Electric Flight – Potential and Limitations

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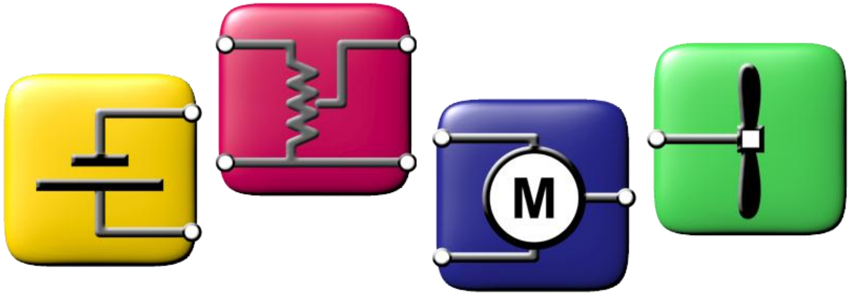
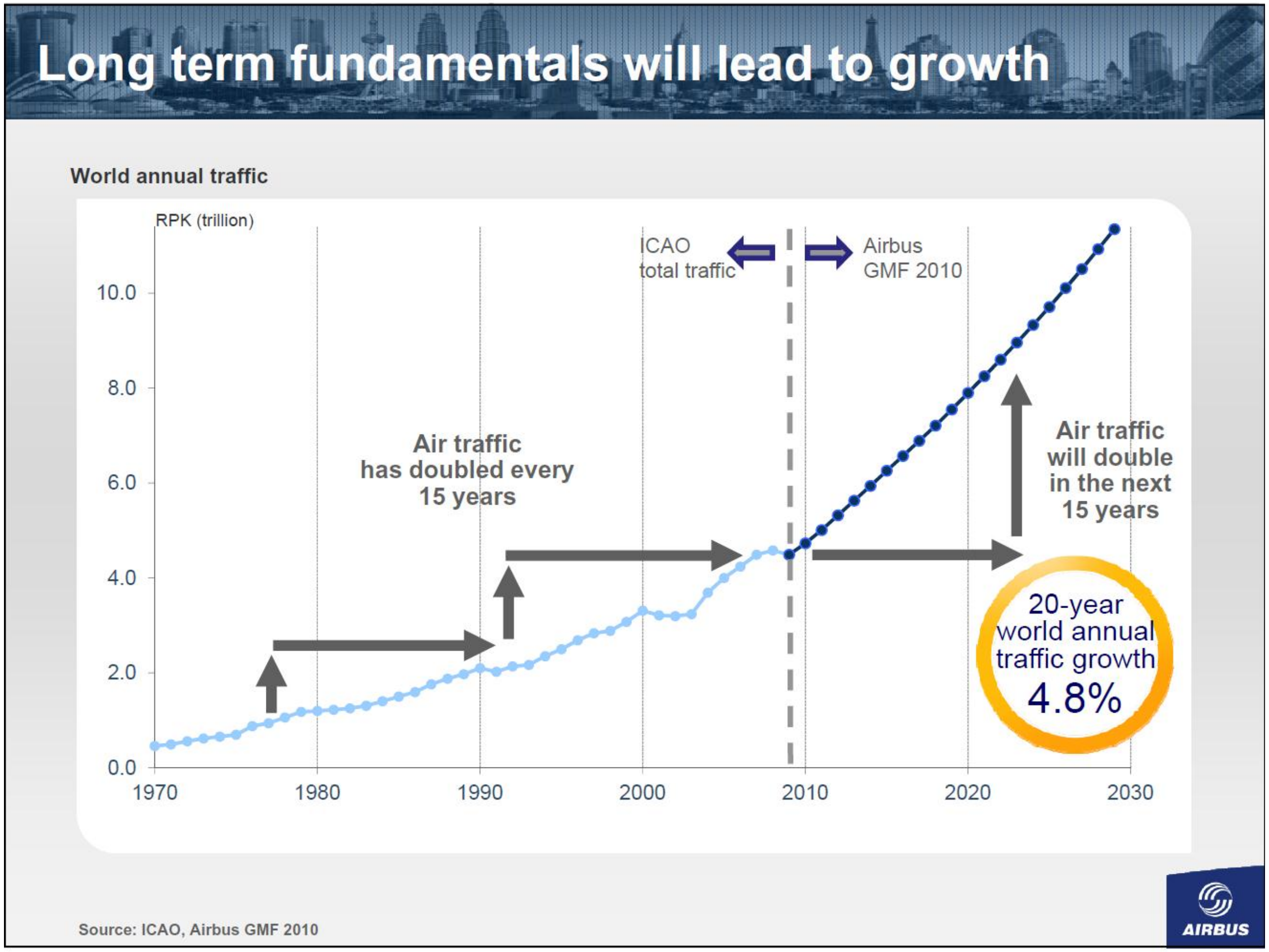


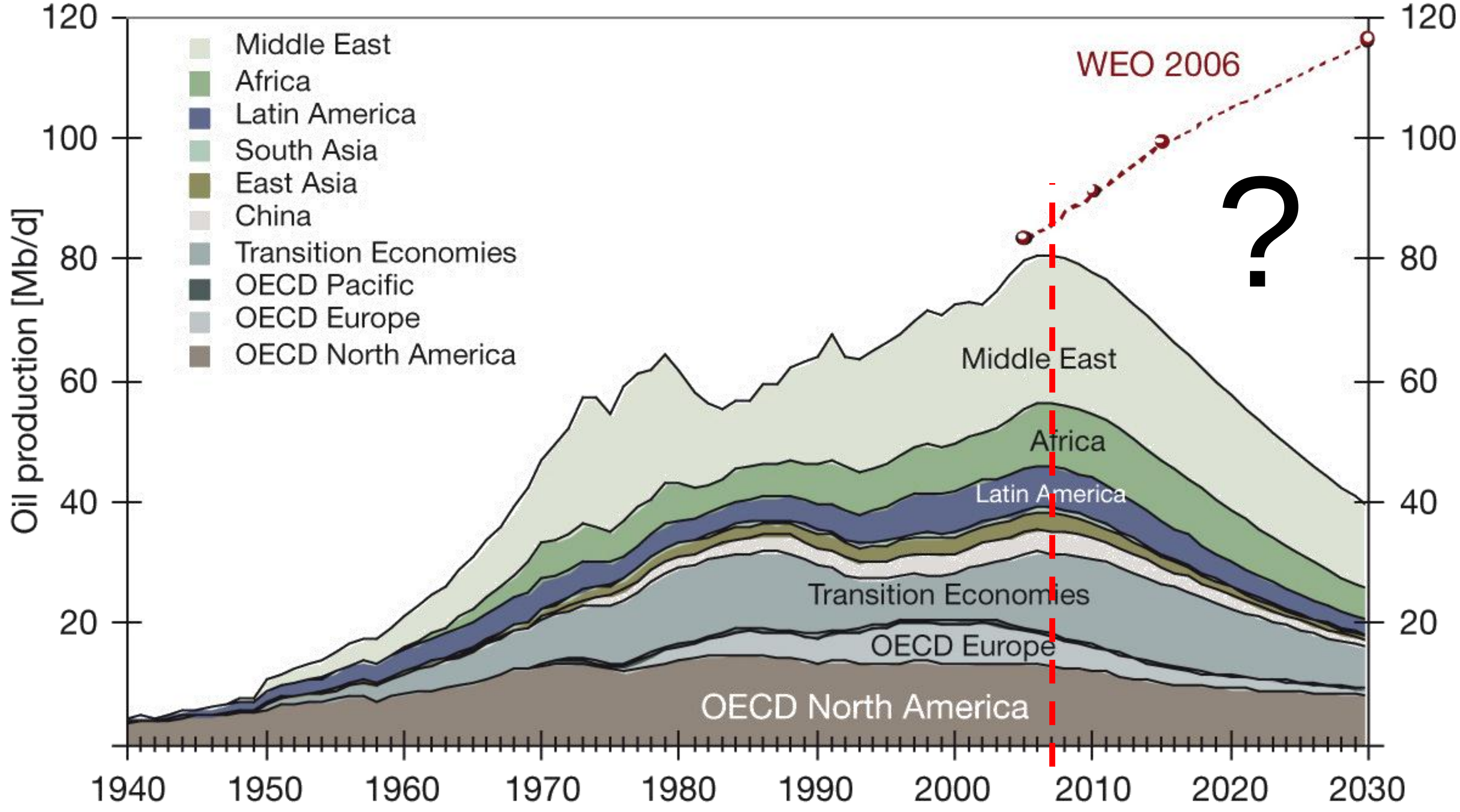
Deutsches Zentrum
DLR für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

History and Predictions – Air Traffic



Quelle: Airbus Global Market Forecast 2010 – 2029

History and Predictions – Oil Production



Ludwig-Bölkow-Systemtechnik GmbH, 2007

Electric propulsion of Aircraft?

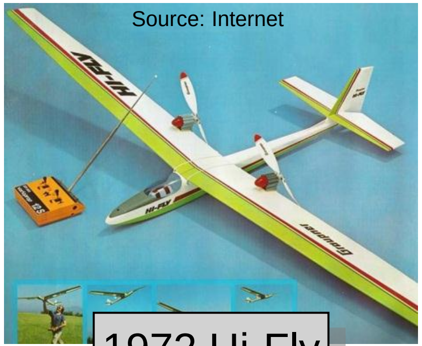
- Motivation:
  - Air traffic is growing.
  - Availability of fossil fuels is be limited.
  - Electric propulsion systems offer high efficiencies.
  - Electric propulsion systems are in situ “zero-emission”.
- Specifics of air transport:
  - Aircraft are already very efficient (3-4 liter/PAX/100km).
  - Aircraft fly over long and very long distances (1000-10000 km).
  - Mass is much more important than in ground transportation.
  - Safety standards are very high.

There is nothing new under the sun...
One of the Pioneers of Electric Flight

- Fred Militky
  - 1940 first trials, after 1945 chief engineer at Graupner.
  - Motor glider MB-E1 (HB-3, b=12 m, m = 440 kg)
    - 21. October 1973: worldwide first flight with electric motor,
    - duration 9-14 Min, altitude 360 m, Pilot Heino Brditschka,
    - performance not reached for 10 years,
    - NiCd batteries by Varta,
    - Motor by Bosch (13 PS @ 2400 1/min).

Source: Internet

1960 Silentius



Source: Internet

1972 Hi-Fly

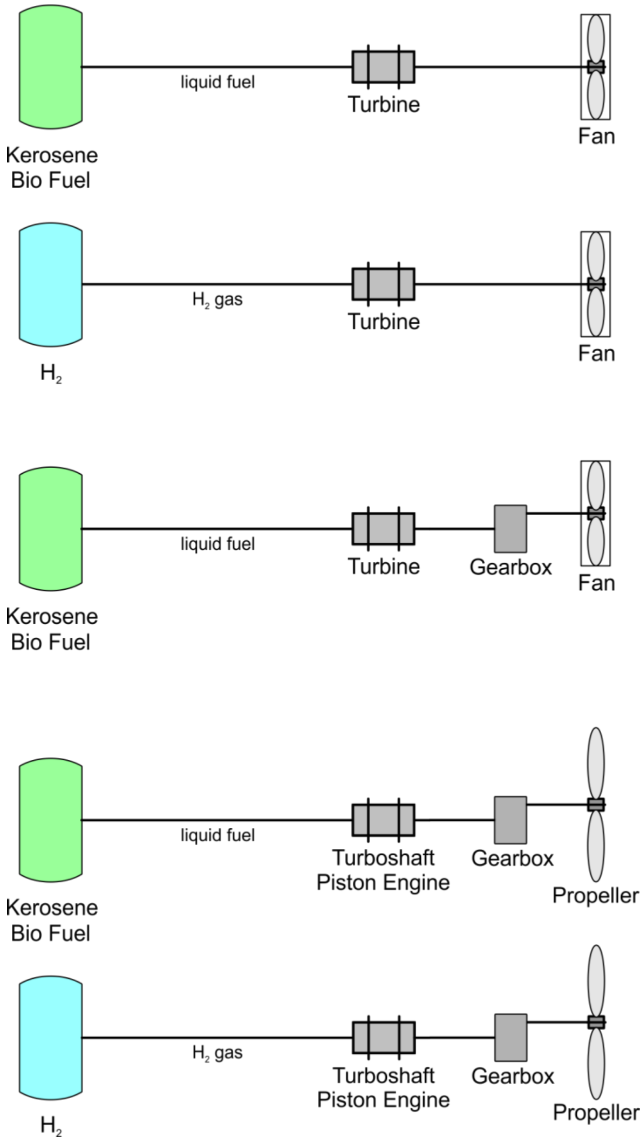
Source: Brditschka

1973 MB-E1

Conventional Propulsion Systems

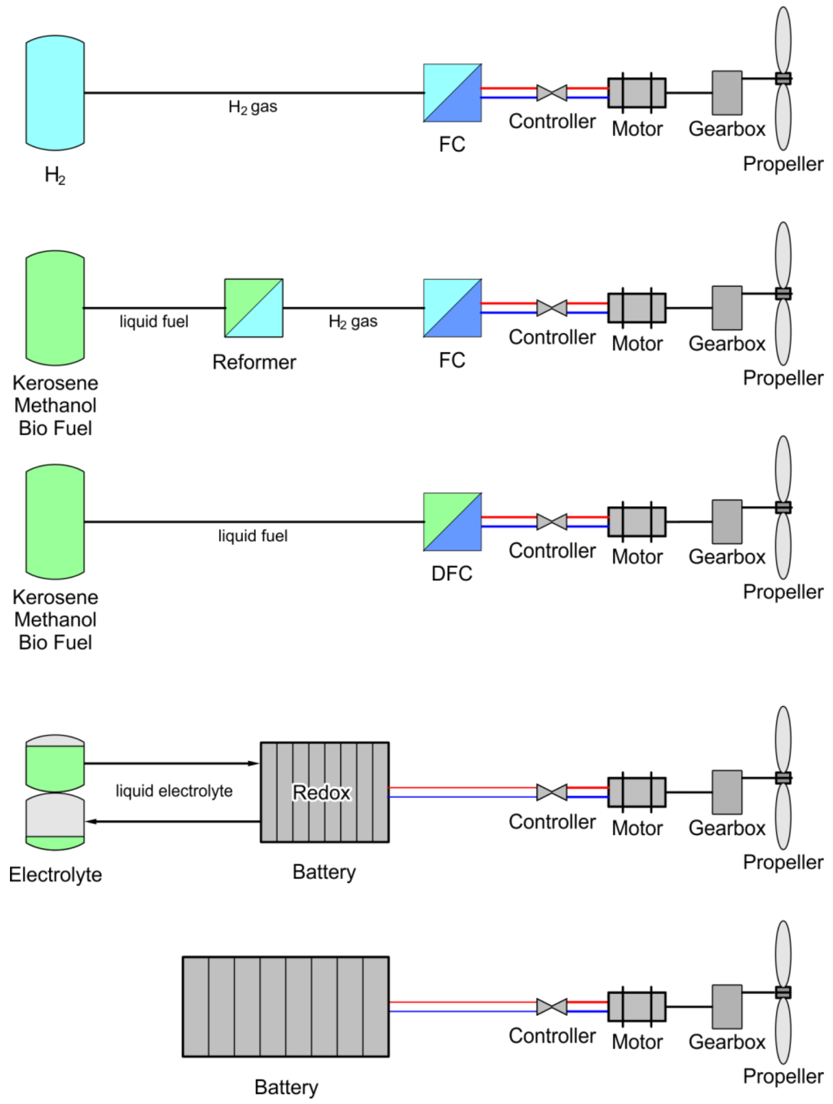
- Energy storage:
  - liquid fuel,
  - alternative: Gas (e.g. H_2).
- Conversion to propulsive power:
  - Turbofan,
  - Turboshaft / piston engine and Propeller,
  - RPM adaption as needed by a gearbox.

- Fuel is burnt, mass reduces with flight time.



Electric Propulsion

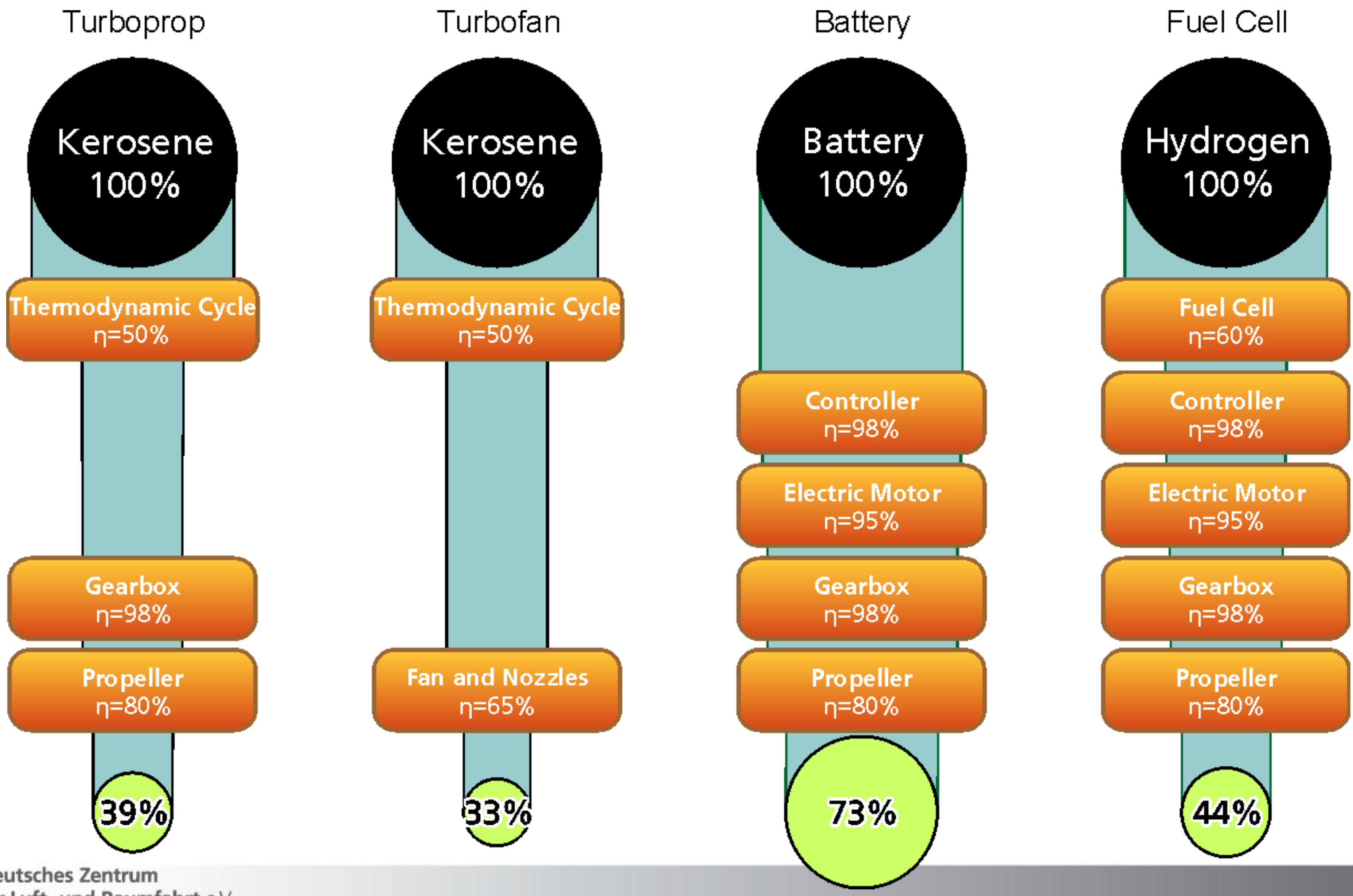
- There are many possibilities.
- Mainly two types of interest.
- <u>Fuel cell systems</u>
  - complex and still expensive,
  - usage of „conventional“ energy storage systems (Kerosene, Methanol, H2),
  - variable mass.
- <u>Batteries</u>
  - simpler systems,
  - much recent development,
  - constant mass.



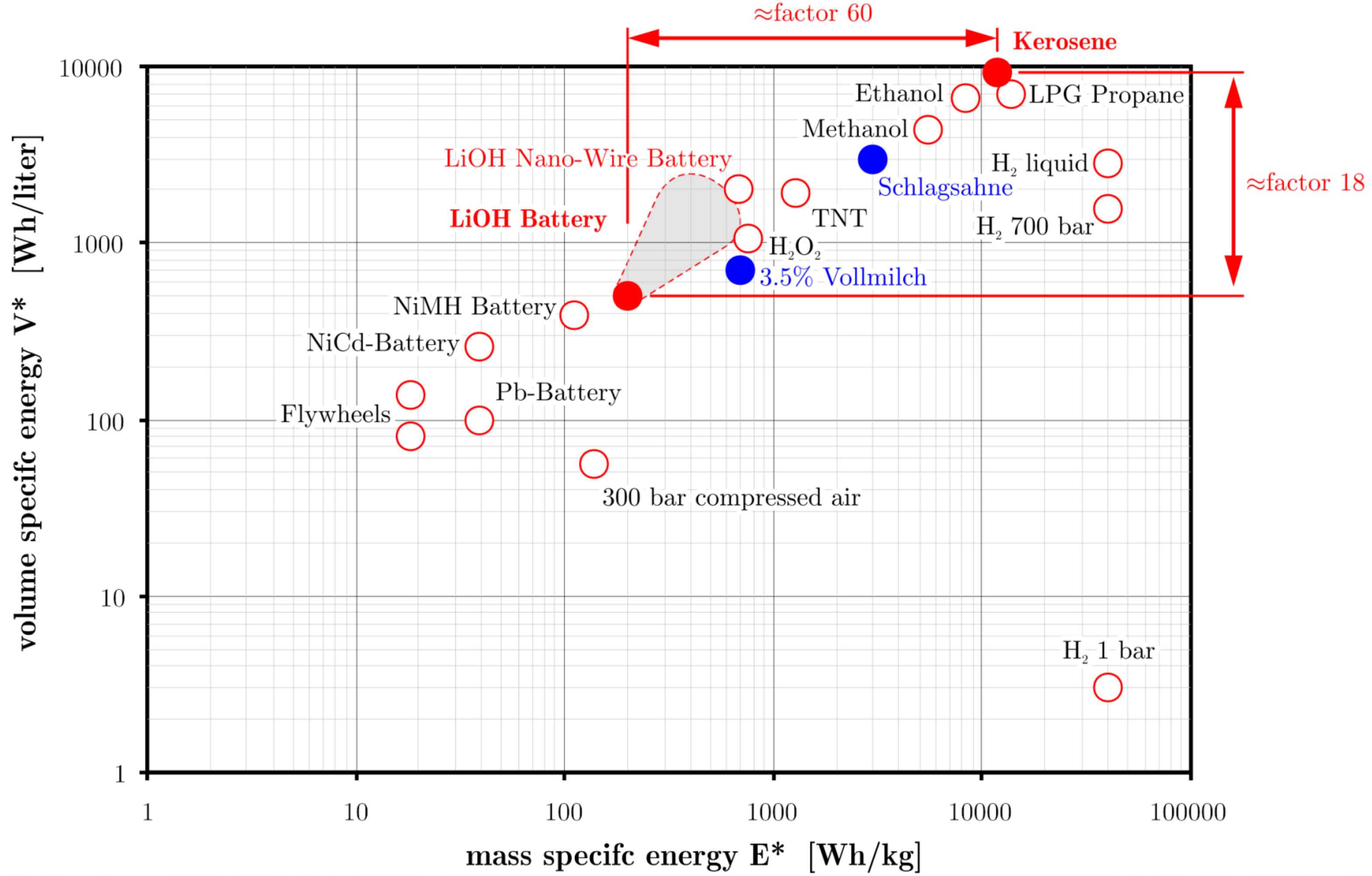
also: hybrid systems

Total Efficiency

The Chain from on-board Energy to Propulsion



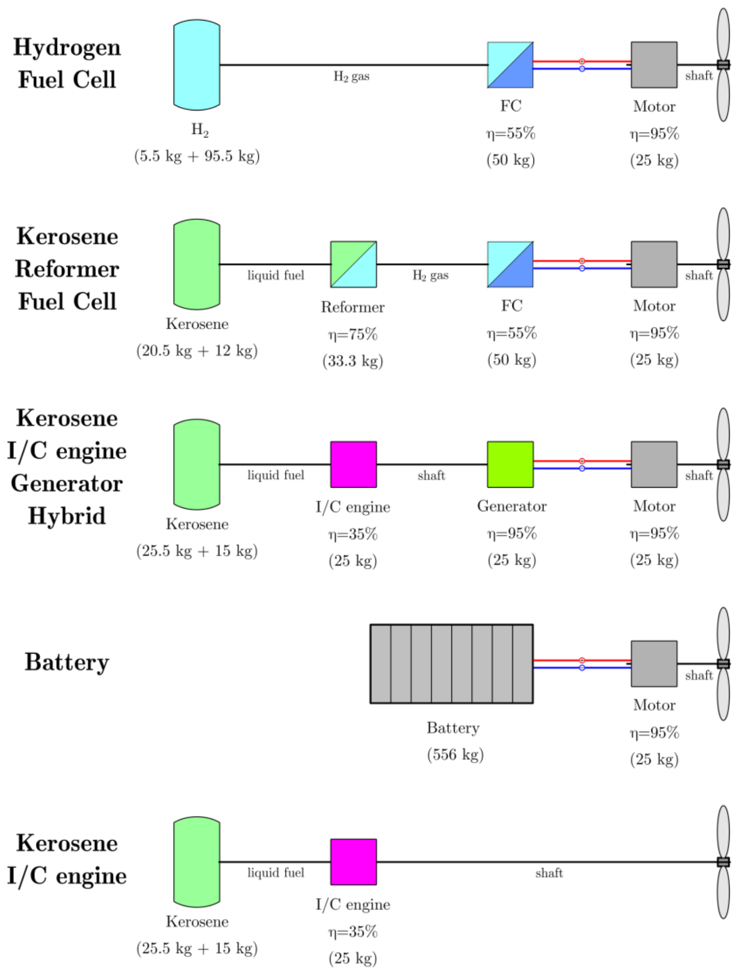
Characteristics of Energy Storage Systems
Specific Energy Content of the „pure“ Energy Carrier

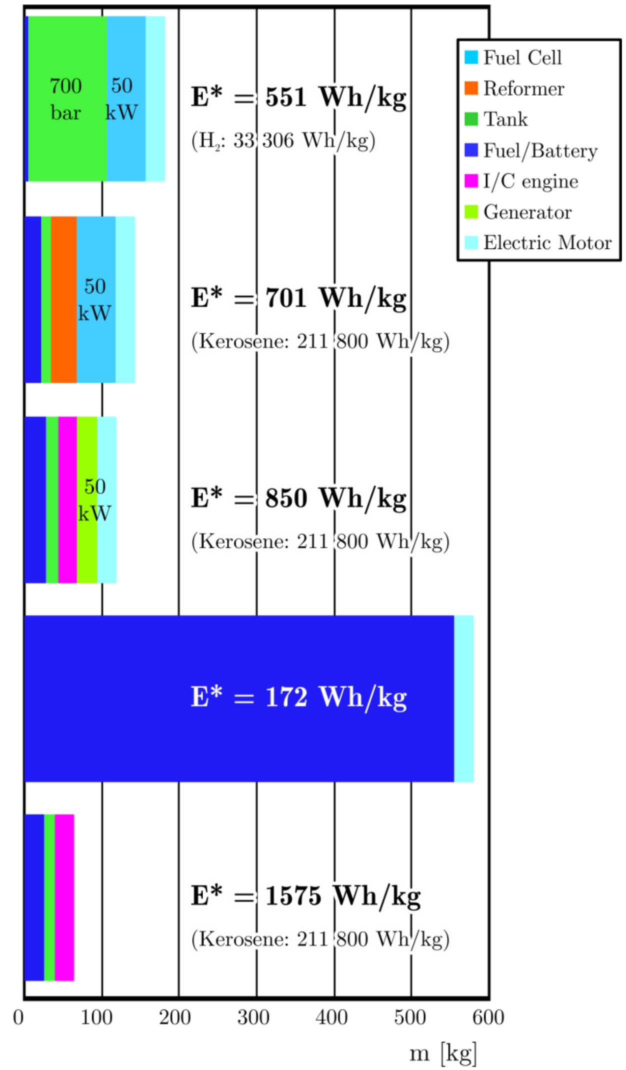


Characteristics of Energy Storage Systems
Not Fuel Mass but System Mass is important

- Kerosene / Gas
  - Tanks, often integral part of the structure, tubing, pumps.
- Hydrogen
  - Gas: high pressure tanks (typical: 350-700 bar), tubing, … ,
  - Liquid: insulated tanks (-250 °C), insulation, tubing, … .
  - structurally integrated tanks (metal-hydrides)?
- Battery
  - Casing, heating, ventilation, wiring,
- Fuel Cell
  - compressors, water, … ,
  - Kerosene/Gas/Alcohol: reformer required.

Equivalent Energy Density of Propulsion Systems





Range of Aircraft with Energy Storage in Batteries

Battery

$$E_{battery} = E^* \cdot m_{battery}$$

Aircraft

$$\begin{aligned} E_{battery} &= P_{battery} \cdot t \\ &= P_{aircraft} \cdot \frac{1}{\eta_{total}} \cdot t \\ &= D \cdot v \cdot \frac{1}{\eta_{total}} \cdot t \\ &= D \cdot \frac{1}{\eta_{total}} \cdot R \\ &= \frac{m \cdot g}{L/D} \cdot \frac{1}{\eta_{total}} \cdot R \end{aligned}$$

$$E^* \cdot m_{battery} = \frac{m \cdot g}{L/D} \cdot \frac{1}{\eta_{total}} \cdot R$$

$$R = E^* \cdot \eta_{total} \cdot \frac{1}{g} \cdot \frac{L}{D} \cdot \frac{m_{battery}}{m}$$

E* = Energy per mass [J/kg, Ws/kg]
P = power [W]
L/D = lift over drag
t = time [s]
v = flight speed [m/s]
m = aircraft mass [kg]
R = range [m]
g = 9.81 [m/s^2]
η = total efficiency from battery

(neglecting fuel reserves as well as takeoff and landing)

Range of Aircraft

- Energy from decomposing / burning fuel (hot or cold):
  - Fuel consumption reduces mass during the flight time.
  - classical range equation („Breguet-equation“) applies.

$$R = E^{*} \cdot \eta_{total} \cdot \frac{1}{g} \cdot \frac{L}{D} \cdot \ln\left(\frac{1}{1 - \frac{m_{fuel}}{m}}\right)$$

- Energy drawn from batteries or solar energy:
  - Mass stays constant.

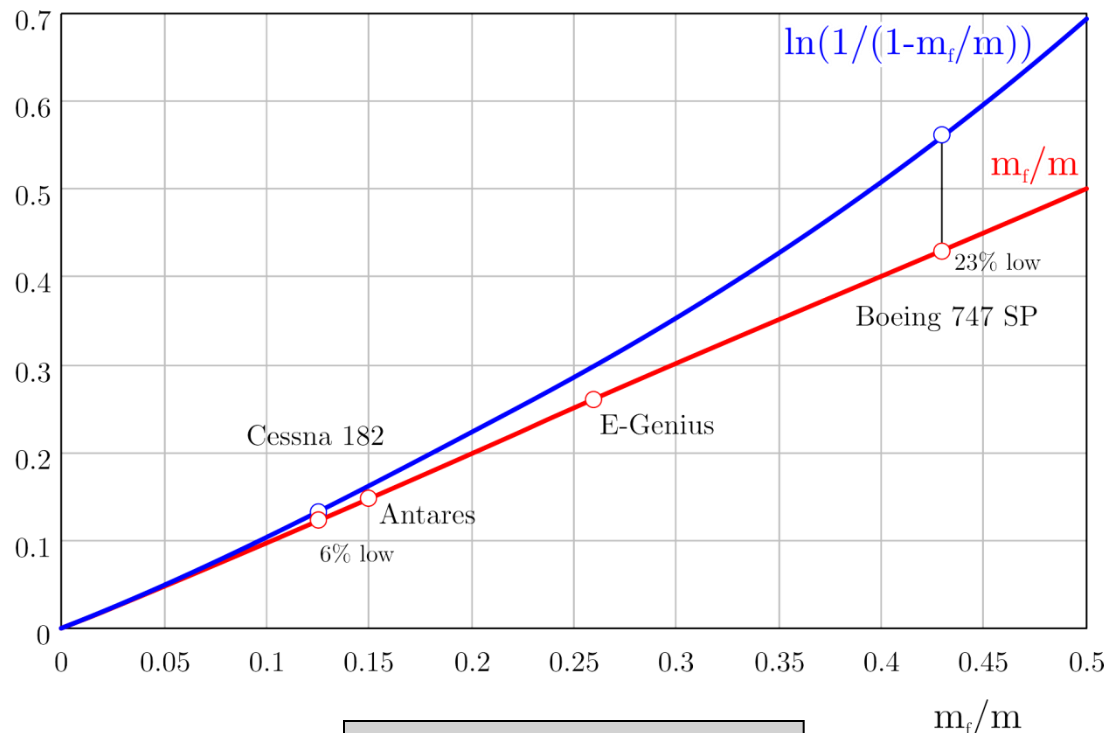
$$R = E^{*} \cdot \eta_{total} \cdot \frac{1}{g} \cdot \frac{L}{D} \cdot \frac{m_{battery}}{m}$$

Impact of variable Mass on Range

$$R = E^* \cdot \eta_{total} \cdot \frac{1}{g} \cdot \frac{L}{D} \cdot \ln\left(\frac{1}{1-\frac{m_{fuel}}{m}}\right)$$

$$R = E^* \cdot \eta_{total} \cdot \frac{1}{g} \cdot \frac{L}{D} \cdot \frac{m_{battery}}{m}$$

- Aircraft with a small mass fraction m_{fuel}/m of energy storage experience a small effect.
- Short range aircraft lose about 5-10% in range.
- Long range aircraft lose about 20-25% of range.
- This effect must be compensated by additional energy or efficiency.



→ fuel mass fraction →

Range of Aircraft with Energy Storage in Batteries

$$R = E^* \cdot \eta_{total} \cdot \frac{1}{g} \cdot \frac{L}{D} \cdot \frac{m_{battery}}{m}$$

- Range with payload

$$R = E^* \cdot \eta_{total} \cdot \frac{1}{g} \cdot \frac{L}{D} \cdot \left(1 - \frac{m_{empty}}{m} - \frac{m_{payload}}{m}\right)$$

- How large is the maximum range with a given technology?
  - payload → zero

$$R_{ult} = E^* \cdot \eta_{total} \cdot \frac{1}{g} \cdot \frac{L}{D} \cdot \left(1 - \frac{m_{empty}}{m}\right)$$

Battery | Systems | Aerodynamics | Structures

  - This limit cannot be exceeded.
  - Limit case, allows for a rapid assessment of “weird” concepts, realistic ranges are always lower!

$$R = E^* \cdot \eta_{total} \cdot \frac{1}{g} \cdot \frac{L}{D} \cdot \left(1 - \frac{m_{empty}}{m} - \frac{m_{payload}}{m}\right)$$

Sizing Equation

Determine required Aircraft Mass for Range

- rearranging the range equation yields the aircraft mass for a given range

$$m = \frac{PAX \cdot m_{pax}}{1 - \frac{m_{empty}}{m} - \frac{g}{E^* \cdot \eta_{total} \cdot L/D} \cdot R}$$

- only a small number of parameters needed:
  - desired range R,
  - number of passengers PAX and mass per PAX m_{pax},
  - empty mass fraction m_{empty}/m,
  - specific energy E* of the battery system,
  - total efficiency of the system from battery to thrust,
  - lift over drag ratio L/D.
  - no direct influence of cruise altitude!
  - for R=0 we obtain the absolute minimum mass of the aircraft.

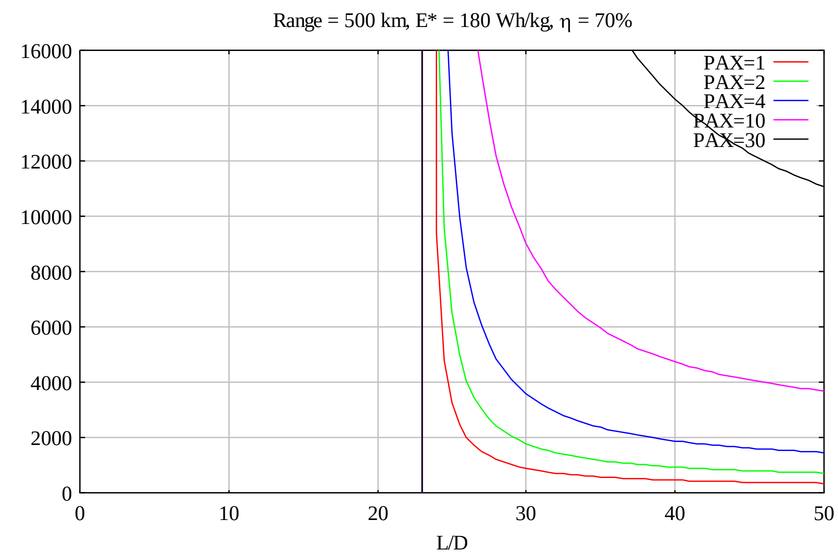
Sizing Limits

- Aircraft mass for given range

$$m = \frac{PAX \cdot m_{pax}}{1 - \frac{m_{empty}}{m} - \frac{g}{E^{*} \cdot \eta_{total} \cdot L/D} \cdot R}$$

- Constraints for solution (m > 0)

$$\frac{L}{D} > \frac{R \cdot g}{\left(1 - m_{empty}/m\right) \cdot E^{*} \cdot \eta_{total}}$$



Sizing Limits

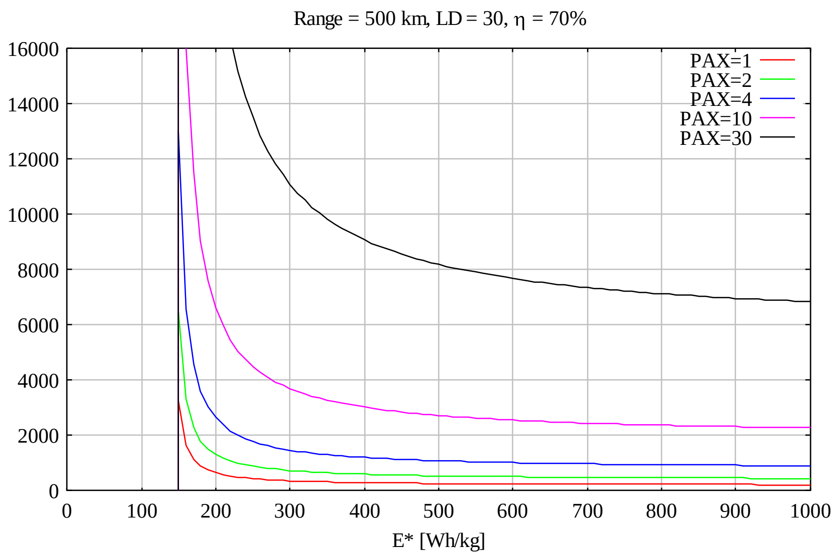
- Aircraft mass for given range

$$m = \frac{PAX \cdot m_{pax}}{1 - \frac{m_{empty}}{m} - \frac{g}{E^* \cdot \eta_{total} \cdot L/D} \cdot R}$$

- Constraints for solution (m > 0)

$$\frac{L}{D} > \frac{R \cdot g}{\left(1 - m_{empty}/m\right) \cdot E^* \cdot \eta_{total}}$$

$$E^* > \frac{R \cdot g}{\left(1 - m_{empty}/m\right) \cdot \eta_{total} \cdot L/D}$$



Sizing Limits

- Aircraft mass for given range

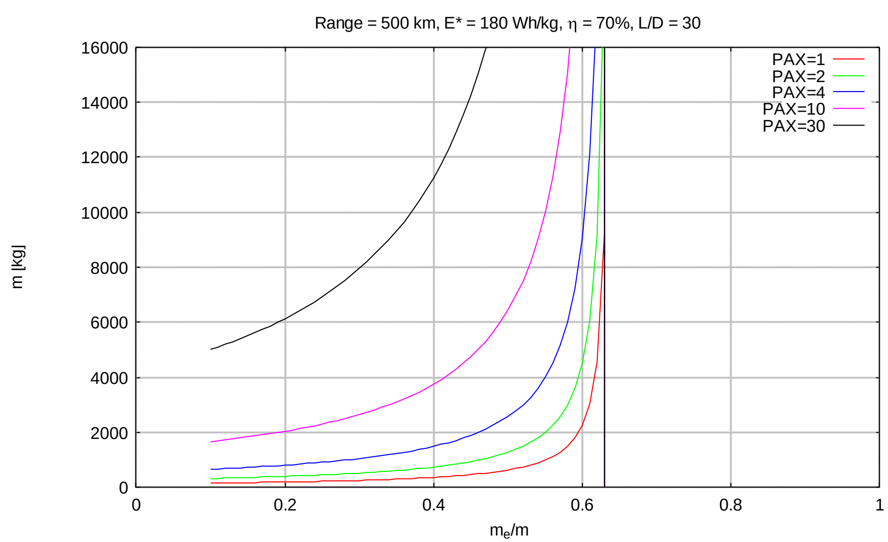
$$m = \frac{PAX \cdot m_{pax}}{1 - \frac{m_{empty}}{m} - \frac{g}{E^* \cdot \eta_{total} \cdot L/D} \cdot R}$$

- Constraints for solution (m > 0)

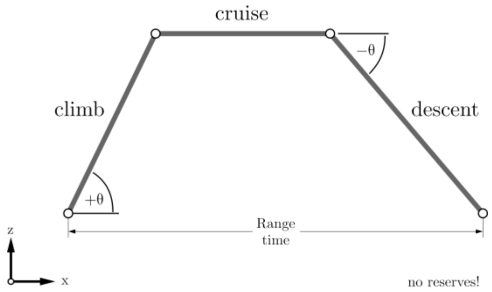
$$\frac{L}{D} > \frac{R \cdot g}{\left(1 - m_{empty}/m\right) \cdot E^* \cdot \eta_{total}}$$

$$E^* > \frac{R \cdot g}{\left(1 - m_{empty}/m\right) \cdot \eta_{total} \cdot L/D}$$

$$\frac{m_{empty}}{m} < 1 - \frac{R \cdot g}{E^* \cdot \eta_{total} \cdot L/D}$$



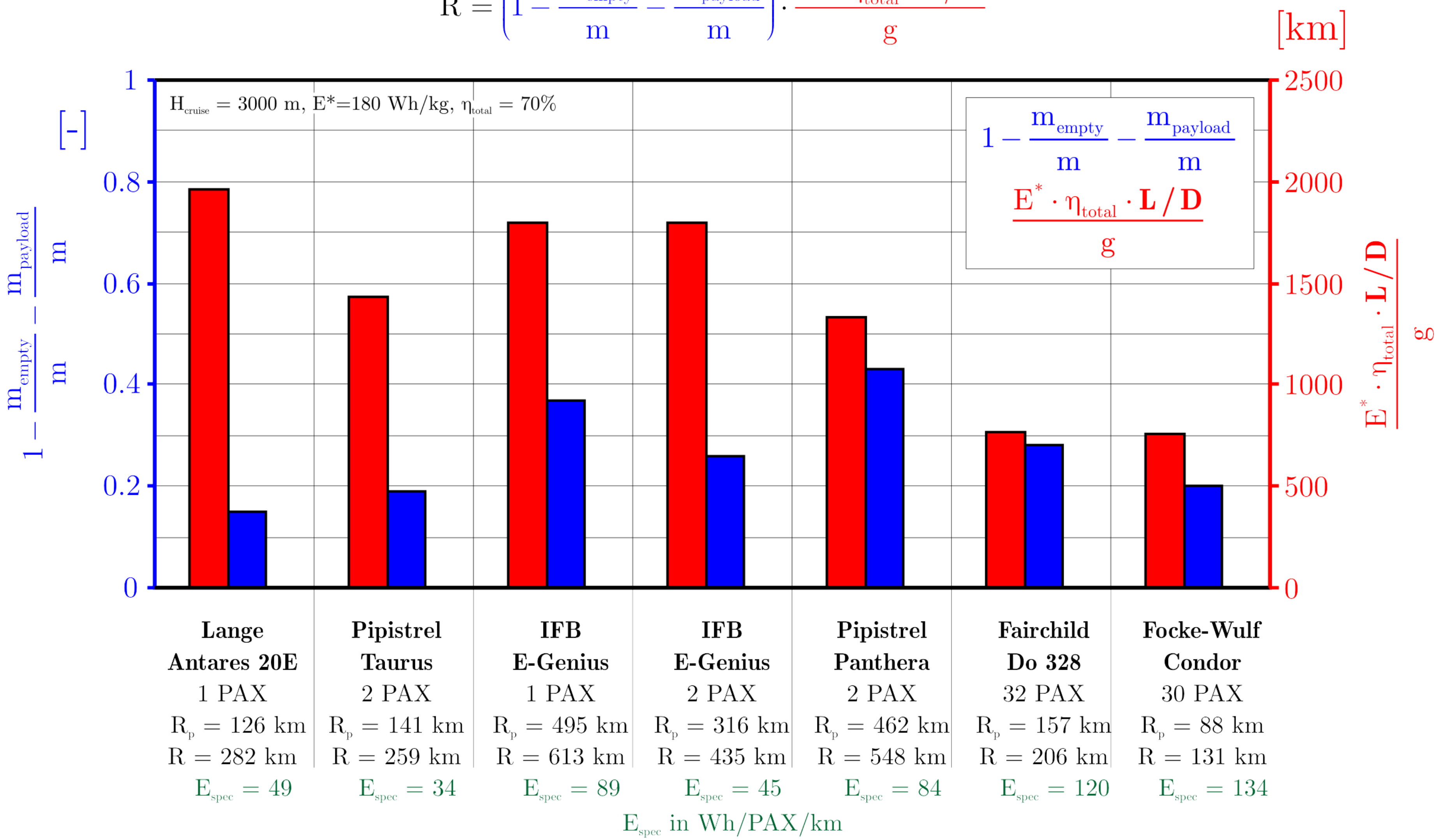
Refined Model



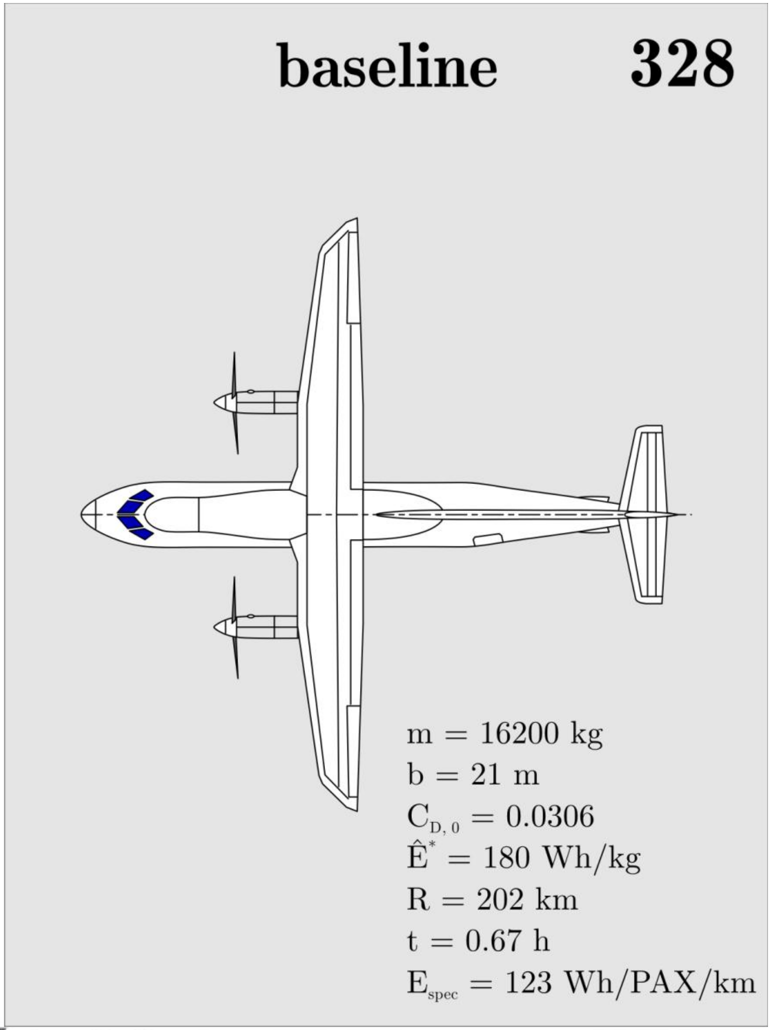
- Aircraft geometry and structures
  - wing span, wing area, empty mass fraction.
- Aerodynamics
  - „square“ polar, zero lift drag, k-factor.
- System
  - Battery: E*, U(t); Motor: P(U), efficiencies.
- Propeller
  - diameter, speed, number → efficiency = f(T, v, H).
- Energy optimized mission
  - climb with optimum speed (incl. propeller),
  - cruise with optimum speed (incl. propeller),
  - descent with max. L/D (only secondary energy consumption),
  - no reserves!

Type	Symbol	Units	Performance Aircraft	Cruiser Aircraft	Cruiser Aircraft	Cruiser Aircraft	Cruiser Aircraft	Regional Aircraft	Regional Aircraft
Example			*Lange Antares 20E*	*Pipistrel Taurus*	*IFB E-Genius*	*IFB E-Genius*	*Pipistrel Panthera*	*Fairchild Do 328*	*Focke-Wulf Condor*
Geometry	b	m	20	15.0	16.7	16.7	10.9	21.0	32.8
	S	m^2	12.6	12.3	14.3	14.3	10.9	40	118
	AR	-	31.8	18.2	19.9	19.9	10.8	11	9.1
Payload	PAX	-	1	2	1	2	2	32	30
Aero	L/D	-	42	32	38	38	29	16	16
	m/S	kg/m^2	42.1	44.2	59.2	59.7	110.1	397	131.8
	m/b^2	kg/m^2	1.3	2.4	3.0	3.0	10.2	36.1	14.5
	$C_{D,0}$	-	0.0118 (2)	0.0142 (2)	0.0103	0.0103	0.0100	0.0306	0.0250
Masses	m	kg	530	545	850	850	1200	15880	15400
	m_{empty}	kg	360	264	450	450	500	8500	9700
	$m_{battery}$	kg	80	101	310	220	520	4500	3000
	m_{empty}/m	-	0.68	0.48	0.53	0.53	0.42	0.54	0.63
	$m_{battery}/m$	-	0.15	0.19	0.37	0.26	0.43	0.28	0.19
	$m_{payload}/m$	-	0.17	0.33	0.10	0.21	0.15	0.18	0.18
Battery power	P_{climb}	kW	47	46	67	67	139	3799	2605
	P_{cruise}	kW	5	8	11	11	33	1102	690
Range	$R_{powered}$	km	126	141	495	316	462	157	88
	R	km	282	259	613	435	548	206	131
	$R_{ultimate}$ (3)	km	622	774	835	835	776	351	280
	$1 - f_e - f_p$	-	0.15	0.19	0.37	0.26	0.43	0.28	0.20
	$E^* \eta L/D/g$	km	1960	1436	1800	1800	1330	765	758
Time	$t_{powered}$	h	1.29	1.3	3.9	2.5	2.3	0.5	0.5
	t	h	2.4	2.2	4.8	3.4	2.6	0.7	0.6
Verbrauch	E_{spec}	Wh/PAX/km	49	34	89	45	84	120	134
Kerosin	E_{equiv}	l/PAX/100km	1.05	0.73	2.04	1.02	1.92	2.79	3.02
Altitude	H	m	3000	3000	3000	3000	3000	3000	3000

$$R = \left(1 - \frac{m_{empty}}{m} - \frac{m_{payload}}{m}\right) \cdot \frac{E^{*} \cdot \eta_{total} \cdot L/D}{g}$$



Example: Regional Aircraft



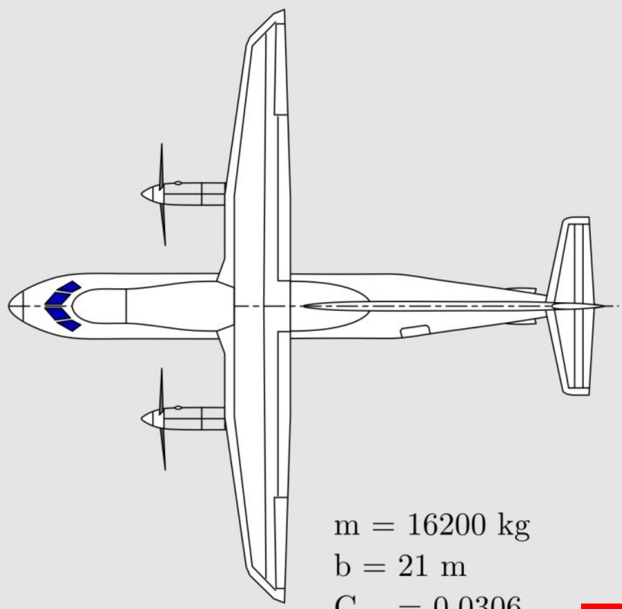
- The range of the aircraft with 32 passengers is about 1200 km.
- With full tanks and 28 passengers it grows to 2200 km.
- The lift over drag ratio is about 16.

- Modification:
  Replacing fuel system and engines by an electric system of identical mass.
- With current technology the aircraft would reach a range of 202 km, however without any reserves (with reserves: R=50 km).

$C_{D,0}$

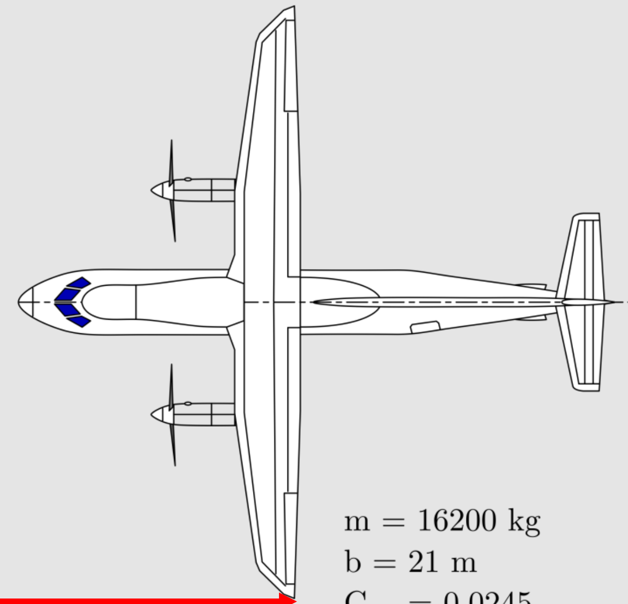
zero lift drag reduced by 20%

baseline 328



$m = 16200$ kg
$b = 21$ m
$C_{D,0} = 0.0306$
$\hat{E}^* = 180$ Wh/kg
$R = 202$ km
$t = 0.67$ h
$E_{spec} = 123$ Wh/PAX/km

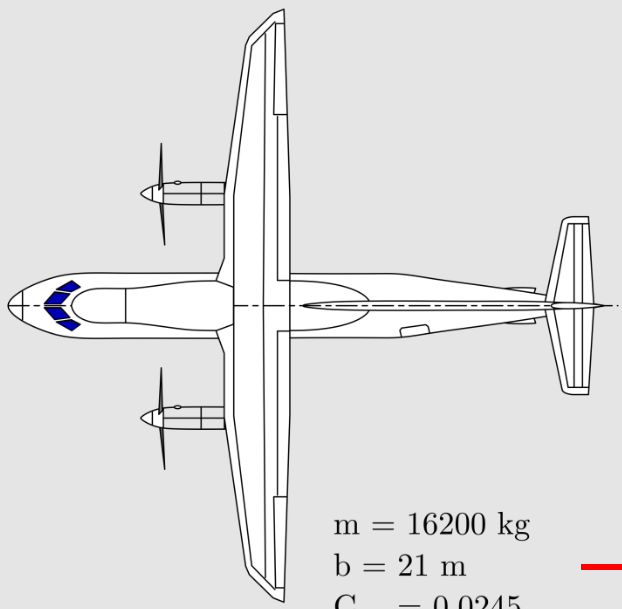
328-L



$m = 16200$ kg
$b = 21$ m
$C_{D,0} = 0.0245$
$E^* = 180$ Wh/kg
$R = 221$ km
$t = 0.67$ h
$E_{spec} = 112$ Wh/PAX/km

$C_{D,0}$	b
zero lift drag reduced by 20%	**span increased by 50%**

328-L



$m = 16200$ kg
$b = 21$ m
$C_{D,0} = 0.0245$
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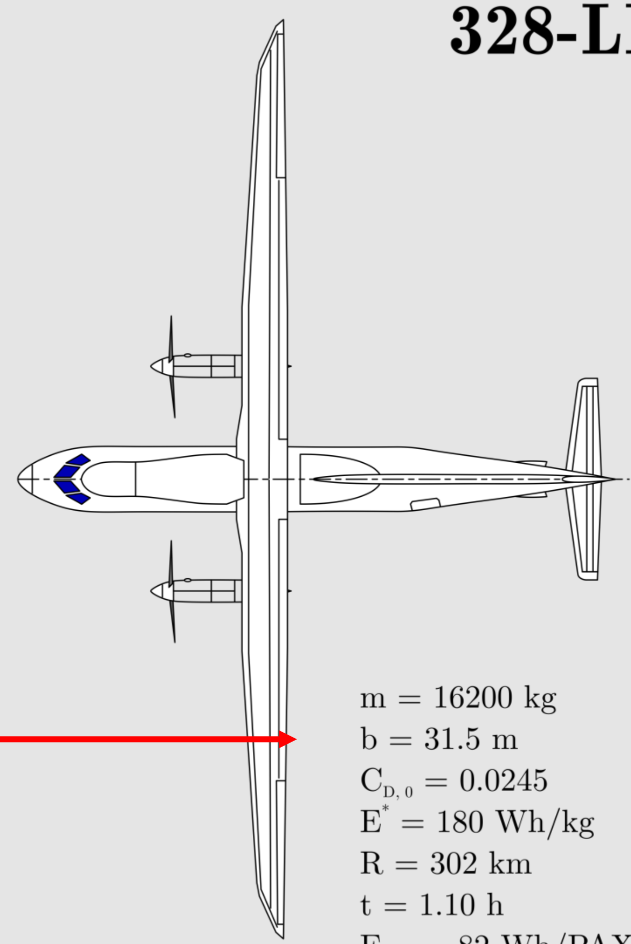
$R = 221$ km
$t = 0.67$ h
$E_{spec} = 112$ Wh/PAX/km

328-LB



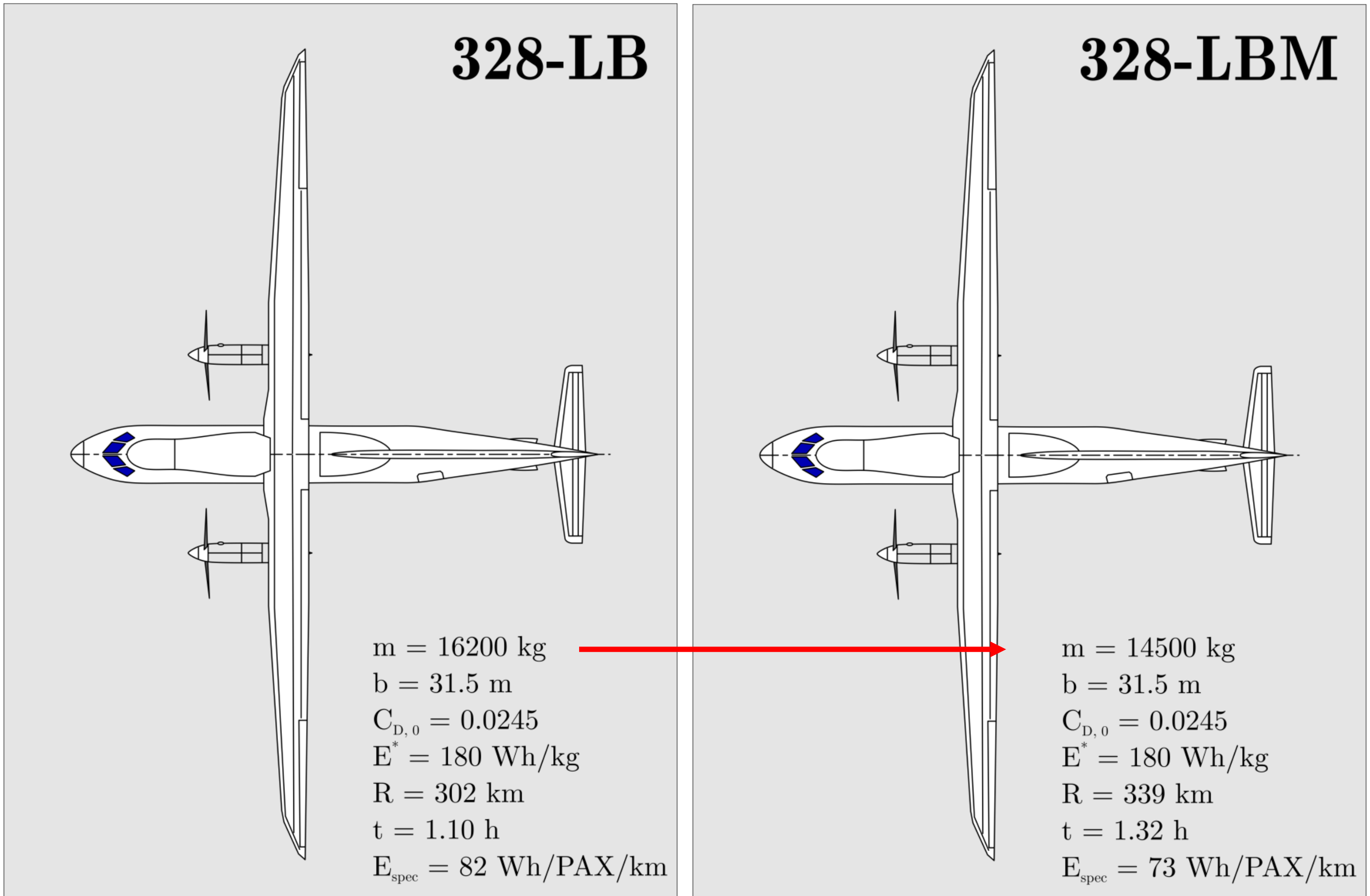
$m = 16200$ kg
$b = 31.5$ m
$C_{D,0} = 0.0245$
$E^{*} = 180$ Wh/kg
$R = 302$ km
$t = 1.10$ h
$E_{spec} = 82$ Wh/PAX/km

b

span increased by 50%

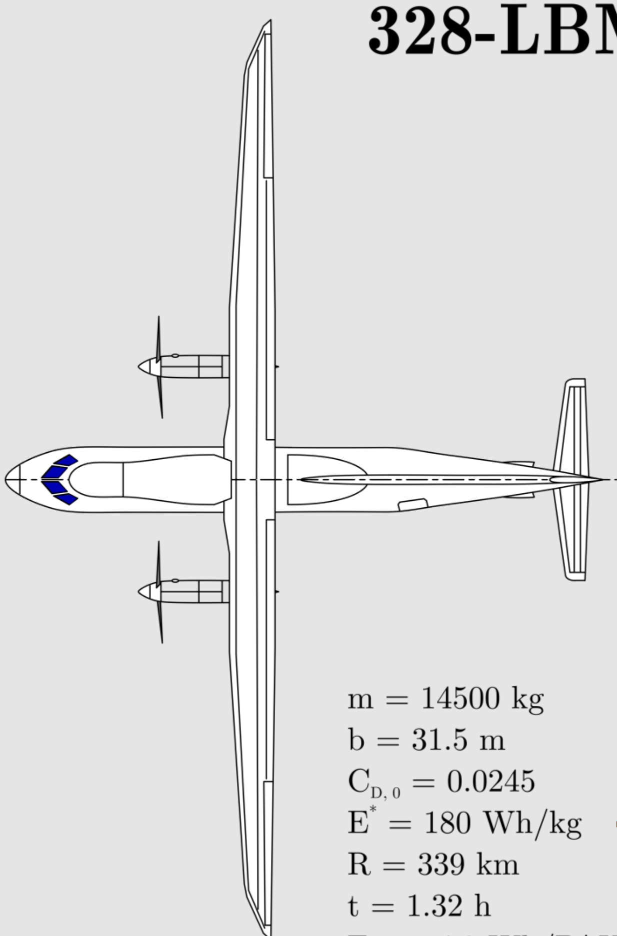
m_e

empty mass reduced by 20%



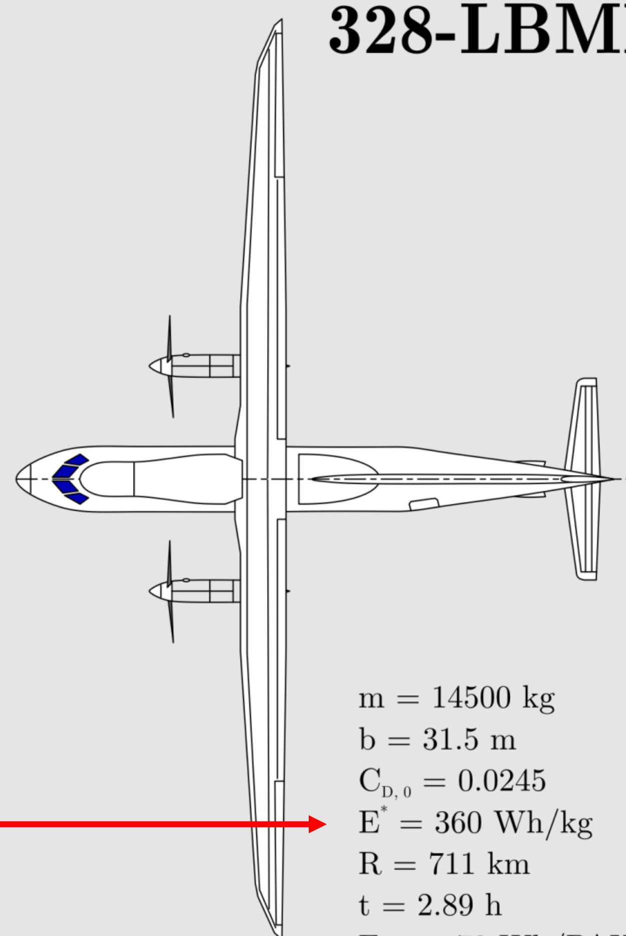
m_e	E^*
empty mass reduced by 20%	**E^* doubled to 360 Wh/kg**

328-LBM



$m = 14500$ kg
$b = 31.5$ m
$C_{D,0} = 0.0245$
$E^* = 180$ Wh/kg
$R = 339$ km
$t = 1.32$ h
$E_{spec} = 73$ Wh/PAX/km

328-LBME



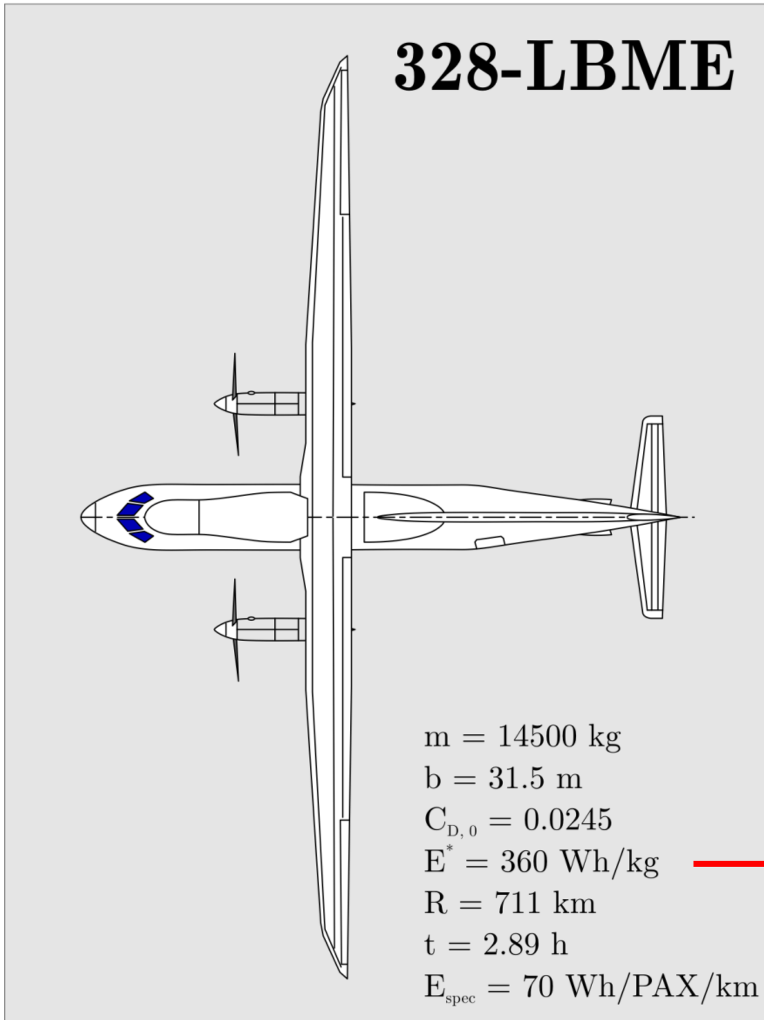
$m = 14500$ kg
$b = 31.5$ m
$C_{D,0} = 0.0245$
$E^* = 360$ Wh/kg
$R = 711$ km
$t = 2.89$ h
$E_{spec} = 70$ Wh/PAX/km

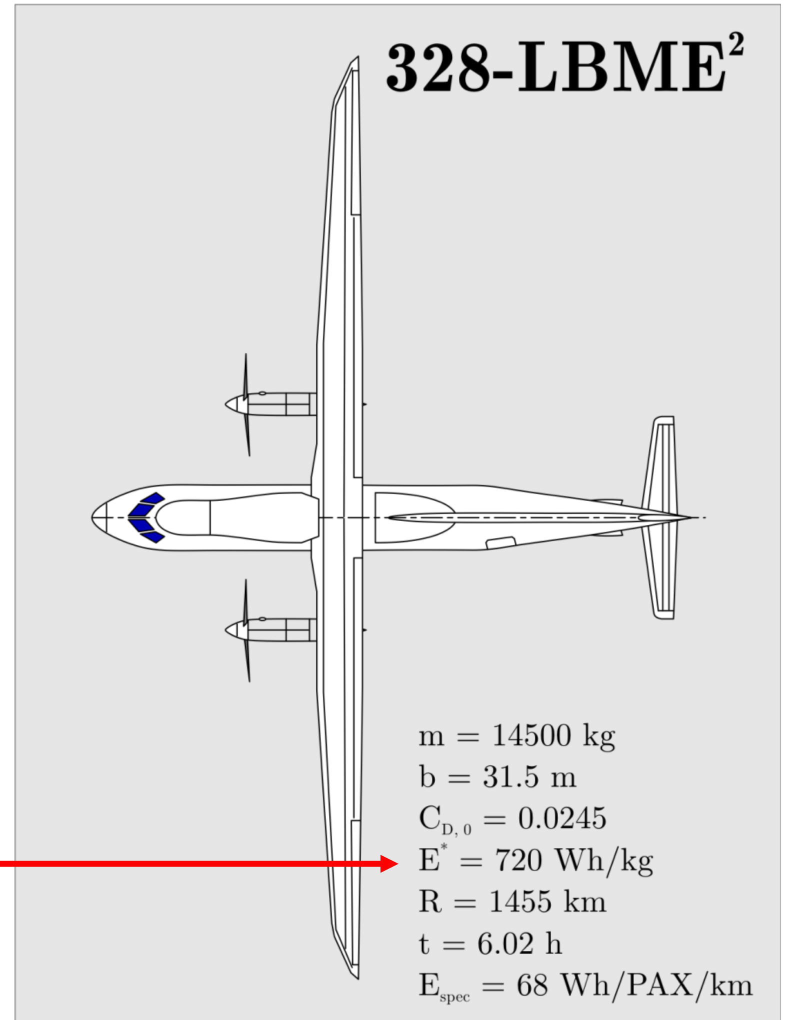
E^*

E* doubled to 360 Wh/kg

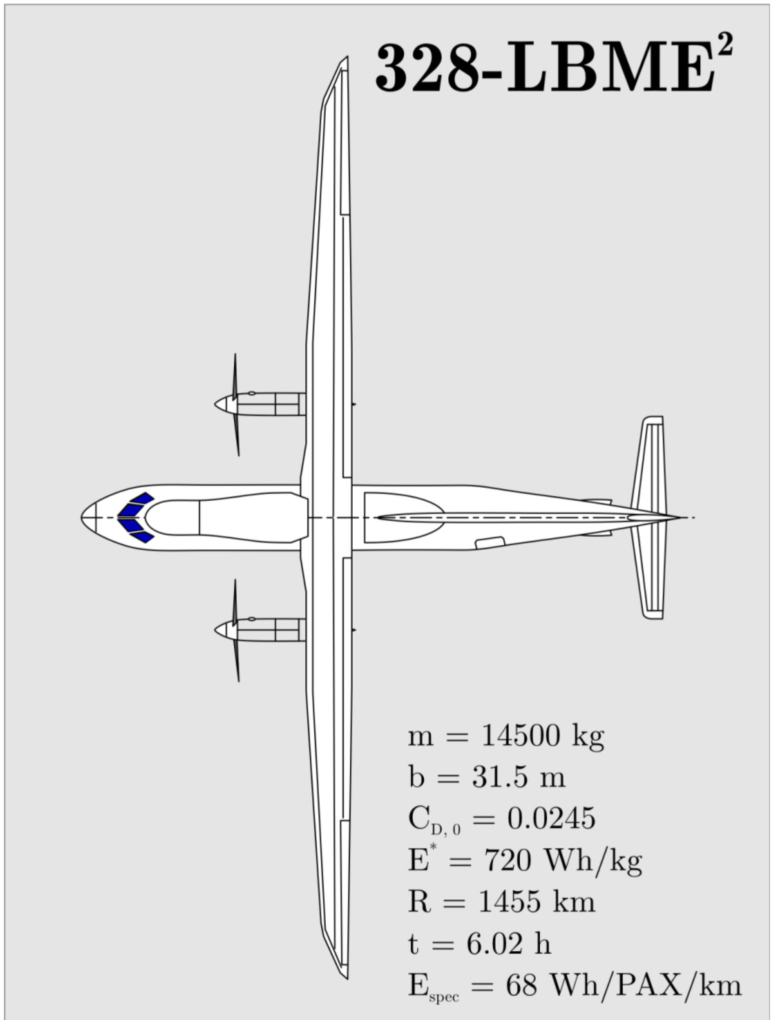
E^*

E* increased to 720 Wh/kg



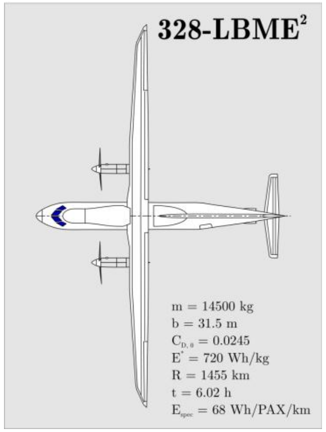


Big Steps in Technology Development are Required.

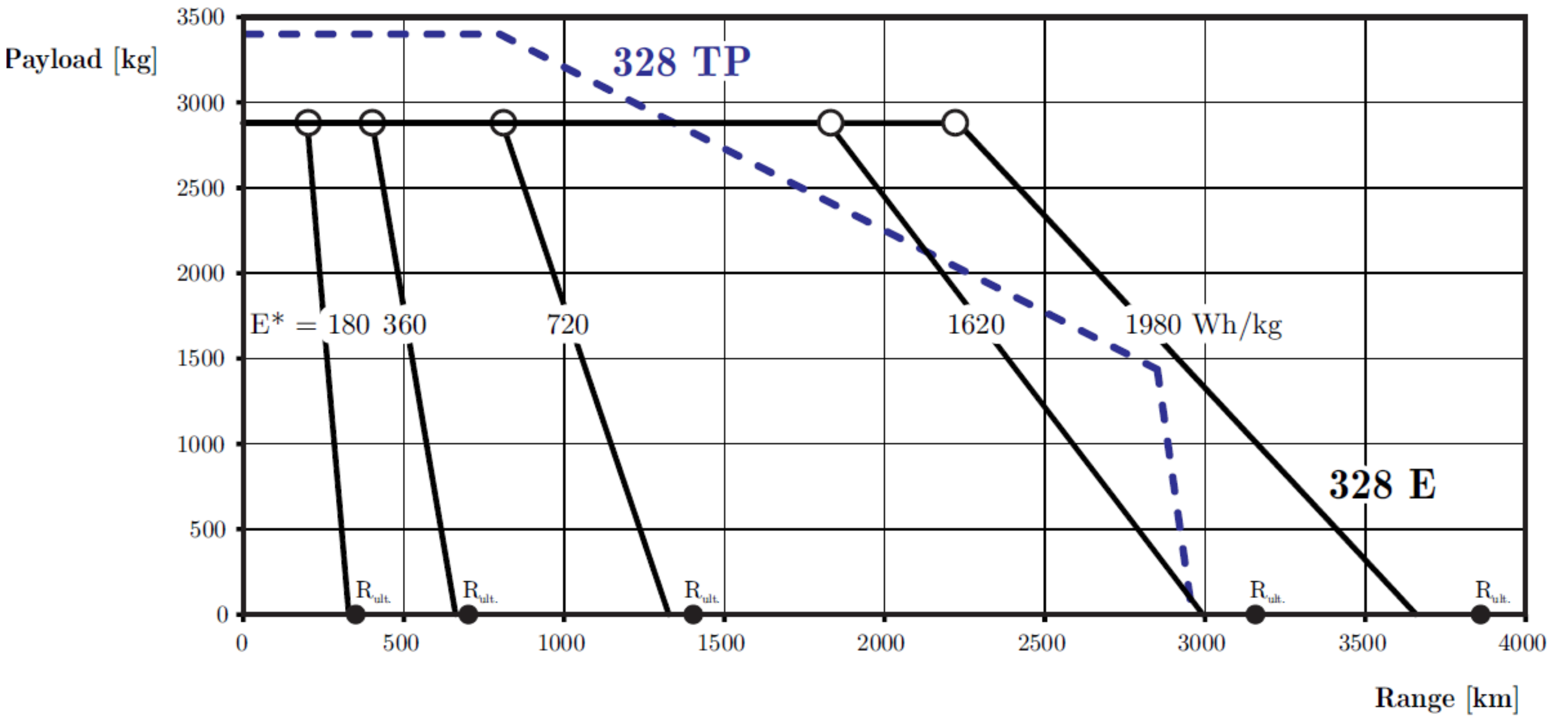


- Energy optimized flight:
  - The cruise speed drops due to higher wing span below 300 km/h
    (The turboprop variant flies at 480 km/h.)
  - L/D = 16 → 27.5
  - The high aspect ratio requires high lift coefficients (climb: 0.9, cruise: 1.2).
  - Consumption with a turboprop would be about
    1.5 Liter/PAX/100km

Note on Range Flexibility



- Trading fuel / batteries for range is more useful for (lightweight) kerosene than for (heavy) batteries.



Battery Powered Aircraft?

- Conclusions:
  - Electric propulsion systems with batteries are possible for small aircraft,
  - The range is strongly limited, but useable for General Aviation and UAVs,
  - For larger aircraft the battery technology must be drastically improved
    to at least 1000 Wh/kg (factor 5),
    This seems to be unlikely within the next 10 years, but may be within 20-40 years.
  - Costs are less relevant as they will shrink due to automotive and consumer industry.

- Many Open Questions:
  - What is the total balance including production and recycling?
    - Are the raw materials for automotive and aviation available in the long term?
    - What happens in hydrogen technology (storage problem)?
    - What happens in fuel cell technology (cost, efficiency)?
    - Should we better use bio fuels, alcohol , synthetic fuels or hydrogen in conventional propulsion systems?
  - What about safety of electric propulsion systems?
    - We are not (yet) accustomed to all-electric aircraft,.
    - Fire in case of damage or crash, effects when ditching in water,
    - Electric interference (high voltages and currents vs. mobile phones).

There is nothing new under the sun...
One of the Pioneers of Electric Flight

- Fred Militky
  - 1940 first trials, after 1945 chief engineer at Graupner.
  - Motor glider MB-E1 (HB-3, b=12 m, m = 440 kg)
    - 21. October 1973: worldwide first flight with electric motor,
    - duration 9-14 Min, altitude 360 m, Pilot Heino Brditschka,
    - performance not reached for 10 years,
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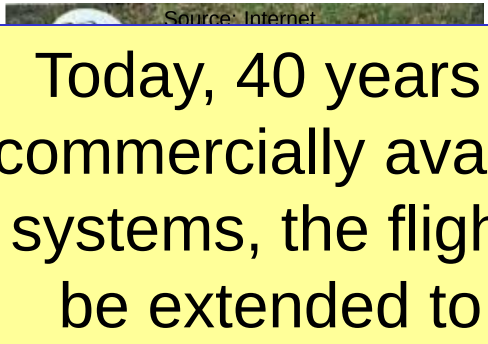
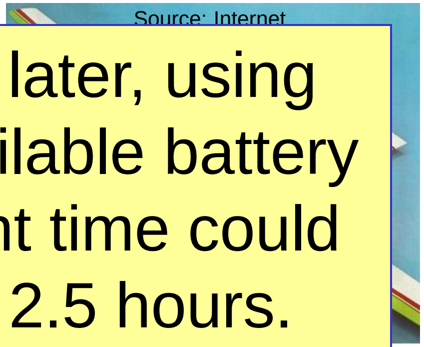

Source: Internet


Source: Internet

Today, 40 years later, using commercially available battery systems, the flight time could be extended to 2.5 hours.

Source: Brditschka

1973 MB-E1

Return to the Future with Whole Milk?

Thank You for Listening!