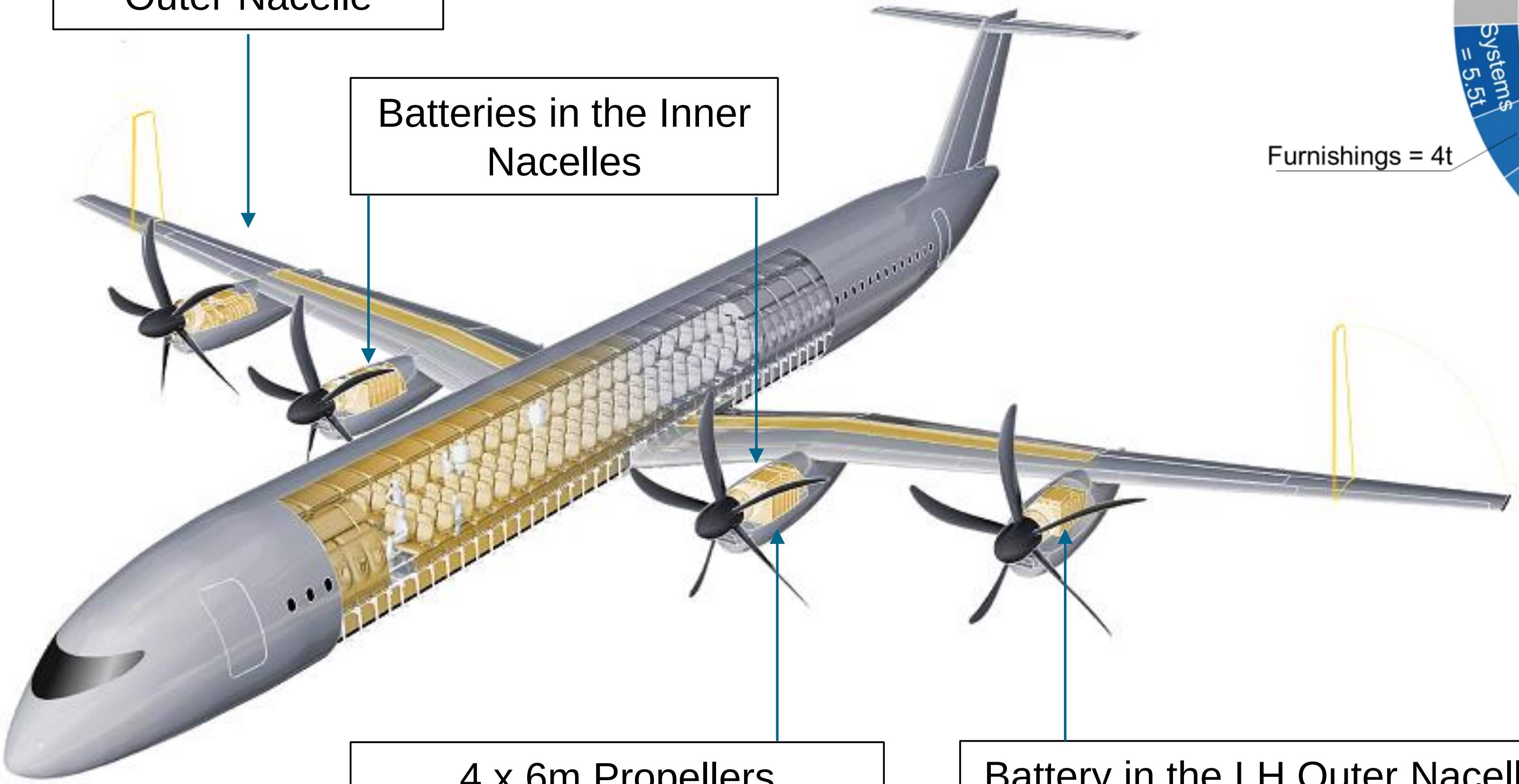
- were modelled consistently with respect to each other (e.g. aerodynamics, structures, engines, etc.);
- were optimized for the global fleet operation costs;
- were compared with the same set of boundary conditions.

This approach ensured consistency and comparability between the models.

Short-Range PHEP Configuration

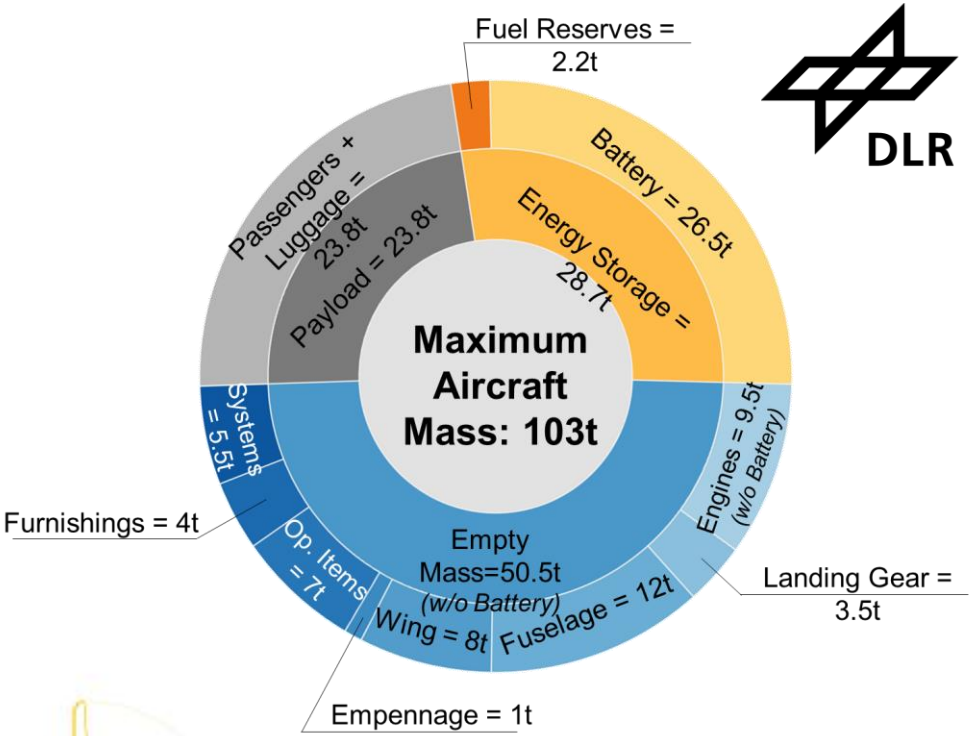
One Range-Extender in the RH Outer Nacelle

Batteries in the Inner Nacelles



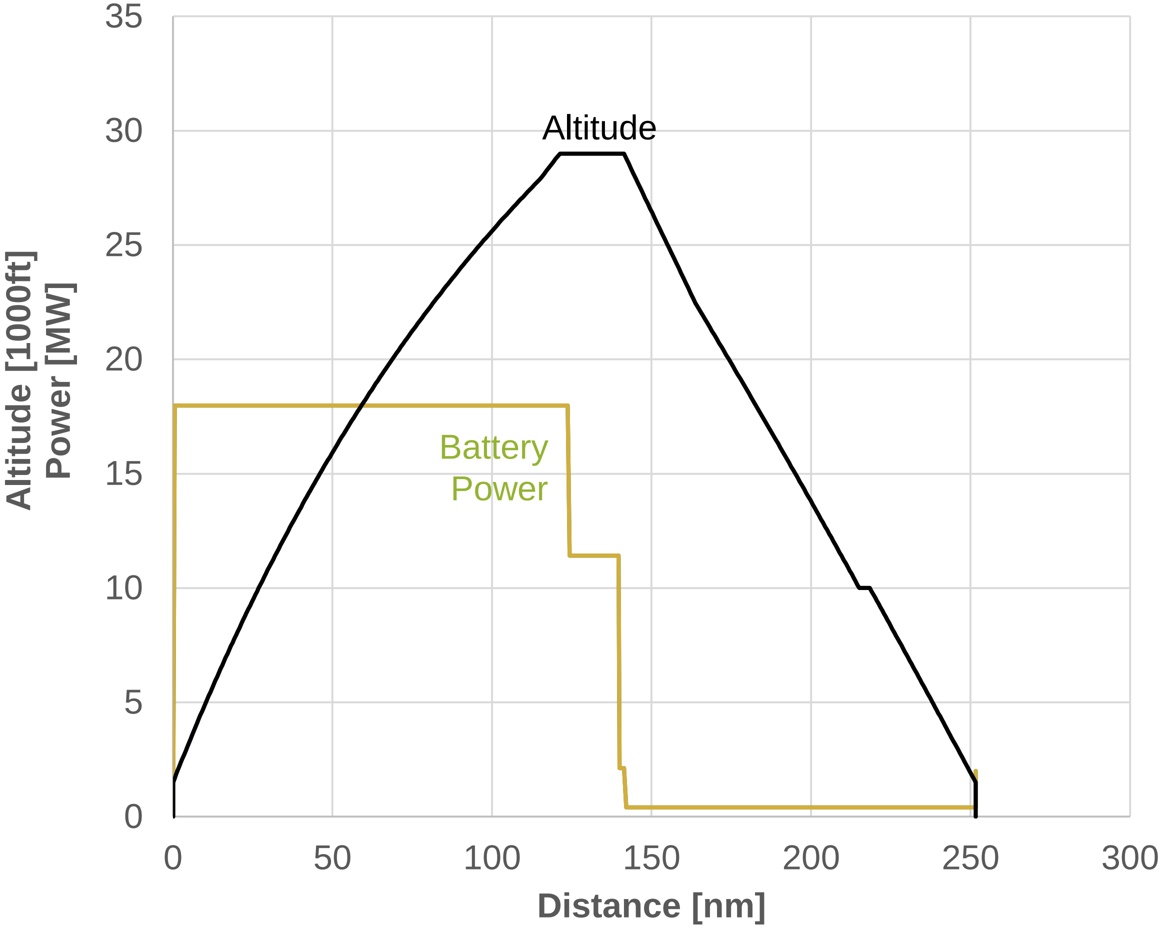
4 x 6m Propellers
4x 4 MW Electric Motors

Battery in the LH Outer Nacelle
Balancing the Range-Extender



- 400Wh/kg batteries
- Electric range ≈ 500 km (270 nm)
- Hybrid range (standard payload) ≈ 2800 km (1500 nm)

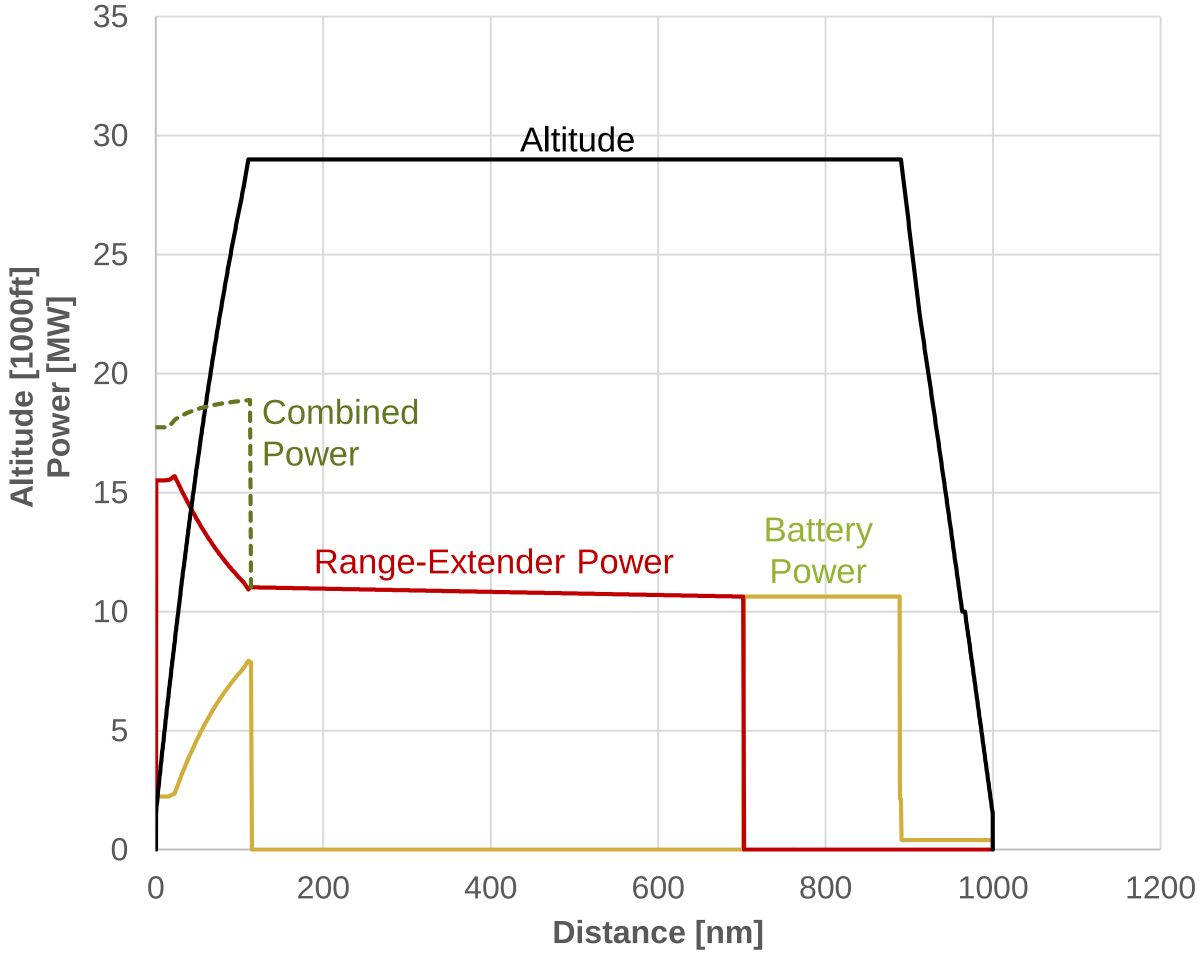
D250-PHEP Power Profile – Electric Mission



- The mission is flown only with battery energy, including taxi, take-off, approach and landing.
- The gas turbine is not used for the main mission but will be started in case reserves are needed.
- Sufficient fuel is carried in case a diversion after the mission is needed.
- ~10% battery capacity remains after the mission:

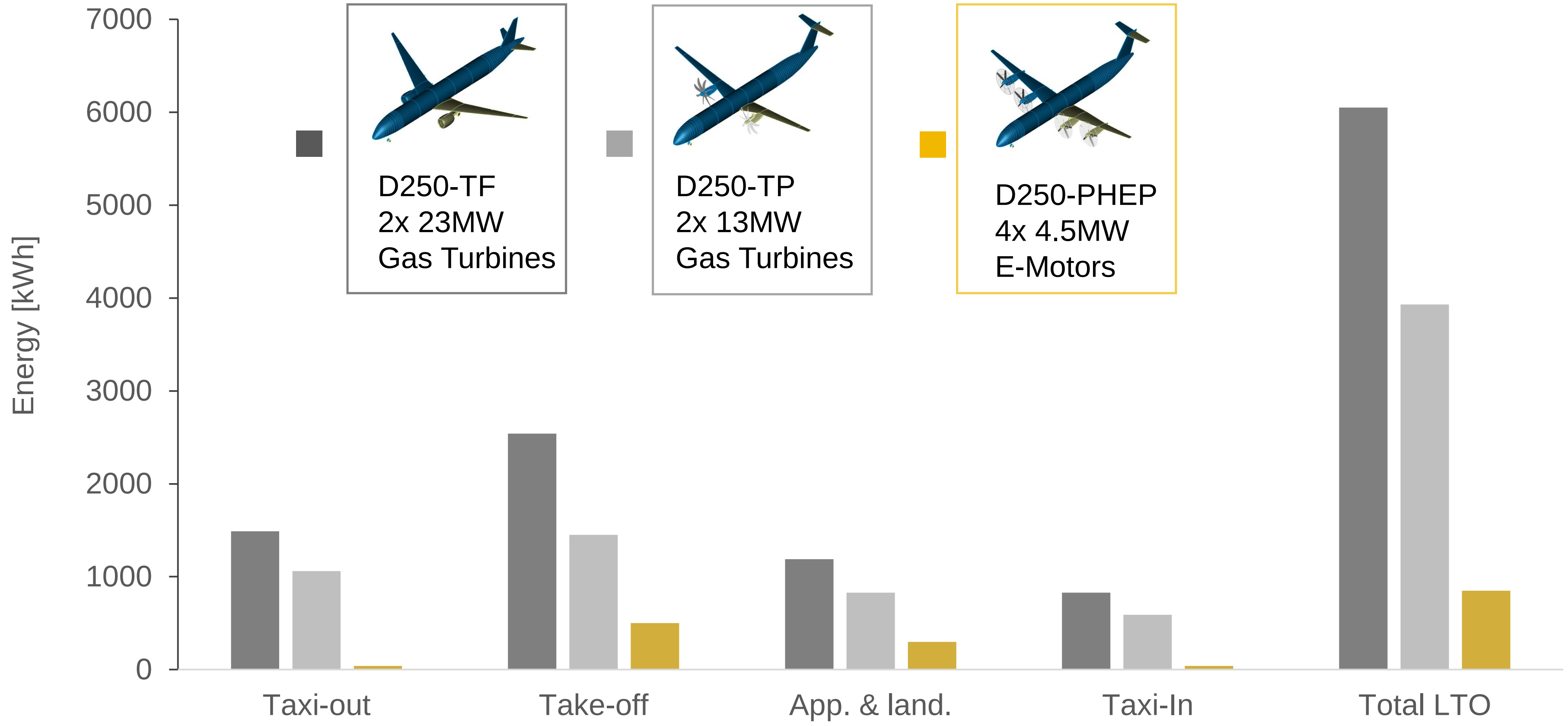
5% contingency + sufficient energy for electric go-around (to allow starting the gas turbine)

D250-PHEP Power Profile – Range-Extender Mission



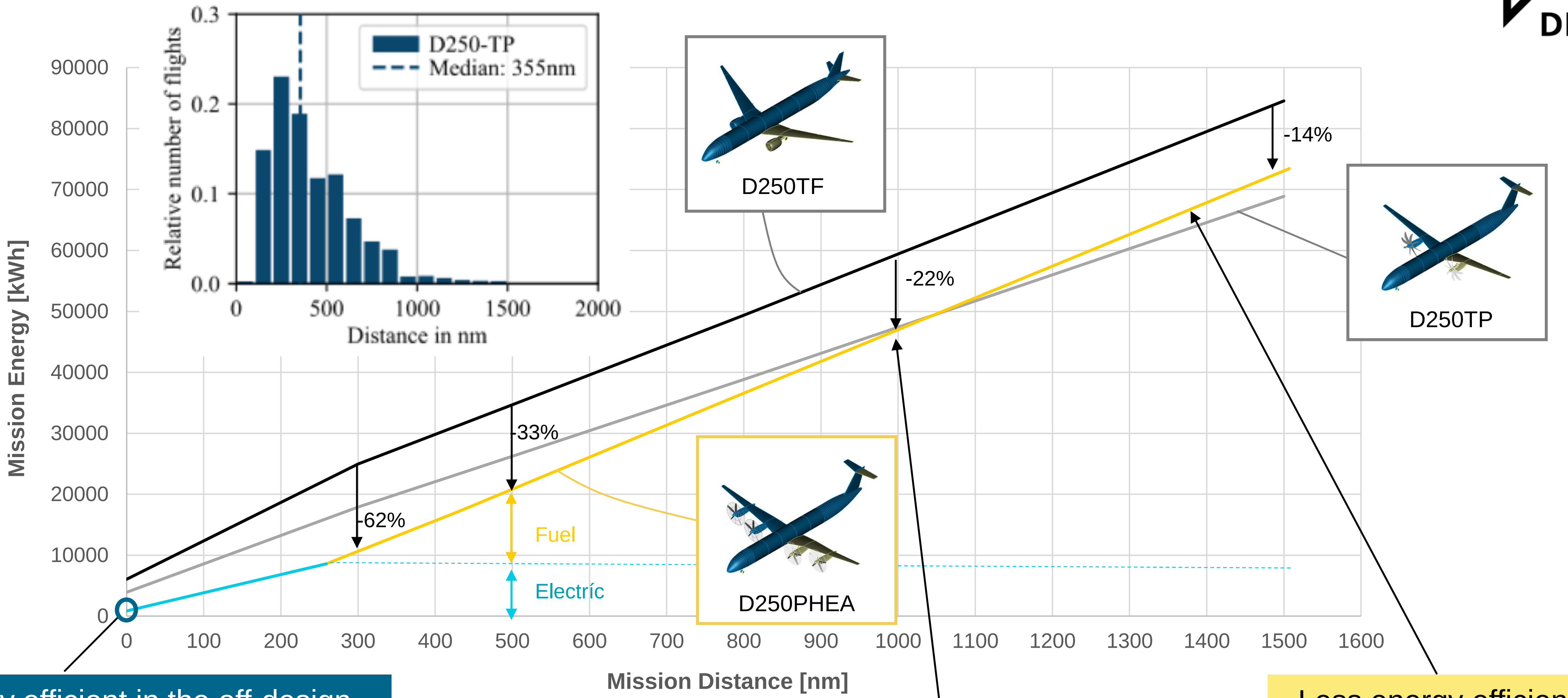
- After electric taxi and takeoff, the fuel is burned, making the aircraft lighter. Sufficient fuel for the reserve mission is spared.
- After the fuel for the main mission is burned, the flight continues electrically without turning on the gas turbine again (except in case of a diversion).
- Should the gas turbine fail during the range-extender phase, the aircraft can divert electrically with ~300 nm diversion radius.
- Since the electric flight starts from cruising altitude, the electric distance is around 300 nm, which is the possible diversion radius in case the gas turbine fails.
- Sufficient fuel is carried in case a diversion after the mission is needed.
- ~10% battery capacity remains after the mission (contingency + go-around)

Off-Design Performance



The Plug-In-Hybrid concept offers an extreme advantage in off-design performance.
→ Highly relevant for short routes.

Energy vs Range Comparison



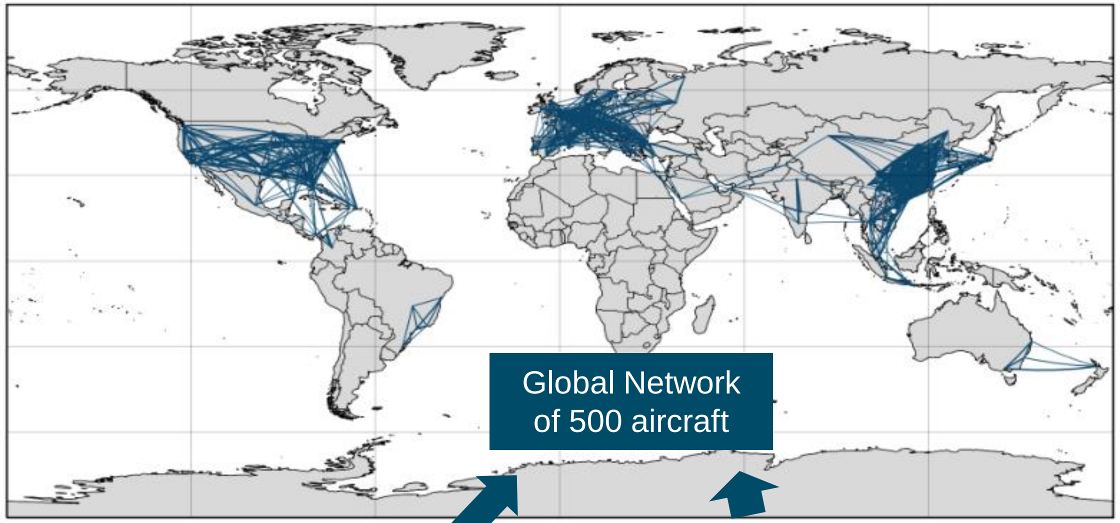
Highly efficient in the off-design phases (e.g. Taxi, Take-off, Approach and Landing)

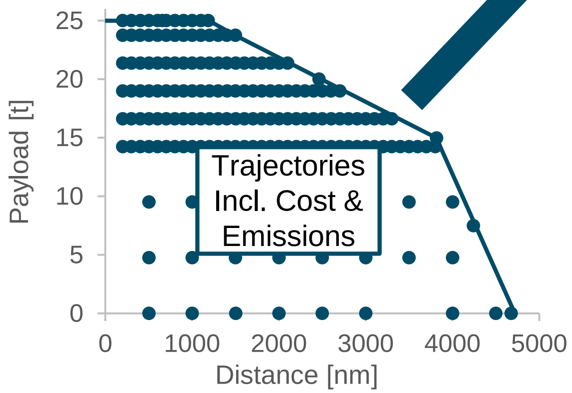
Highest energy efficiency below 1000nm **(1850km),** due to high portion of electric energy.

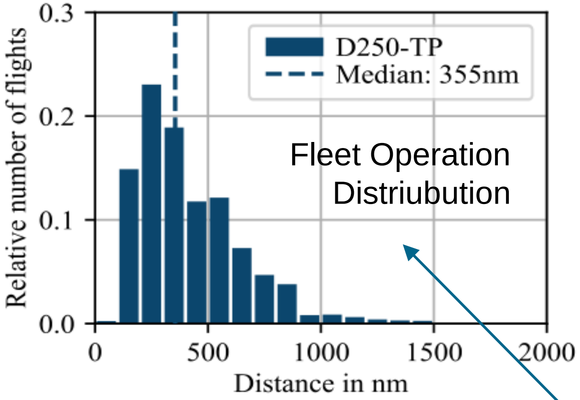
Less energy efficient than the turboprop at longer missions.

EXACT - Overview

A typical short-range turbofan operator is simulated







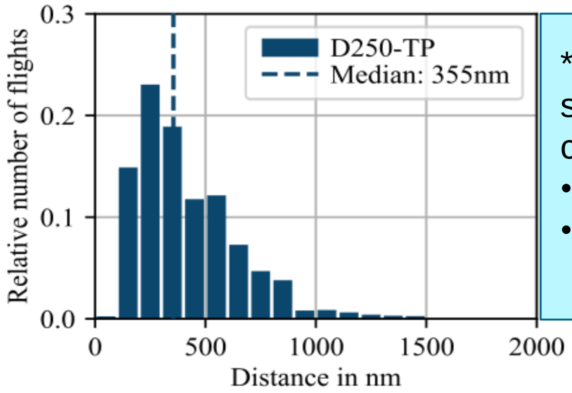
The aircraft are compared on a global network of 500 vehicles simulated over a course of the aircraft life.

The simulation is used to calculate:

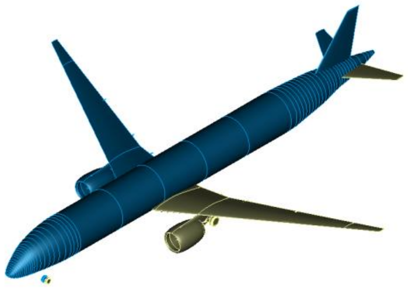
- **Fleet yearly operating costs** (including maintenance checks & overhaul, crew costs, day-night cycle etc.)
- **Total fleet climate impact** (including materials production & logistics)

This fleet operation distribution is one of the scenarios used in EXACT, which is the base for the fleet-level results of the next slide

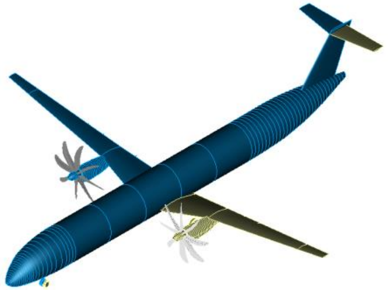
Fleet-Level Efficiency Comparison



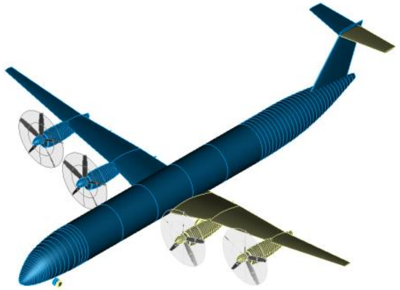
* Identical fleet operation scenario applied on each concept:
- 85% cabin utilization
- Fixed fleet operational profile (shown on the left)



D250TF



D250TP



D250PHEA

Fleet-Average Transport Energy:
19.0 kWh/PAX/100km*

Pros:
- Mature, low-risk technology

Cons:
- Highest fleet energy consumption of the three concepts

Fleet-Average Transport Energy:
14.3 kWh/PAX/100km*

Pros:
- **~-25% fleet energy**
- -6% MTOW
- -7% Airframe & Propulsion mass

Cons:
- +10% average fleet operation time.

Fleet-Average Transport Energy:
10.5 kWh/PAX/100km*

Pros (vs D250-TF):
- **~-45% fleet energy**

Cons (vs D250-TF):
- ~+30% MTOW
- +10% Airframe & Propulsion mass (w/o battery)
- +10% average fleet operation time

Overview of the Overall PHEP Results in EXACT

The EXACT results conclusions on the 250-seater PHEP concept:

- By far the most energy-efficient concept
- The concept with the highest potential for climate impact reduction (only matched by hydrogen aircraft)
- The concept with the highest potential for operating costs reduction (especially when expensive sustainable fuels are used)

D250-PHEP

More details about the project boundary conditions and results: www.exact-dlr.de

Thank you for your attention!