BATTERY AS THE PRIMARY POWER PROVIDER FOR AN ULRTA-EFFICIENT SHORT-RANGE AIRCRAFT: A PLUG-IN HYBRID CONCEPT

Exploring the limits of aircraft energy efficiency within the EXACT Project

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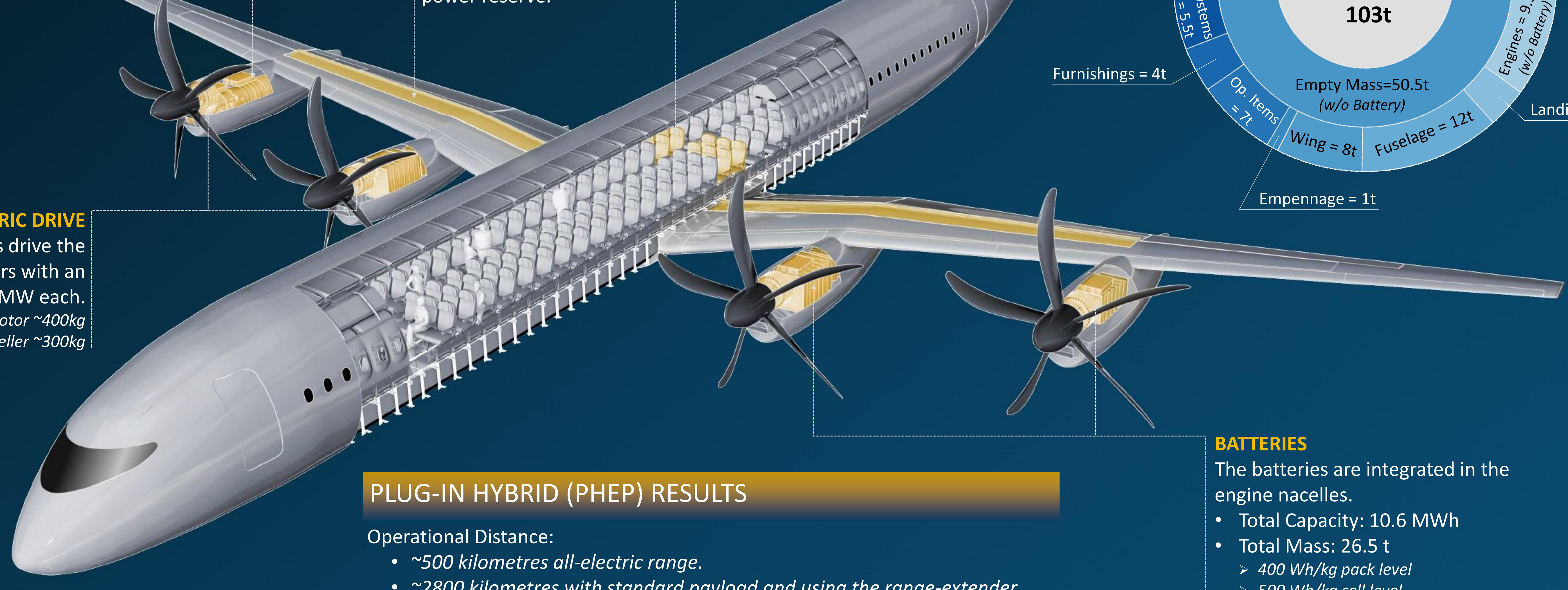
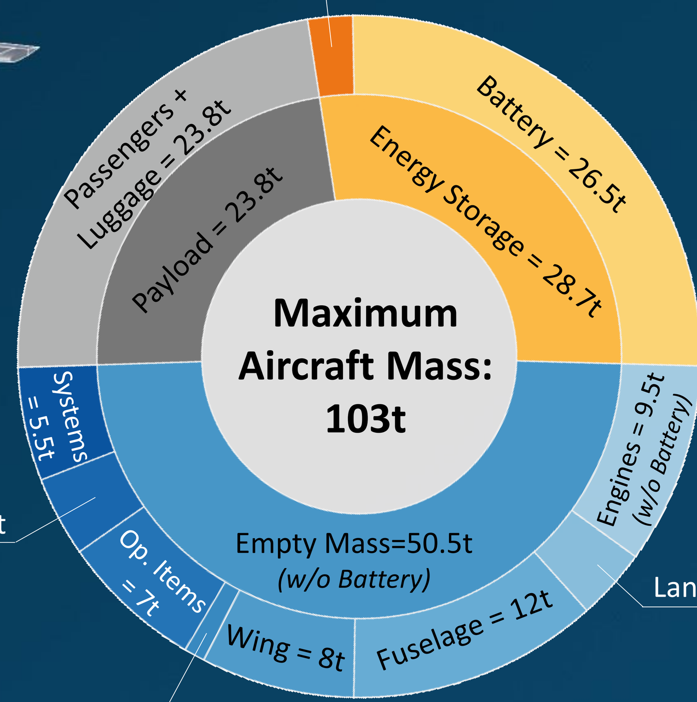
ONE GAS TURBINE RANGE-EXTENDER
A single large gas turbine is more fuel efficient and cheaper than two smaller ones. Maintenance costs are lower as it is not used for every mission. The gas-generator output is 10-14MW, provided by an 800kg el. generator & 2300kg gas turbine

FUEL TANK
Kerosene / synthetic kerosene for the gas turbine is used to extend the range and as an emergency power reserve.

CABIN
A 6-abreast, single-aisle cabin with a capacity of 250 passengers. This would be the stretch version of an aircraft family.
For comparison: the A321 seats up to 244 passengers.





ELECTRIC DRIVE
The electric motors drive the 6 meter propellers with an output of 4.25 MW each.
Mass each e-motor ~400kg
Mass each propeller ~300kg

BATTERIES
The batteries are integrated in the engine nacelles.
- Total Capacity: 10.6 MWh
- Total Mass: 26.5 t
  - *400 Wh/kg pack level*
  - *500 Wh/kg cell level*
- Technology targets:
  - *Recharging time target: 20-30 min (to avoid longer turn-around)*
  - *> 2000 cycles @ 100 €/kWh to reduce replacements costs*

PLUG-IN HYBRID (PHEP) RESULTS

Operational Distance:
- *~500 kilometres all-electric range.*
- *~2800 kilometres with standard payload and using the range-extender*

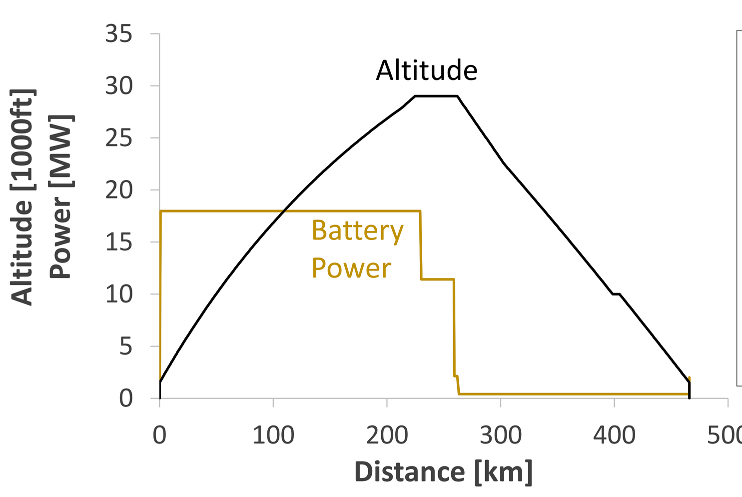
Cruising speed: ~750 kilometres per hour

Energy consumption: ~9 kWh/PAX/100 km

Comparison with a conventional aircraft of the same class and technology level:
- *Climate impact reduction potential: 65-95 percent*
- *Operating cost reduction potential: 5-15 percent*

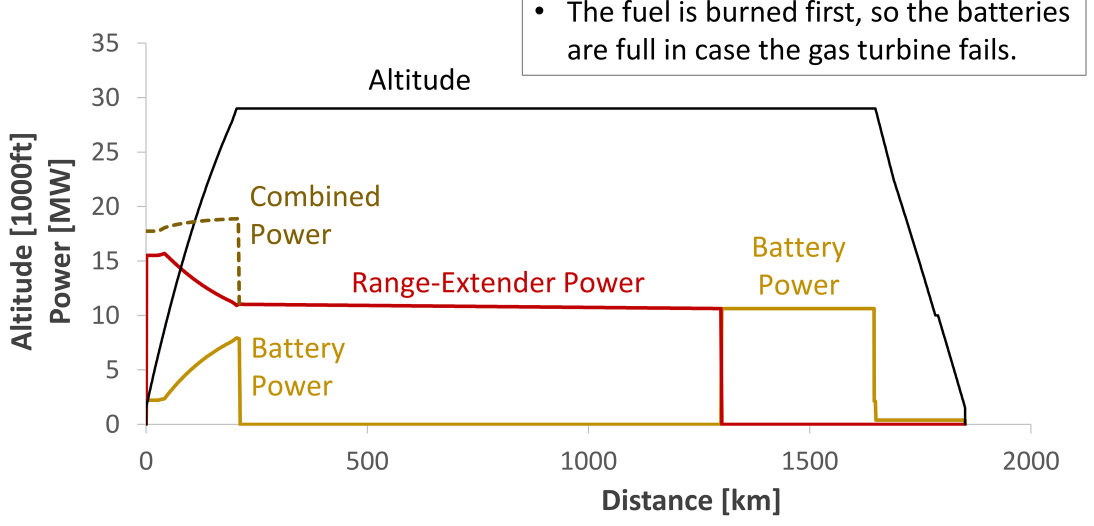
The PHEP Concept

The Plug-in Hybrid-Electric (PHEP) concept relies on the battery as the main power provider. The motivation to use batteries as an energy carrier is that they are by far the most efficient means of using renewable electricity for propulsion, i.e. the "well-to-wheel" efficiency, or in the context of green aviation "power-outlet-to-shaft" efficiency. The most dominant limitation, however, is the low energy density achievable by batteries, which strongly limits the practical operational range of electric aircraft. A plug-in architecture tackles this problem directly. The aircraft can operate fully electrically on short missions but is also able to serve longer routes using a range-extender.



Electric Operation:
- Fully electric flights up to 500km.
- Fully electric airport operation.
- 2000kg kerosene carried for reserves → the batteries can be used fully for the trip.

Range Extender Operation
- Range extender used also allows >2000km flights.
- The fuel is burned first, so the batteries are full in case the gas turbine fails.



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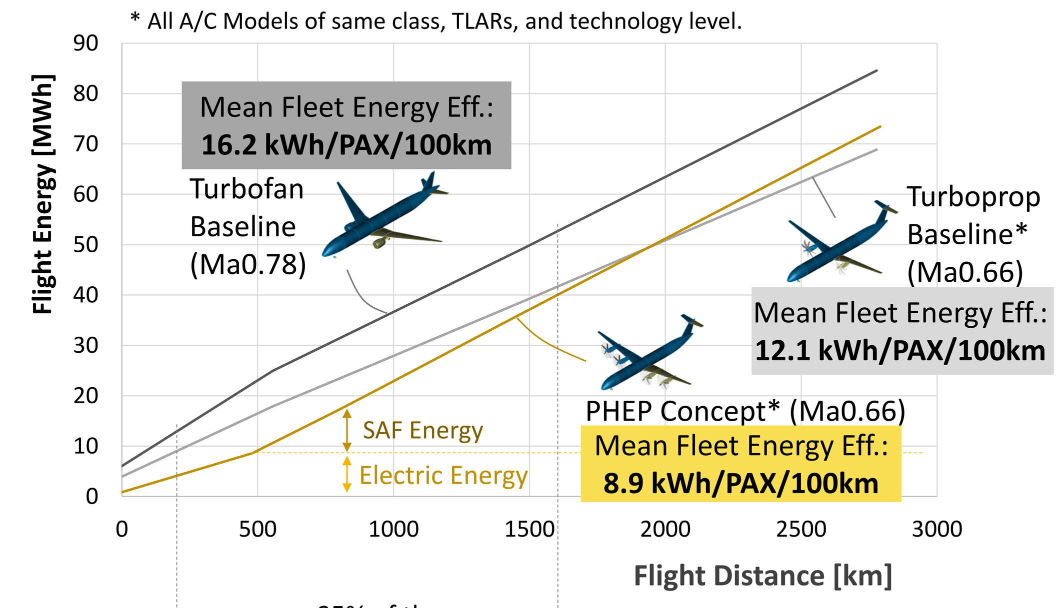
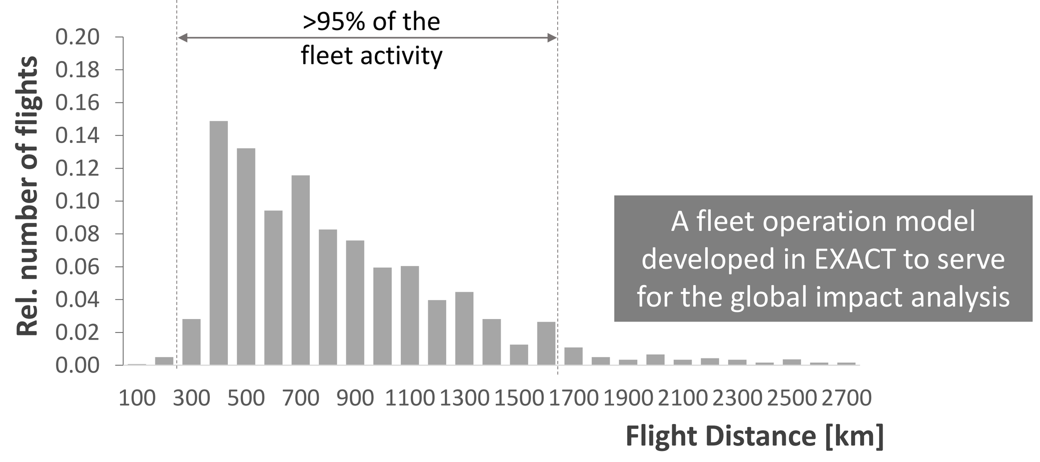
Ultra-Efficient Fleet Operation

A PHEP aircraft is ultra-efficient up to certain distances but tends to be less efficient than a conventional aircraft at longer missions. However, as shown below, short trips usually dominate a single-aisle fleet's operational profile. Even for the short-range class modelled in EXACT, the majority of the flights are at distances, where using batteries for propulsion is highly advantageous.





In the PHEP fleet model shown above, all-electric flights (up to ~500km) make up over 25% of the routes. When the flight distance increases, the gas turbine is used only as much as needed to achieve the additional range and turned off otherwise. Hence, the ultra-efficient electric flight makes up a significant portion of the operation even for flights around 1000km. As a result, approx. 55% of the whole fleet energy consumption is electric (in the above model).

PHEP Cruise Performance

	MASS (cruise)	L/D	THRUST	EFF PROP		$\frac{P_{shaft}}{V}$	EFF POWER	Energy / Distance
Turbofan Baseline*	76.4 t	19.9	37.7kN	76%	FL350 Ma0.78	13.7 kWh/km	Gas Turb. & Gearbox 52%	26.3 kWh/km
Turboprop Baseline*	72.6 t (-5%)	21.7	32.8kN (-13%)	84%	FL310 Ma0.66	10.8 kWh/km (-21%)	Gas Turb. & Gearbox 49%	22 kWh/km (-16%)
PHEP Concept* ELECTRIC MODE	103 t (+35%)	22.1	45.7kN (+21%)	86%	FL310 Ma0.66	14.7 kWh/km (-7%)	Battery & E-Motor.: 93%	15.9 kWh/km (-40%)
PHEP Concept* RANGE EXTENDER MODE	100 t (+31%)	21.9	44.8kN (+19%)	86%		14.5 kWh/km (+5%)	Gas Turb. with Turbo-electric 51%	28.2 kWh/km (+7%)

* All A/C Models of same class, technology level, and TLARs (except cruise speed).

As demonstrated above, even if the aircraft is significantly heavier, the electric cruise is still roughly 30% more efficient than a comparable turboprop of the same speed class and 40% more efficient vs the faster turbofan baseline. However, a large portion of the overall energy efficiency benefit comes from the operation at the airport (Landing-Take-Off cycle – LTO). The reason is that gas turbines are not efficient at low altitudes (e.g. take-off) and extremely inefficient at low-power off-design operation, i.e. taxi or descent. The diagram below shows the large energy benefit of electric operation during the LTO cycle.

Energy at the Airport (Landing-Take-off Cylce)