AERO Hydrogen & Battery Summit 2025, Friedrichshafen, Germany

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ZAV Centre for Aviation

Challenges for the Optimisation of Hybrid-Electric Propulsion Systems

Dr.-Ing. Wilm Friedrichs
Head of Aerodynamics and Aircraft Design

ZHAW Zurich University of Applied Sciences
School of Engineering
ZAV Centre for Aviation
Winterthur, Switzerland

Hybrid-Electric Propulsion Systems

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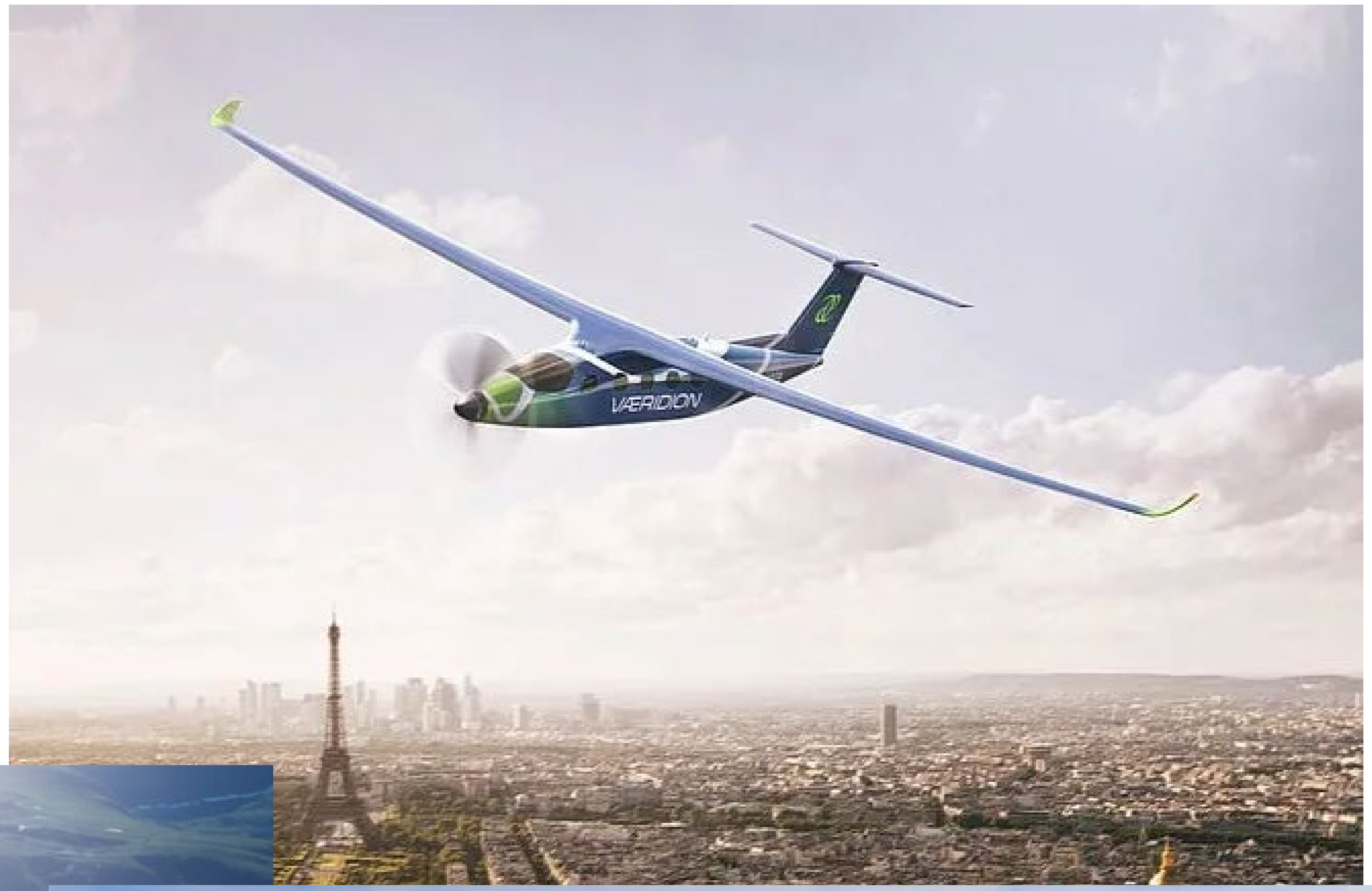
Trends at the AERO Hydrogen & Battery Summit 2024

<u>Battery</u>
- Only for short ranges
- Moderate improvement of energy density

<u>Components</u>
- Lots of progress and new solutions
- Obviously still many challenges

<u>Propulsion type</u>
- Mostly propeller aircraft

<u>Aircraft design</u>
- Retrofit for demonstration
- Clean sheet preferred



Sources: Vaeridion, Elfly, APUS

Challenges for the Optimisation of Hybrid-Electric Propulsion Systems

Overview

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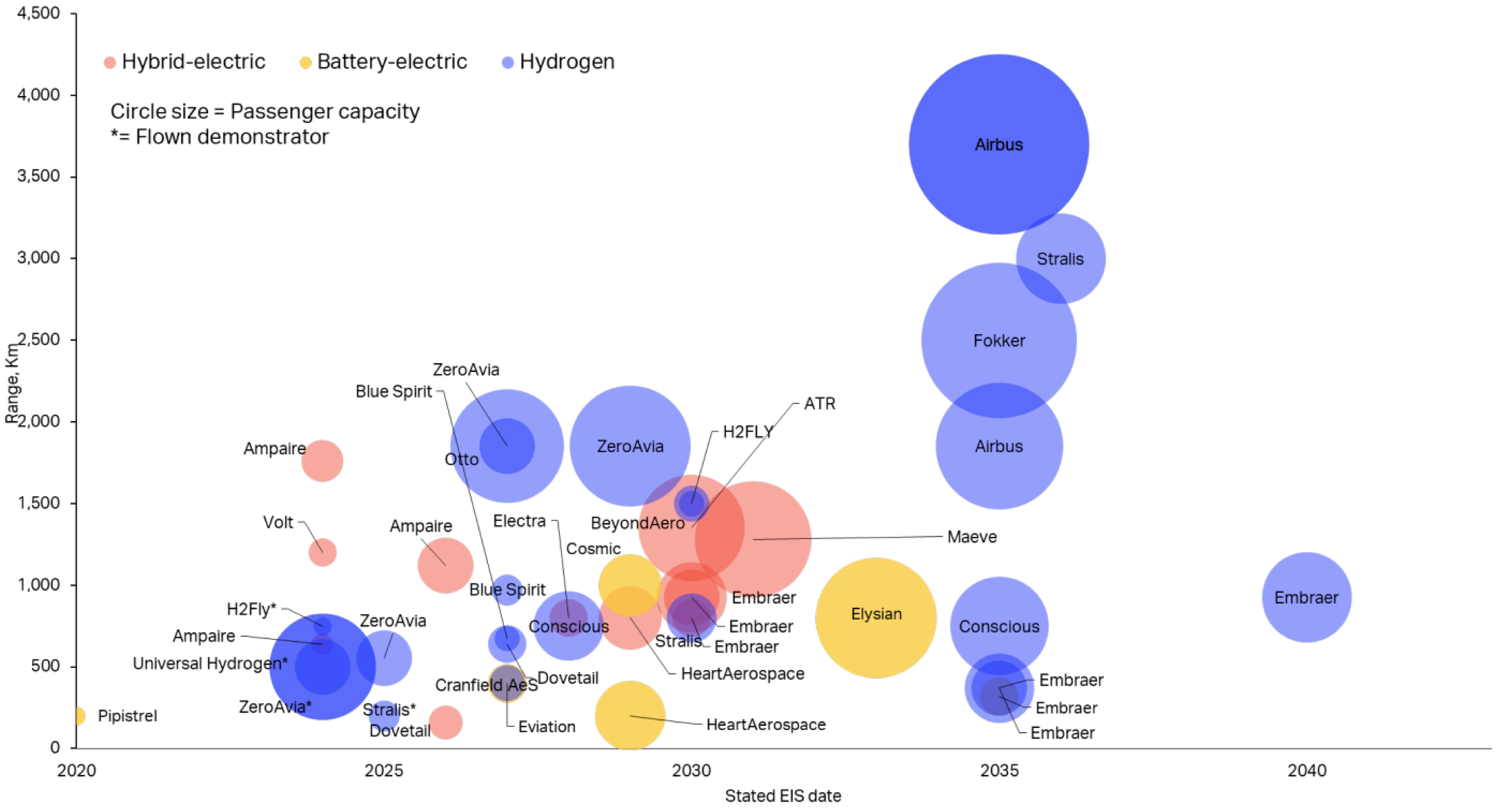
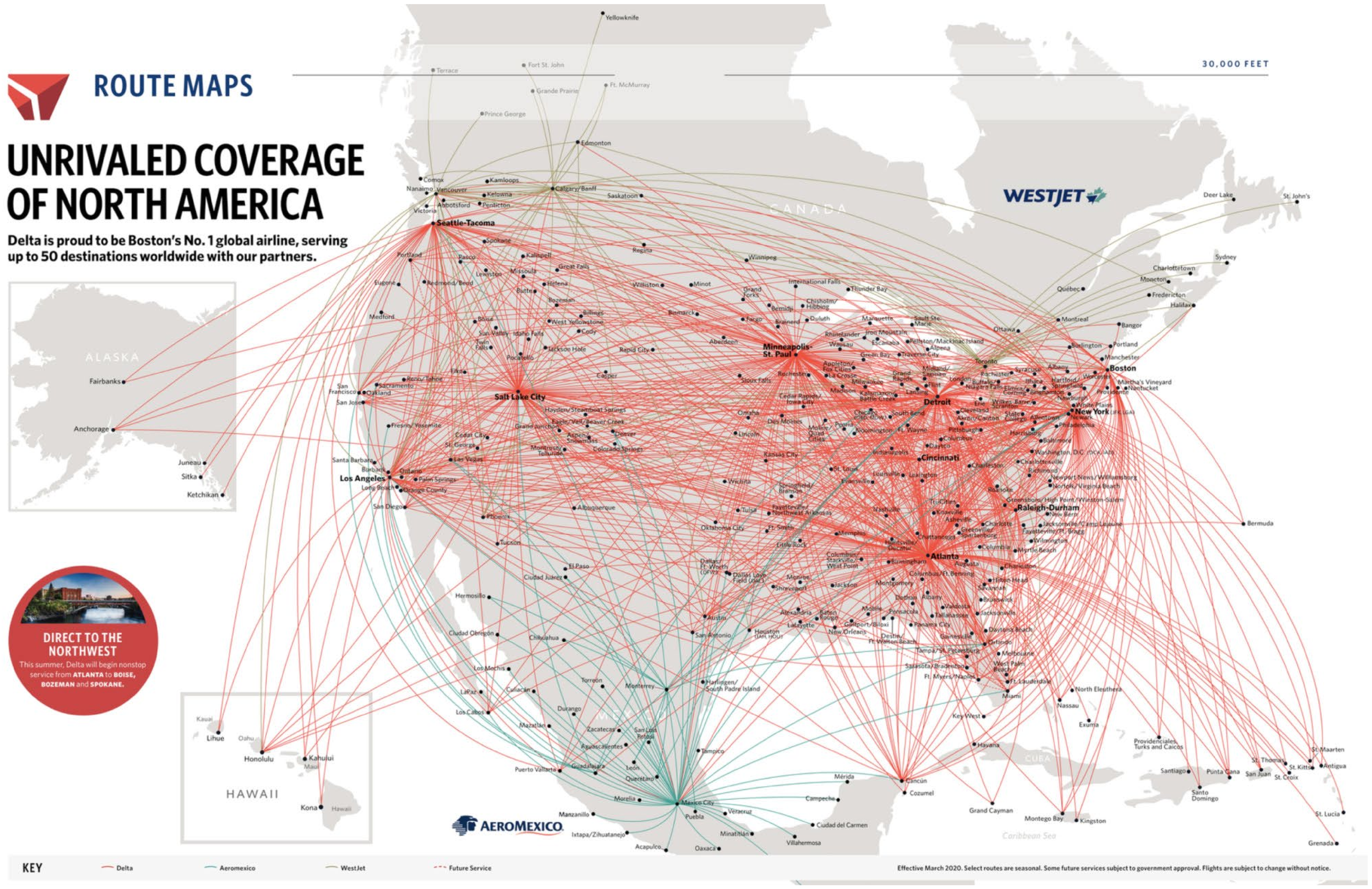
- Aircraft missions
- Airspeed, range, altitude, size
- Technology review
- Range & endurance
- Efficiency & sustainability
- Key challenges



Sources: IATA

Propeller Aircraft Missions

Size, Range, and Airspeed



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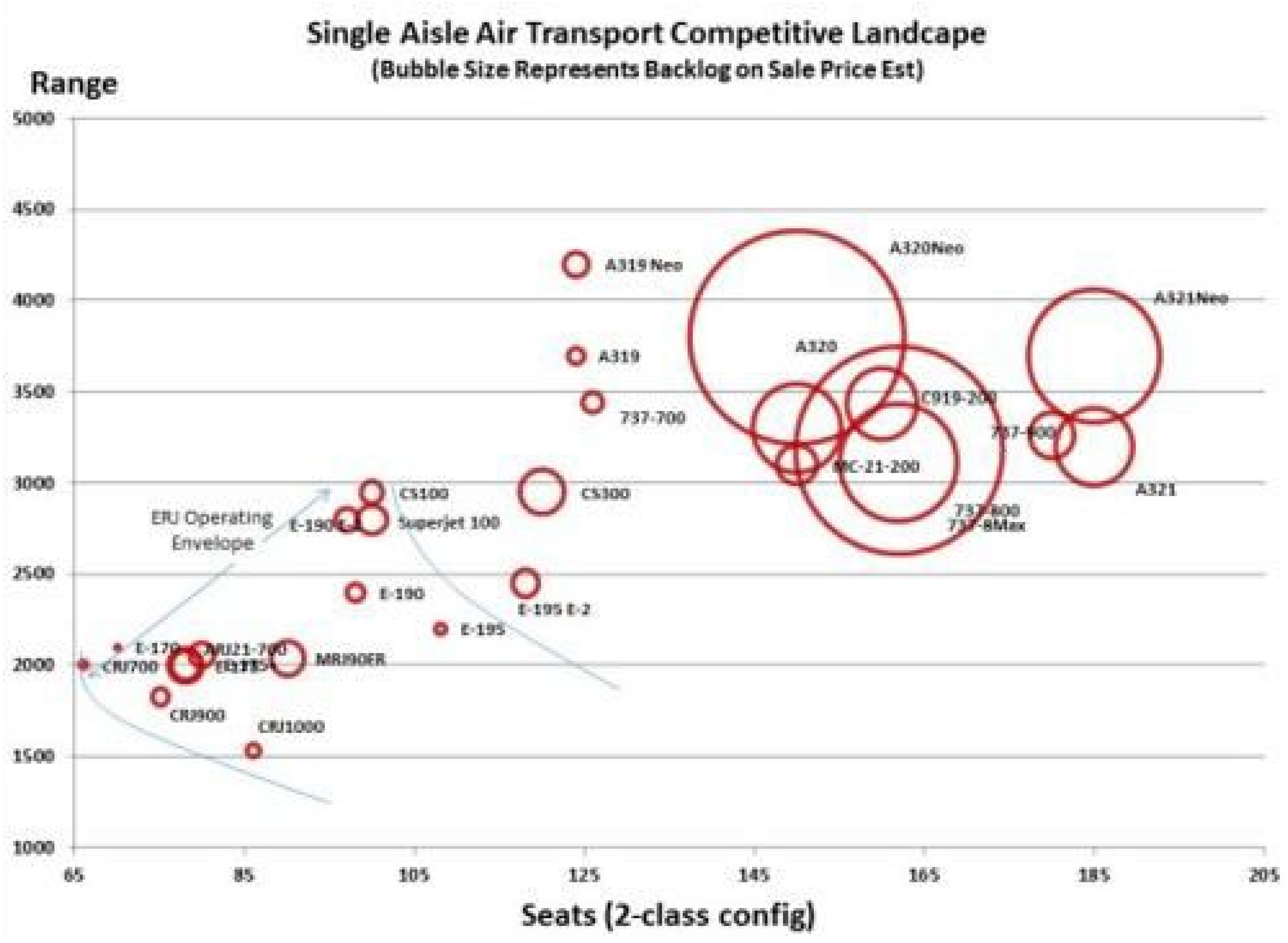
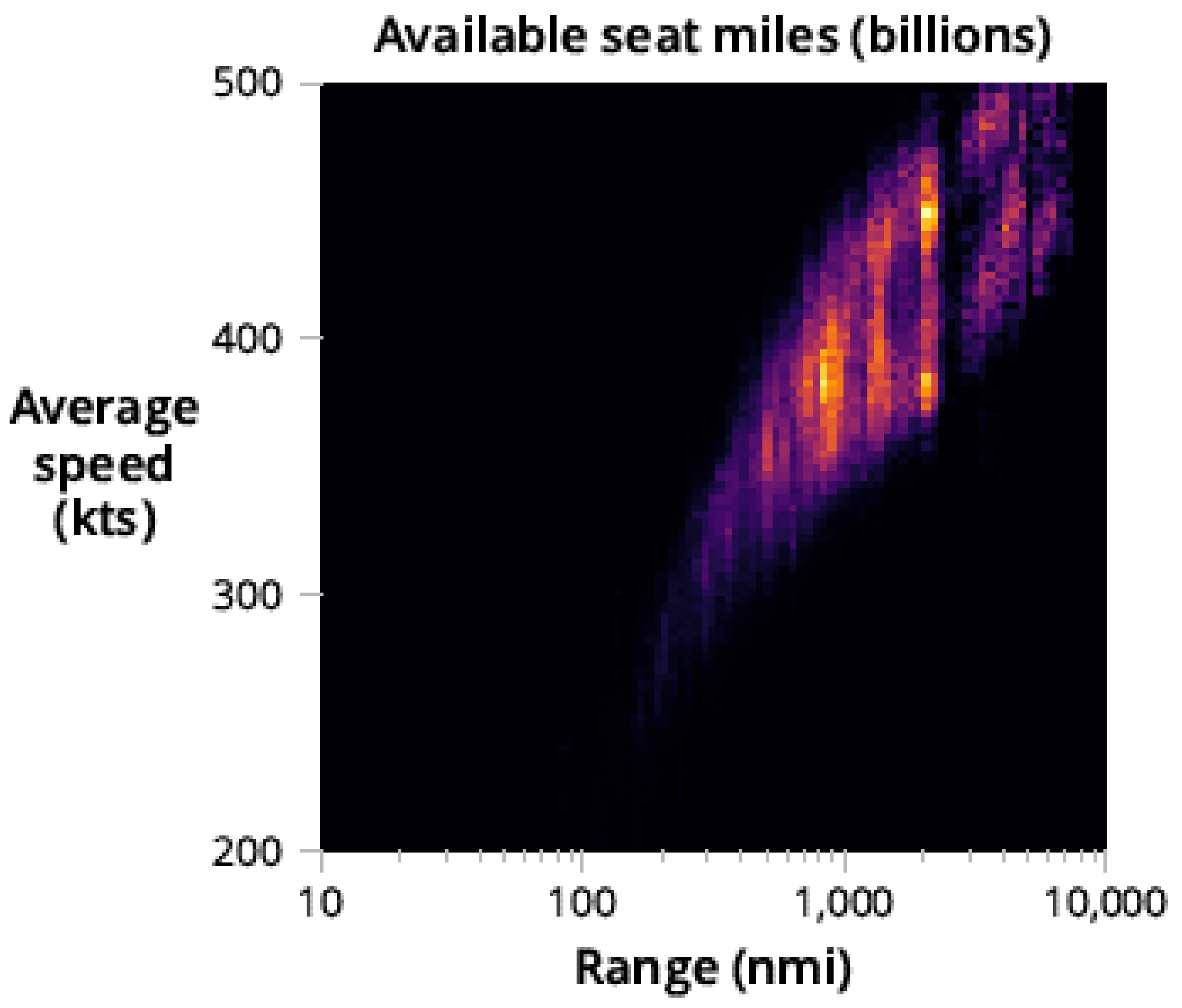
Mission

Mostly used for shorter direct or feeder flights

Correlation

- Shorter range
  - Fewer seats
  - Lower speeds





Sources: Delta Airlines, Walton, Adler

Propeller Aircraft Missions

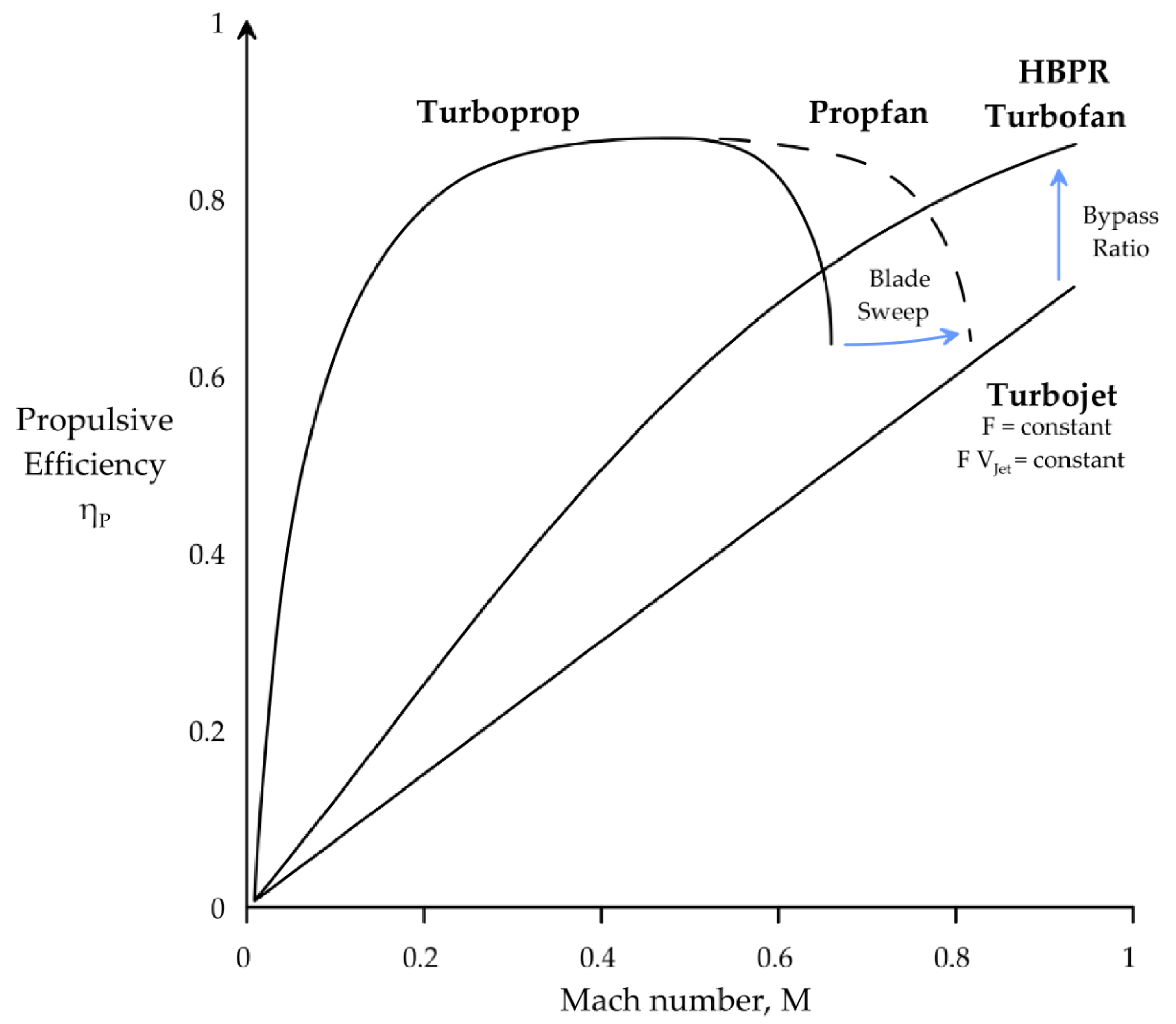
Flight Envelope

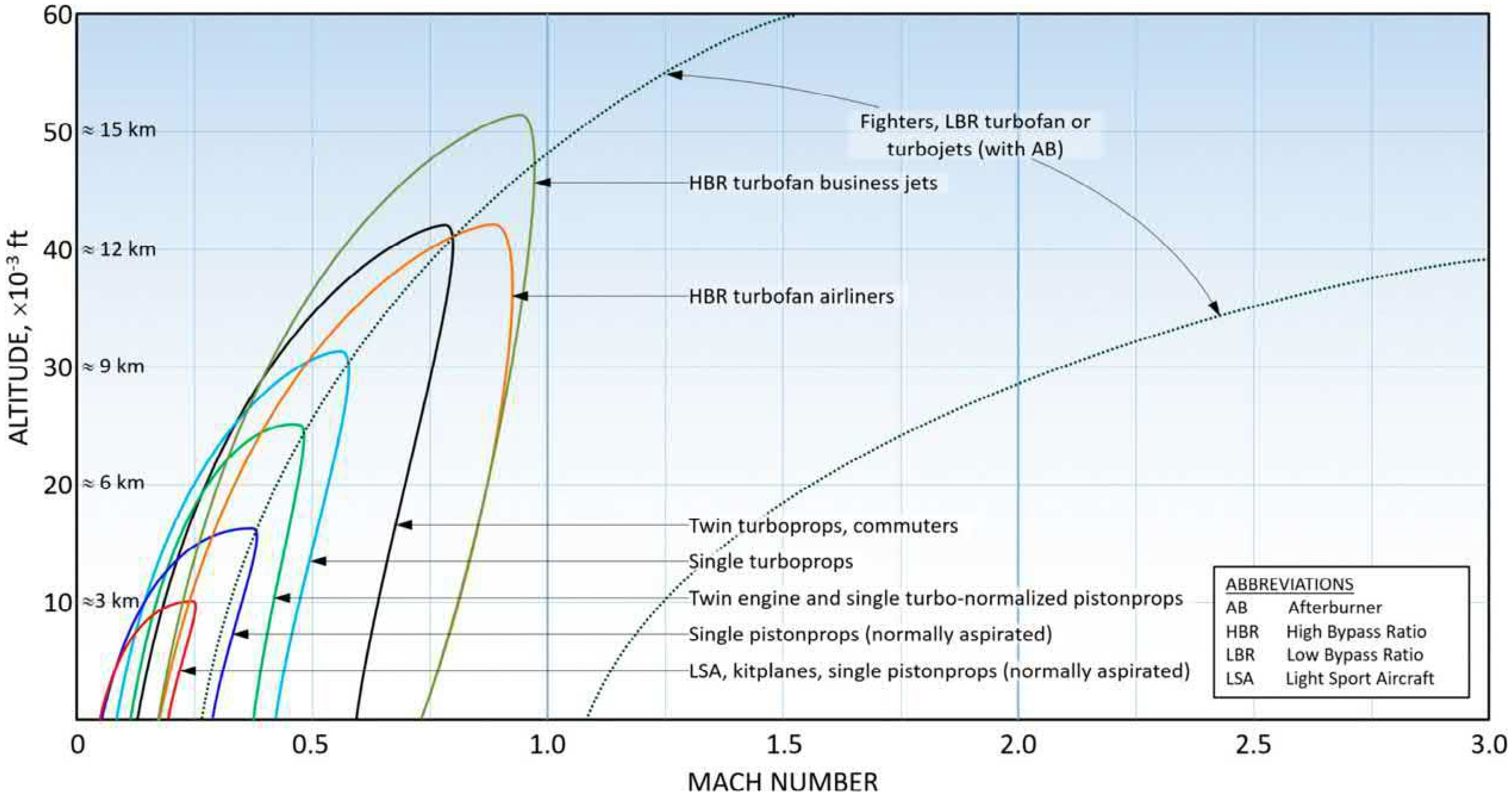
- Propellers are most efficient at moderate airspeeds

- At higher Mach numbers transonic effects result in noise and lower efficiency

<u>Typical multi-engine piston</u>
- 130 – 200 kn
- Ceiling FL 150 – 250
- Range 1,000 – 2,000 km

<u>Typical turboprop</u>
- 260 – 330 kn
- Ceiling FL 250 – 300
- Range 1,500 – 2,500 km





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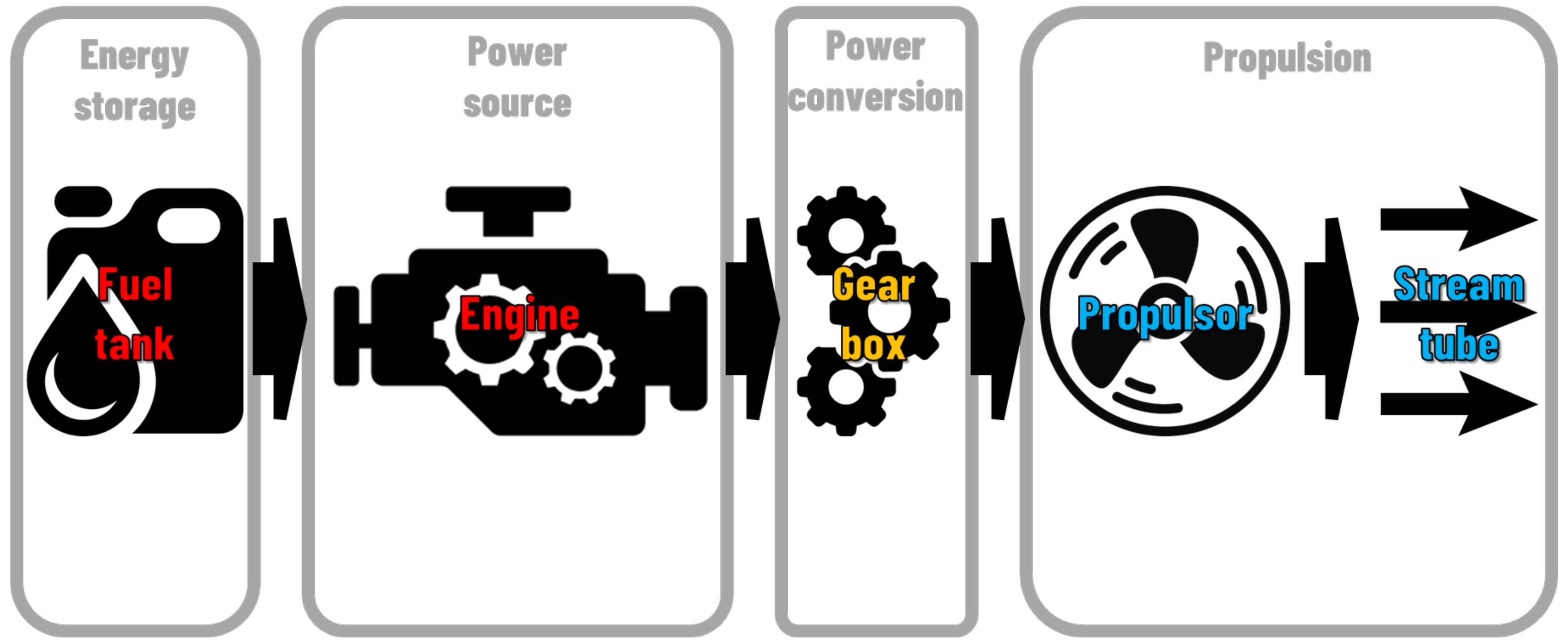
Sources: Alves, Gudmundsson

Technology Review

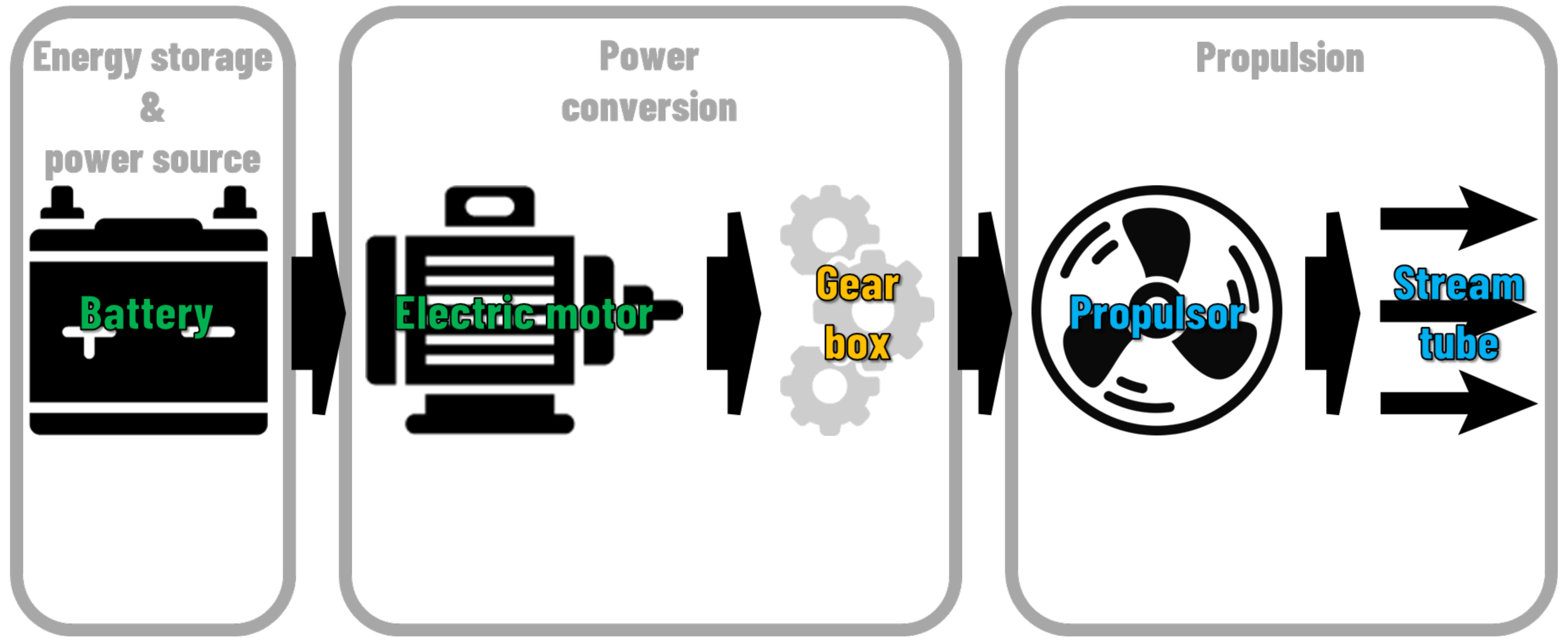
Range Characteristics: Breguet Equations

- Jet: $R = \frac{2}{TSFC*g}\frac{\sqrt{C_L}}{C_D}\sqrt{\frac{2}{\rho S}}\left[\sqrt{W_1}-\sqrt{W_2}\right]$
  - High altitude beneficial

- Propeller: $R = \frac{\eta_p}{BSFC*g}\frac{C_L}{C_D}\int_{W_2}^{W_1}\frac{dW}{W} = \frac{\eta_p}{BSFC*g}\frac{C_L}{C_D}\, ln\left(\frac{1}{1-\frac{m_{fuel}}{MTOM}}\right)$
  - No apparent altitude dependency for propeller



- Battery-powered propeller: $R = \frac{\eta_p}{BSEM*g}\frac{C_L}{C_D}\frac{m_{Bat}}{MTOM}$
  - BSFC not valid for battery, use of BSEM
  - No consumption of fuel mass

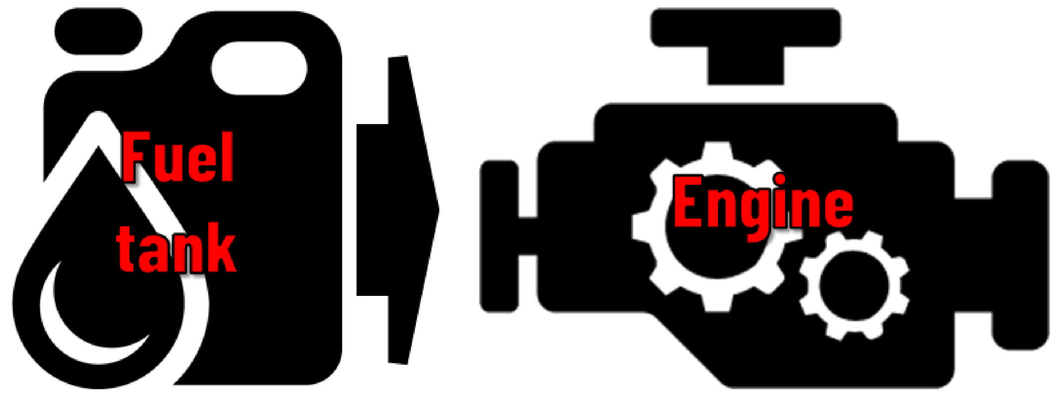


Sources:

Technology Review

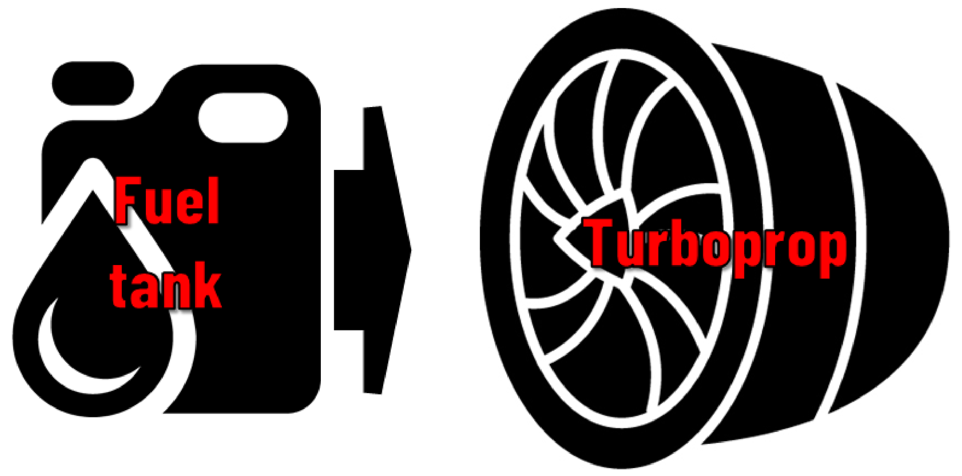
Typical Fuel Consumption

$12.14 \frac{kWh}{kg}$



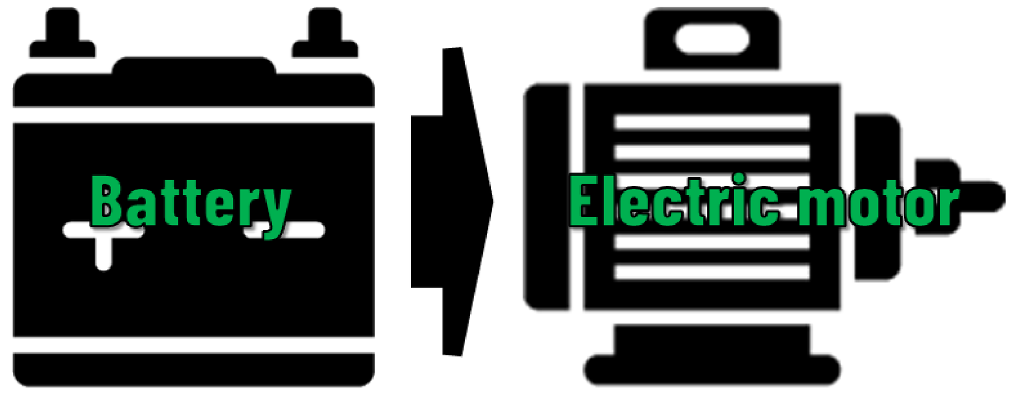
30%

$11.99 \frac{kWh}{kg}$



25%

$400 \frac{Wh}{kg}$



90%

$33.31 \frac{kWh}{kg}$ 15%

$50\% \cdot 90\%$

Piston engine fuel mass flow per brake power

$$BSFC_{Piston} = \frac{1}{e_{Avgas}\ \eta_{Piston}} = \frac{1}{12.14 \frac{kWh}{kg}\ 30\%} = 0.28 \frac{kg}{kWh}$$

Turboprop fuel mass flow per brake power

$$BSFC_{Turboprop} = \frac{1}{e_{JetA1}\ \eta_{Turboprop}} = \frac{1}{11.99 \frac{kWh}{kg}\ 25\%} = 0.33 \frac{kg}{kWh}$$

Battery mass per brake energy

$$BSEM_{EM} = \frac{1}{e_{Bat}\ \eta_{EM}} = \frac{1}{400 \frac{Wh}{kg}\ 90\%} = 2.8 \frac{kg}{kWh}$$

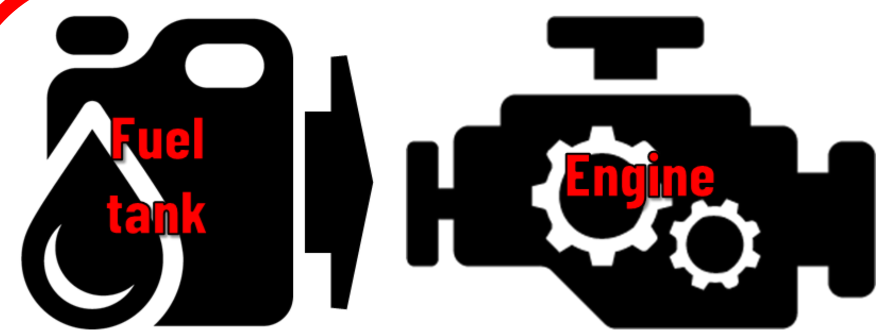
Fuel cell including storage mass and electric motor efficiency

$$BSEM_{FC} = \frac{1}{e_{H2} \frac{m_{H2}}{m_{Tank}}\ \eta_{FC}\eta_{EM}} = \frac{1}{33.31 \frac{kWh}{kg}\ 15\%\ 45\%} = 0.45 \frac{kg}{kWh}$$

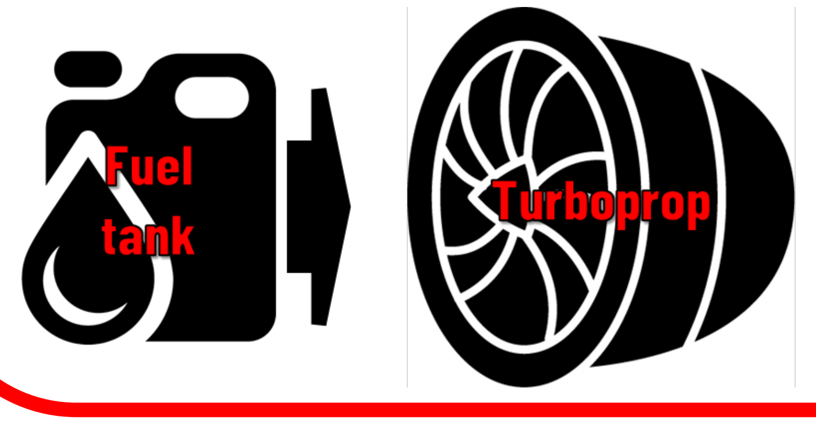
Sources:

Technology Review

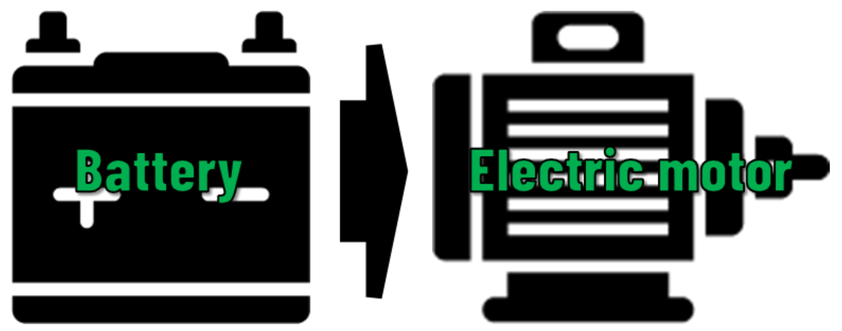
Mass over Endurance



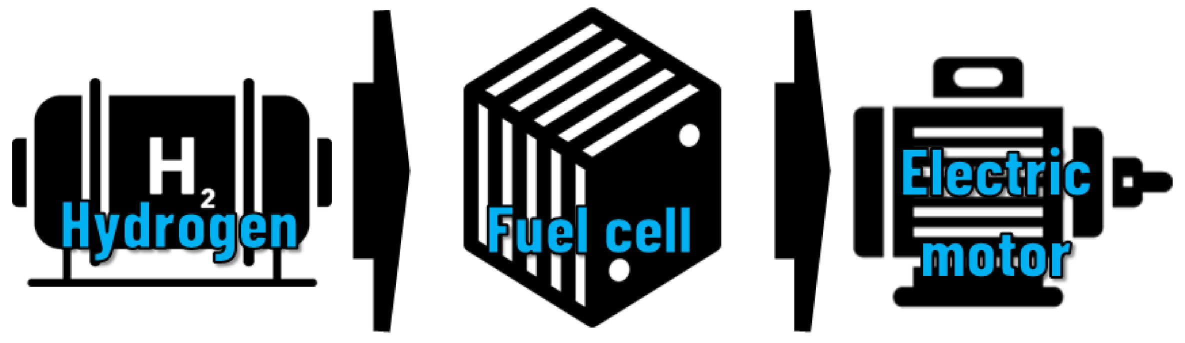
$$1\,\frac{kW}{kg}$$



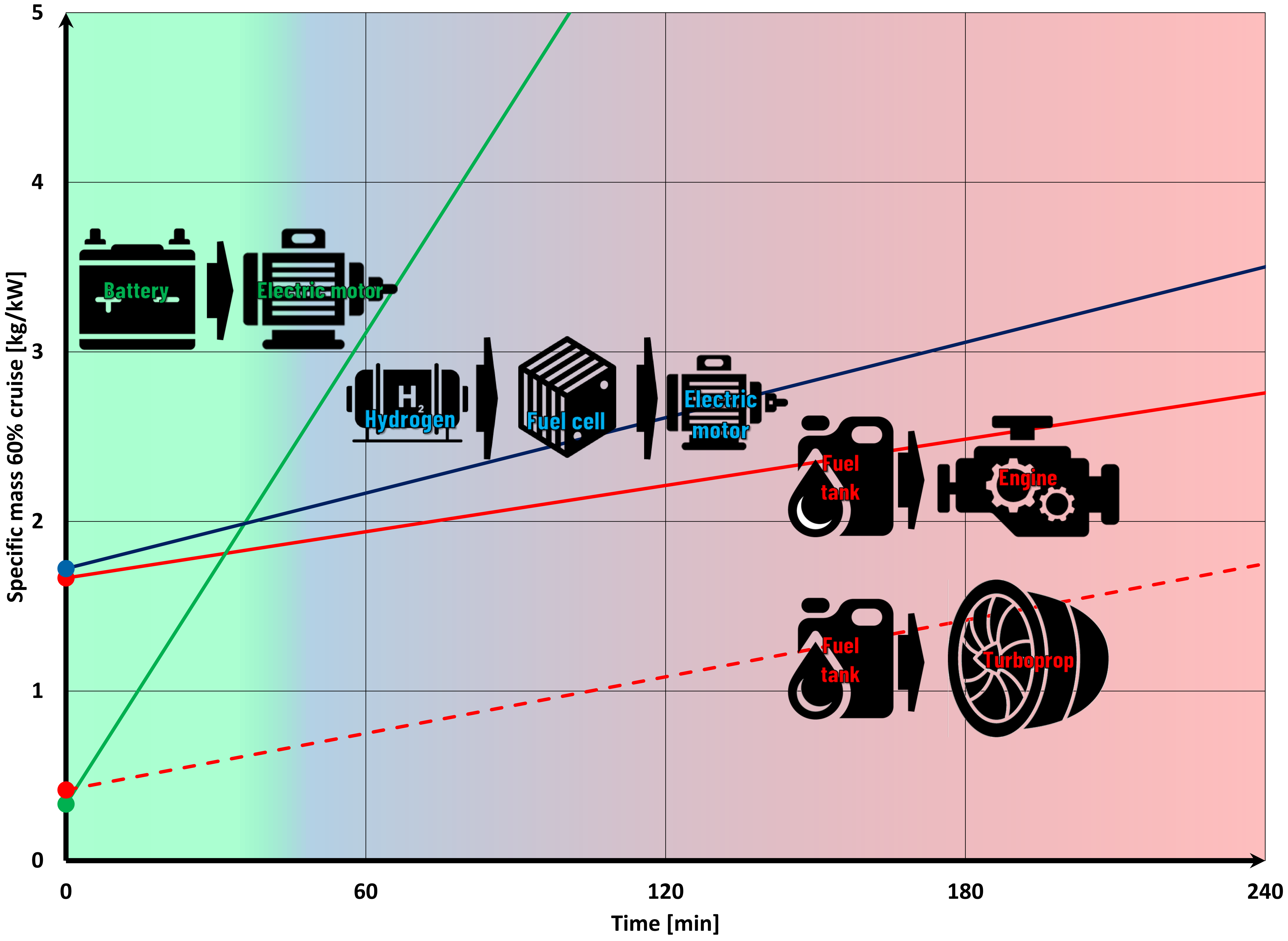
$$4\,\frac{kW}{kg}$$



$$5\,\frac{kW}{kg}$$



$$1.2\,\frac{kW}{kg}\ \&\ 5\,\frac{kW}{kg}$$



Sources:

Technology Review

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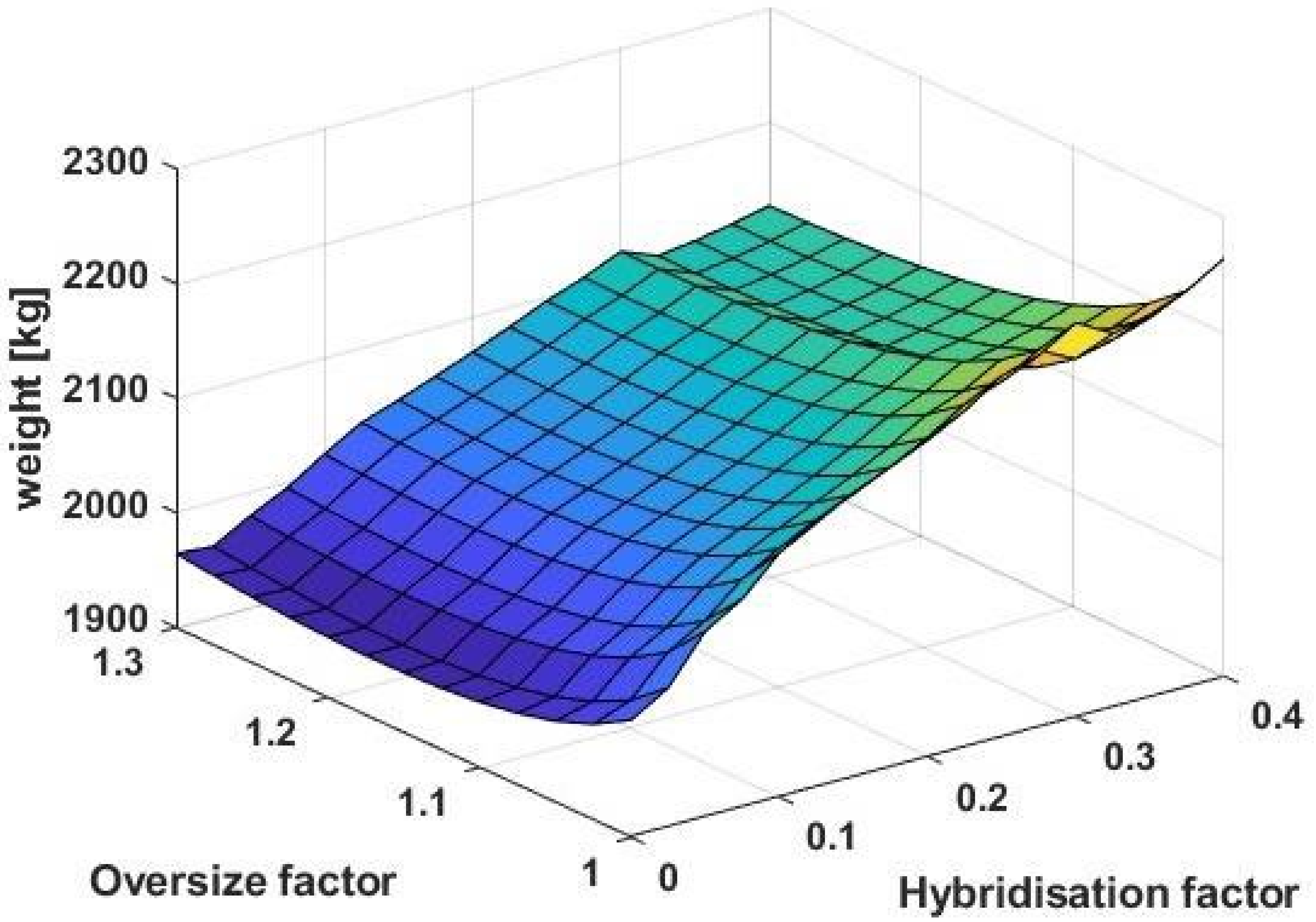
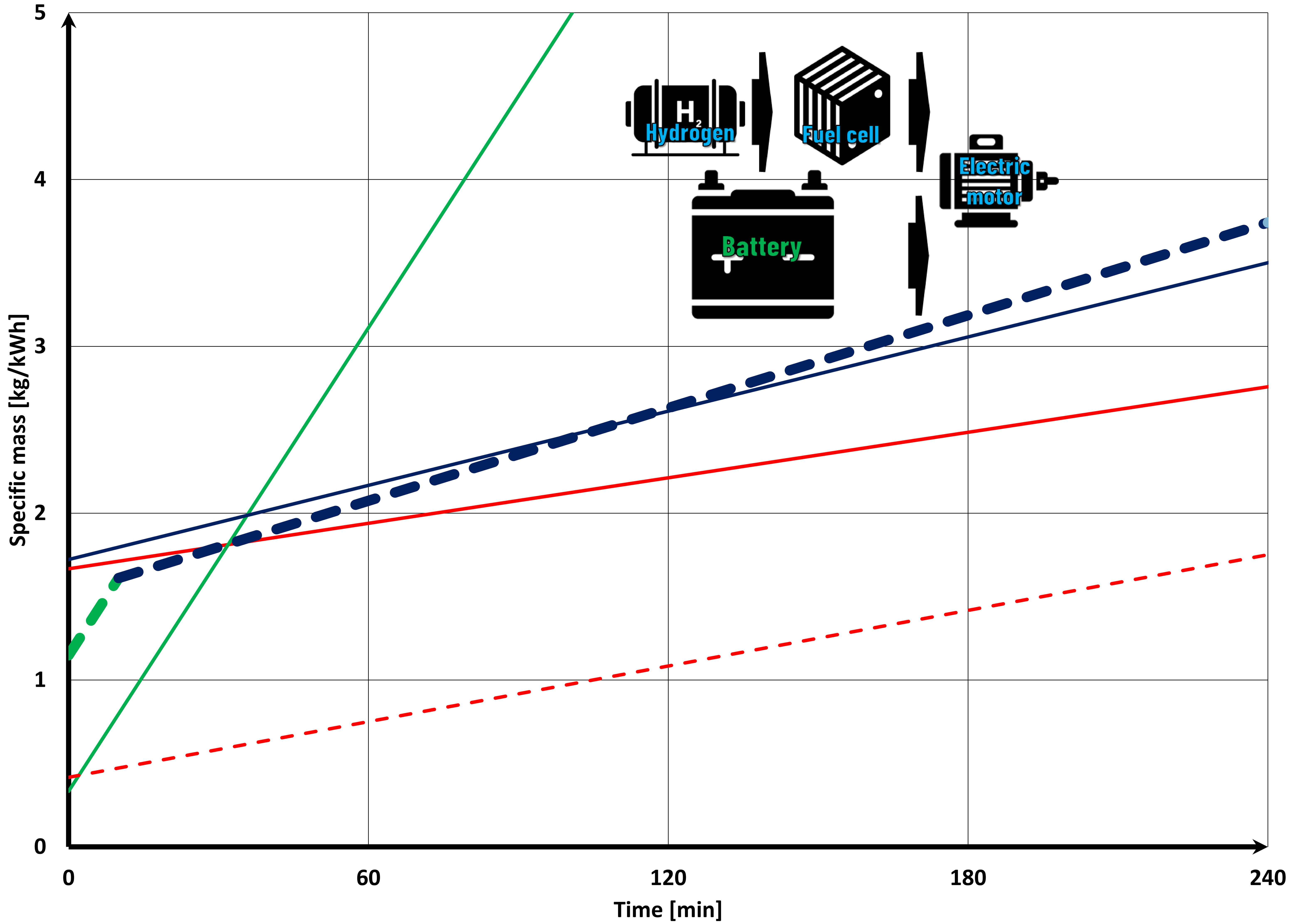
Fuel Cell Hybrid Propulsion System

- Fuel cell can be sized for cruise
- Less mass, but also less efficiency
- Might be viable for other reasons, e.g. safety, dynamic behaviour





Sources: Frischknecht

Technology Review

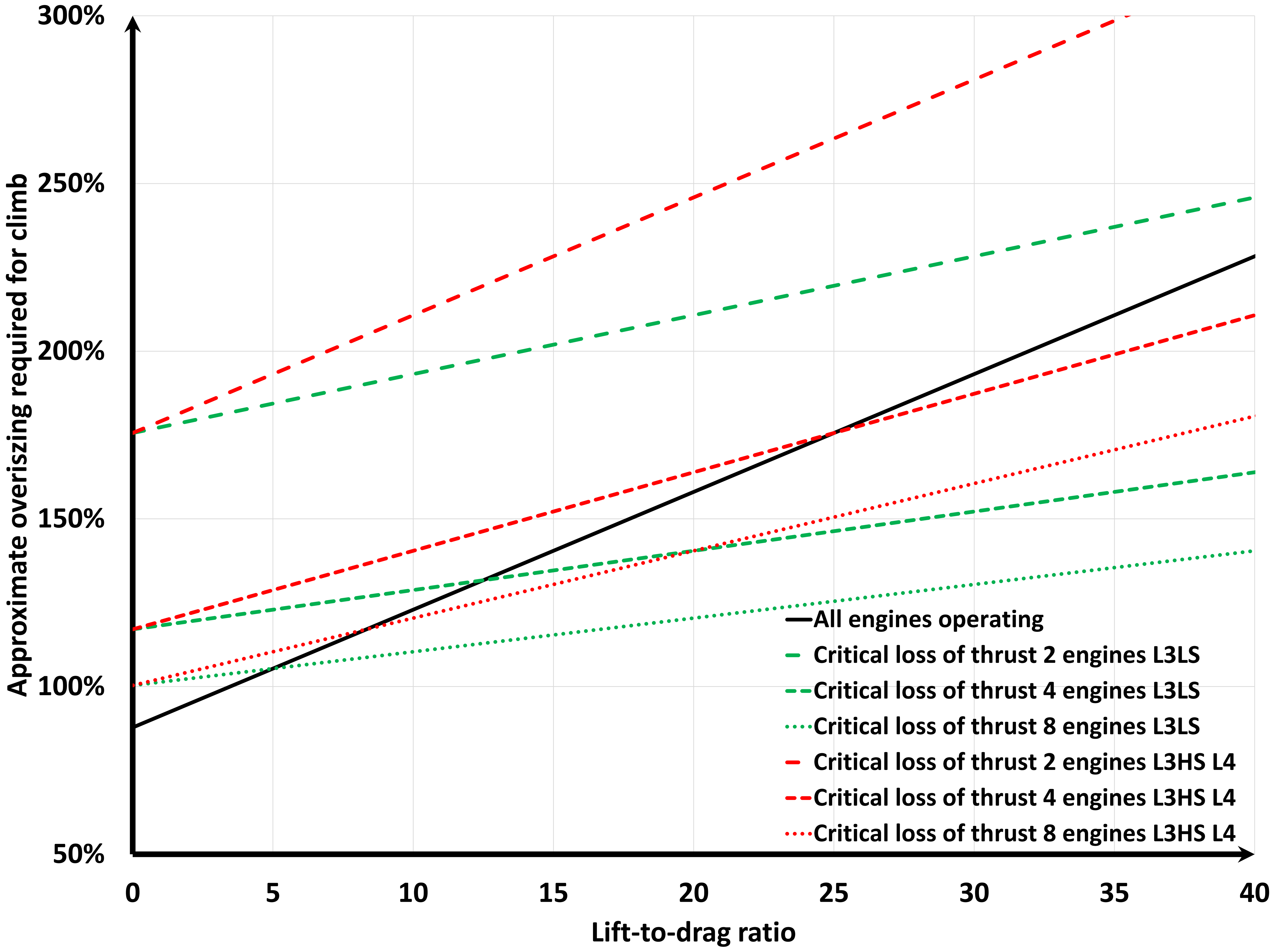
Oversizing

Climb gradient requirements

- Oversizing with regard to cruise power is necessary
- Less oversizing required with more redundance

Redundance

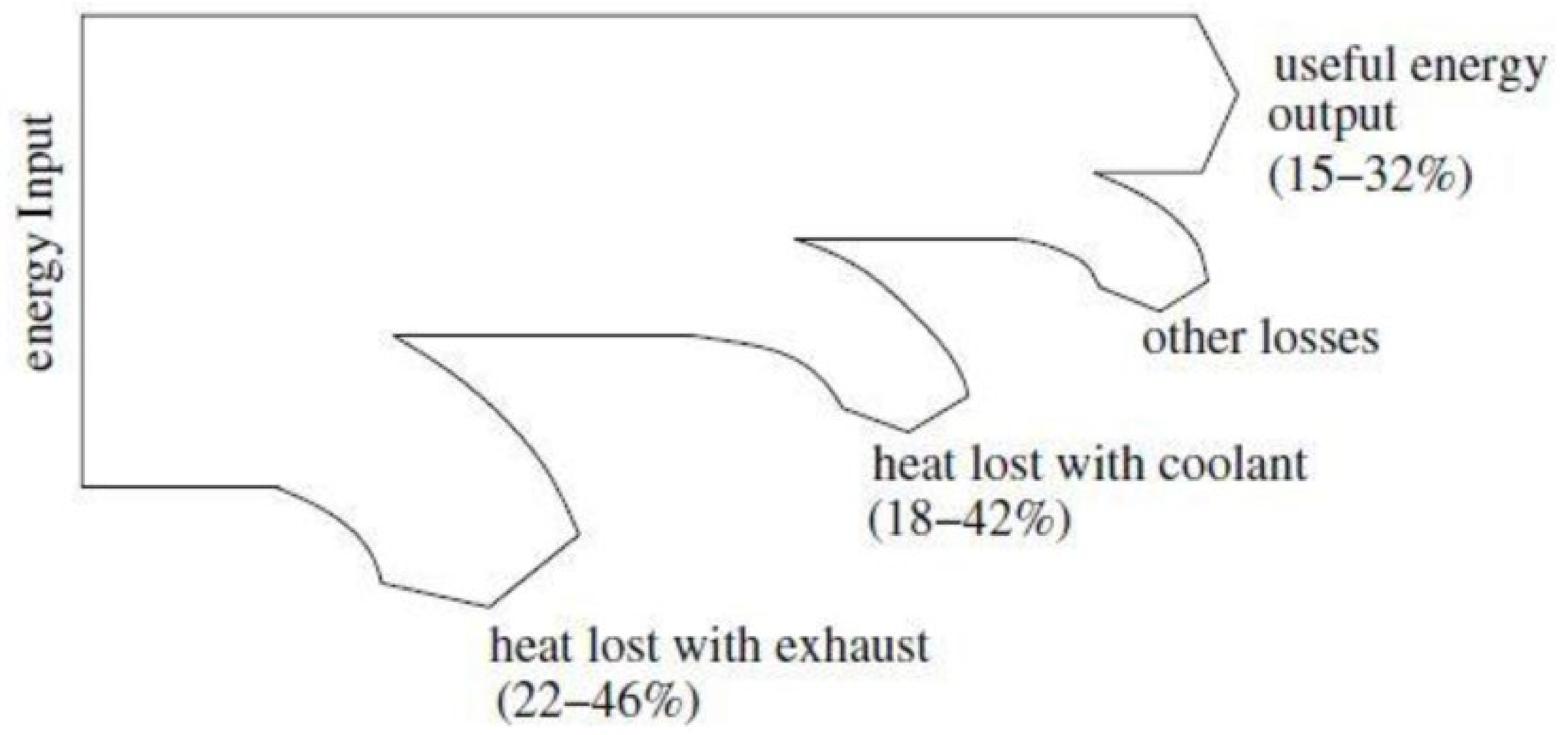
- Electric motors and fuel cells can be scaled better than piston/turboprops
- Probability of failure goes up with number of systems
- Complexity goes up
- Propeller efficiency very much dependent on thrust loading

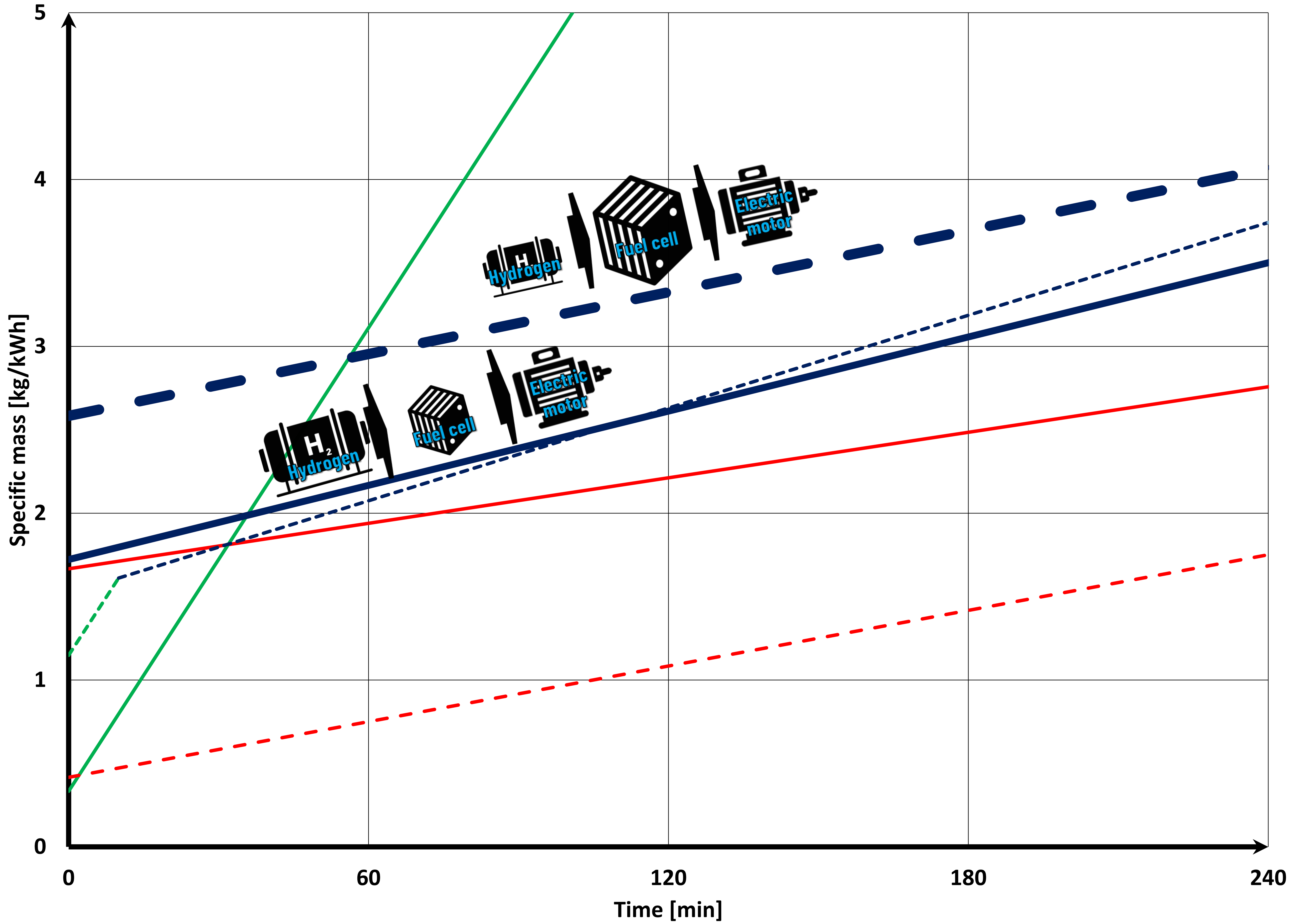


Technology Review

Oversized Fuel Cell

- High initial mass, better efficiency
- Lower mass only for long flights
- Also less cooling drag
  - 50% efficiency → 50% heat → 1/1
  - 40% efficiency → 60% heat → 1/1.5
- Small heat loss with exhaust compared to piston/turboprop





Sources: Stobart et al.

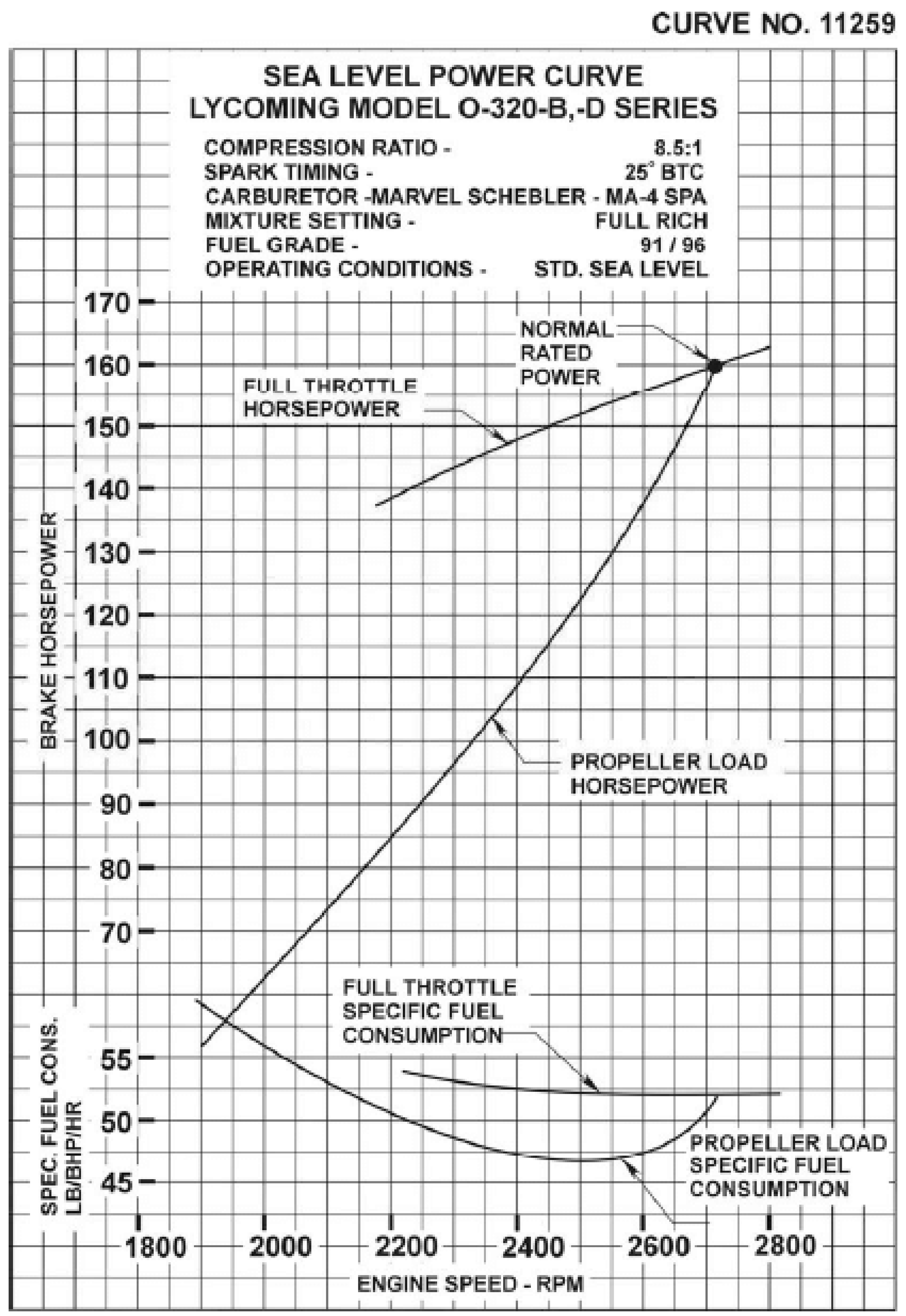
Technology Review

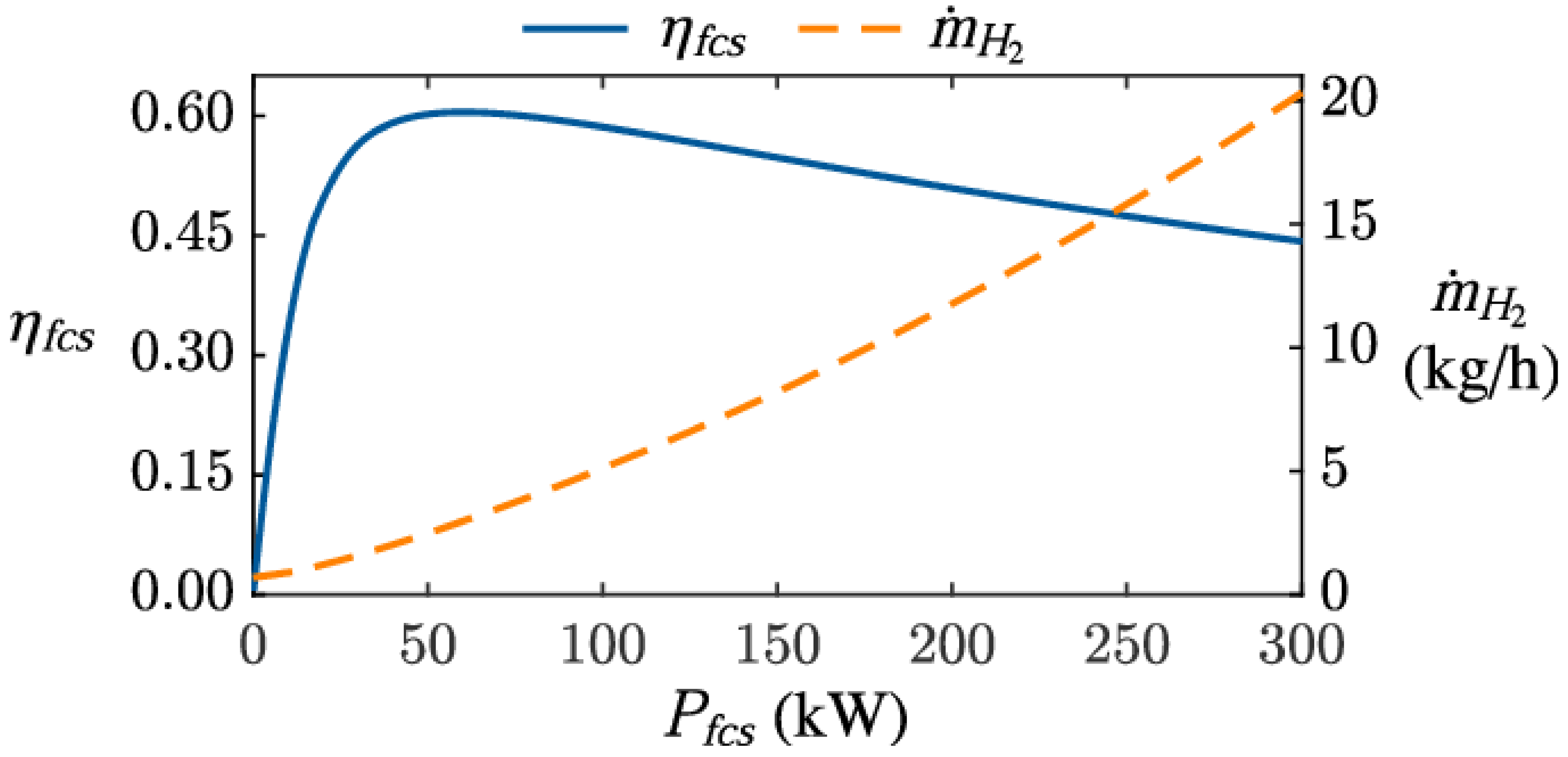
Power Setting

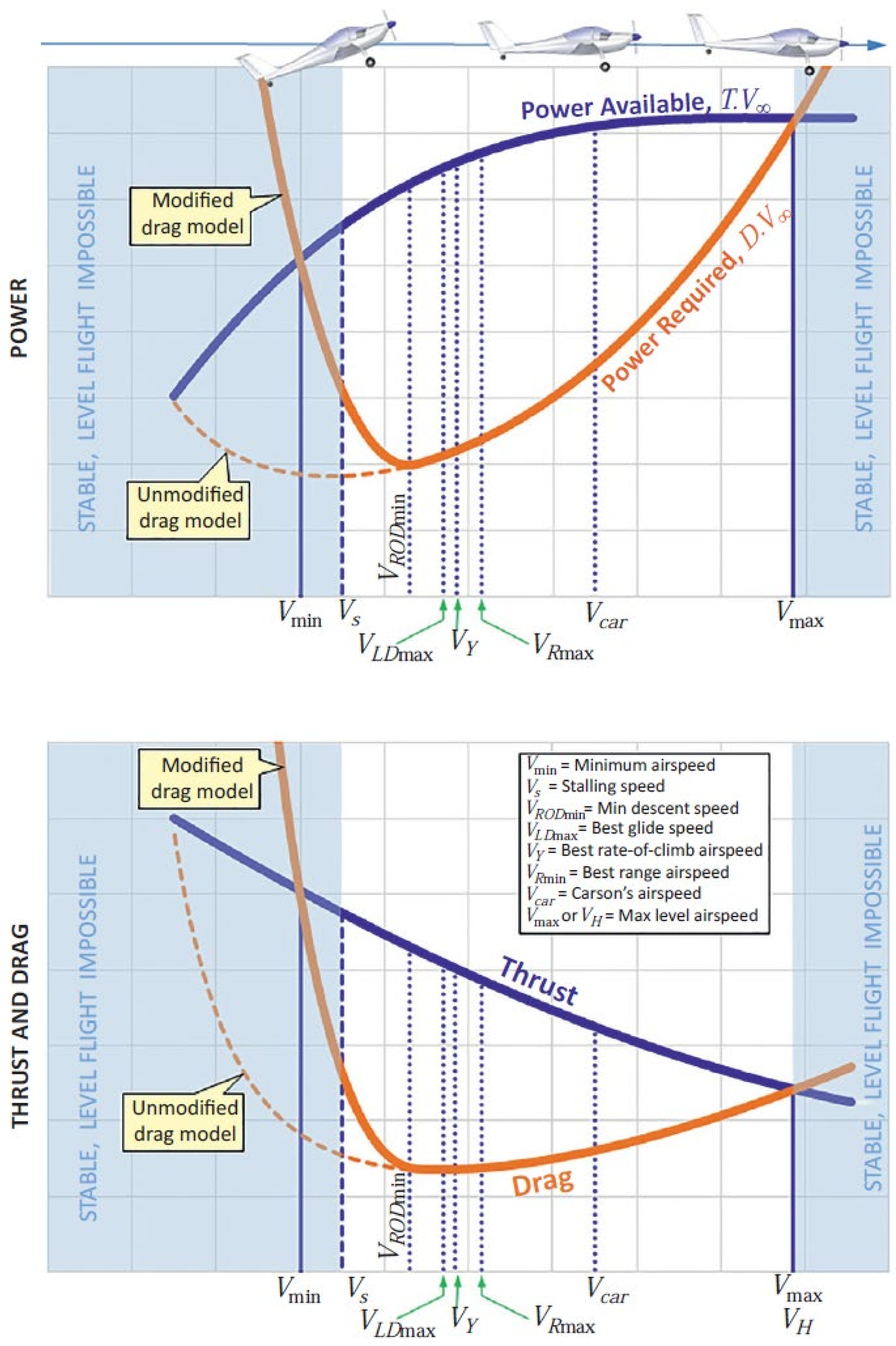
Aircraft
- Best range at best L/D
- Propeller more efficient at higher speed (up to transonic)

Piston engine
- Usually an optimum around 70 – 80% of rated power
- Leads to high cruise speeds

Fuel cell
- Better efficiency at low power settings
- Lower cruise speeds interesting



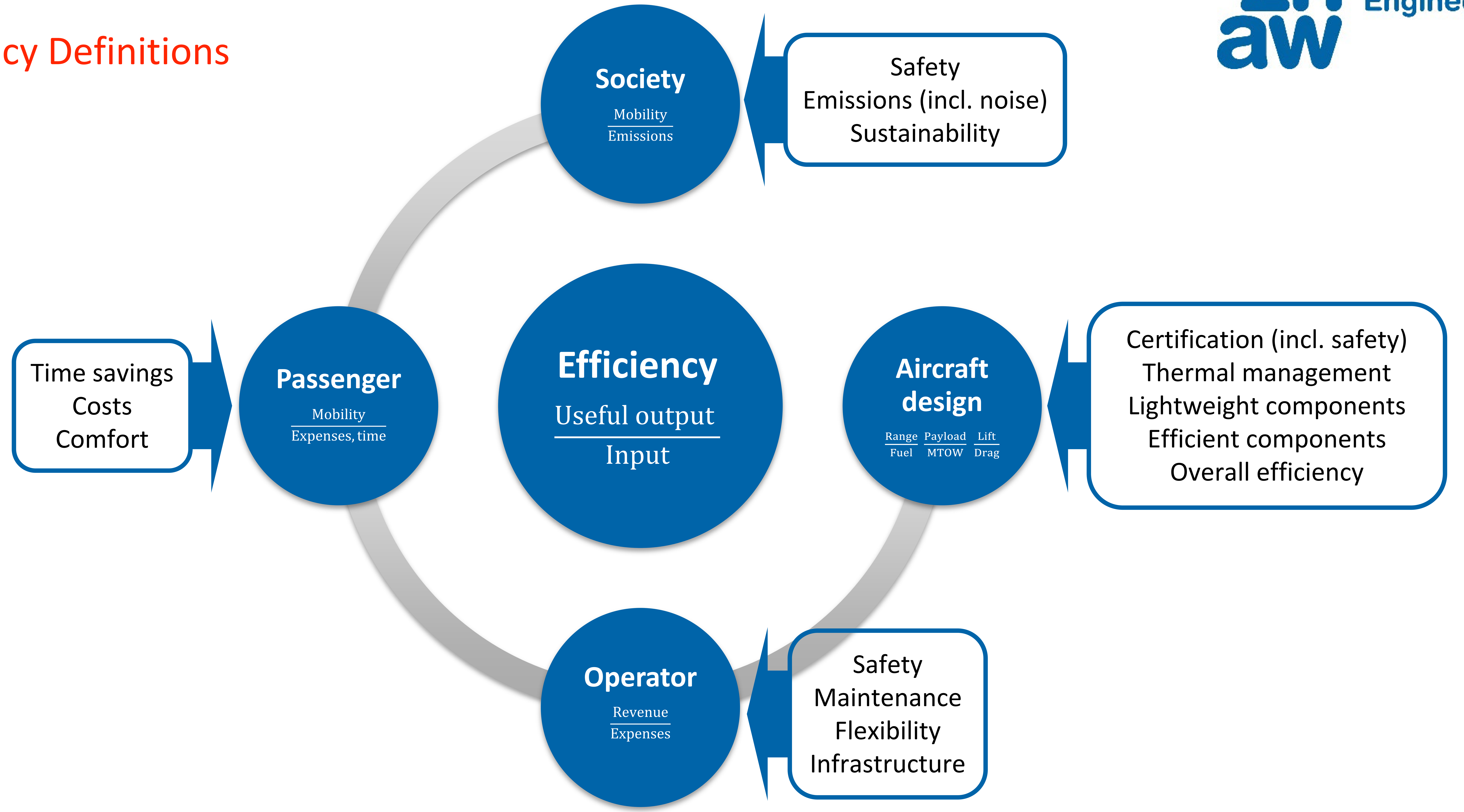




Sources: Ferrara et al., Lycoming, Gudmundsson

Efficiency & Sustainability

Efficiency Definitions



Sources:

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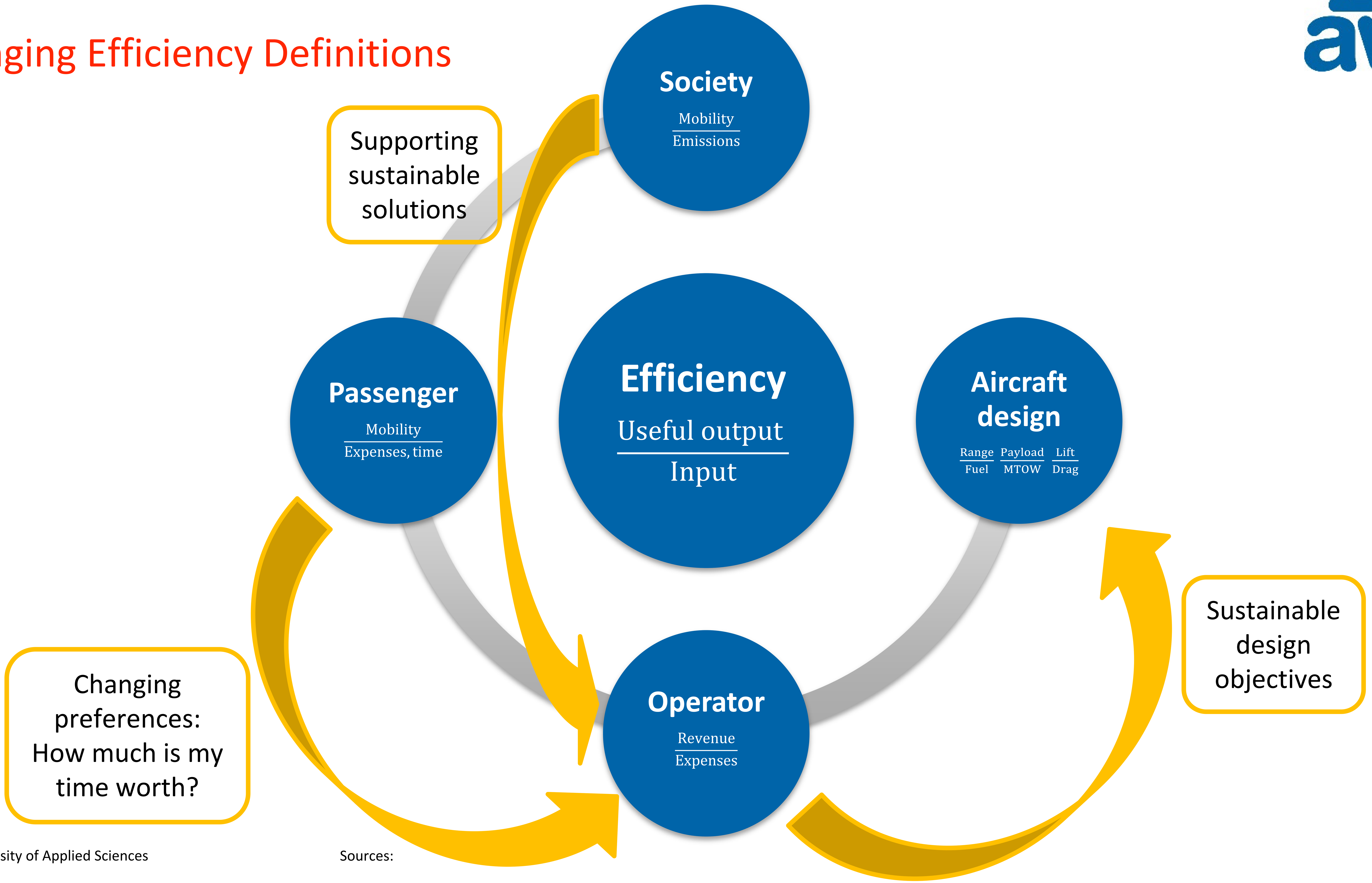
Changing Efficiency Definitions



Sources:

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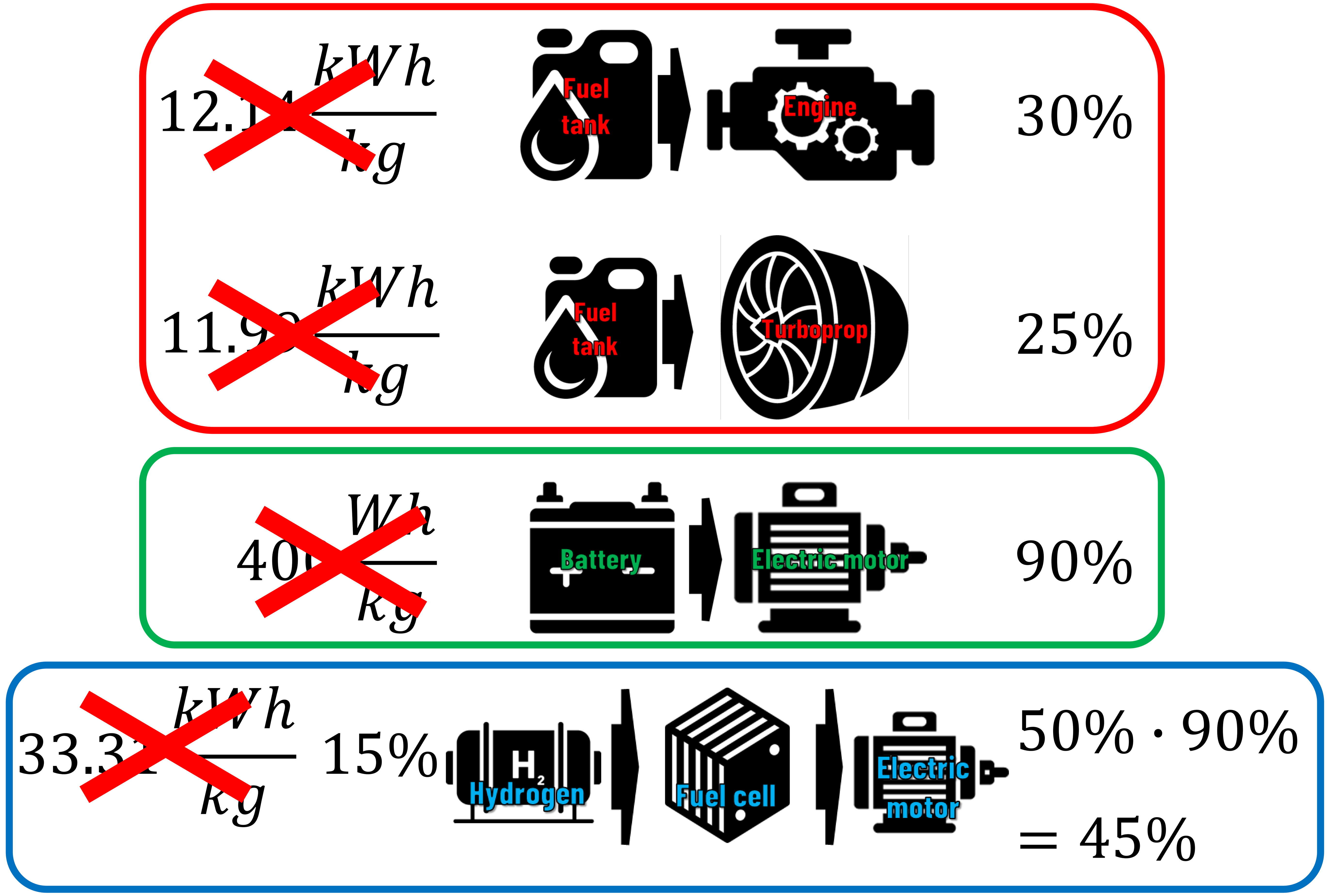
Typical Energy Consumption



<u>Emissions based rating</u>

- Typical measure: g CO2 / (person km)
- Complex topic

<u>Rating of energy use</u>

- Ratio of useful energy for propulsion per energy input to the aircraft
- Neglects emissions from production, logistics,…
- Still useful for the subsystem «aircraft»
- But also neglects useful output, i.e. transported payload

Efficiency & Sustainability

Weighted Efficiency

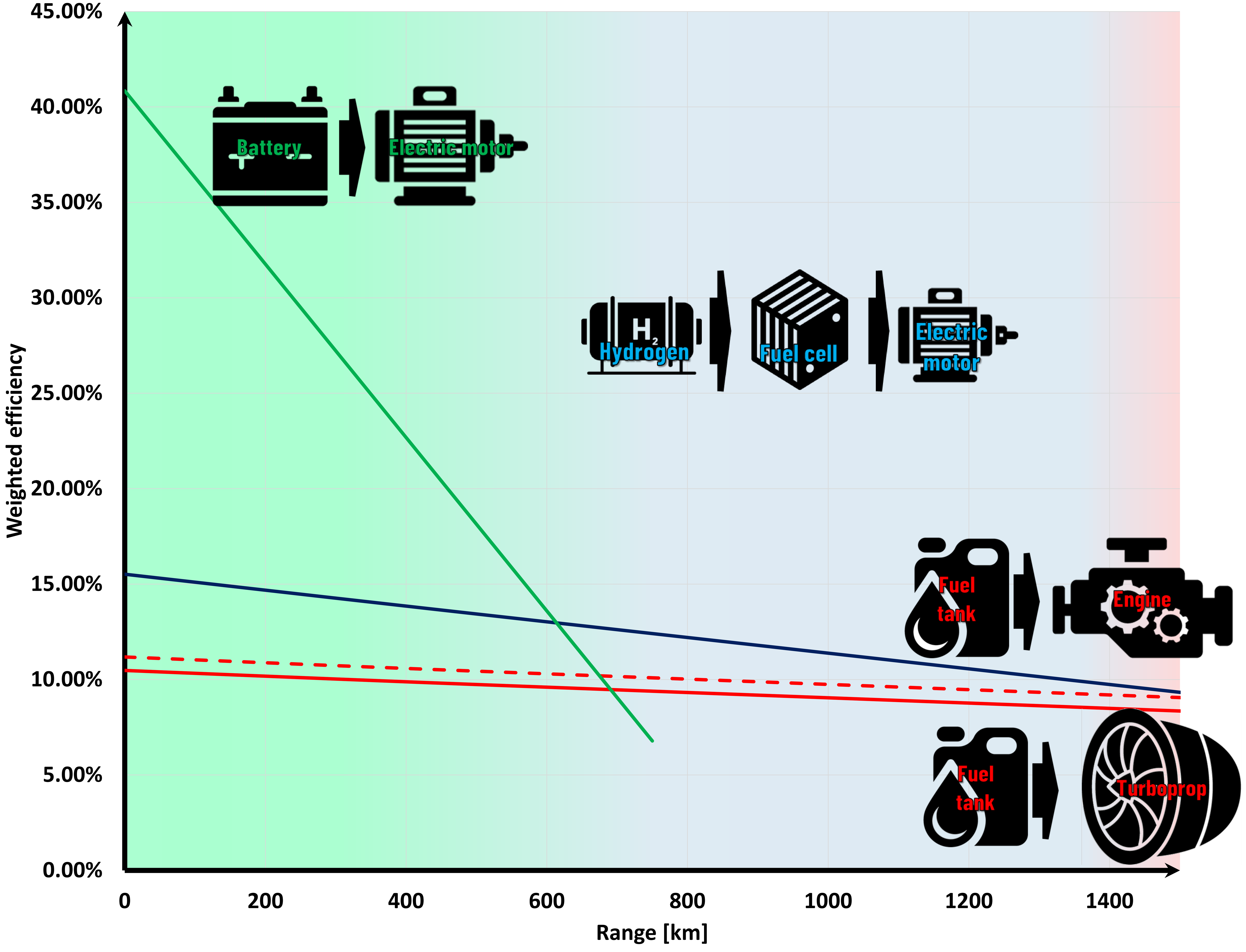
Efficiency, but taking into account the ratio between payload to MTOW

<u>Simplified model</u>

- 40% structural mass & systems
- *L/D* 15
- 80% propeller efficiency

<u>Result</u>

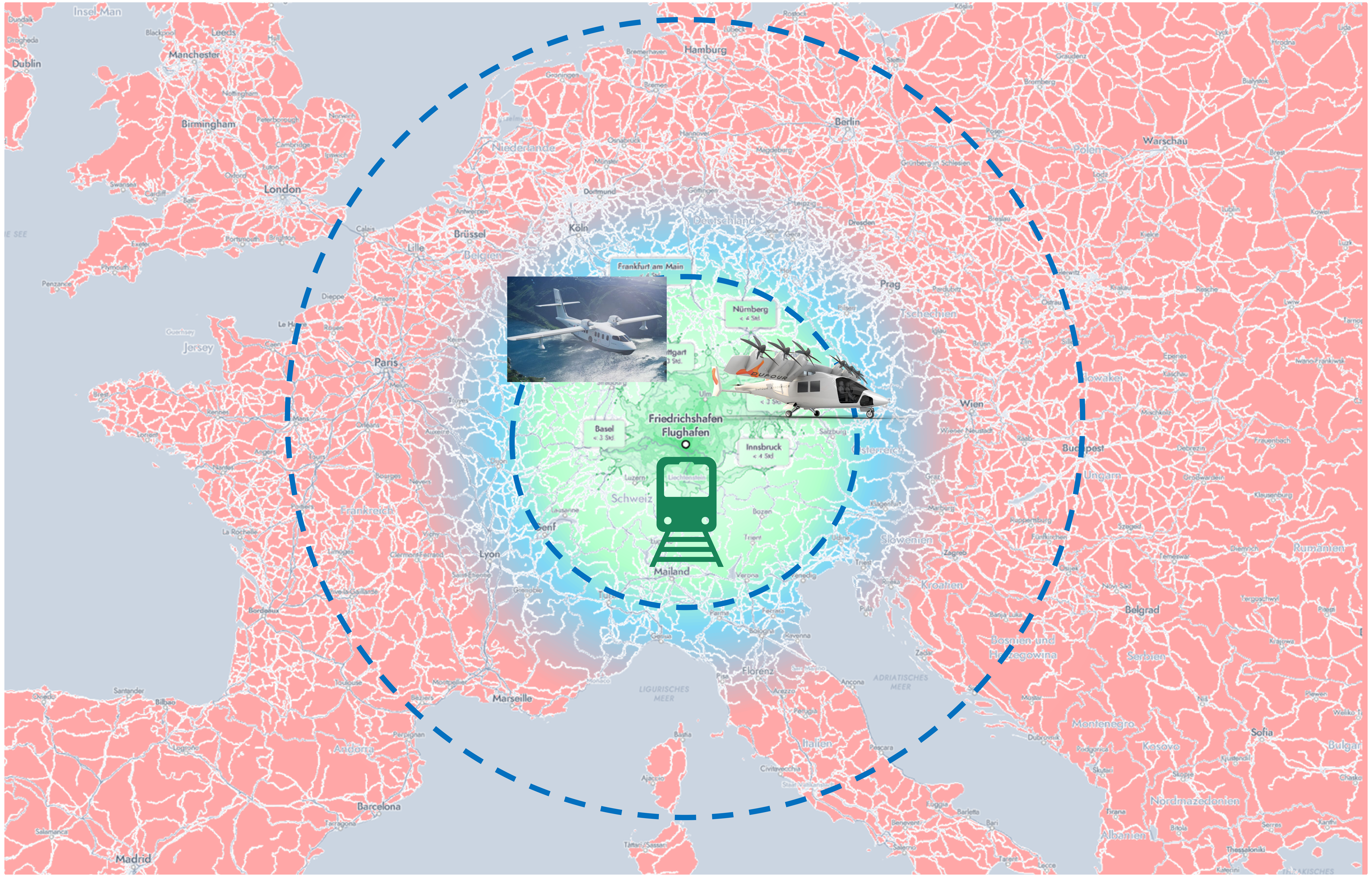
- Heavier systems can still be more energy-efficient



Sources: Ferrara et al., Stobart et al.

Efficiency & Sustainability

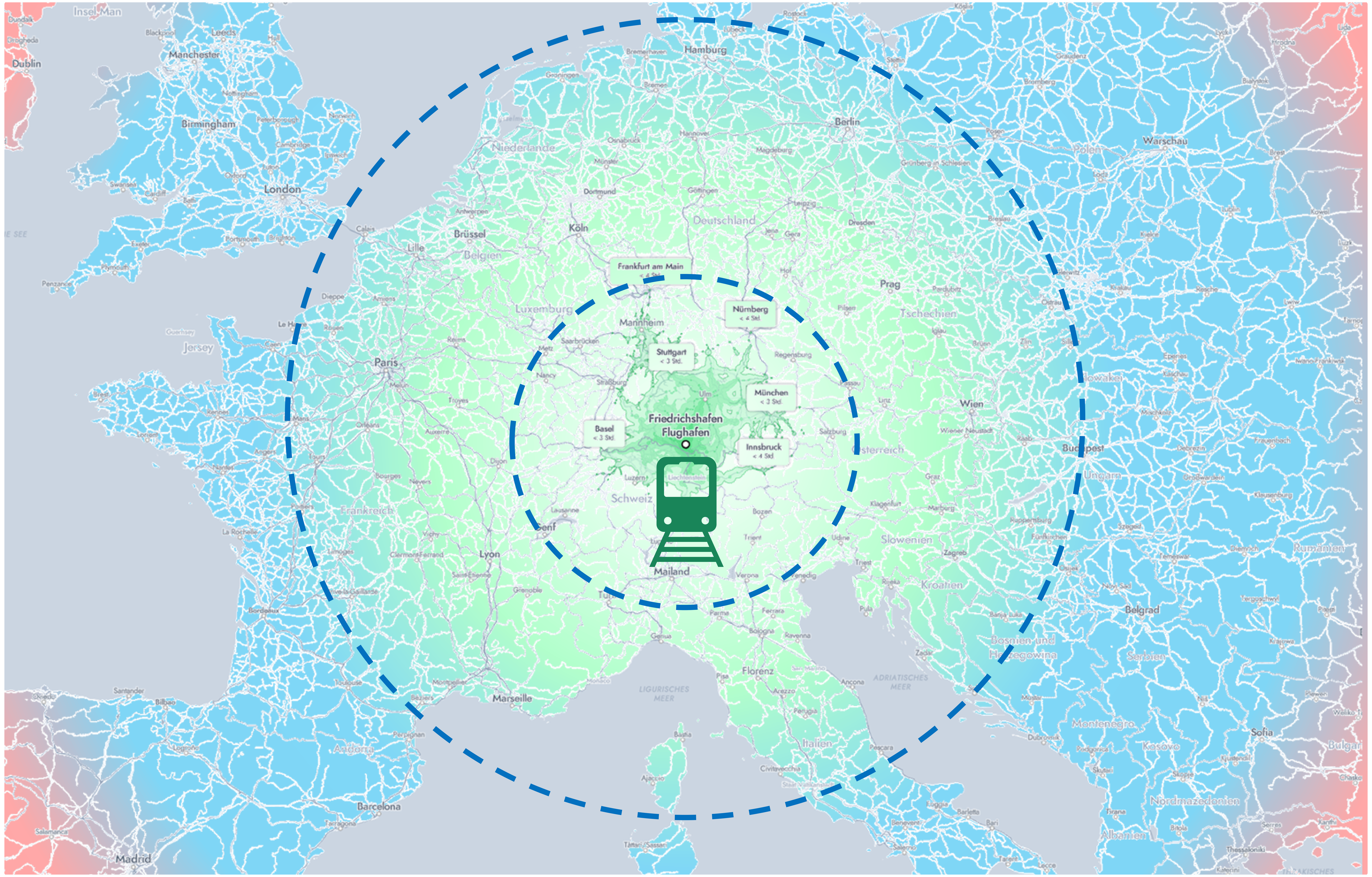
Mission



Sources: Chronotrains.com, openstreetmap, Elfly, Dufour

Efficiency & Sustainability

Mission

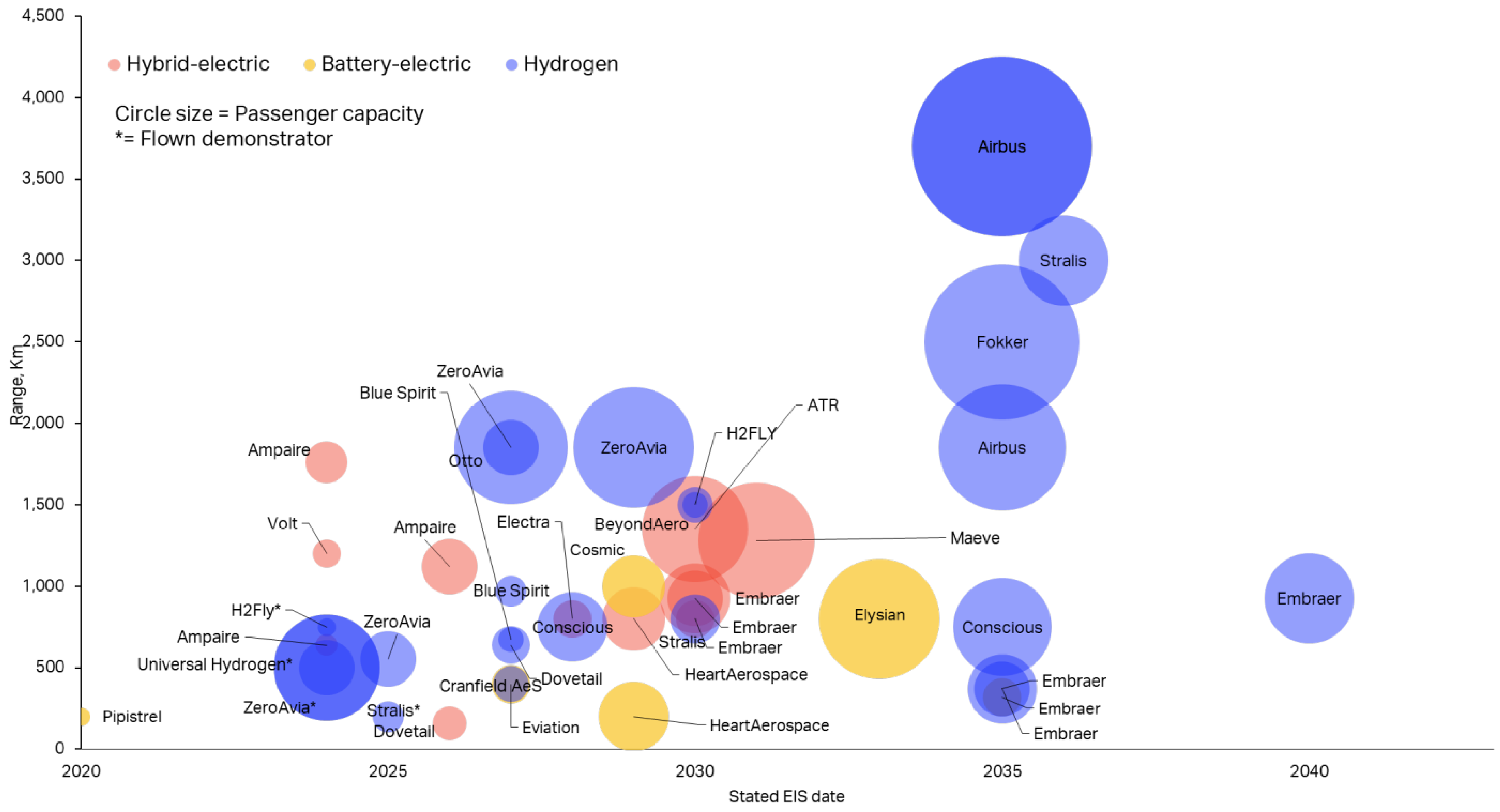


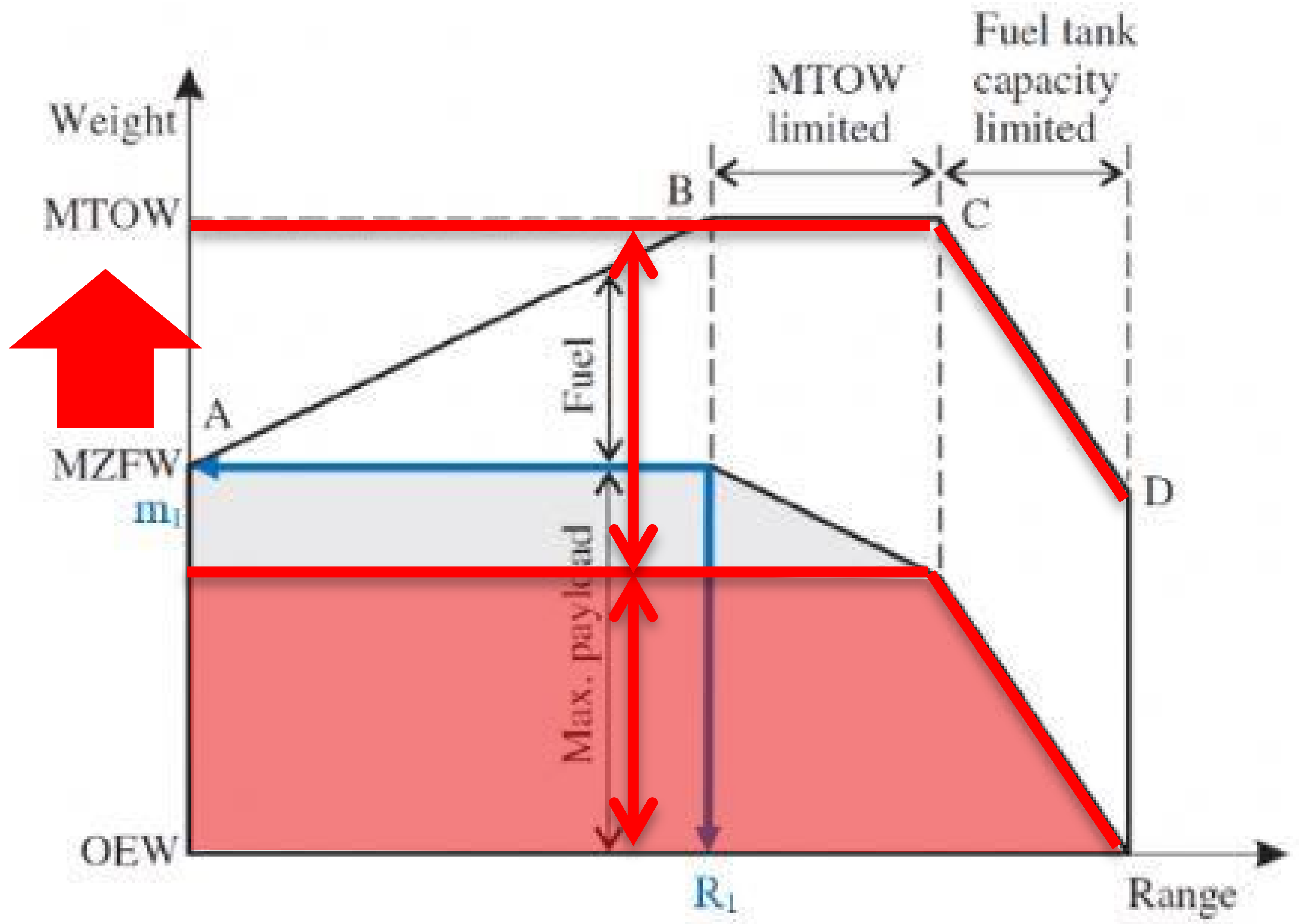
Sources: Chronotrains.com, openstreetmap, Elfly, Dufour

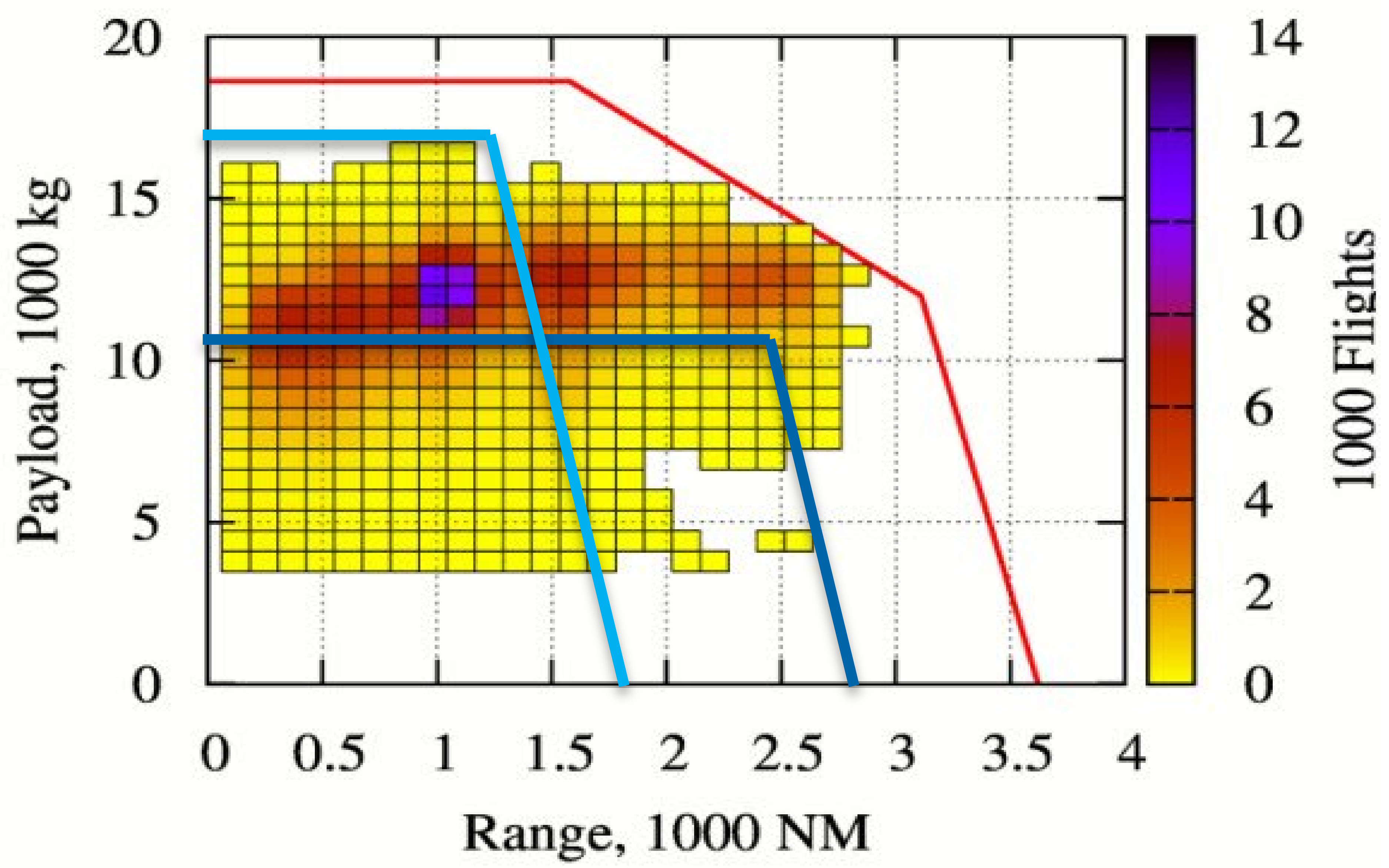
Efficiency & Sustainability

Impact on Payload-Range

- Less flexible, (almost) no trade-off payload vs fuel
- More sensitive to deviations from design point







Sources: Husemann et al, Young, IATA

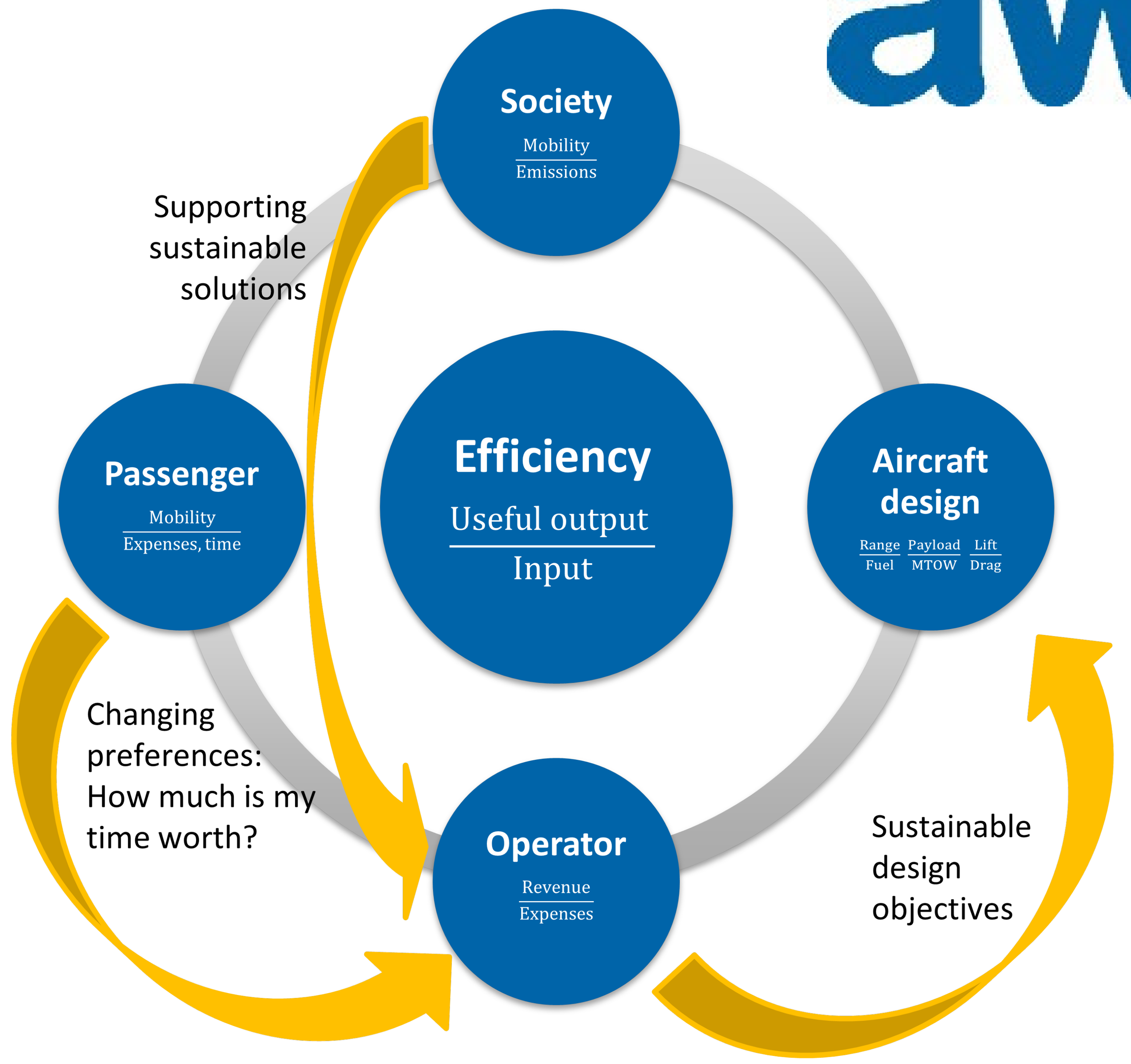
Challenges for the Optimisation of Hybrid-Electric Propulsion Systems

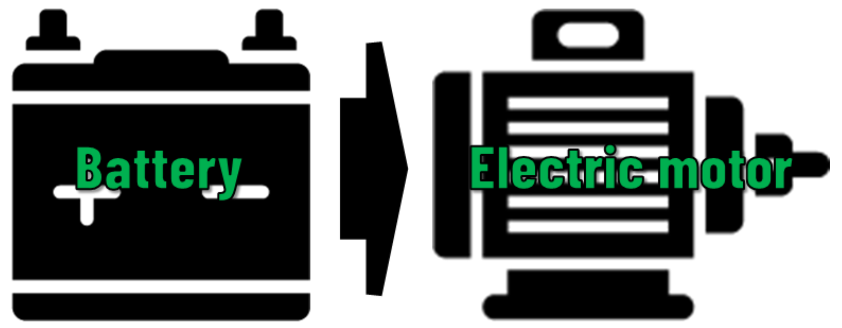
The Challenges

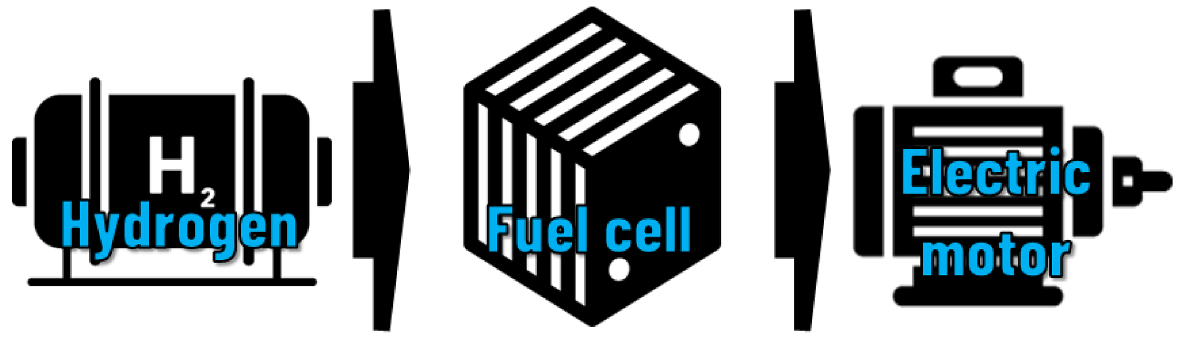
Market & society
- Battery-electric vs. ground-based transport
- More direct and shorter connections
- Fuel cell and hybrid can be more sustainable solutions
- Politics will have huge impact on competitiveness

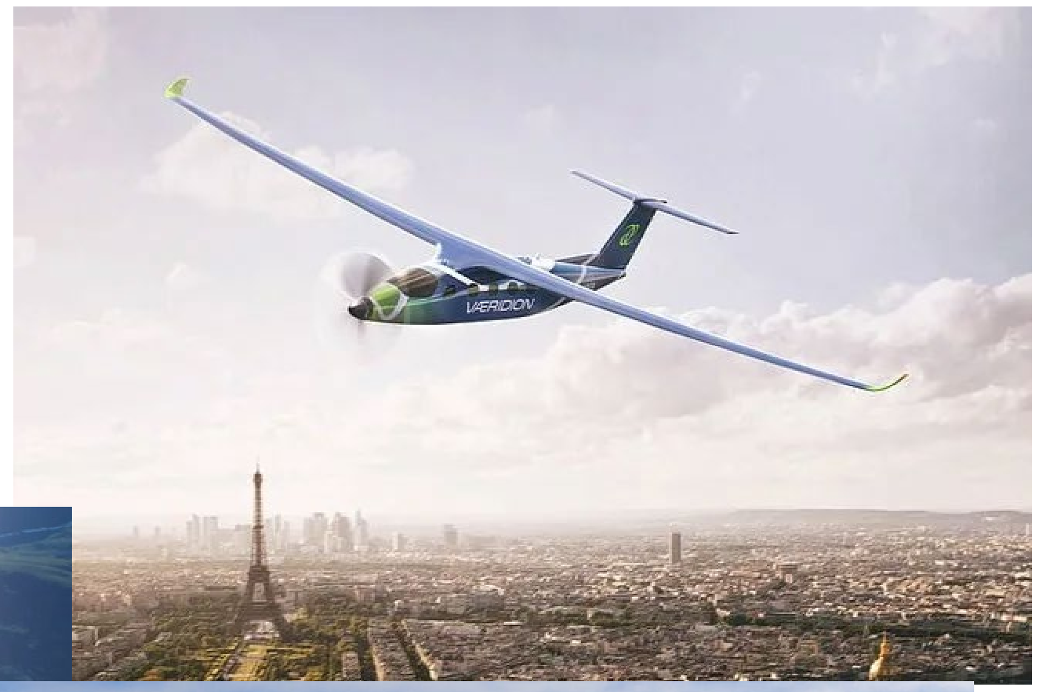
Propulsion system
- Hydrogen storage can change everything
- Thermal management
- Mass vs. efficiency vs. drag optimisation
- Safety and certification
- Human-machine interface for complex system
- More monitoring than maintenance

Aircraft design
- From GA & commuter to larger aircraft
- Optimised for certain mission
- Optimum dependent on many parameters
- Short range, low airspeeds, small capacity, but heavy
- *L/D* important, high aspect ratios









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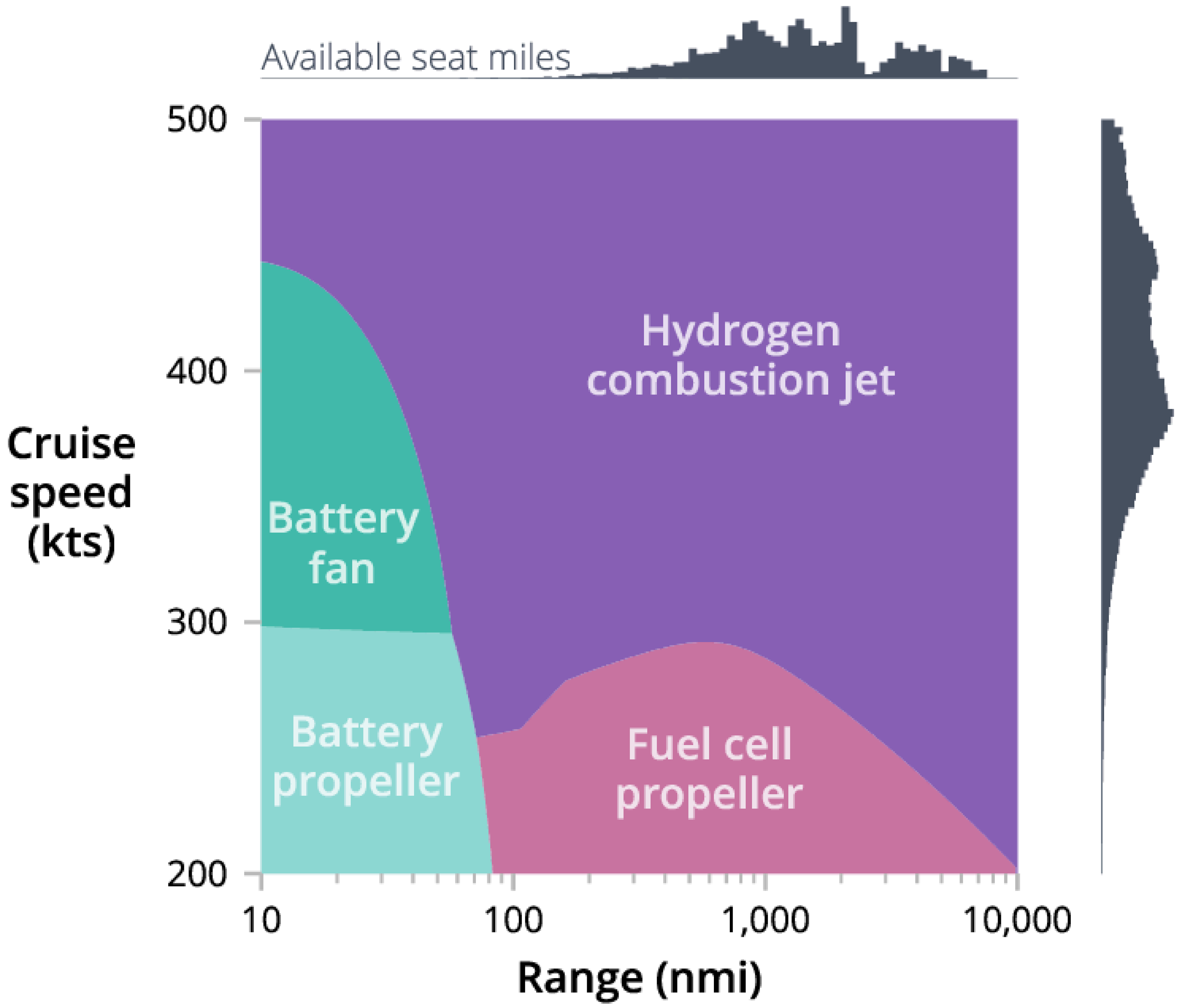
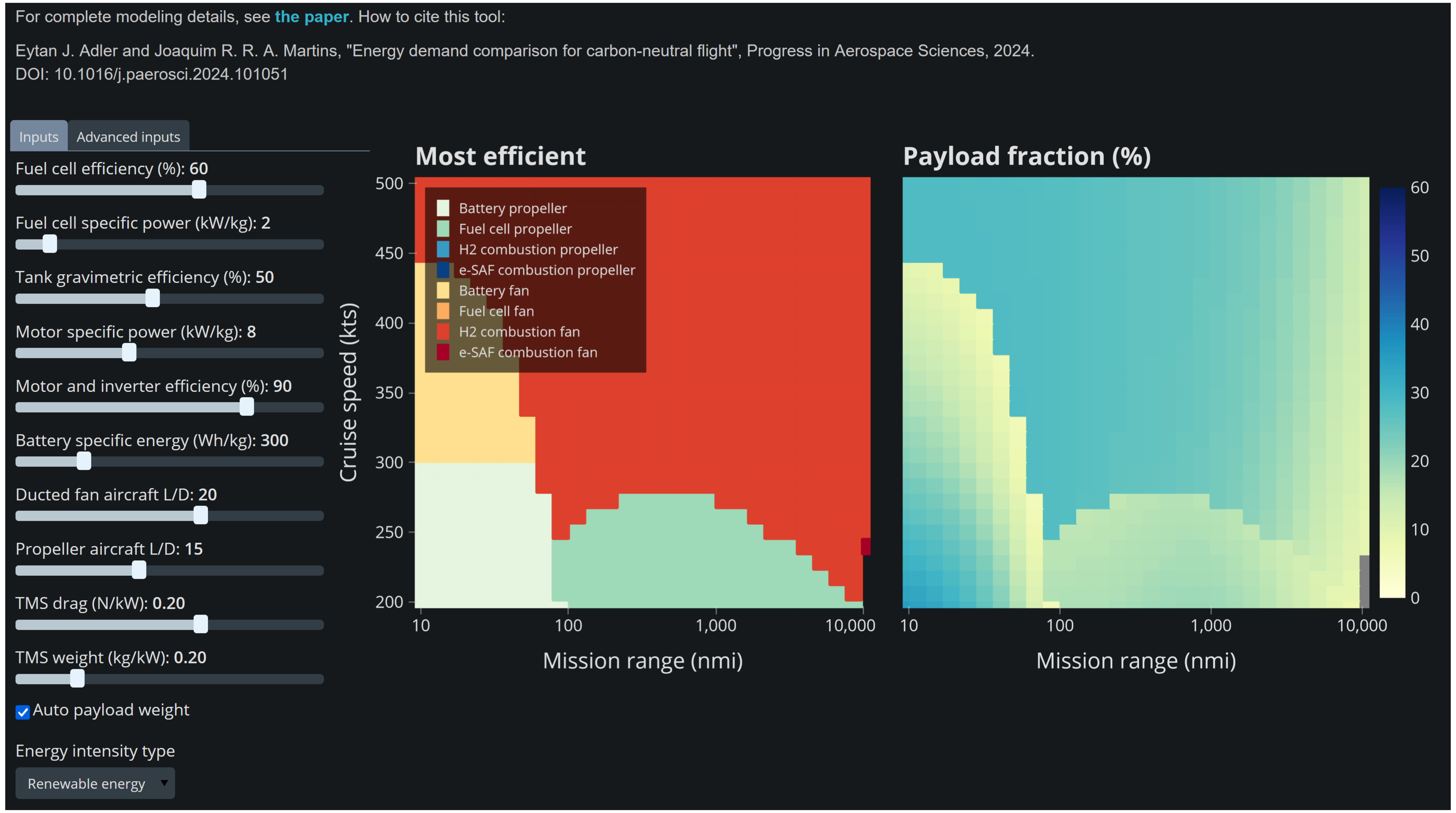
Winterthur, Switzerland

Efficiency & Sustainability

University of Michigan Stratifly Tool

https://stratifly.engin.umich.edu/gui





Sources: Adler & Martins