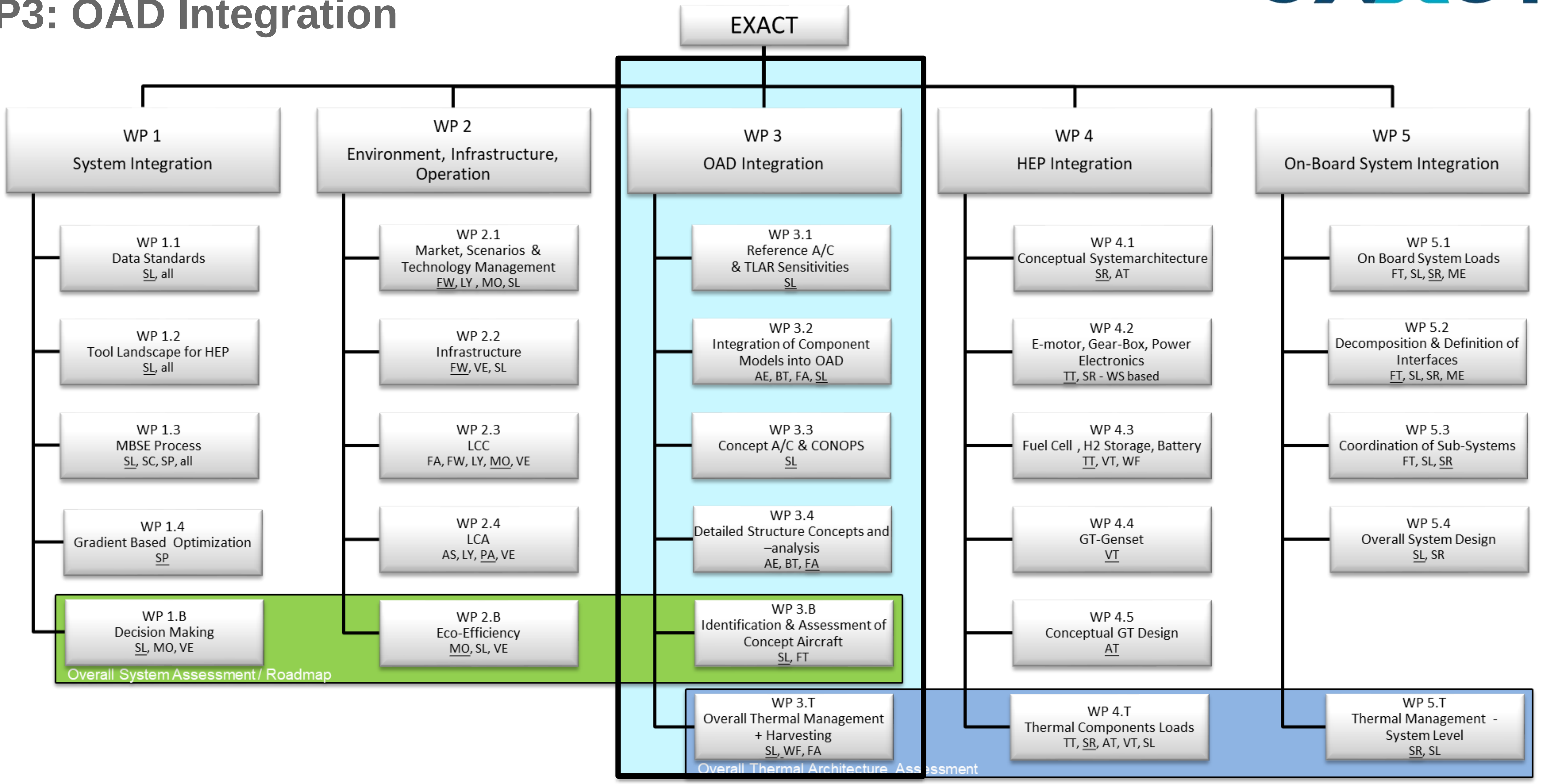
Deutsches Zentrum für Luft- und Raumfahrt

DLR

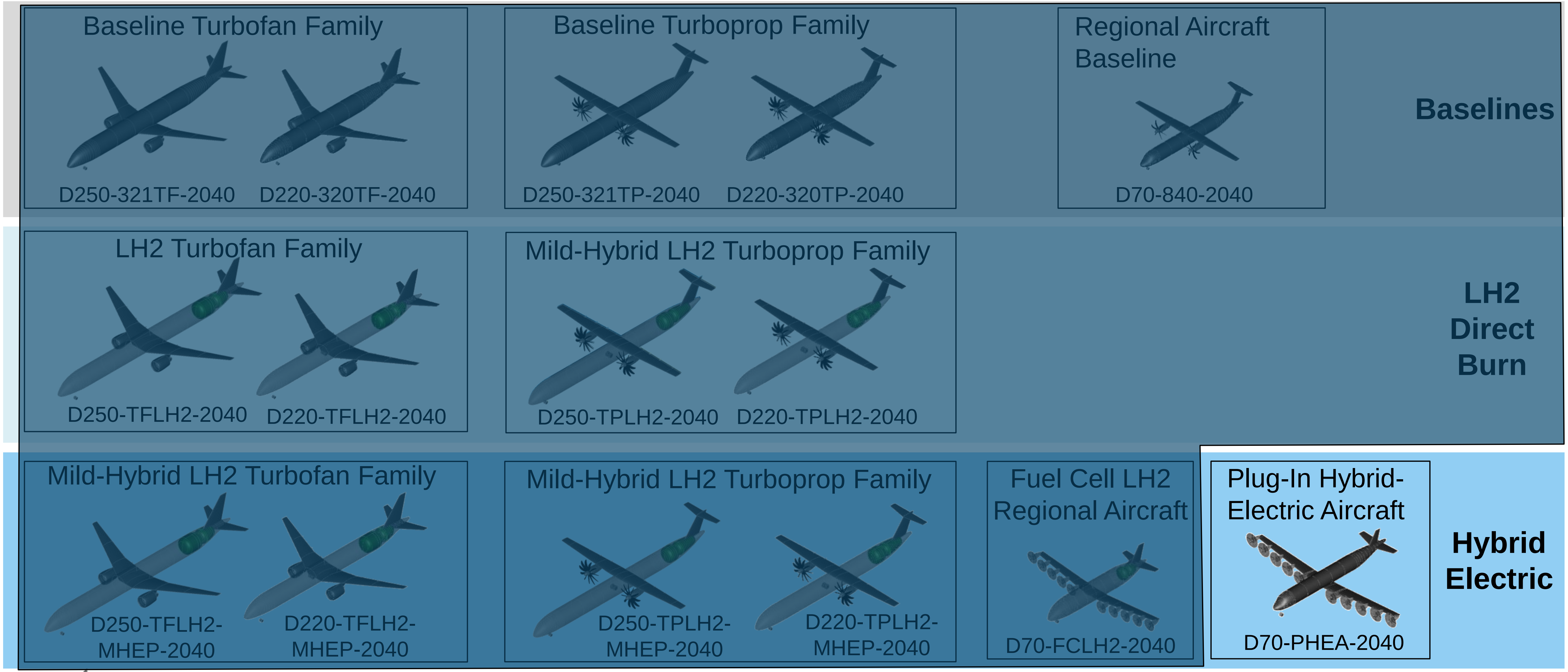
Concept Introduction:
70 PAX Plug-In Hybrid-Electric Aircraft (D70 PHEA)

Presenter: Georgi Atanasov

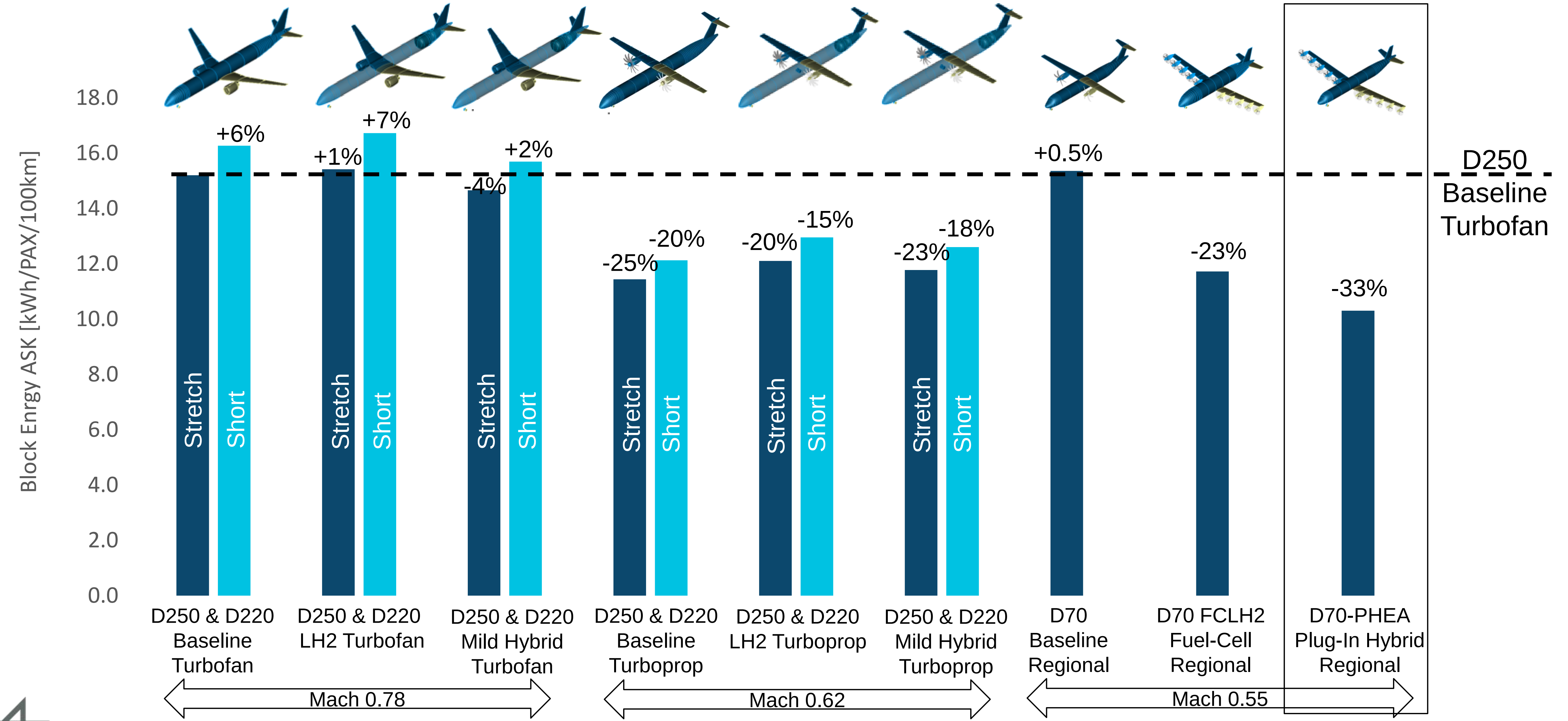
WP3: OAD Integration



Models Overview



Block Energy Comparison @ 500nm & Standard Payload



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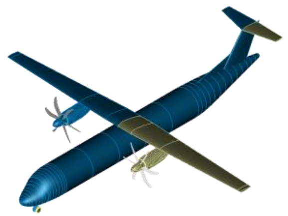
Motivation for Electric Aircraft

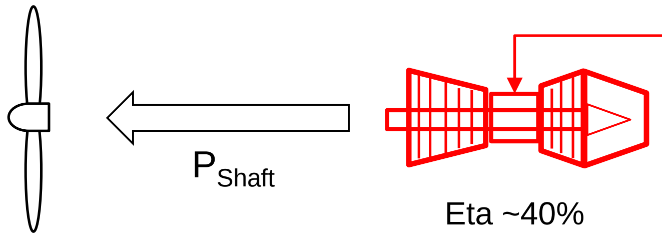
Aircraft Type	Propulsive power	Power Generation	Energy Flow	Syn Fuel Cost



D70-Baseline

Cruise:
FL290, Ma0.55
L/D =17.5
eta_Prop = 0.9
m_Aircraft = 20t

P_shaft / PAX = 32kW / PAX



Eta ~40%

Gas Turbine
(70PAX A/C size, EIS2035)

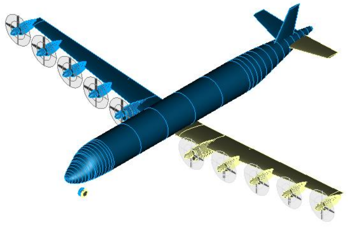
Fuel Energy Flow

80 kWh / PAX / FH

10 € / PAX / FH

Synthetic Fuels Production & Logistics

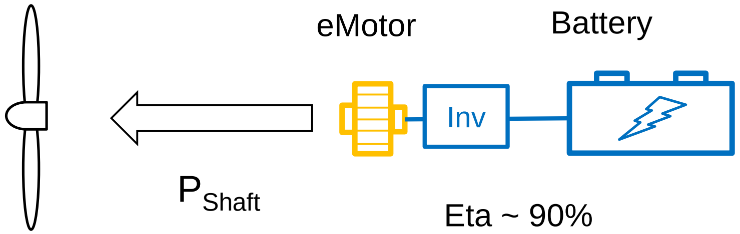
2040 Assumptions:
0.125 € / kWh



Electric Aircraft

Electric Cruise:
FL290, Ma0.55
L/D =17.5
eta_Prop = 0.9
m_Aircraft = 30t

P_shaft / PAX = 50 kW / PAX

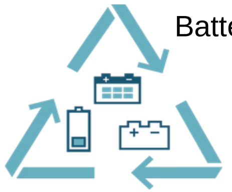


Eta ~ 90%

Electric Energy Flow

55 kWh / PAX / FH

4.4 € / PAX / FH



Battery production, recycling & charging

(3000 Cycles)

2040 Assumptions:
0.08 € / kWh
(0.045 €/kWh Energy
0.035 €/kWh Battery Cost)

The energy cost for electric flight is potentially ~30% more energy efficient and over 50% cheaper than flying with synthetic fuel.

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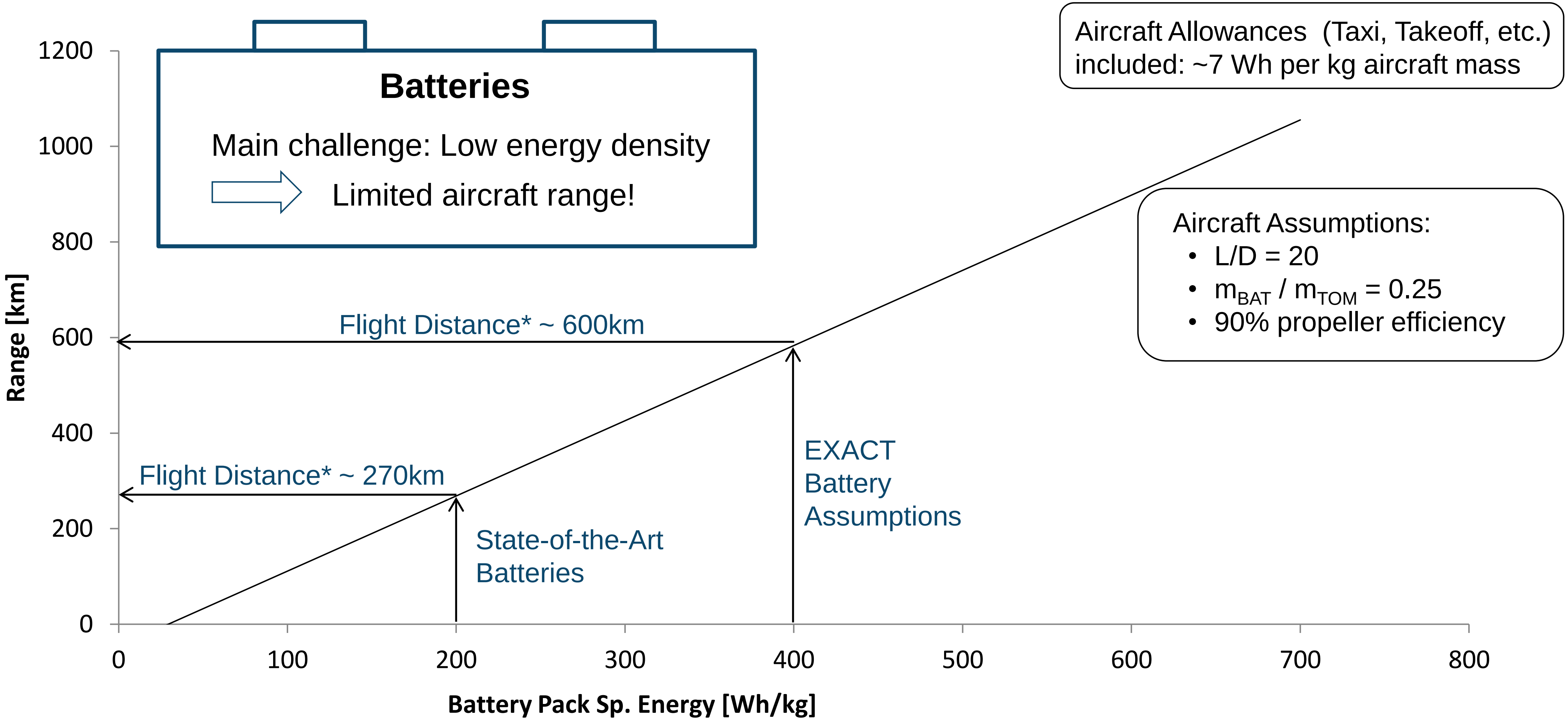
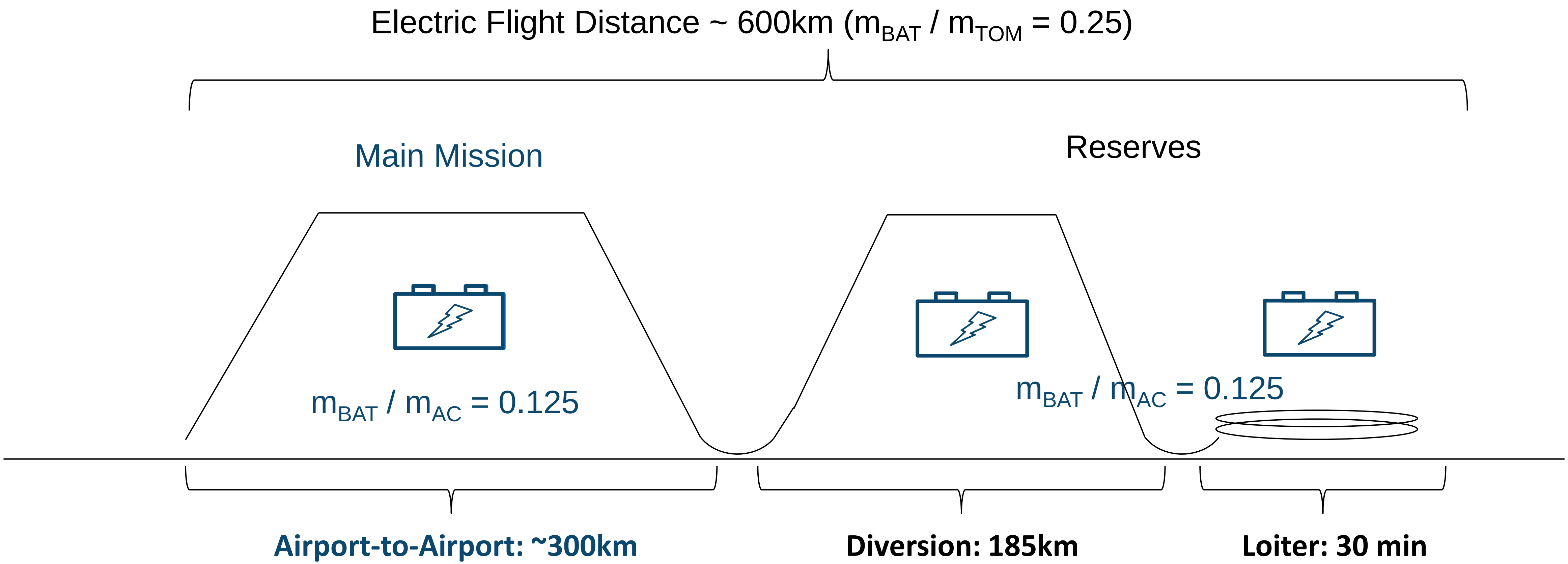
Challenges for Battery Flight



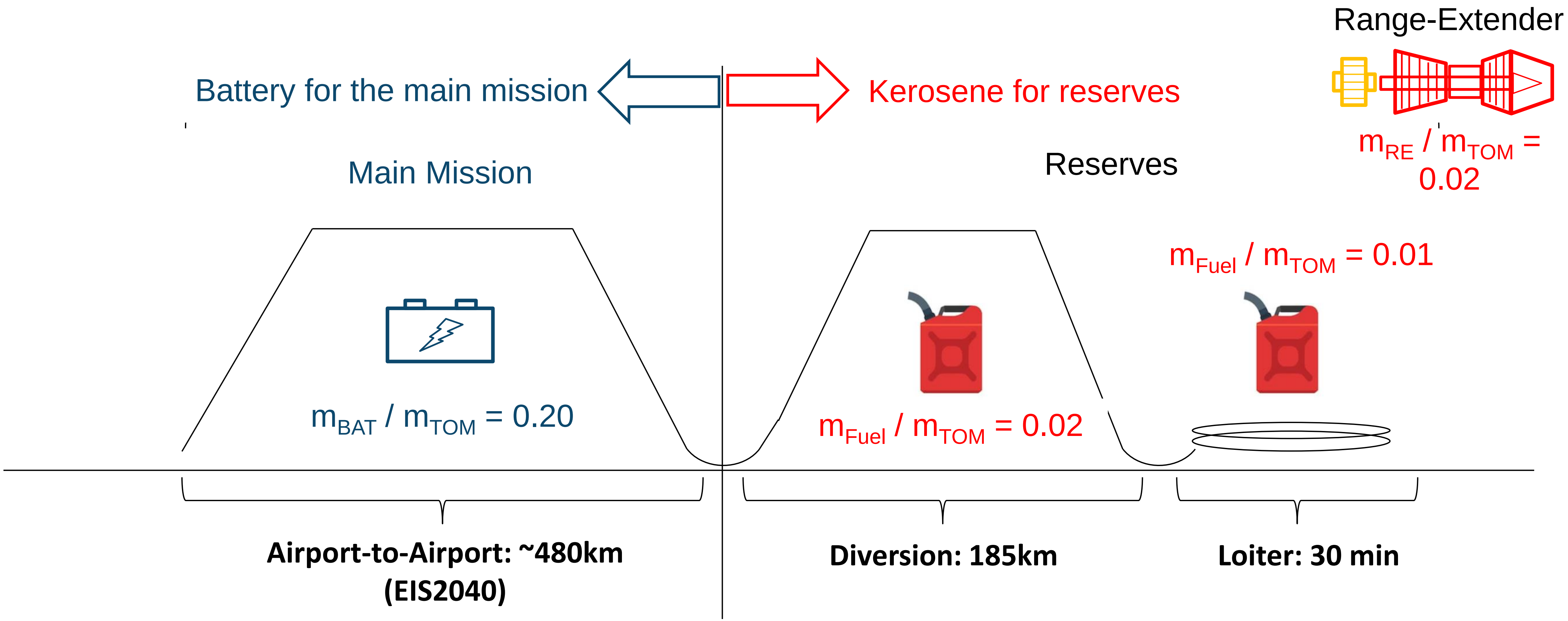
*Flight distance without taking into account operational reserves

Range Extender for Increased Electric Range



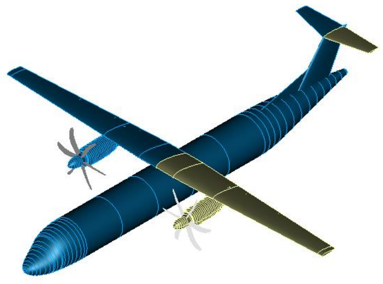
The reserves take up a significant part of the available range.

Range Extender for Increased Electric Range



More achievable electric range by using a range extender with kerosene for reserves.

Baseline Aircraft and Assessment Metrics



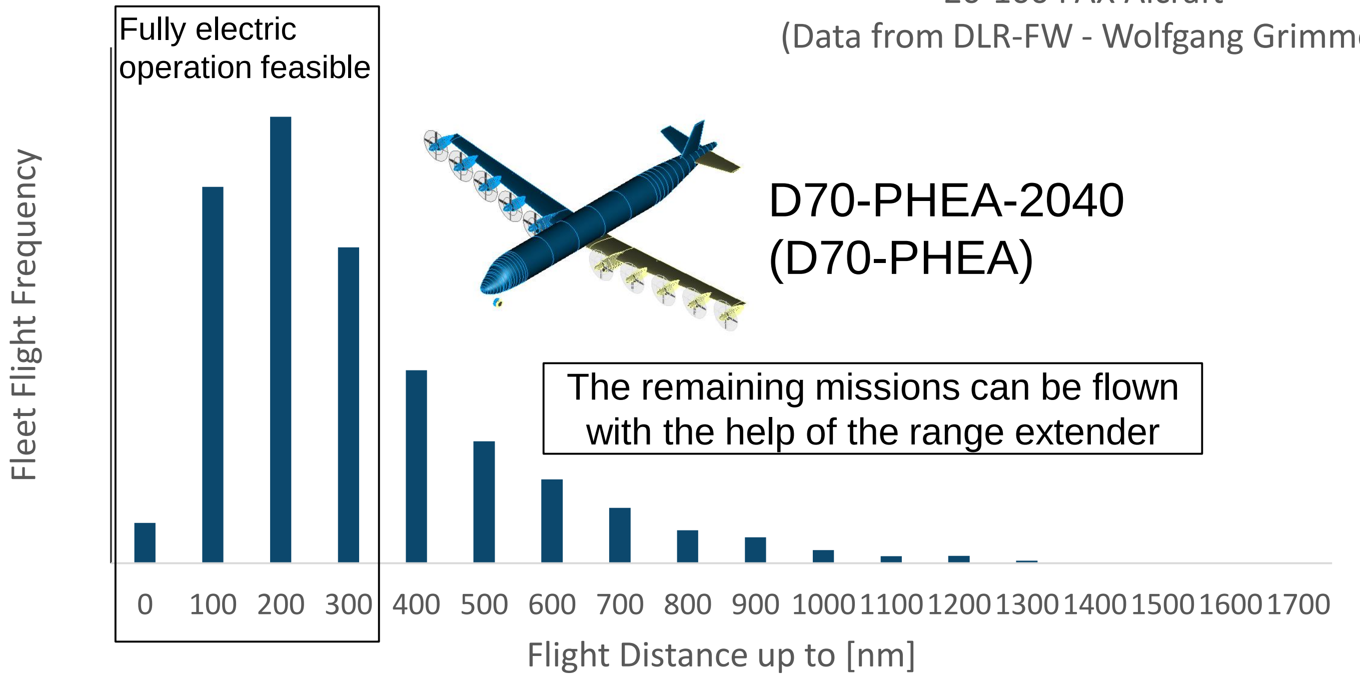
Baseline aircraft designation:
D70-840-2040
(D70-BL)

Top-Level-Aircraft Requirements (TLARs)

EIS	Year	2040
Design Range	[nm]	1000
Design PAX (single class)	[-]	70
Design Payload	[kg]	6650
Max. Payload	[kg]	7500
Cruise Mach number	[-]	0.55
Max. operating altitude	[ft]	29000
OEI Ceiling	[ft]	8000
TOFL (ISA +0K SL)	[m]	1500
Approach Speed (CAS)	[kt]	<120
Wing span limit	[m]	<=36

Assumed operation:

Global fleet flights for 2018
20-100 PAX Aicraft
(Data from DLR-FW - Wolfgang Grimme)



Assessment metric: **Fleet-level energy consumption**

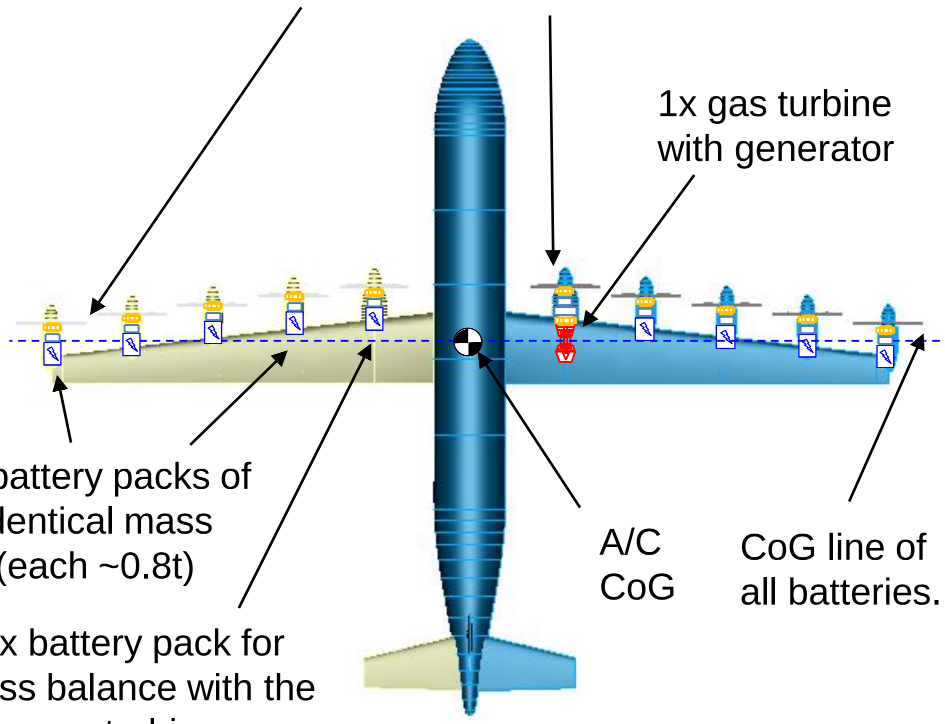
- Assumed that the opeation of the aircraft coincides with the assumed fleet operation profile.
- The fleet-level fuel is determined by multiplying the flight frequency at a given distance with the block energy needed for this distance and integrating across the entire distance profile.

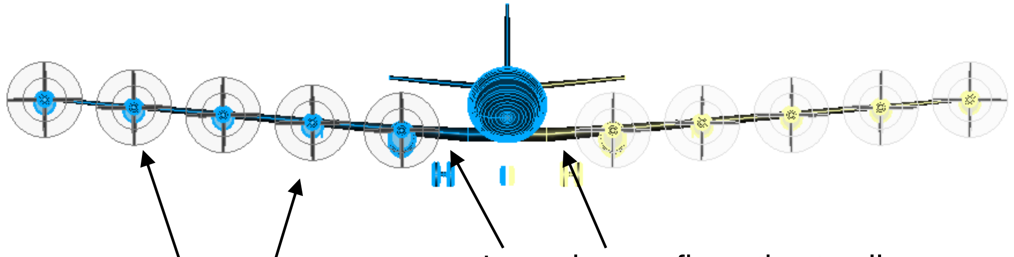
D70-PHEA Configurational Aspects

MTOW ~ 29t

Propulsion System ~10t

Propulsion + Wing + Fuel ~ 45% of MTOM

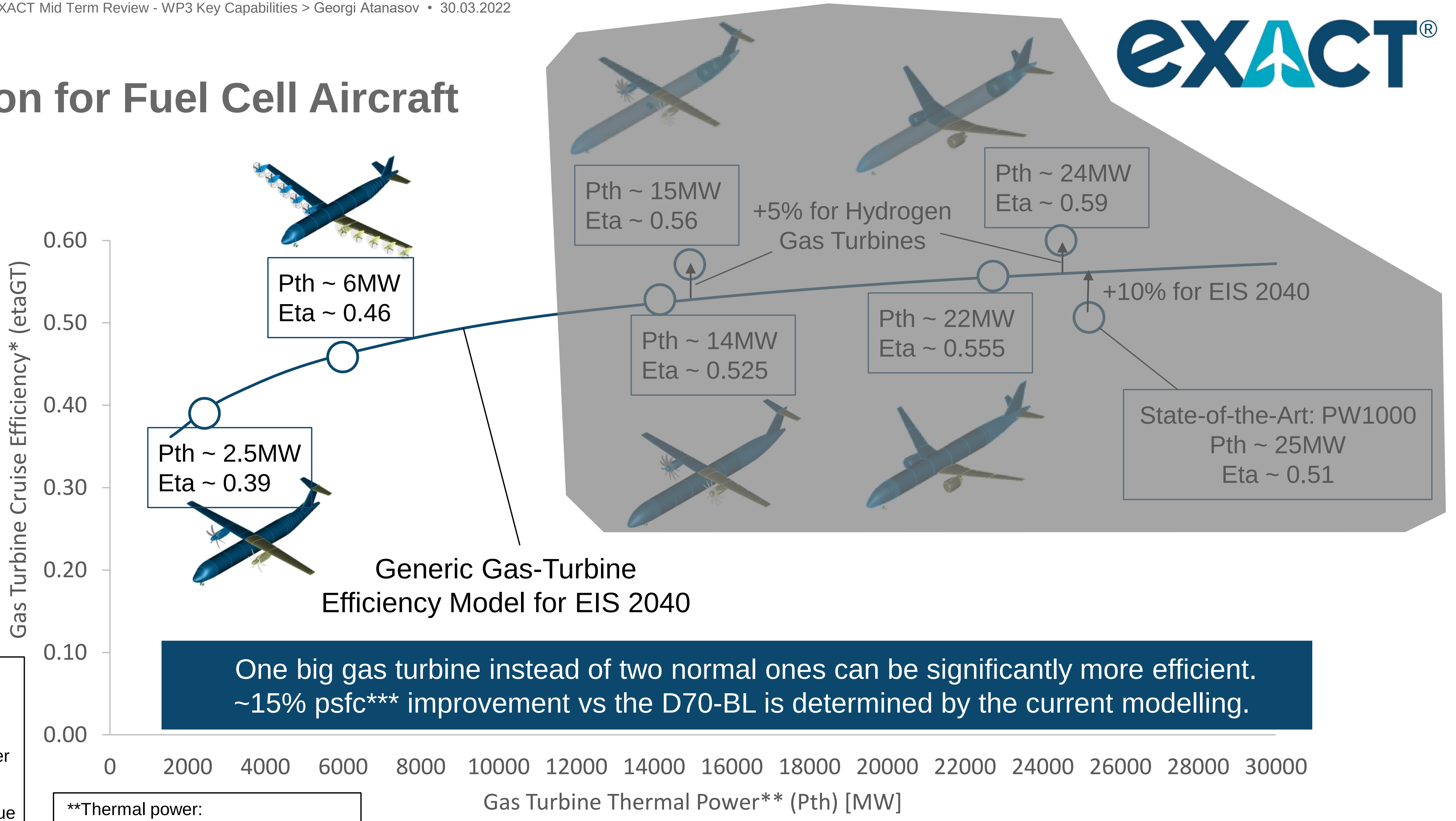




Additional considerations:

- The low-wing configuration is enabled by distributed propulsion.
- Around 3% propeller efficiency improvement due to reduced propeller loading.
- Battery distributed along the wing span to alleviate wing loads **(hard landing loads tbc)**
- The center of gravity of each battery pack needs to be ideally in front of the front spar to avoid flutter problems.
- The VTP size is reduced, as the OEI yaw moment is no longer a dominating sizing constraint.
- A conventional tail is chosen, as a T-Tail in a combination with a smaller VTP might result in too low aspect ratio of the VTP.

Motivation for Fuel Cell Aircraft



One big gas turbine instead of two normal ones can be significantly more efficient.
~15% psfc*** improvement vs the D70-BL is determined by the current modelling.

*GT efficiency:

$$etaGT = \frac{P_{eq}}{\dot{m}_{Fuel} \cdot LHV}$$

P_{eq} Equivalent power

$\dot{m}_{Fuel}$ Fuel flow

LHV Low heating value

**Thermal power:
Achievable power at sea-level static ISA conditions & TET limit withtout any mechanical power limitations or flat rating.

***psfc – power-specific fuel consumption

D70-PHEA Modular Battery Pack Design

The battery packs are to be modelled with flexibility in mind:

- They are assumed to be detachable for potential battery swapping during turnaround
  - Swapping batteries during turnaround potentially improves battery life and reduces turnaround time
- The battery packs are assumed to be configurable in terms of amount of battery cells
  - Reducing the total number of battery cells reduces the total mass of the battery, which can allow for tanking more fuel to increase range (i.e. trading 500kg of battery for 500kg of fuel will increase the range by ~300nm).
  - This can improve payload-range flexibility.

The current design assumes three main operational configurations (all with the same MTOM).

More Battery → Less Max. Payload

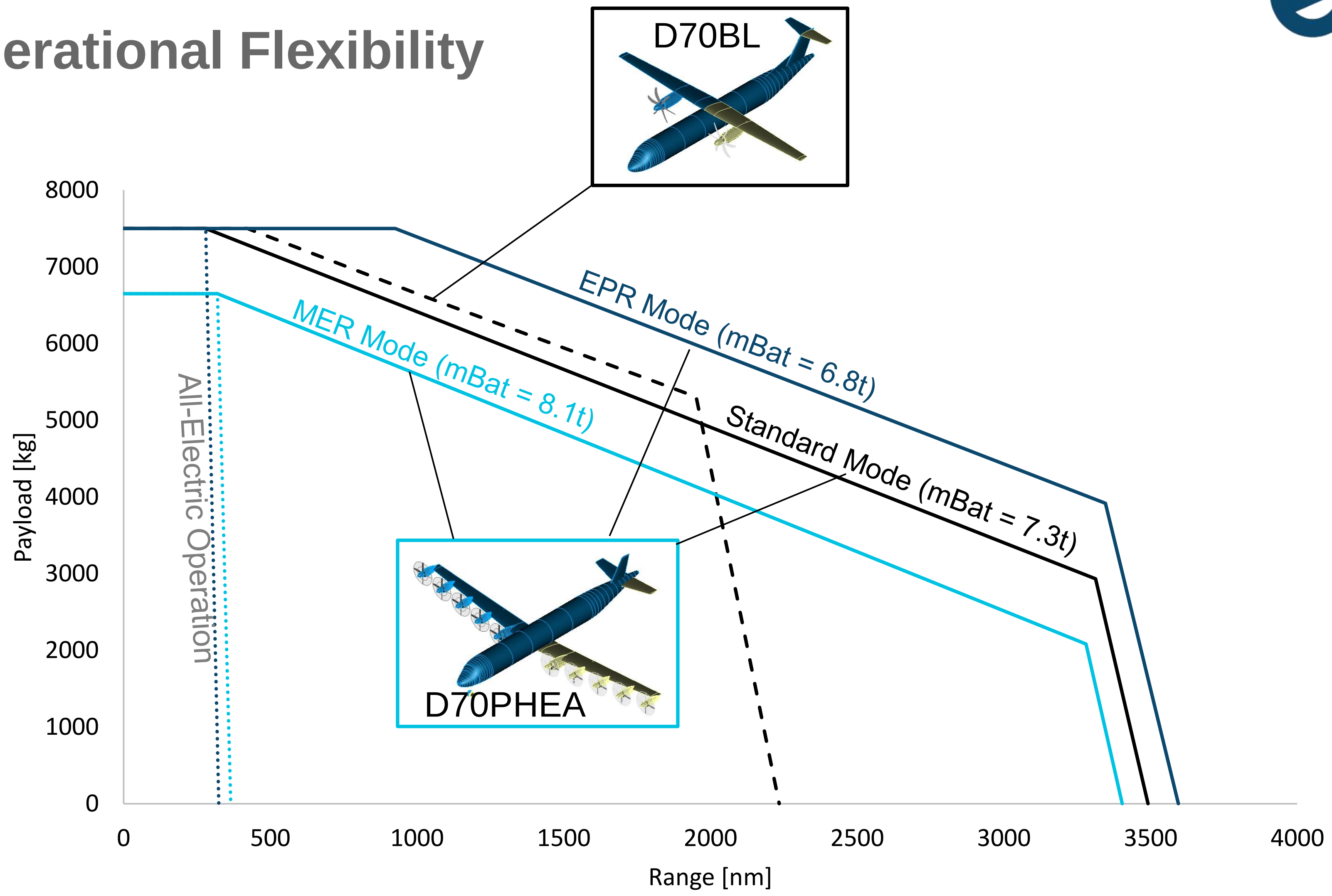
MER Mode (Max. Electric-Range)**:**
- Battery = 8110kg
- Max. payload = 6650kg (= Des. Payload)
- Electr. Range = 320nm

Standard Mode:
- Battery = 7260kg
- Max. payload = 7500 kg
- Electr. Range* = 285nm
- Hybrid Range* = 880nm
  (*with des. payload 6650kg)

Less battery → More fuel

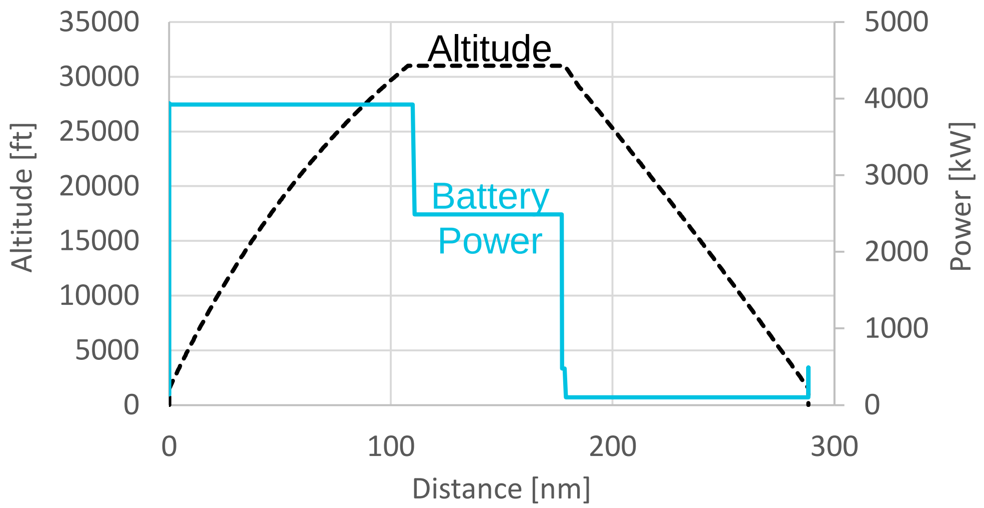
EPR Mode (Extended Payload-Range):
- Battery = 6760kg
- Max. payload = 7500kg
- Electr. Range* = 265nm
- Hybrid Range* =1500nm
  (*with des. payload: 6650kg)

D70-PHEA Operational Flexibility

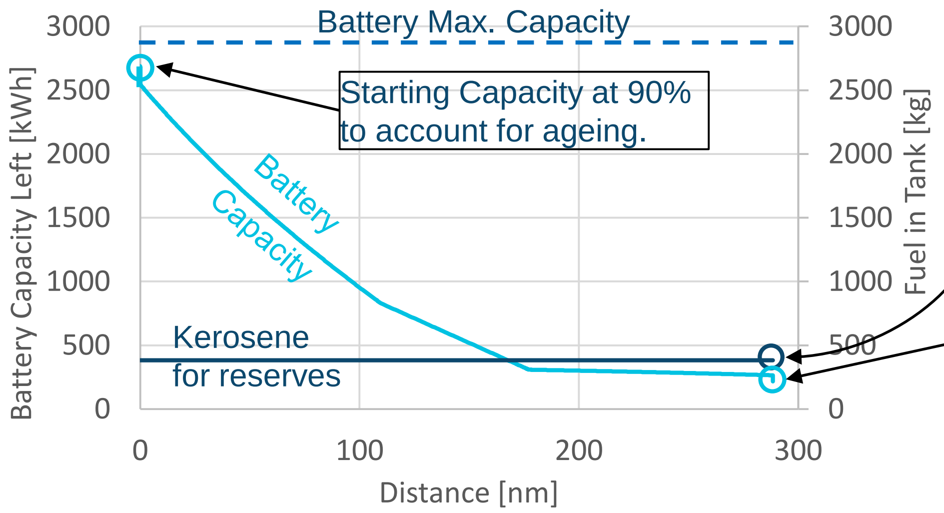


A configurable battery could improve the payload-range flexibility compared to conventional turboprops.

D70-PHEA Operational Aspects – Electric Mission



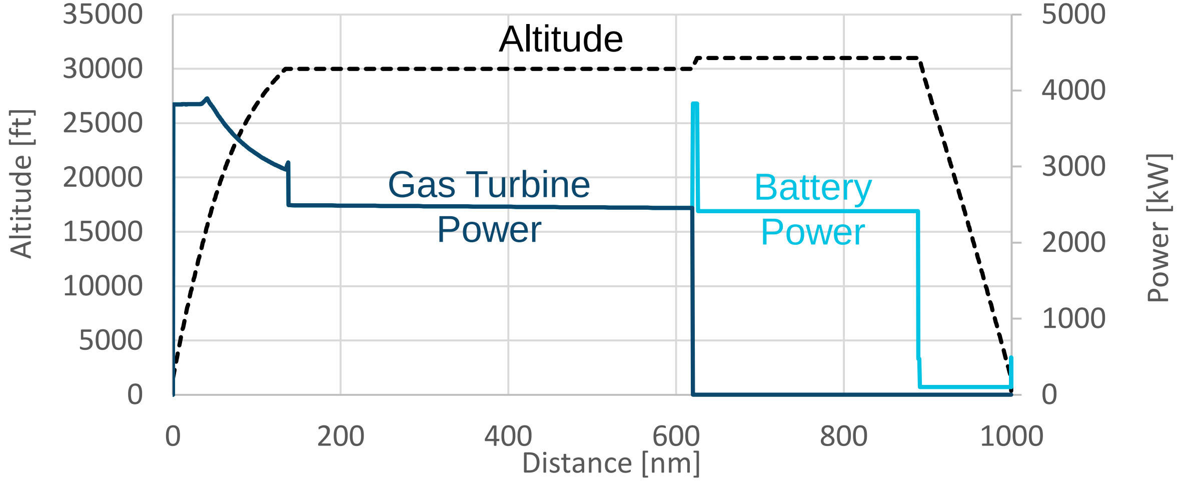
- The mission is flown only with battery energy, including taxi, take-off, approach and landing.
- The gas turbine is not used for the main mission but will be started in case reserves are needed.

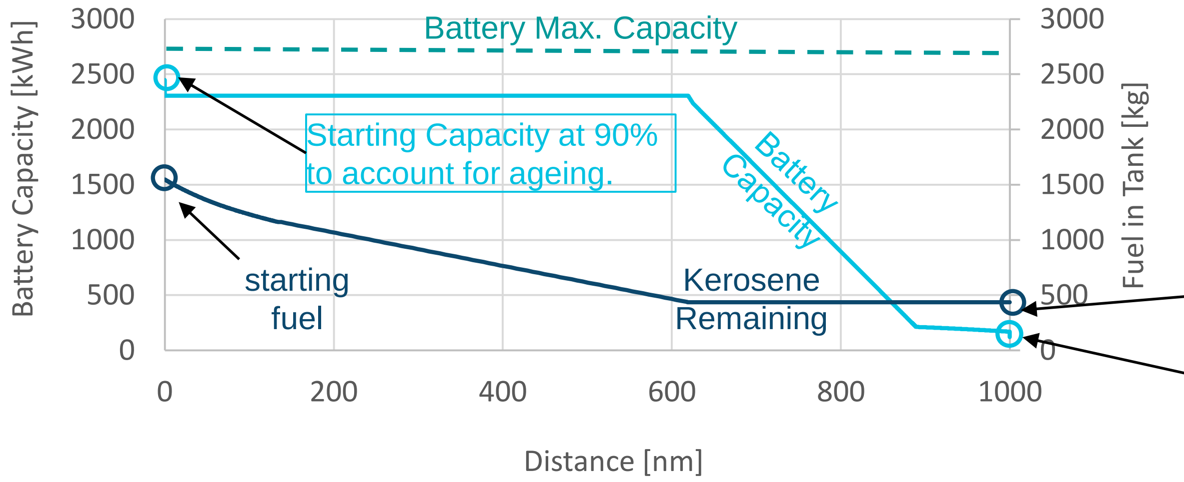


- Sufficient fuel is carried in case a diversion after the mission is needed.
- ~10% battery capacity remains after the mission:

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

D70-PHEA Operational Aspects – Range Extender Mission

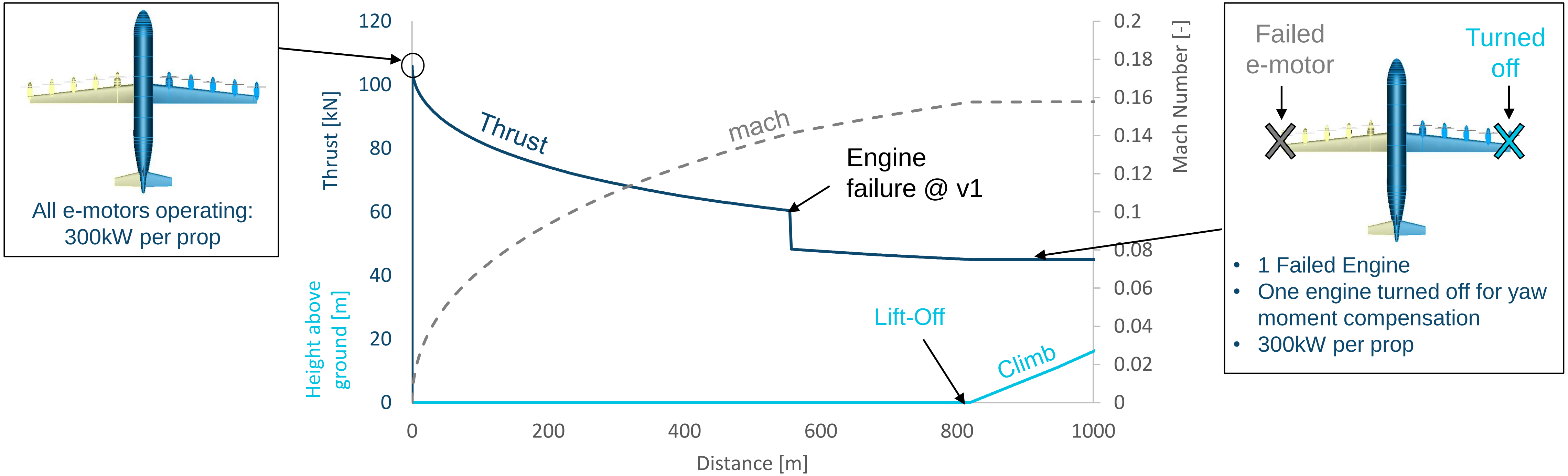




- After electric taxi and takeoff, the fuel is burned, making the aircraft lighter. Sufficient fuel for the reserve mission is spared.
- After the fuel for the main mission is burned, the flight continues electrically without turning on the gas turbine again (except in case of a diversion).
- Should the gas turbine fail during the range-extender phase, the aircraft can divert electrically with ~400nm diversion radius.
- Since the electric flight starts from cruising altitude, the electric distance is around 400nm, 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)

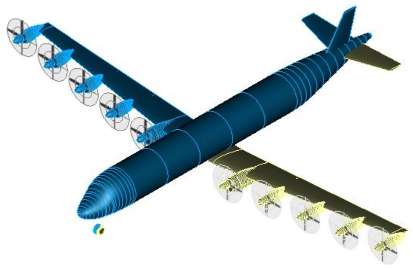
Low-Speed Performance

C_{LmaxTO} = 3.3
→ Achievable due to blown wing effect.



TOFL ~ 1000nm with a requirement of 1500m, with e-motors sized only for sufficient climb power.

Electric Aircraft Modelling



Assumptions for Battery Aircraft Modelling EIS 2040

DISCIPLINE/PARAMETER	INPUT	COMMENTS
E-MOTORS & INVERTERS		
Sp. Power e-Motors (incl. Inverter)	10 kW/kg	Direct drive assumed
Efficiency e-Motors (incl Inverter)	97.5%	Direct drive assumed
Sp. Power Generator (incl. Rectifier)	12.5 kW/kg	Direct drive assumed
Efficiency Generator (incl. Rectifier)	98.0%	-
Installation Mass Penalty	10%	-
BATTERIES		
Sp. Energy Battery Cells	500 Wh/kg	@1C discharge (2C discharge capabilty)
Sp. Energy Battery Pack	400 Wh/kg	
Cost Cells	100 €/kWh	
Cost Pack	200 €/kWh	
Cycles	3000	

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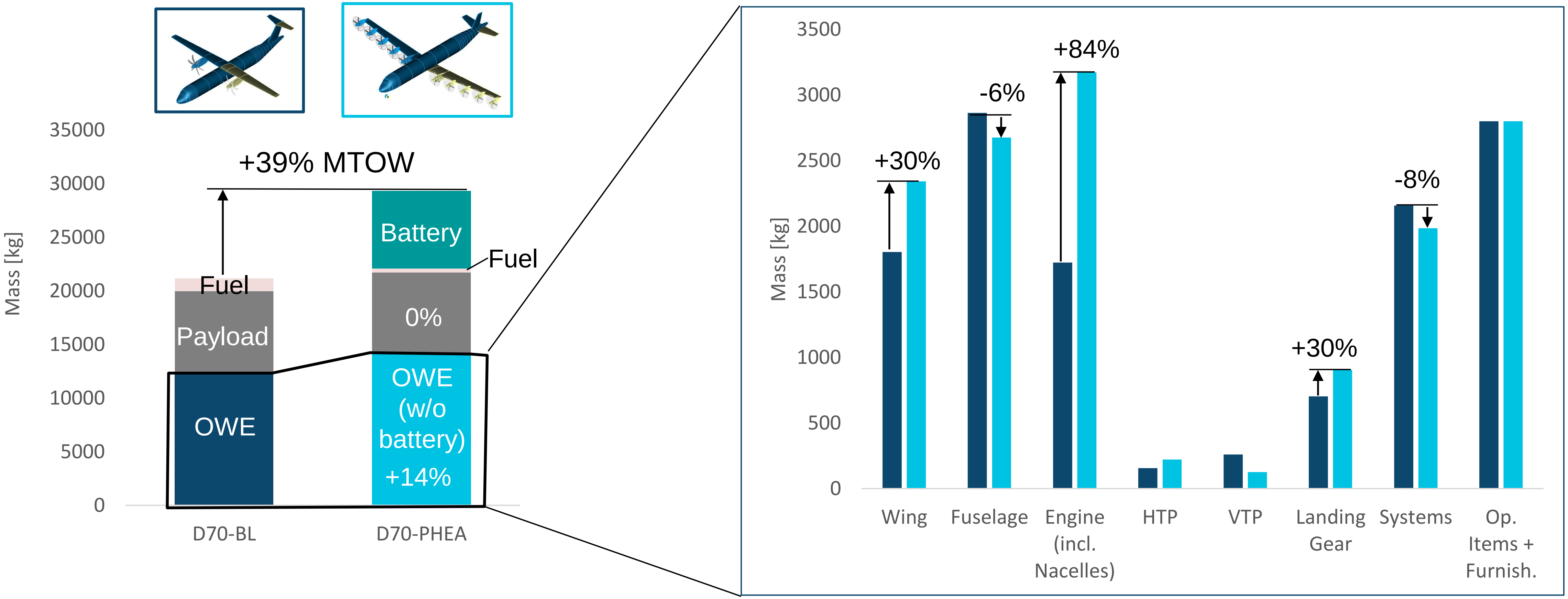
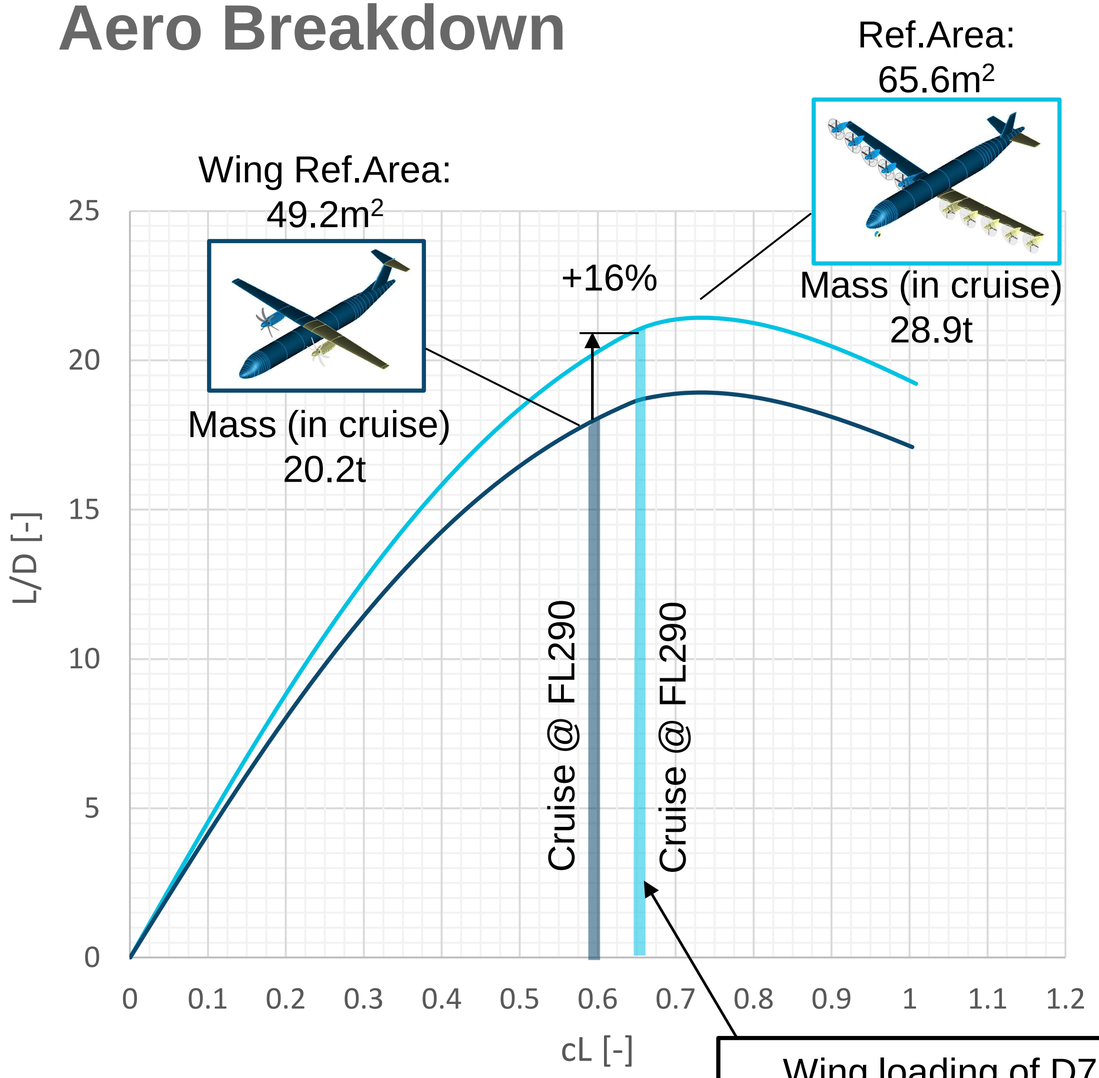
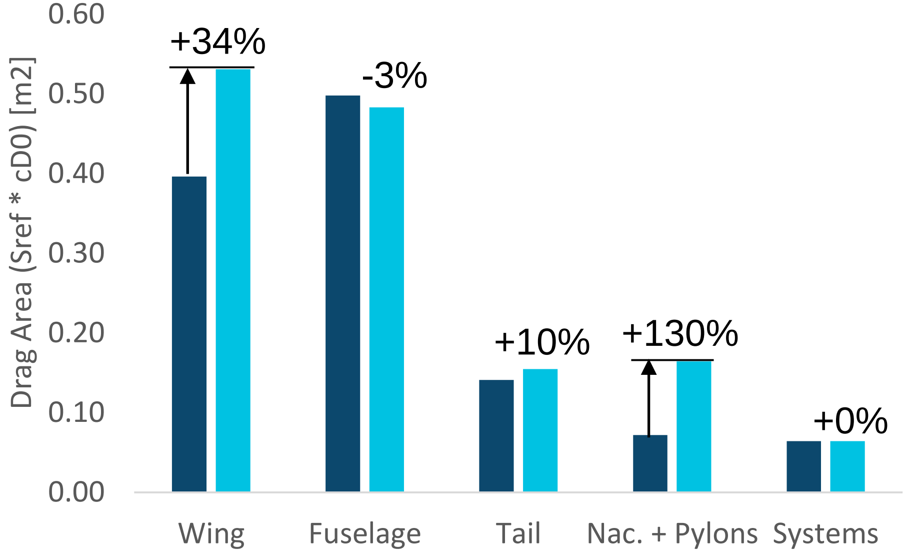
Mass Breakdown Comparison.

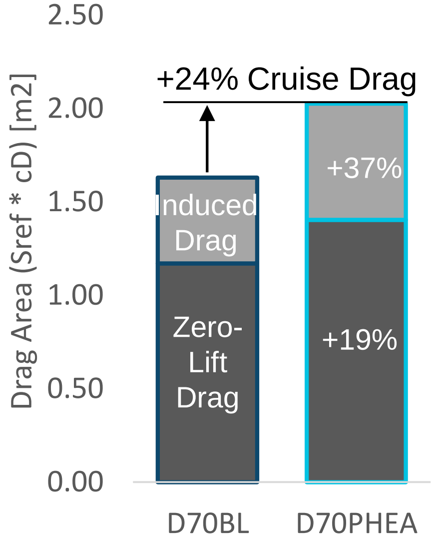


An MTOW increase of 38.5% is mostly due to the heavy battery.
The empty mass of the aircraft increases only 14%.

Aero Breakdown





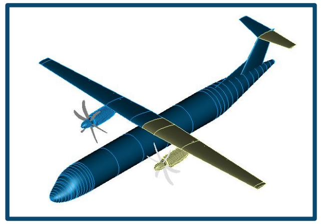


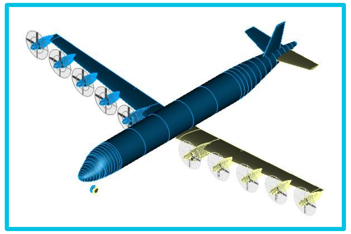
The L/D is a dimensionless parameter:

- The mass of the D70-PHEA is 43% higher
  - → The lift in cruise is 43% higher
  - → The total drag is 24% higher (zero-lift + induced)
  - → The resulting L/D is 16% higher

Wing loading of D70-PHEA is ~10% higher, due to assumed max. lift coefficient improvement in approach due to the „blow-wing“ effect:
→ A higher cruise CL is possible, while still keeping the approach speed TLAR

Cruise Performance Comparison

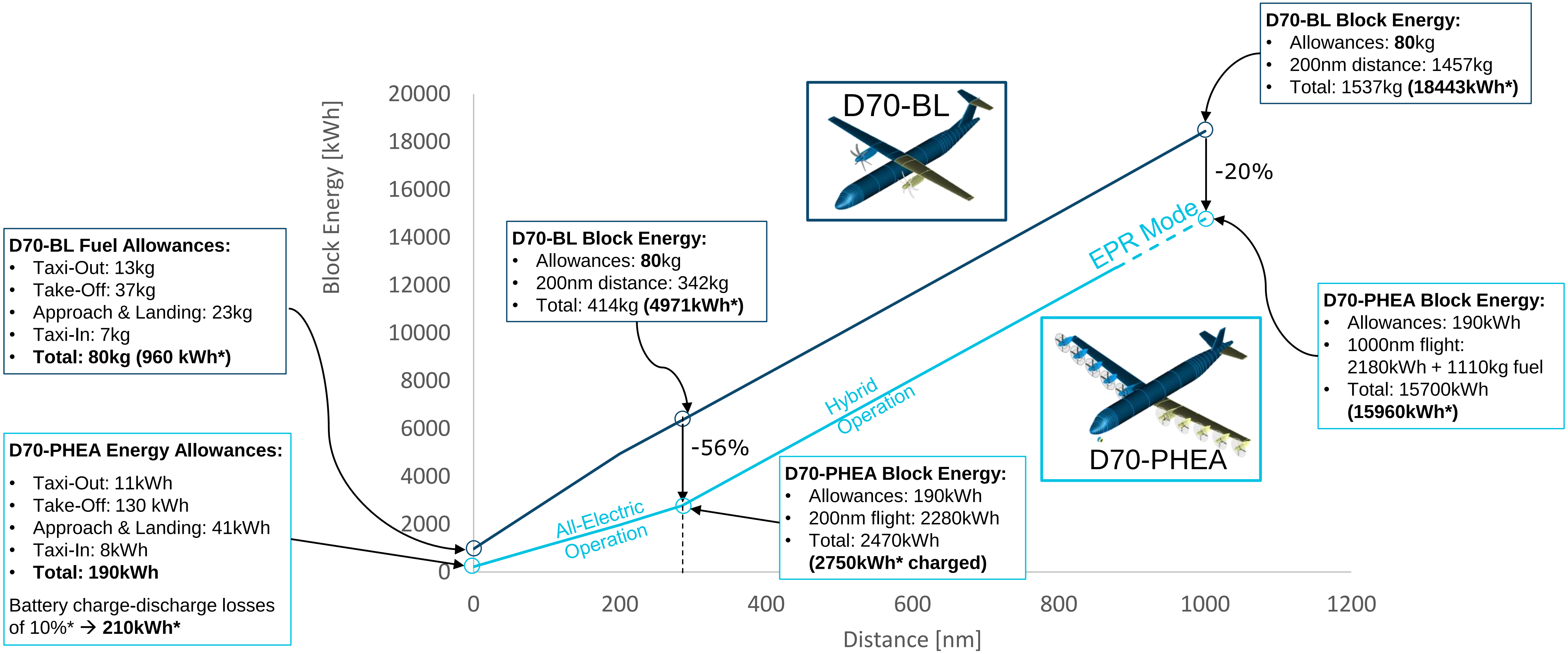




Parameter	Units	D70BL	D70PHEA (RE Mode)	Rel. Diff.	D70PHEA (E-Mode)
Operation Mode	-	-	Gas-Turb. Cruise		El. Cruise
Cruise Altitude	ft	29000	29000		31000
Mach	-	0.55	0.55		0.55
Aircraft Mass	t	20.2	28.9	+43%	28.5
L/D	-	18	21	+16%	21.4
Total Thrust	kN	11.0	13.6	+24%	13.2
eta Prop	-	90.5%	93.1%	+3%	93.1%
Eta Transmission Chain		98.5%	95.1%	-4%	97.5%
Total Eq. Power	kW	2070	2570	+19%	2430
eta Power Provider	-	39.3%	46.4%	+15%	90%
Total Energy Flow	**kWh/h**	**5260**	**5540**		**2700**
Rel. Energy Flow VS D70BL	**-**	**-**	**+5.3%**		**-49%**

The significant mass increase of the plug-in hybrid is mostly compensated by an overall bigger wing with a greater span and a significantly more efficient gas turbine due to its large size.
In electric mode, the aircraft is has just 50% of the energy consumption.

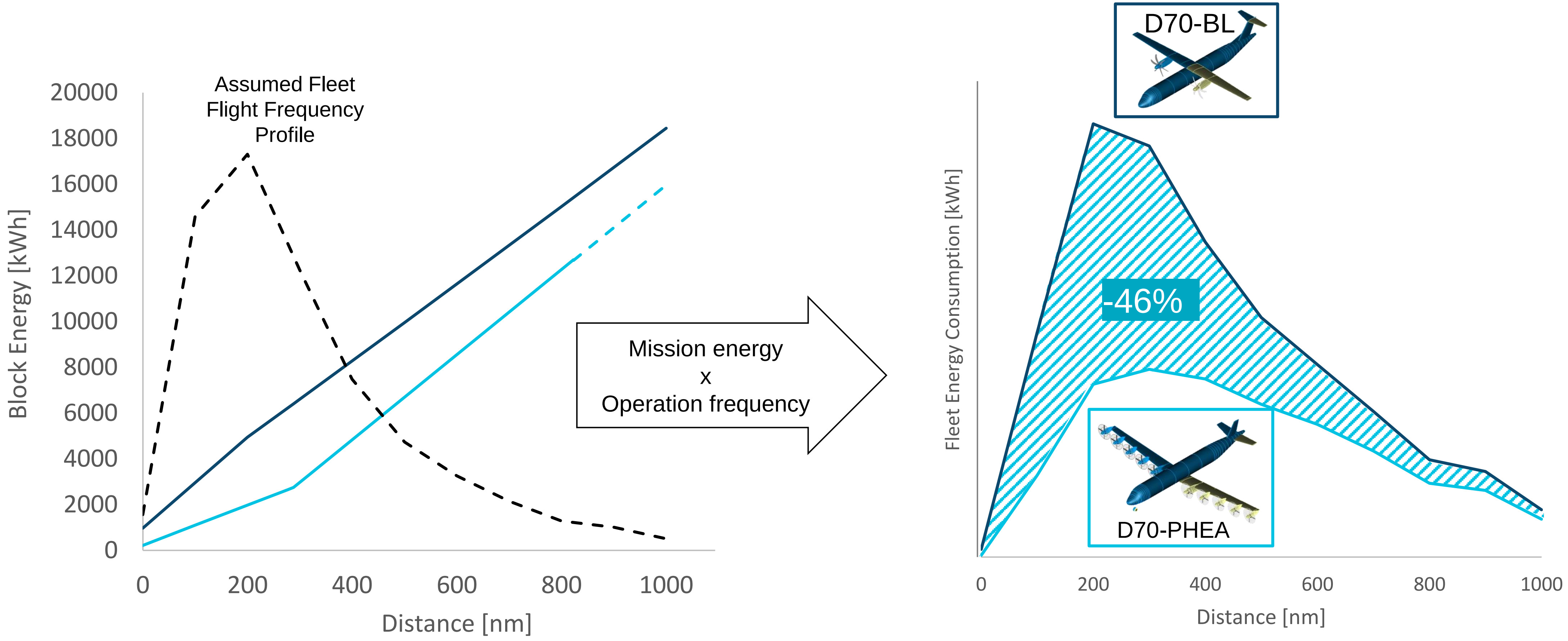
D70-PHEA Performance Assessment



PHEA offers energy savings of around 60% for operation up to 300nm & efficiency improvement even at 1000nm.

*Block Enegy Calculation Assumptions:
- Kerosene sp. Energy of 12kWh/kg
- Battery Charge-Discharge efficiency of 90%

D70-PHEA Fleet-Level Assessment

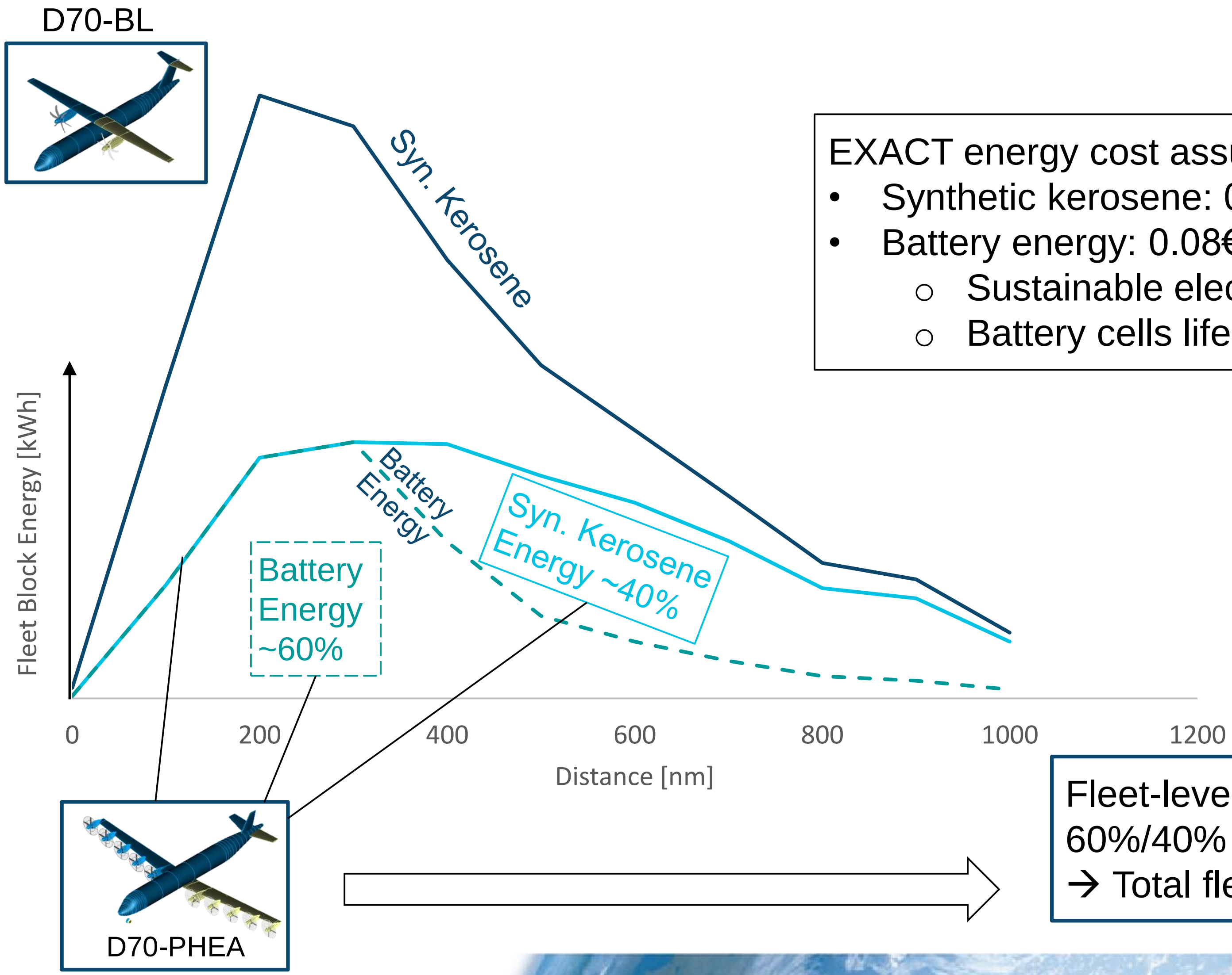


Since the regional fleet mostly operates at lower distances, plug-in hybrid operation can almost cut the operational energy consumption in half.

*Block Enegy Calculation Assumptions:

- Kerosene sp. Energy of 12kWh/kg
- Battery Charge-Discharge efficiency of 90%

Regional Aircraft Fleet-Level Assessment

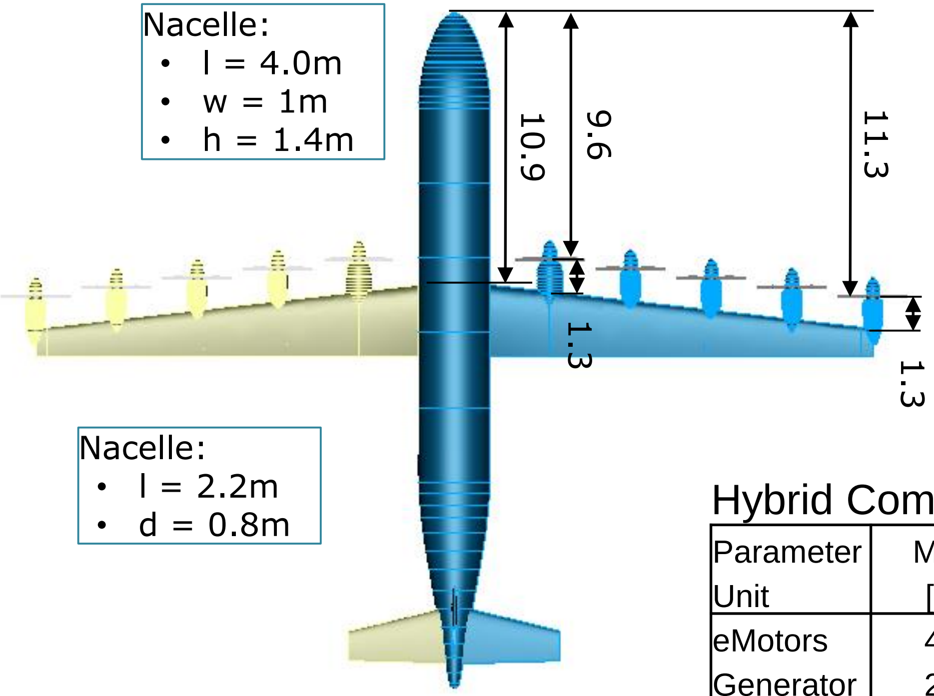


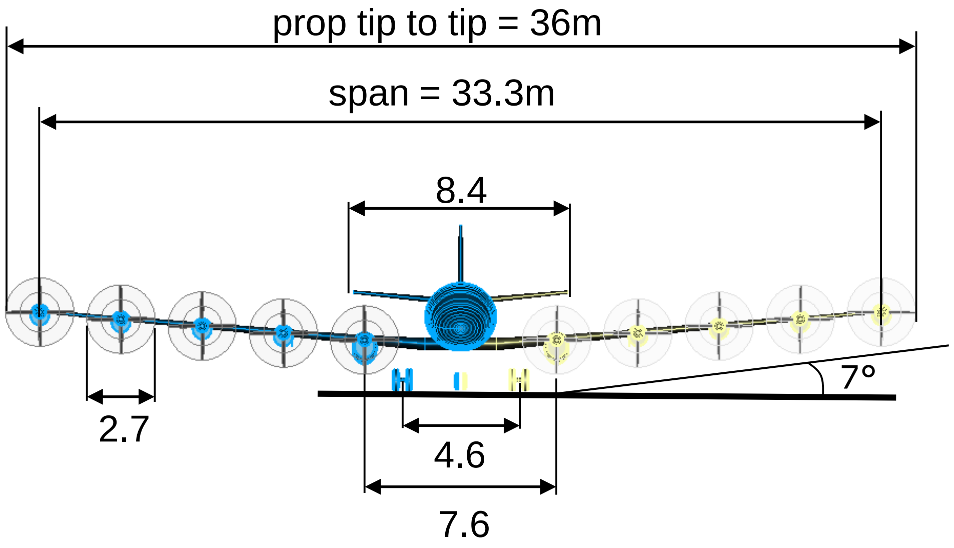
EXACT energy cost assumptions:

- Synthetic kerosene: 0.125€/kWh
- Battery energy: 0.08€/kWh
  - Sustainable electricity: 0.045€/kWh
  - Battery cells life cycle: 0.035€/kWh

Fleet-level energy reduction of ~46%
60%/40% battery energy / kerosene energy:
→ Total fleet energy cost reduction ~50%

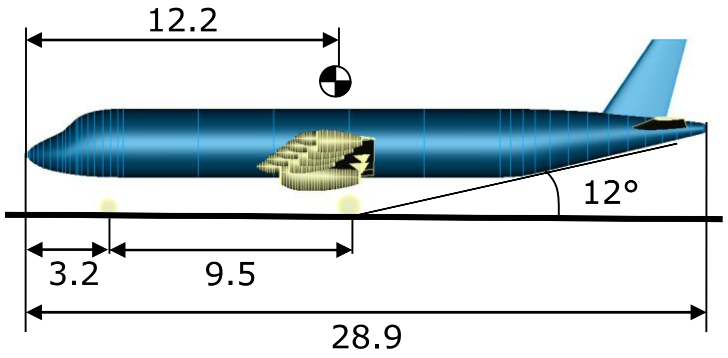
D70-PHEA Aircraft Overview





Hybrid Components Breakdown

Parameter	Mass	Power	eta	Energy
Unit	[kg]	[kW]	[-]	[kWh]
eMotors	410	3730	0.975	-
Generator	230	2520	0.980	-
Cables	140	-	0.996	-
Cooling	70	110.9	-	-
Battery	7260	3800	0.850	2620



Summary and Outlook

Plug-In hybrid concept results:

- A configuration offering a fleet-level energy cost reduction of ~60% with the EXACT modelling assumptions.
- Fleet-level energy consumption decrease of ~50%.
- The airframe mass increase of ~15% and ~40% higher MTOW is the main drawback of the concept.

Outlook:

- Feeding back data from the other work packages.
- Optimization studies in loop with the other work-packages, including operational assessment & life-cycle studies.

Thank you for your attention.

Reach out to: georgi.atanasov@dlr.de