Seminario

IL TRASPORTO AEREO DEL FUTURO

Aula Bobbio, Università di Napoli Federico II
5 APRILE 2022

Design of hybrid/electric aircraft and feasibility study of 19/50 pax commuter/regional turboprop

Fabrizio Nicolosi
Dip. Ingegneria Industriale

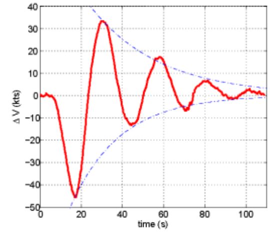
Università degli Studi di Napoli Federico II

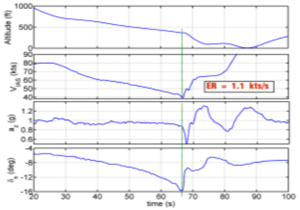
Dipartimento di Ingegneria Industriale

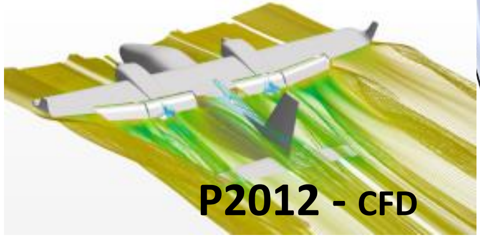
Design of Aircraft and Flight technologies
RESEARCH GROUP
www.daf.unina.it

Research activities
FLIGHT PHYSICS

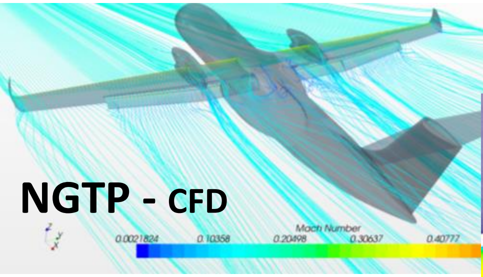
P2006
Flight Tests



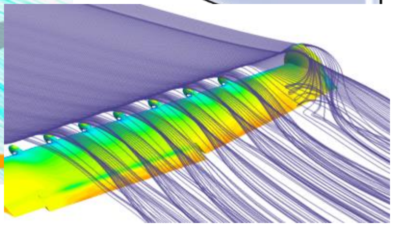


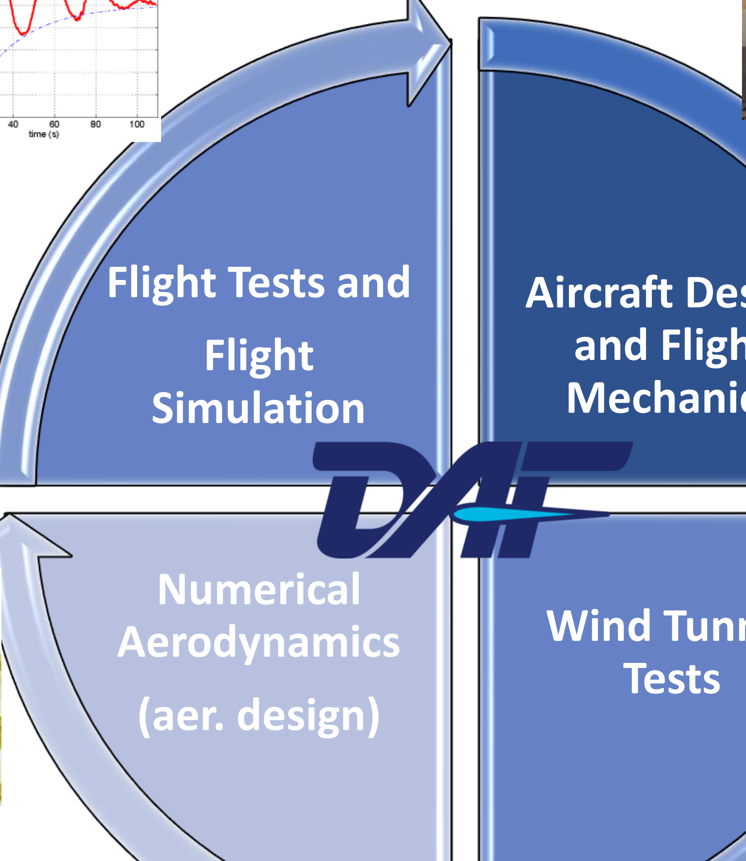


P2012 - CFD



NGTP - CFD



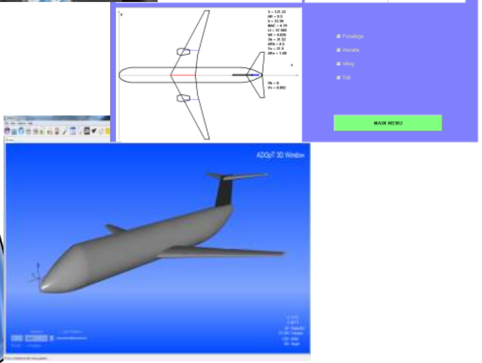


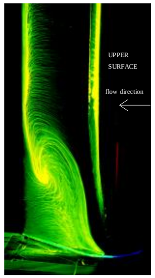
Flight Tests and Flight Simulation

Aircraft Design and Flight Mechanics

Numerical Aerodynamics (aer. design)

Wind Tunnel Tests





P2012
WT Tests

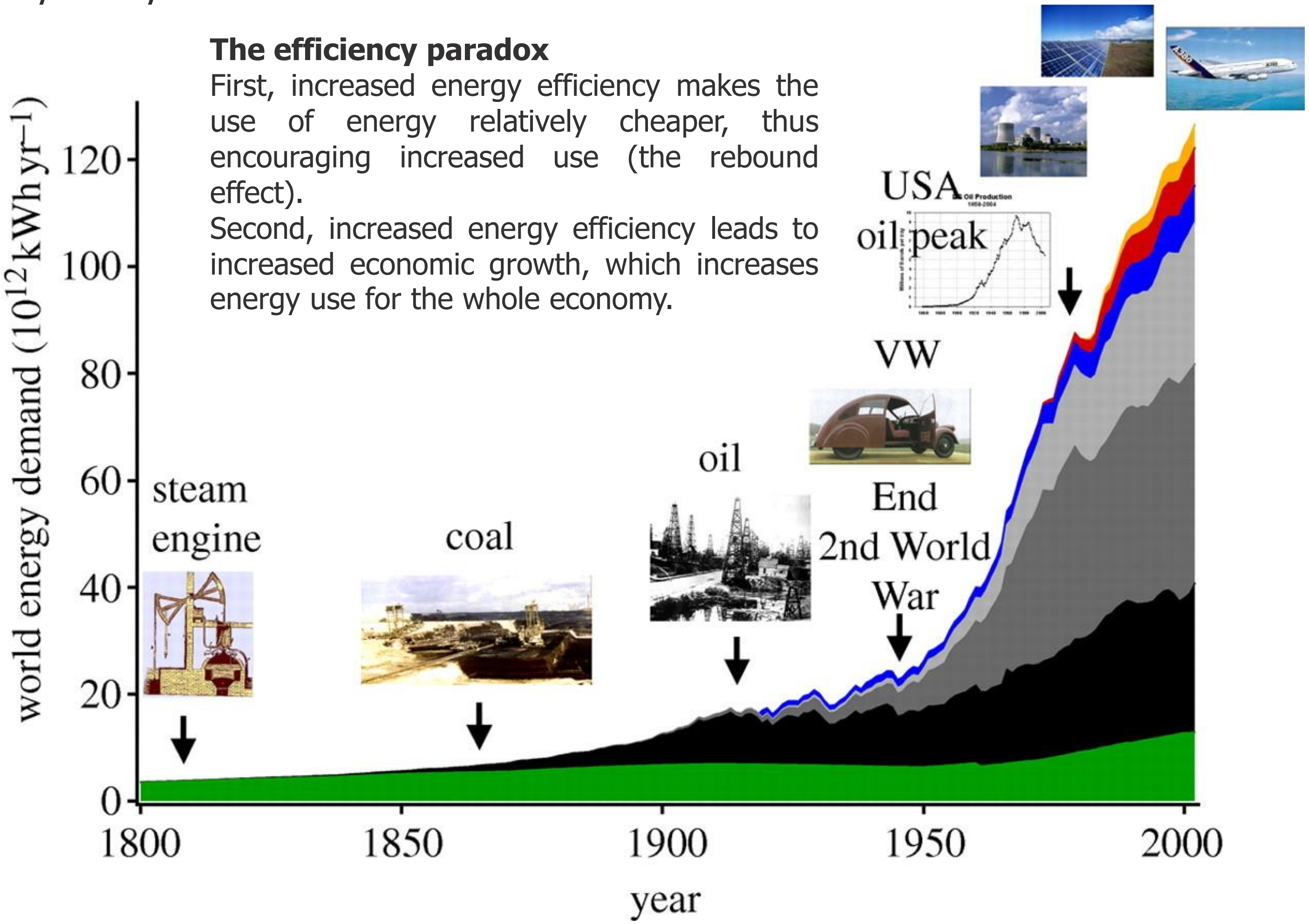
Energy demand

The population of human beings increased during the twentieth century by a factor of **6**, but the energy consumption increased by a factor of **80**. The worldwide average continuous power consumption today is 2 kW *per capita*.

1900-2000

- Popolazione x 6
- Energia x 80

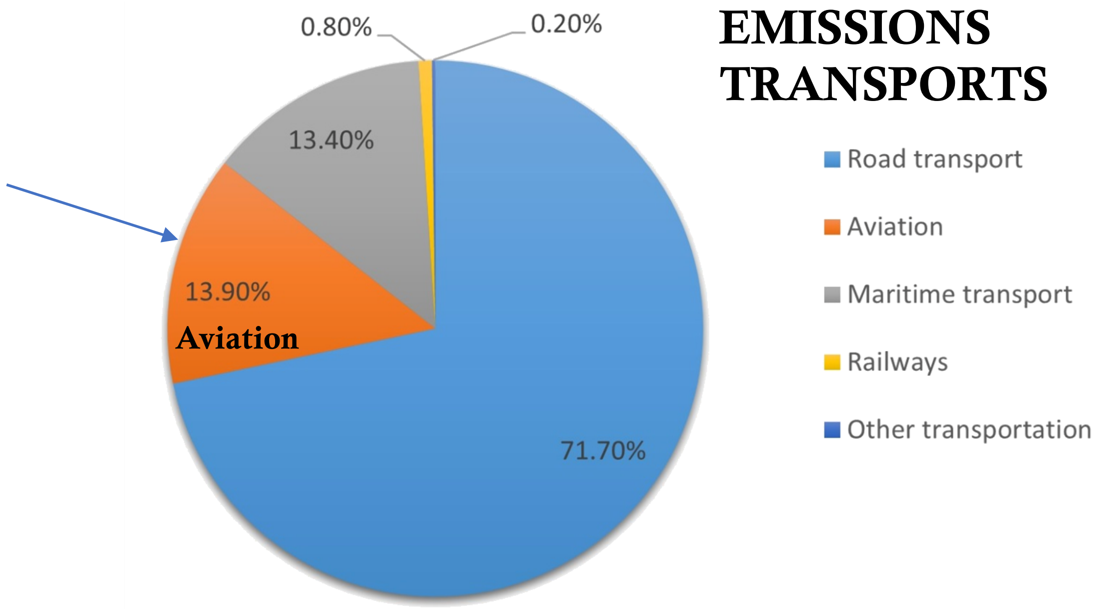
The efficiency paradox
First, increased energy efficiency makes the use of energy relatively cheaper, thus encouraging increased use (the rebound effect).
Second, increased energy efficiency leads to increased economic growth, which increases energy use for the whole economy.

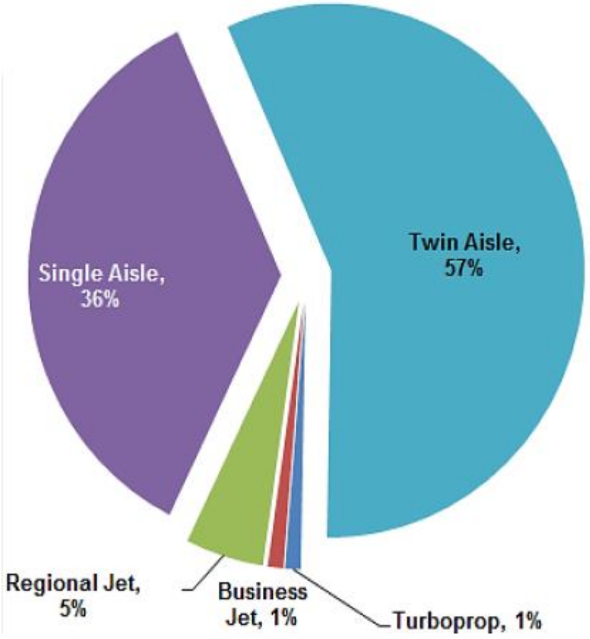


Impatto inquinante del settore aeronautico

L'aviazione è la seconda principale fonte di inquinamento tra i **trasporti**

Circa **2-3% delle emissioni globali** (non solo settore trasporti)





Global civil aviation fuel consumption
Yutko and Hansman, 2011

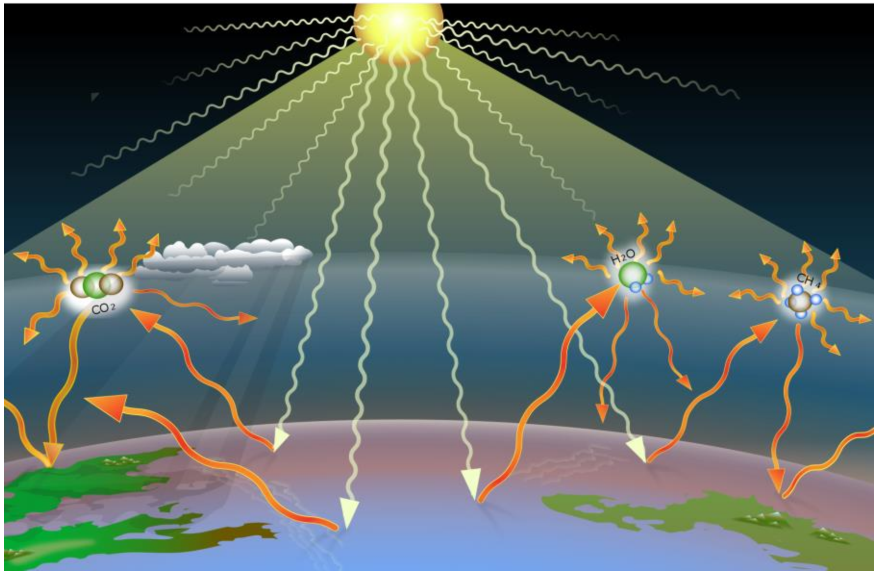
More than 90% of emission due to large transport jet aircraft (more than 100 pax)
However, due to strong limitations due to battery weight, first applications for electric/hybrid propulsive systems have been developed and will be Implemented on regional turbopropo and general aviation aircraft

GWP and AP

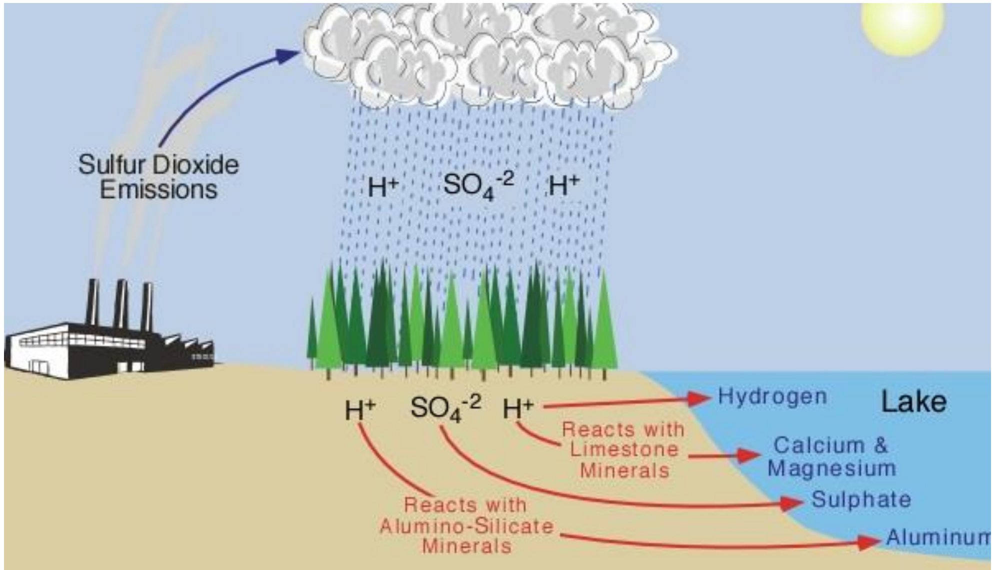
Le emissioni considerate sono: CO_2 H_2O CO SO_x NO_x

Anidride carbonica, monossido di carbonio, ossidi di zolfo e ossidi di azoto

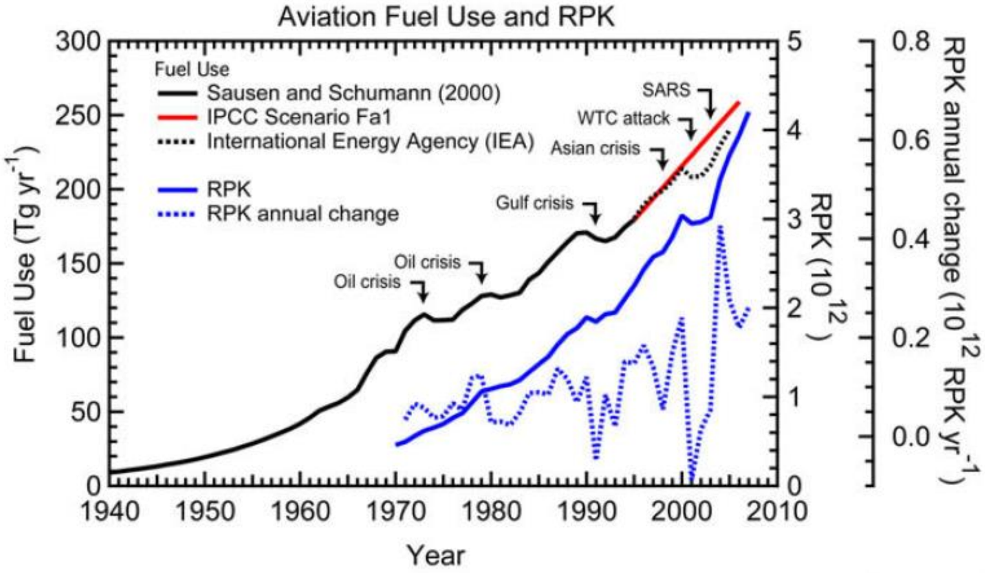
Global Warming Potential



Acidification Potential

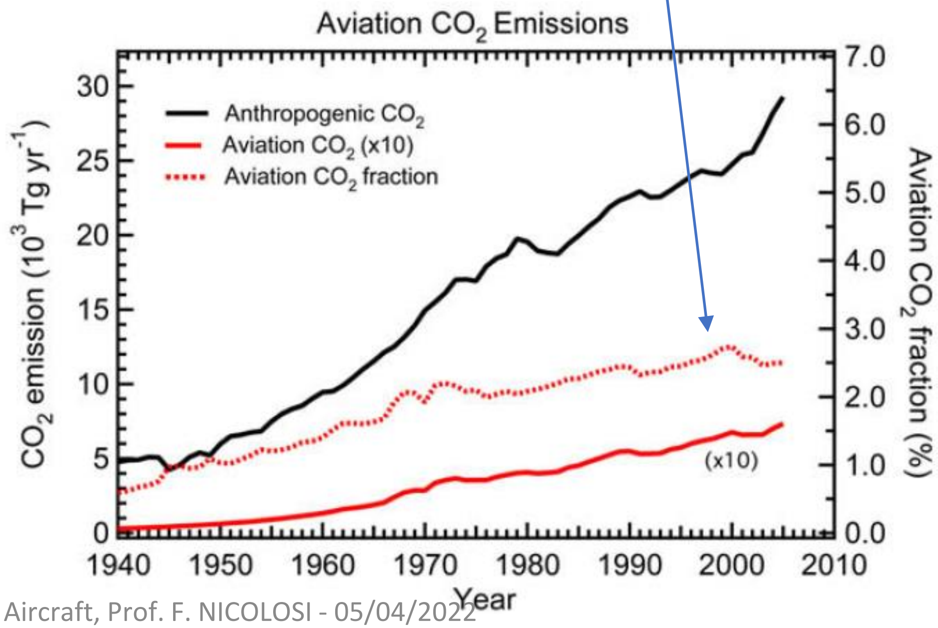


CO2 emission and Aviation Transport Volume



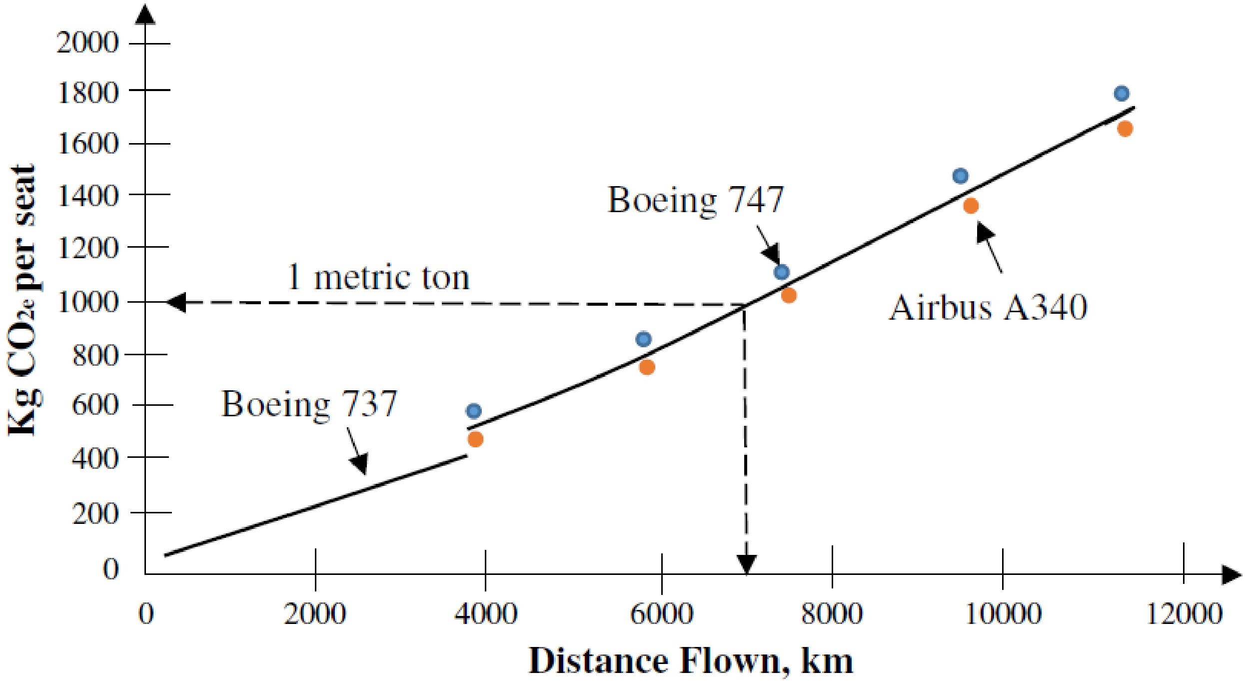
% of Emissions due to Aviation is rising due to the increase of Traffic Volume

Aviation passenger transport volume in terms of revenue passenger kilometres (RPK) has continued to grow strongly at an average rate of 5.2% per annum over the period 1992–2005, despite world-changing events such as the first Gulf War, the World Trade Center attack and outbreaks of Severe Acute respiratory Syndrome (SARS)



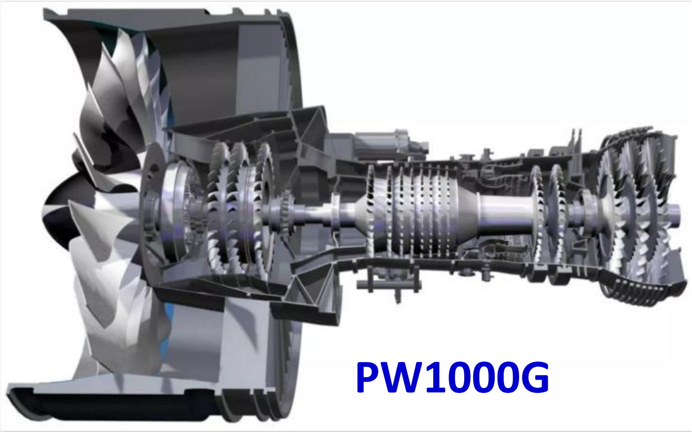
10^3 Tg/y= Miliardi di tonnellate/anno

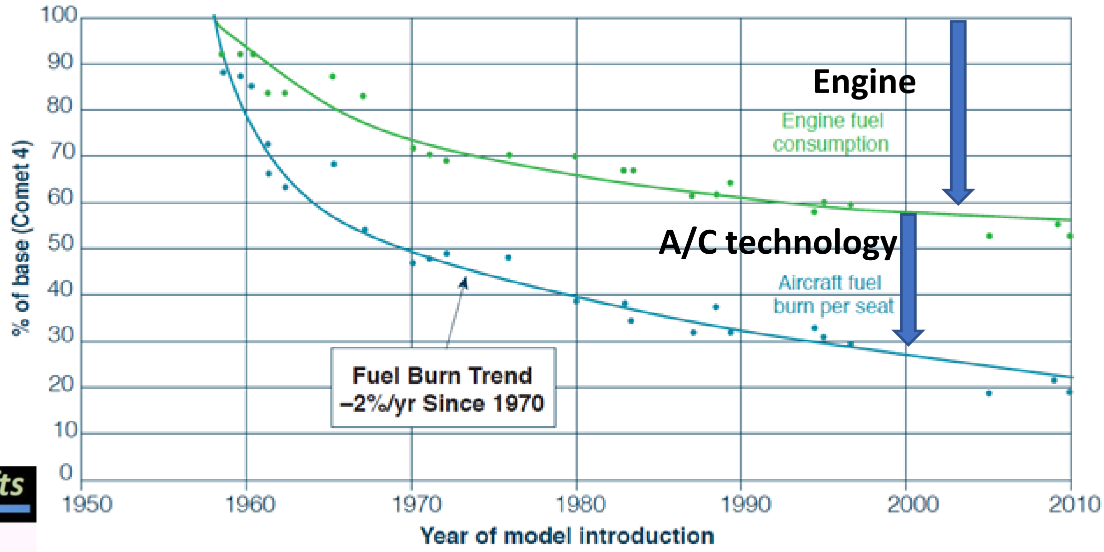
Toward Carbon Neutral Growth

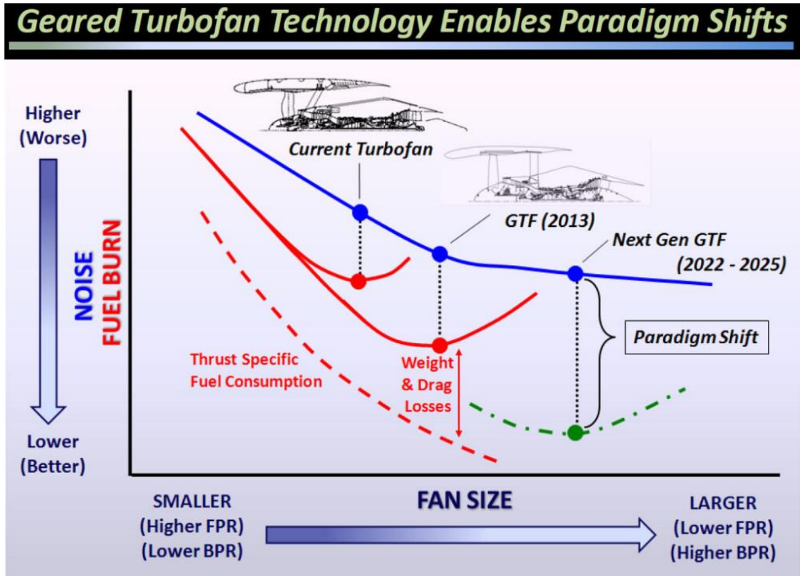


Here it is shown the emission *per seat* for three aircraft, in *equivalent* kilogram of CO2e, which accounts for the overall impact of aircraft CO2 emissions that include the lifecycle GHG emissions attributable to the aircraft fuel that includes its broader environmental impact on eco system. To put some of these numbers in perspective, a 7000 km (or 4350 mi) trip creates 1 metric ton of CO2 emission per seat.

Improving Gas-Turbine Engine efficiency and aircraft technology

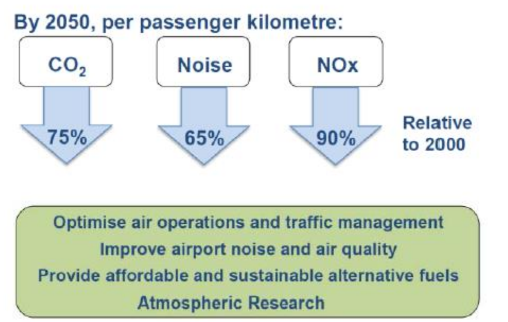






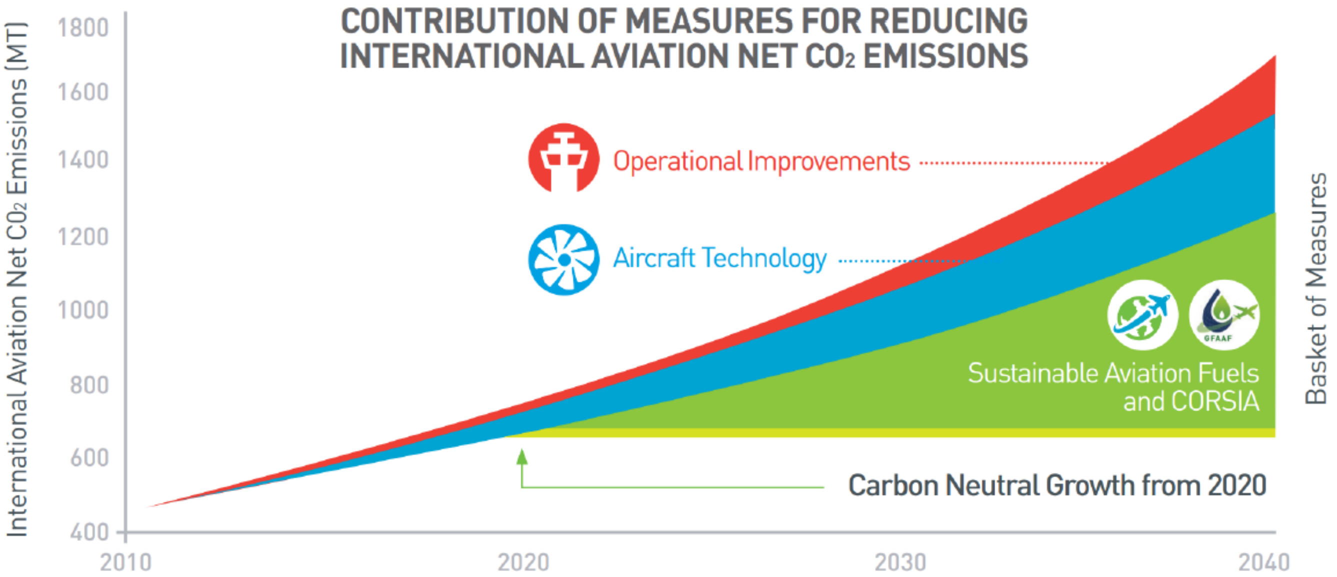
Toward Carbon Neutral Growth

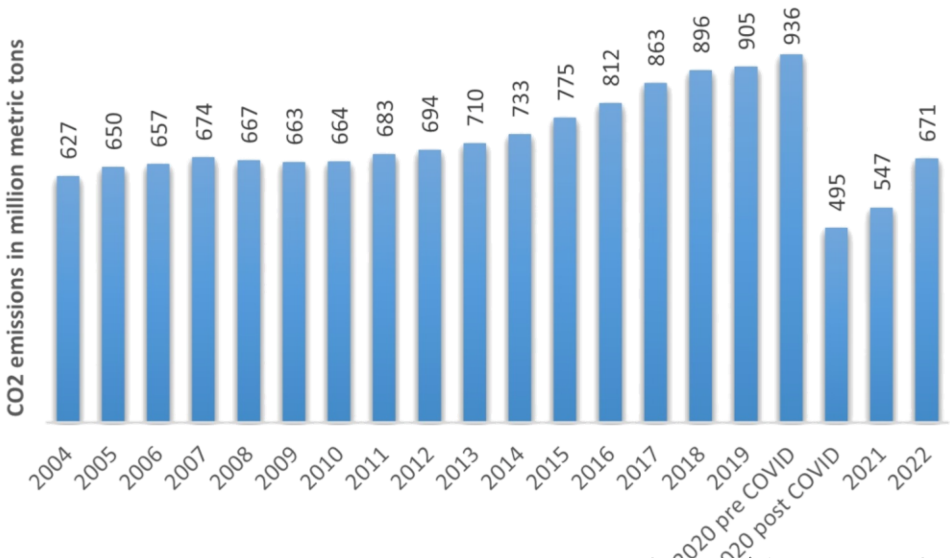
ACARE's Flightpath 2050:



By 2050, per passenger kilometre:

Optimise air operations and traffic management
Improve airport noise and air quality
Provide affordable and sustainable alternative fuels
Atmospheric Research

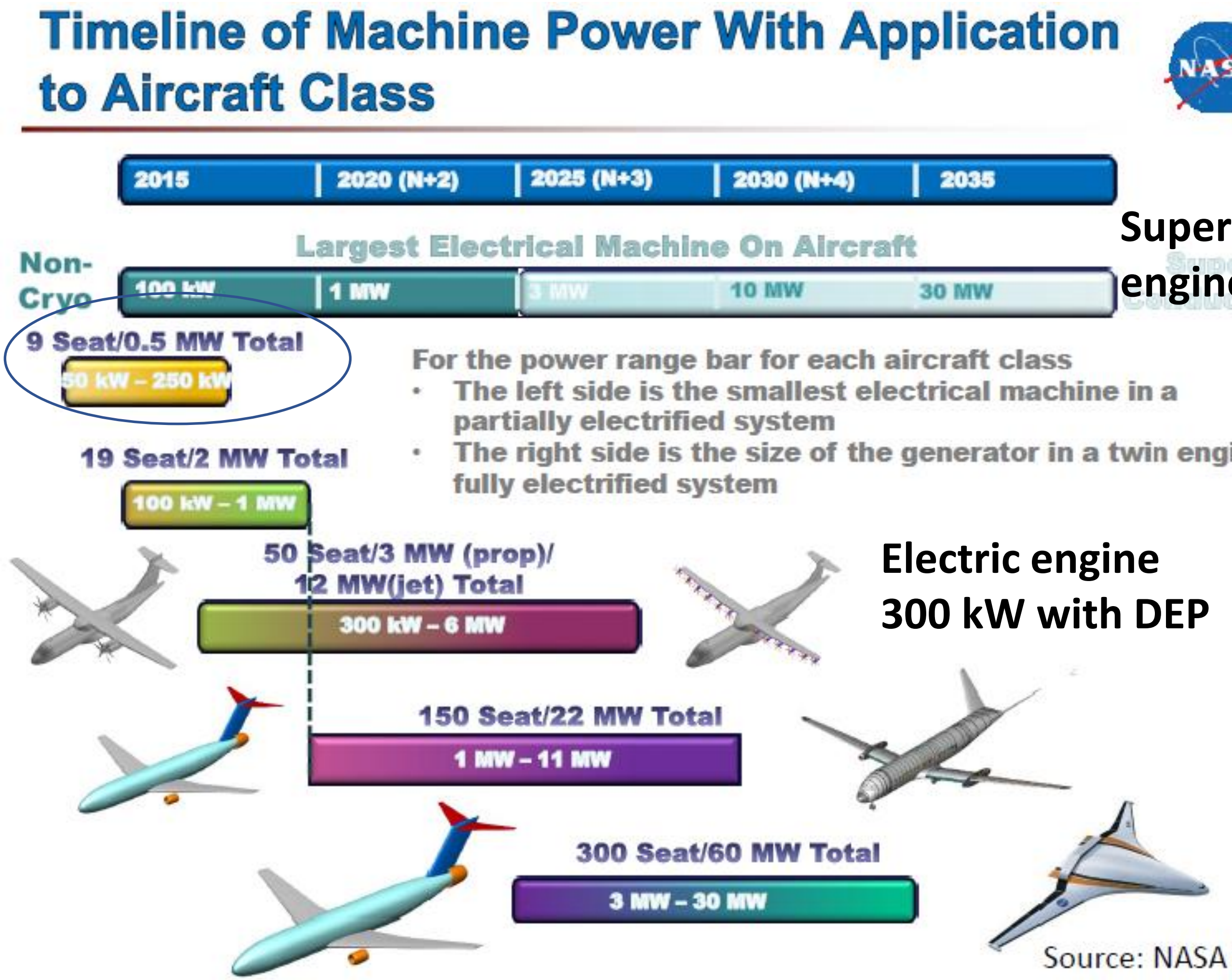




Prima del COVID-19 si prevedeva per il 2050 un valore triplo di emissioni rispetto al 2015.

Il Covid ha cambiato questa prospettiva, ma la previsione è scesa solo a poco più del doppio.

Electric propulsion technology



Timeline of Machine Power With Application to Aircraft Class

2015 | 2020 (N+2) | 2025 (N+3) | 2030 (N+4) | 2035

Largest Electrical Machine On Aircraft

Non-Cryo: 100 kW | 1 MW

Super Conducting: 3 MW | 10 MW | 30 MW

9 Seat/0.5 MW Total: 50 kW – 250 kW

19 Seat/2 MW Total: 100 kW – 1 MW

50 Seat/3 MW (prop)/12 MW(jet) Total: 300 kW – 6 MW

150 Seat/22 MW Total: 1 MW – 11 MW

300 Seat/60 MW Total: 3 MW – 30 MW

For the power range bar for each aircraft class
- The left side is the smallest electrical machine in a partially electrified system
- The right side is the size of the generator in a twin engine fully electrified system

Source: NASA

Super conducting engine ?

Electric engine 300 kW with DEP

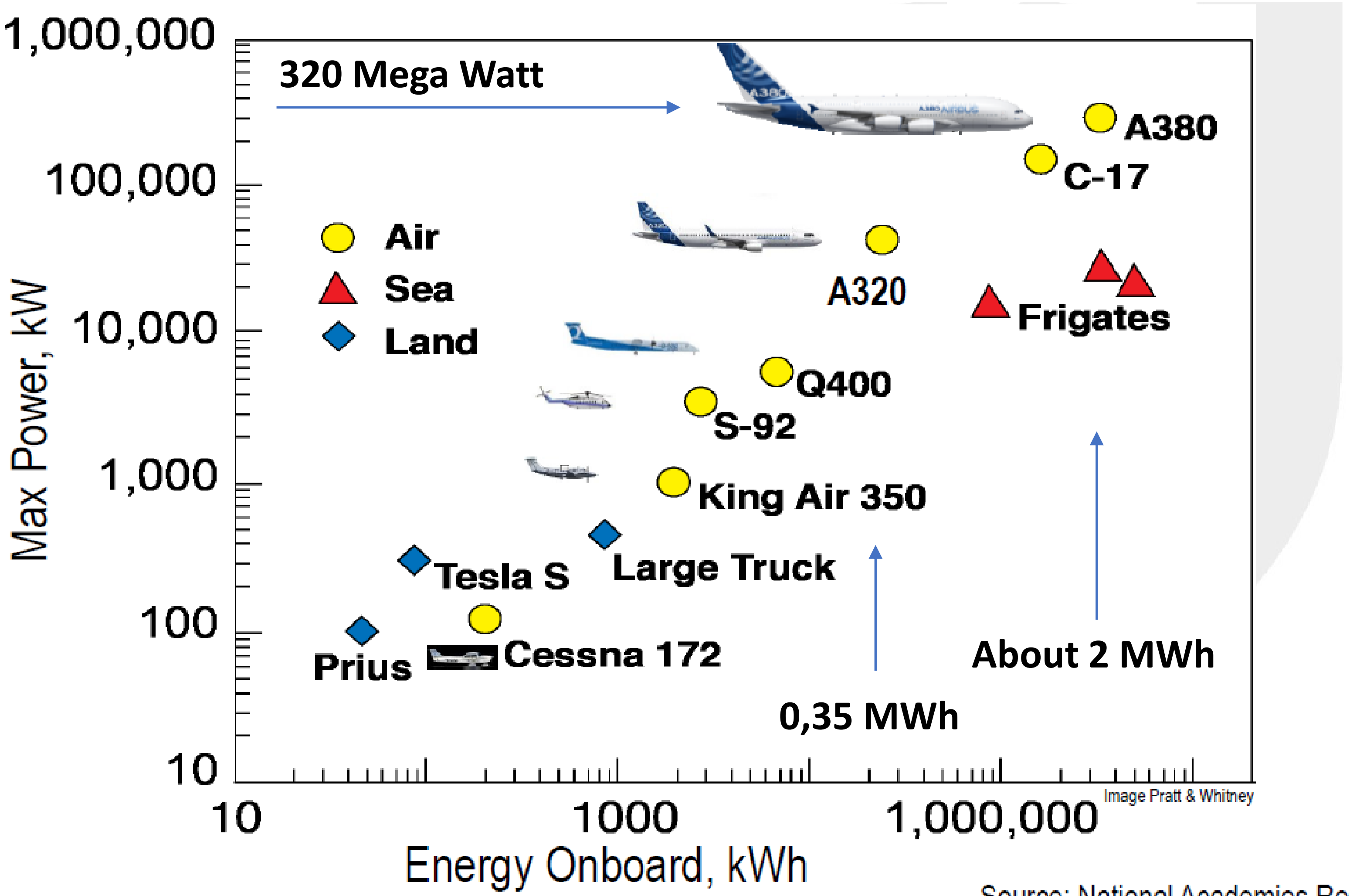
Electric Motor Drive size

P_{cont} = 261 kW
N_{max} = 2500 rpm
M_{cont} = 1000 Nm
η_{260kW} = 95 %

- P_{mech} : 0,26 MW continuous,
- scalable
- Power density: 5 kW/kg

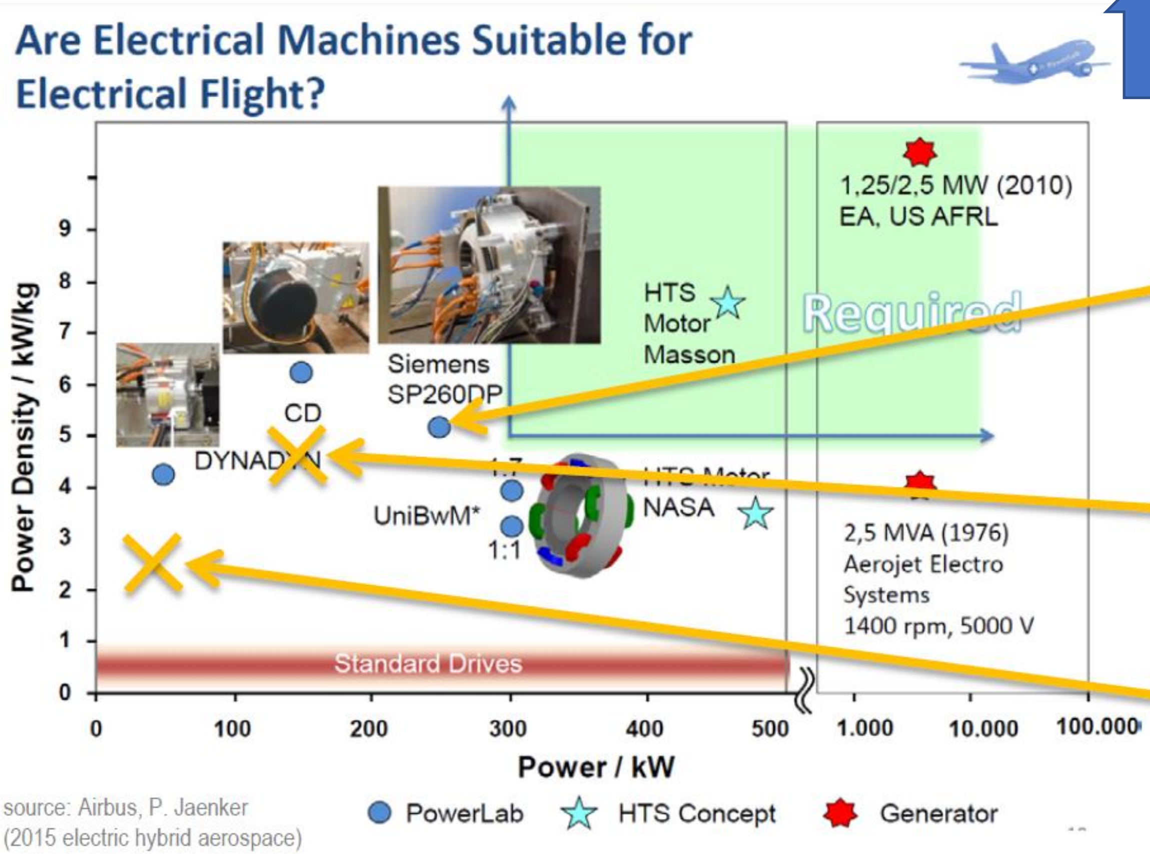
- **High electric freq for high torque density**
- **Smart magnetic circle**
- **Optimized structural design (light)**
- **Optimized cooling**

Energy and power of several aircraft



Source: National Academies Report

Electric motor drives. Are we ready ?



source: Airbus, P. Jaenker
(2015 electric hybrid aerospace)

1 MW, 20 kW/kg

IH2 cooling (superconductive)

full scale

oil cooling

sub-scaled

water cooling

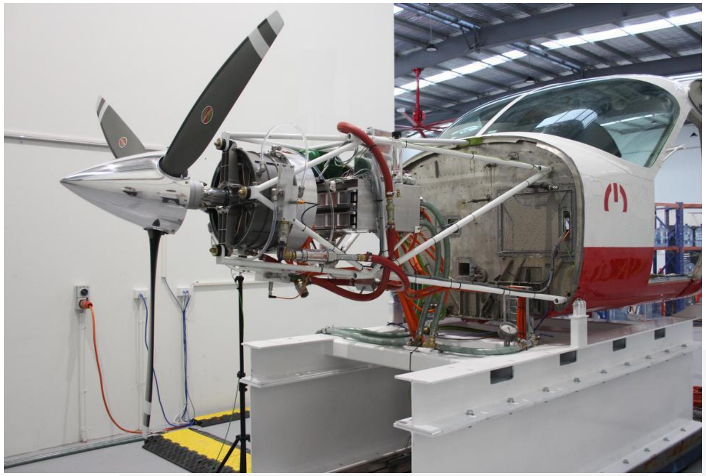
full scale

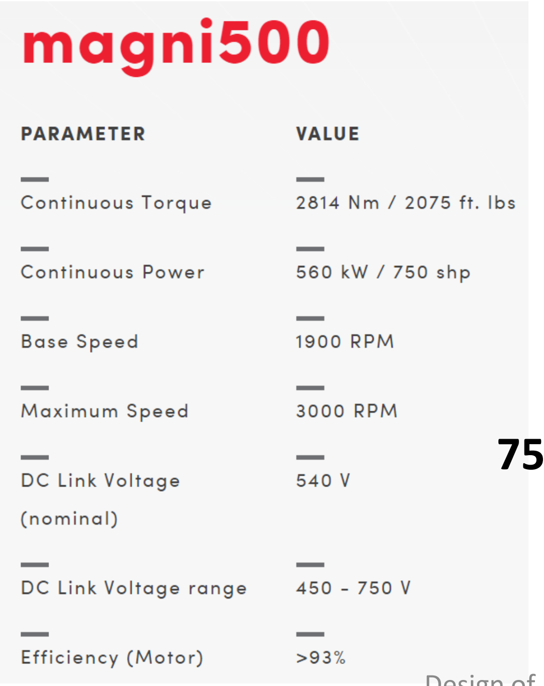
no forced cooling

Siemens SP260 D

- **Power output:** 261 kW (350 hp)
- **Voltage:** V nominal
- **Diameter** 418 mm
- **Best efficiency:** 95
- **Weight** 50 Kg
- **Power-to-weight ratio**: 5.22 kW/kg

Electric motor drives.

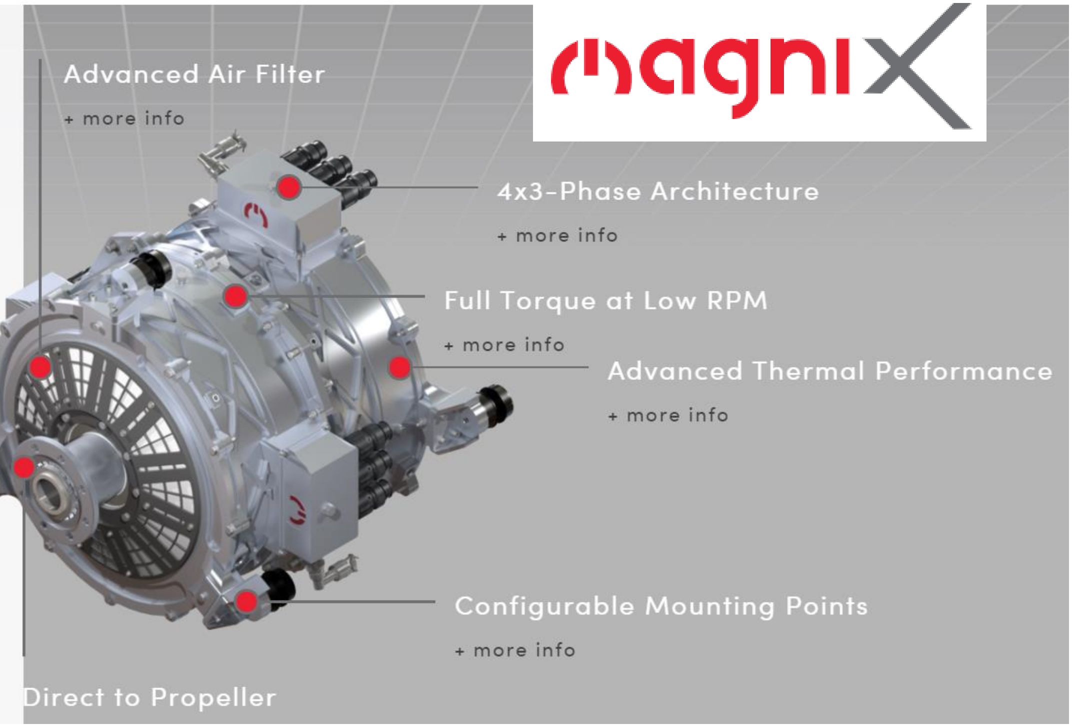




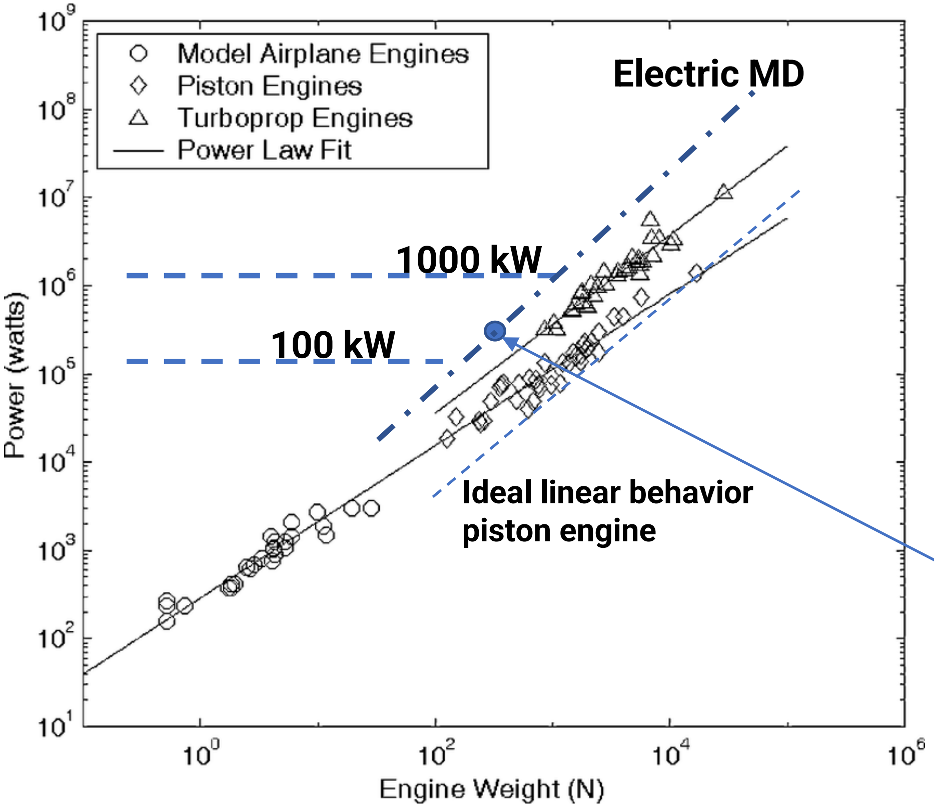
magni500

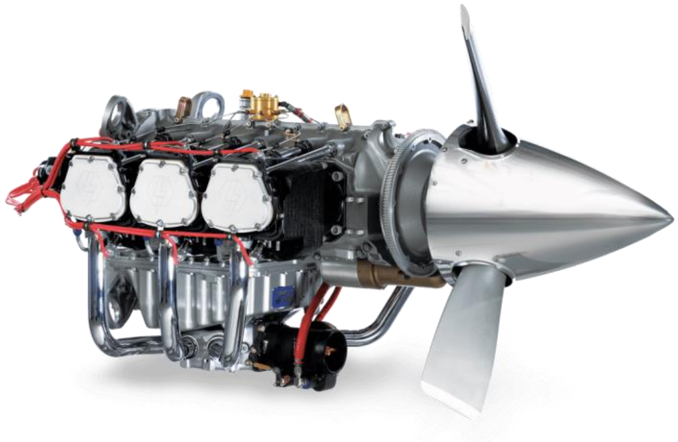
PARAMETER	VALUE
Continuous Torque	2814 Nm / 2075 ft. lbs
Continuous Power	560 kW / 750 shp
Base Speed	1900 RPM
Maximum Speed	3000 RPM
DC Link Voltage (nominal)	540 V
DC Link Voltage range	450 - 750 V
Efficiency (Motor)	>93%

750 hp



Electric motor drives high scalability





Power output: 261 kW
Dry weight: 50 kg

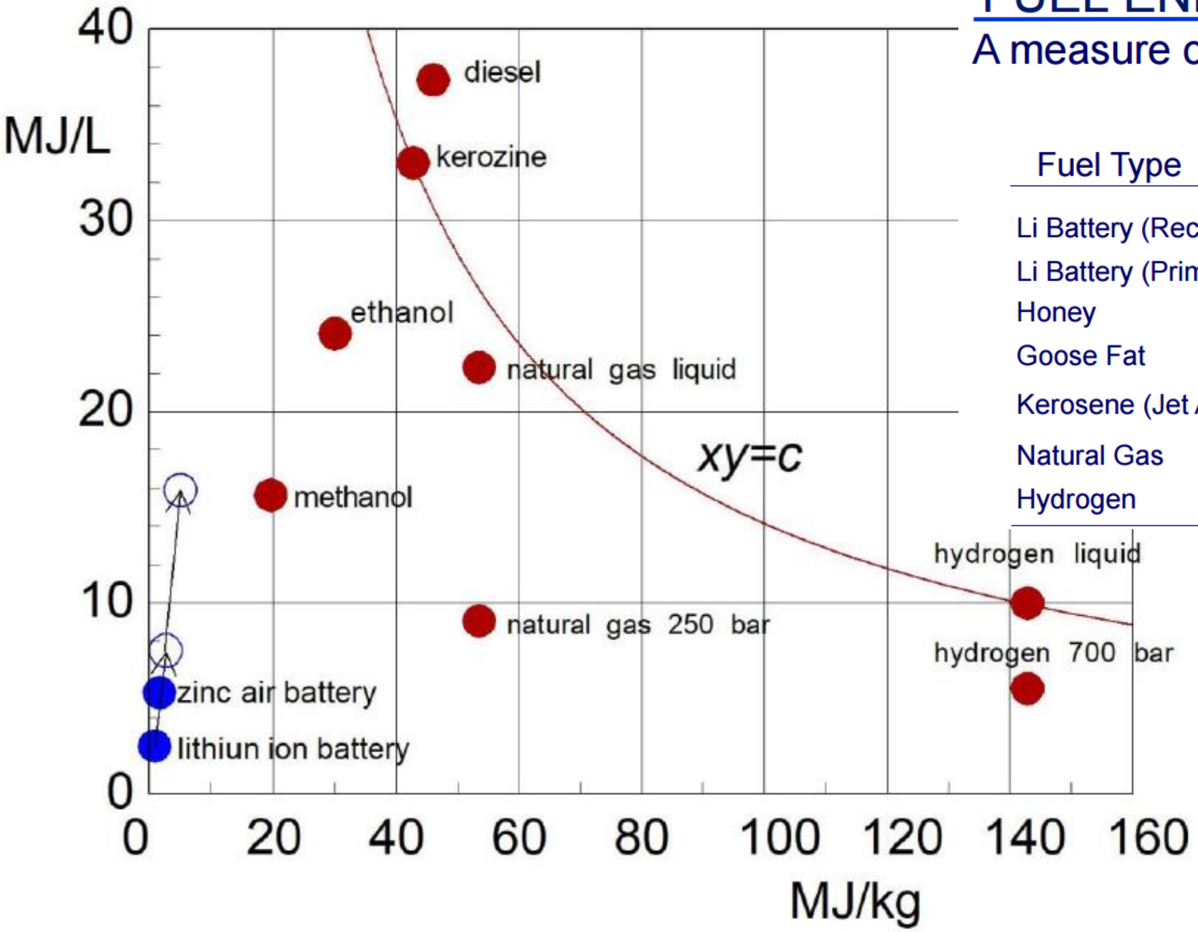
Siemens SP260D

Power-to-weight ratio: 5.22 kW/kg

For a 1800 kW tprop engine (PW124, ATR42) the weight is about 600 Kg. 1000 kW about 350-400 Kg.

For an equivalent electric motor drive, the weight should be 200 (5kW/Kg) or even lower.

ENERGY SOURCES : Fuel and batteries compared



FUEL ENERGY PER UNIT MASS

A measure of aircraft range capability

Fuel Type	MJ / kg	$ / MJ
Li Battery (Rechargeable)	0.25	0.03
Li Battery (Primary)	0.5	200
Honey	14	0.29
Goose Fat	38	0.26
Kerosene (Jet A)	44	0.018
Natural Gas	45	0.005
Hydrogen	117	0.436

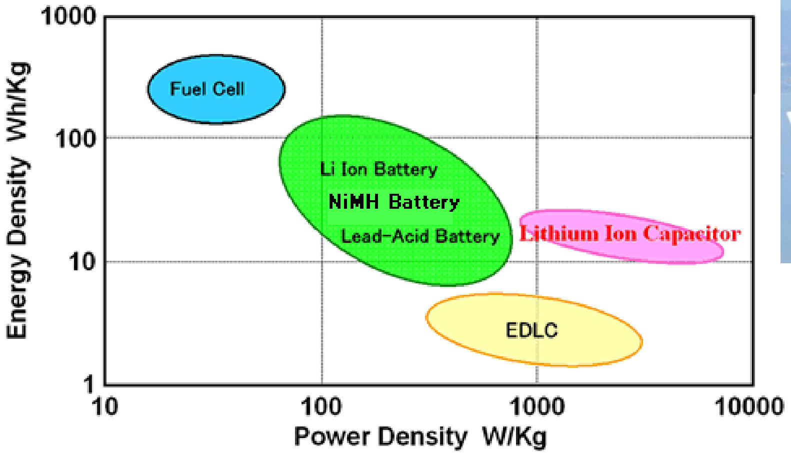
JET FUEL energy density
42 MJ/kg = 12000 Wh/Kg

Li-Ion Battery energy density
0,87 MJ/kg = 250 Wh/Kg
(@ cell level)

Gravimetric energy density … but also
VOLUMETRIC energy density

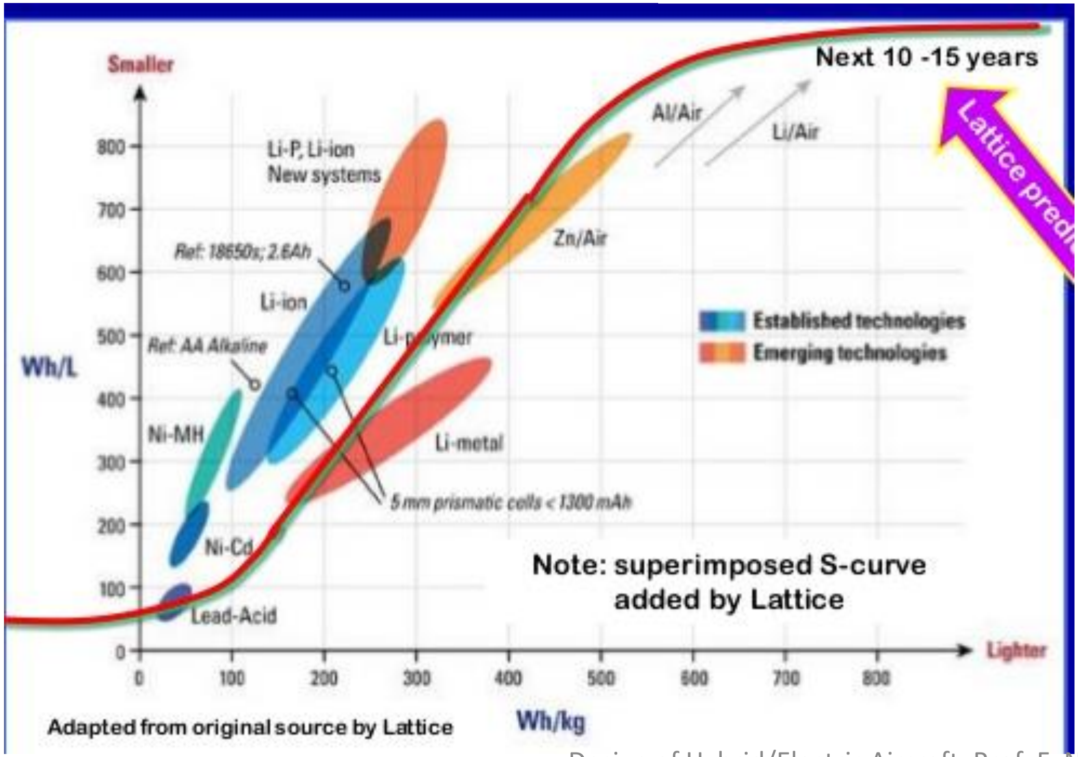
BATTERIES

- **ENERGY gravimetric DENSITY**
- **ENERGY volumetric DENSITY**
- **POWER DENSITY**



NASA X-57

About 10.8 Wh/48 gr
= 225 Wh/Kg
(@ cell level)



X-57 Battery pack

Assuming 3C discharge rate
=> 3 x 225 W /Kg = 675 W/kg

Assuming 5C (max declared) discharge rate
=> 5 x 225 W /Kg = 1125 W/kg

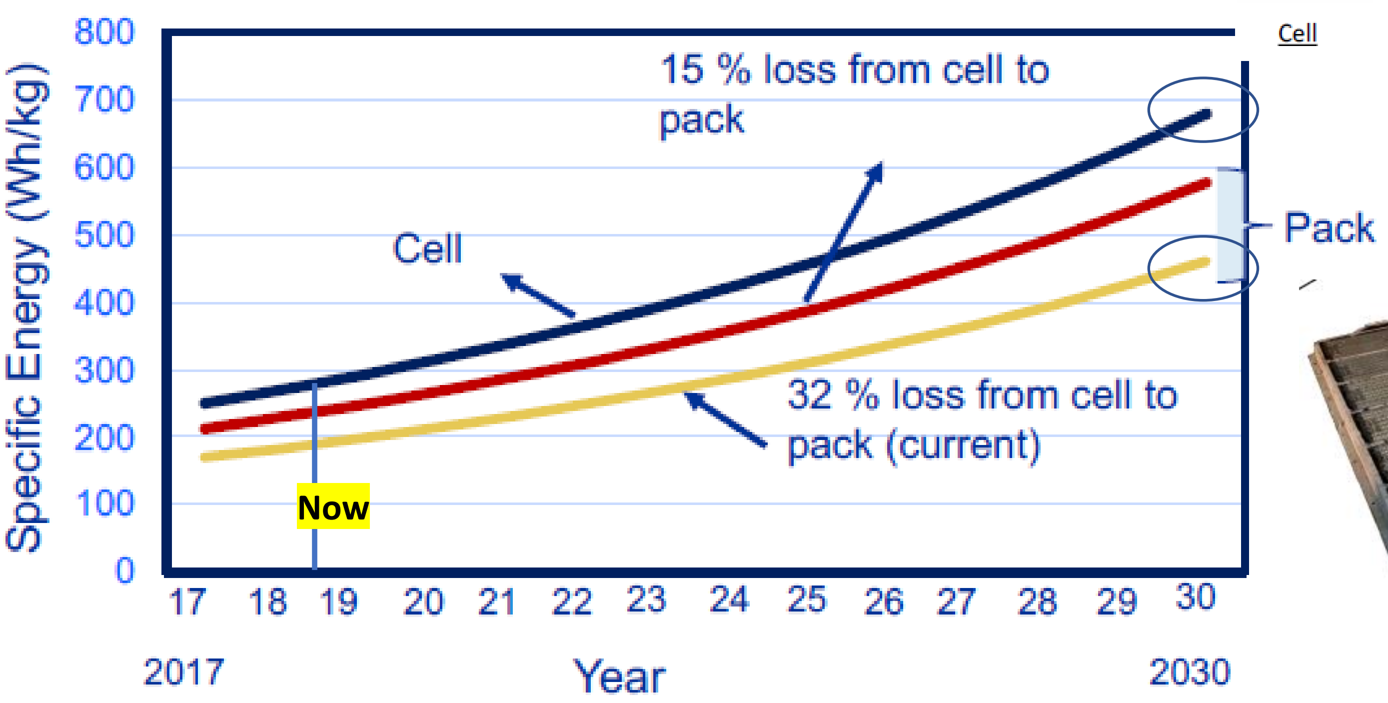
BATTERIES

From Cell to Pack….

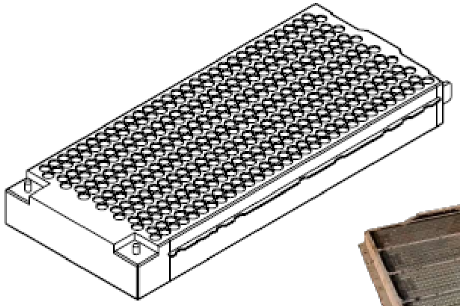
2030 possible values:

@ CELL LEVEL =	**680 Wh/Kg**
@ pack level	**470 Wh/Kg**

Assuming 8% increase per year at cell level



Cell



Module

Cells, Current collection, Fusing, Integral Cooling, Structure

CAN WE HAVE A FULL ELECTRIC TRANSPORT AIRCRAFT ?

B737-800

About 140 pax
Max Take-Off Weight 58000 Kg
Jet-A Fuel : 15000 Kg

Jet-A has very high energy/weight (11,900 Wh/Kg)

15000 Kg => **178,500 Wh of energy**

Assuming an energy density for batteries of **250 Wh/Kg** (actual value for Li-Ion packs is about 150-200 Wh/Kg including battery control and cooling system)

- ⇒ **IT TAKES 714,000 Kg of BATTERIES (714 tons) to reach the same energy of 15 tons of Jet-A fuel.**
- ⇒ **714 000 Kg are Equivalent to more than 12 airplanes @ MTOW (fuel included) !!**

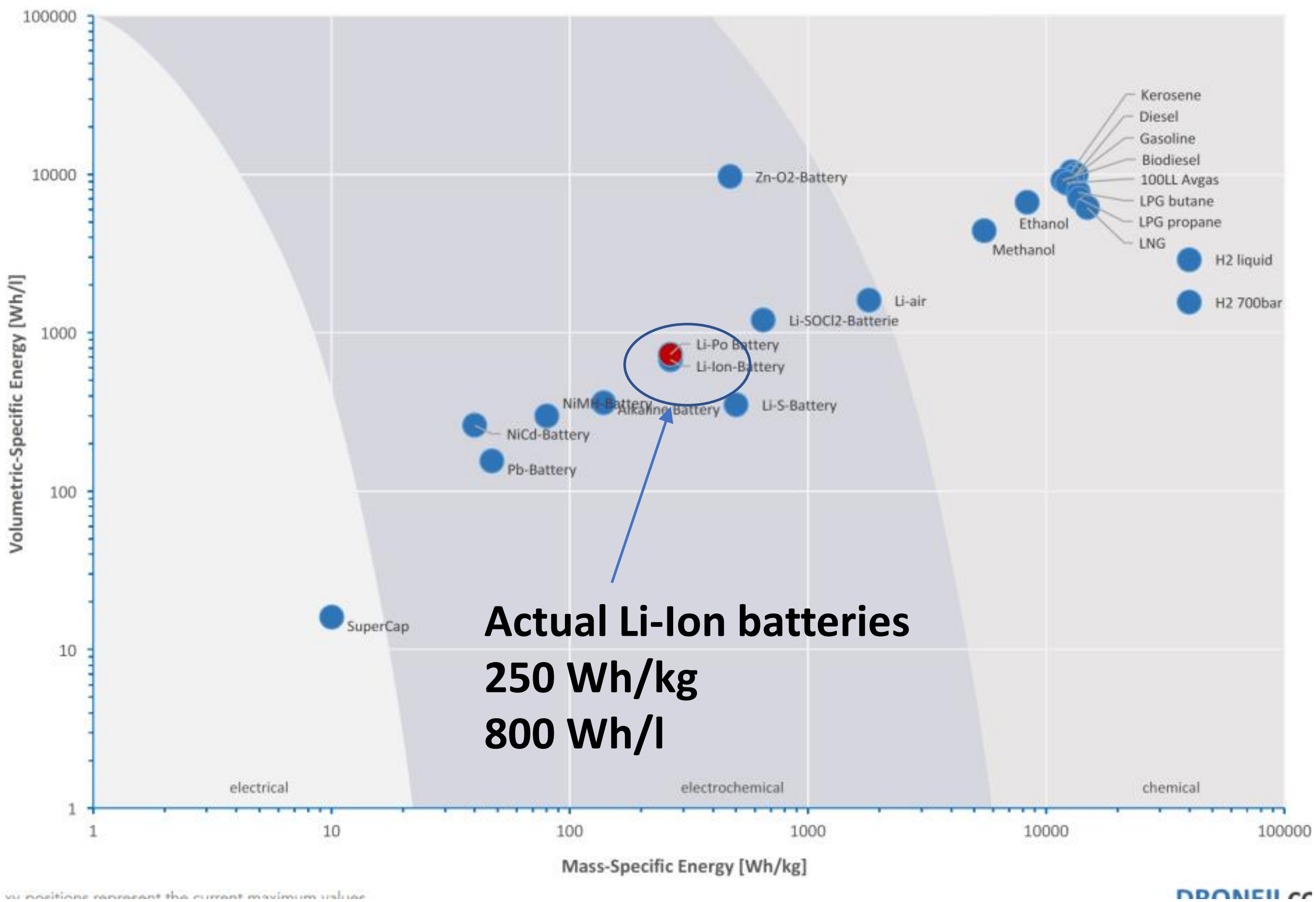
The aircraft is carrying the battery or battery is the aircraft itself ?

714,000 Kg of BATTERIES

12 airplanes @ MTOW

BATTERIES

- Li-S Batteries
- Li-Air Batteries
- Solid-state batteries



Actual Li-Ion batteries
250 Wh/kg
800 Wh/l

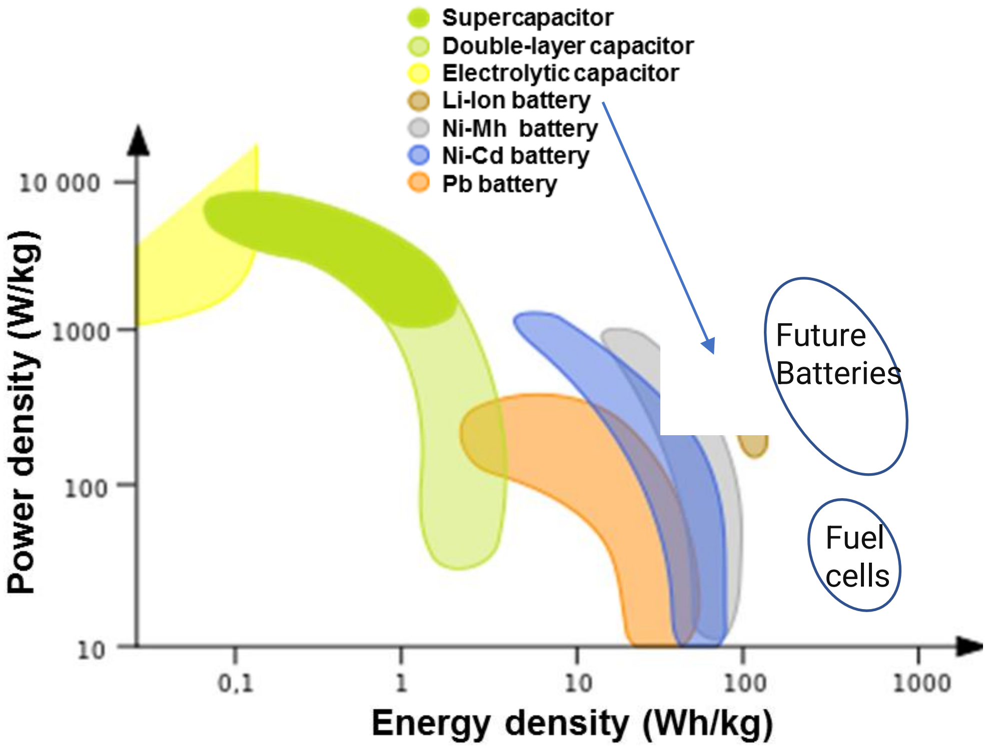
BATTERIES

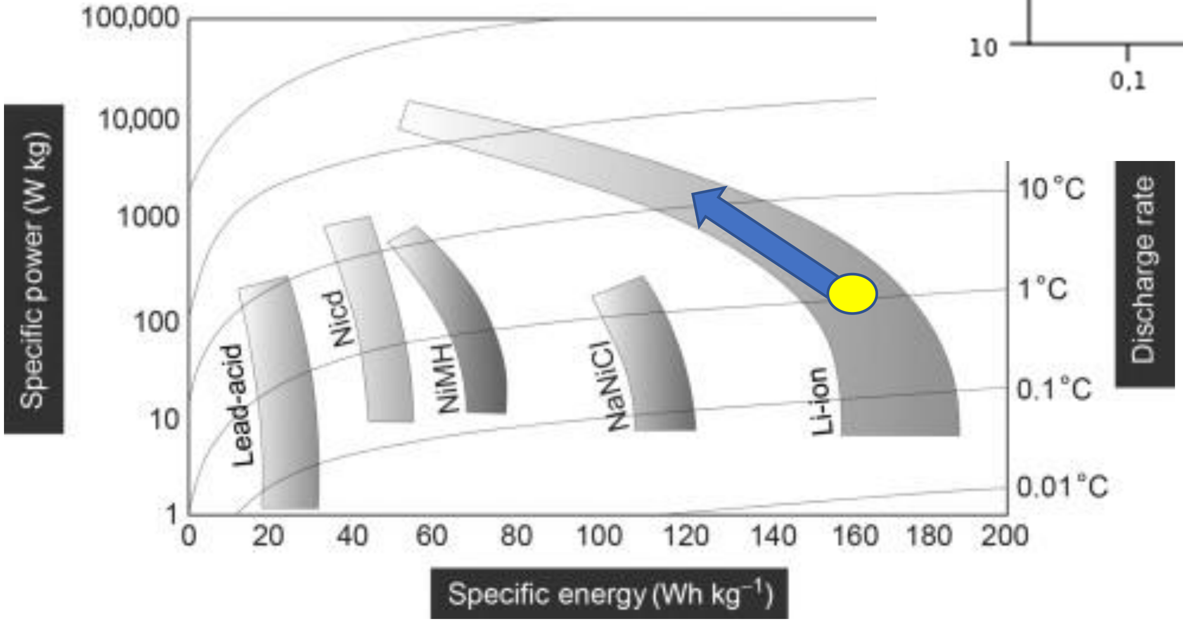
IF WE ARE INCREASING BATTERY DELIVERED POWER (High current) => HIGH C-rate

- The possible energy delivered from battery will reduce (dissipation for battery heating)

WHICH USE ?

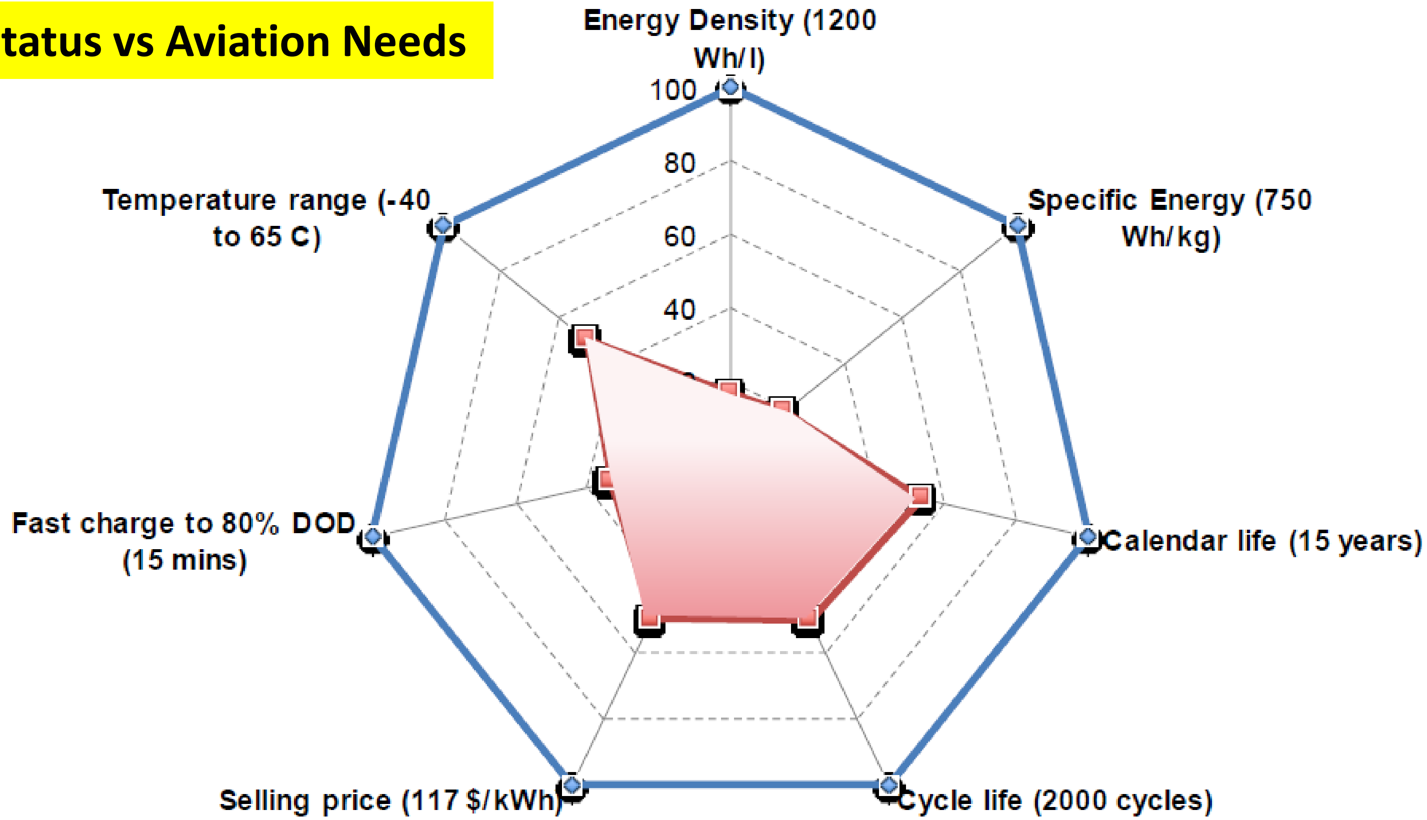
HIGH ENERGY or HIGH POWER ?





BATTERIES GLOBAL PERFORMANCE

Where are we ? Status vs Aviation Needs



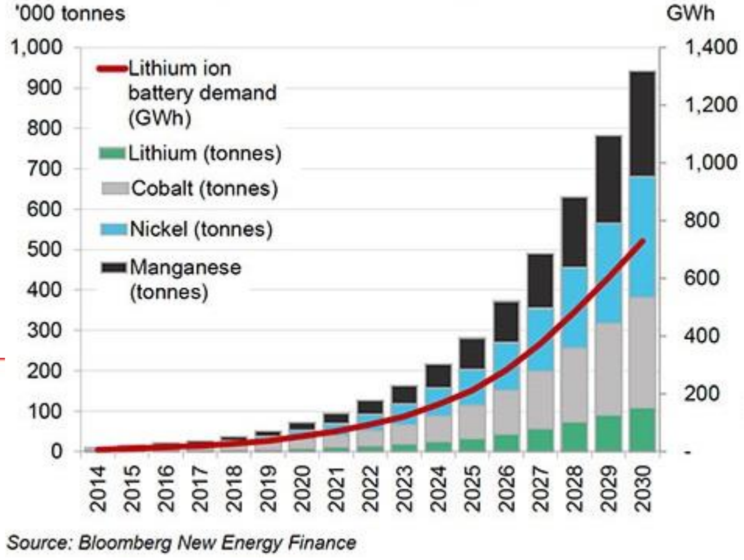
750 Wh/kg is a challenging target.

Innovation is needed at the material level and the pack level

BATTERIES PRODUCTION CAPACITY

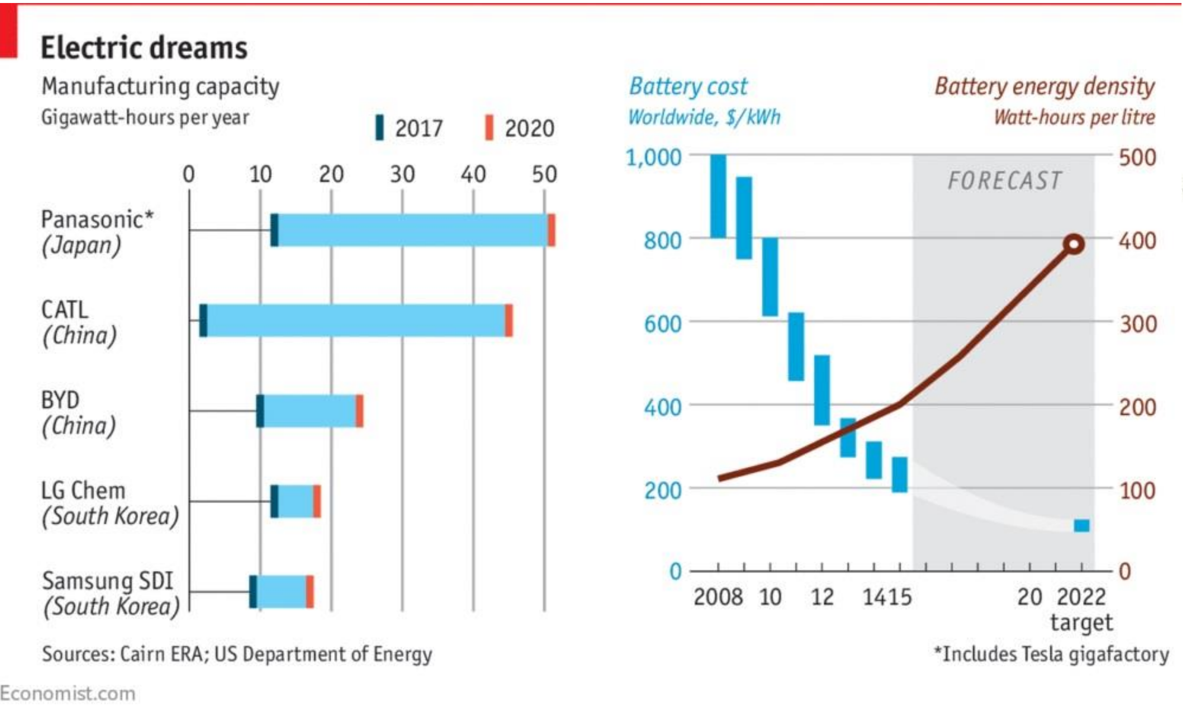
Material demand for batteries:

- Lithium
- Cobalt
- Nickel
- Manganese



Global lithium-ion and materials demand forecast from EV sales, 2015–2030 (thousands of tonnes, GWh)

Source: Bloomberg New Energy Finance



Electric dreams

Manufacturing capacity

Sources: Cairn ERA; US Department of Energy

*Includes Tesla gigafactory

Economist.com

IS HYBRID-ELECTRIC THE FUTURE? FOR ALL?

Let’s suppose that all the major companies would like to go electric…

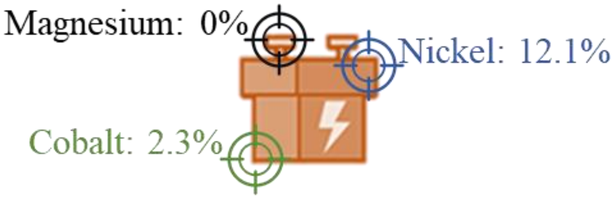
Considering the major fleet in the world (around 80%) among regional and mainlines aircraft, let’s verify if the electrification process is affordable!

Aircraft fleet			
Mainline aircraft: top 10 fleet	**Number of Aircraft**	**Regional aircraft: top 10 fleet**	**Number of Aircraft**
Airbus A320ceo family	7198	Embraer 170/175/190/195	1491
Boeing 737	6492	ATR 42/72	1209
Boeing 777	1515	Bombardier CRJ700/900/1000	843
Airbus A330ceo/A340 family	1478	Embraer ERJ-135/140/145	686
Airbus A320neo family	1377	Bombardier CRJ100/200	677
Boeing 737	976	De Havilland Canada Dash 8-400	553
Boeing 787	965	Bombardier Dash Q8	435
Boeing 767	800	Beechcraft 1900	384
Boeing 757	715	De Havilland Canada Twin Otter	368
Boeing 747	497	Fairchild Swearingen Metroliner	262
Total	22013	**Total**	6908

IS HYBRID-ELECTRIC THE FUTURE? FOR ALL?

Now, supposing a battery mass of about 3000 kg per each aircraft, the resulting battery mass necessary is…

Batteries			
Mainline aircraft: top 10 fleet		**Regional aircraft: top 10 fleet**	
Number of batteries	22013	**Number of batteries**	6,908
Mean battery weight (kg)	3000	**Mean battery weight (kg)**	3000
Weight of batteries (kg)	66039000	**Weight of batteries (kg)**	20724000



Considering an NCA battery, whose main components are Nickel and Cobalt, the following quantities in kg are required…

Weight of batteries (kg)	86763000
Cobalt (kg)	1995549
Nickel (kg)	10498323
Magnesium (kg)	0

86700 tonnellate di batterie

2000 tonnellate di Cobalto

10500 tonnellate di Nickel

IS HYBRID-ELECTRIC THE FUTURE? FOR ALL?

Weight of batteries (kg)	86763000
Cobalt (kg)	1995549
Nickel (kg)	10498323
Magnesium (kg)	0

The resulting impact of aviation on the global market would be astonishing…

COBALTO NECESSARIO:

- 350 % circa della produzione annua USA
- 85% circa della produzione annua CINA
- 1.4% circa della produzione mondiale

N.B. In Congo si produce 180 volte il Cobalto prodotto in USA

NICKEL NECESSARIO:

- 65 % circa della produzione annua USA
- 9% circa della produzione annua CINA
- 0.4% circa della produzione mondiale

N.B. In Indonesia si produce 40-50 volte il Nickel prodotto in USA

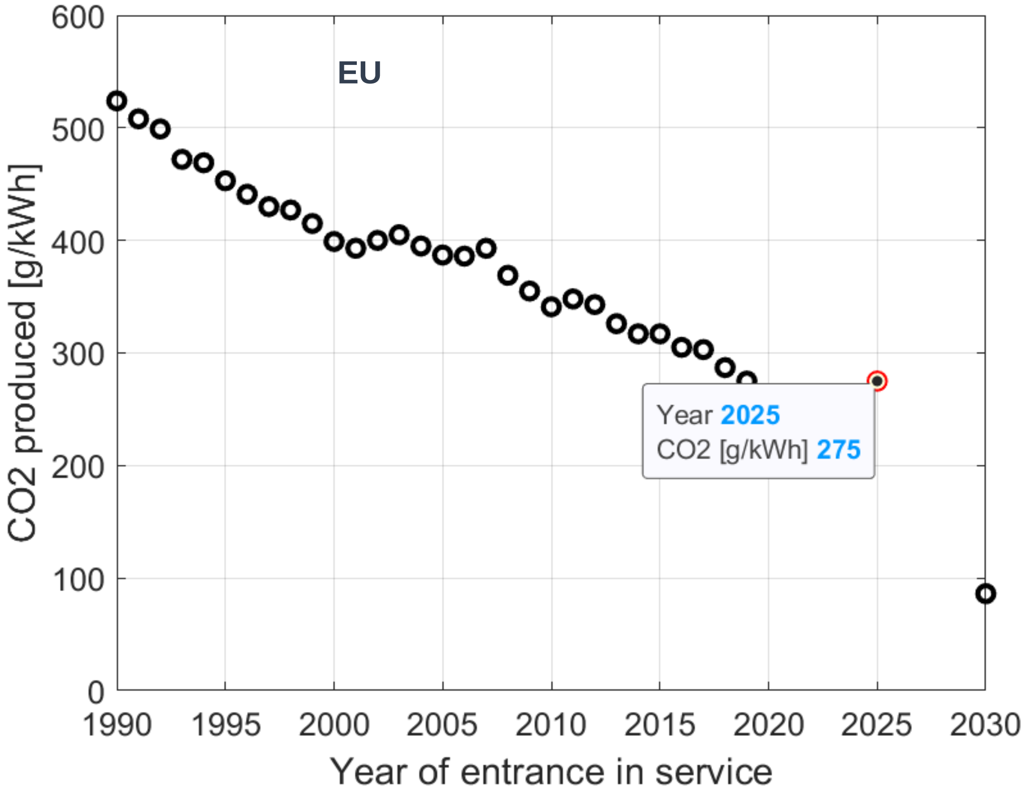
LE BATTERIE SARANNO SEMPRE PIU' RICHIESTE PER TUTTE LE APPLICAZIONI

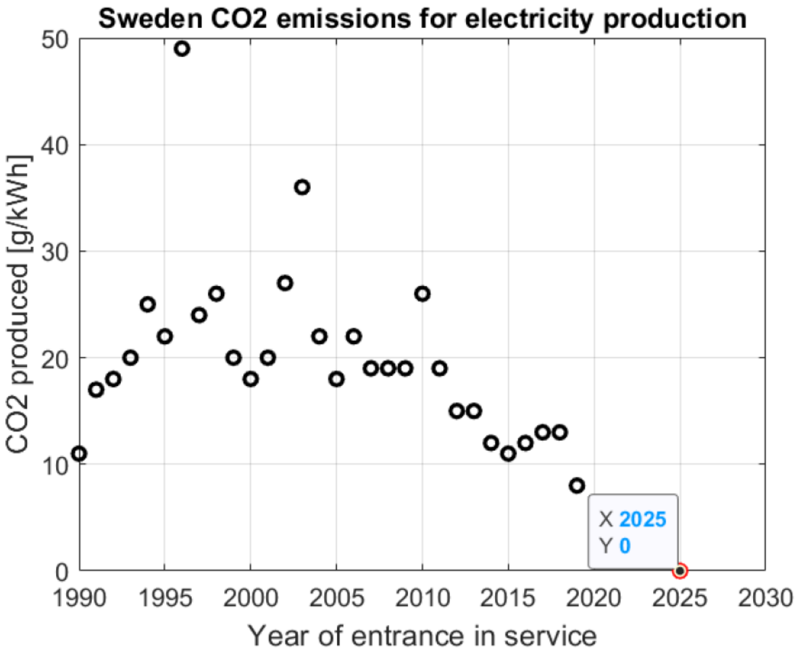
	Aviation absorption of cobalt produced (%)		
	Production in 2019	**Production in 2020**	**Reserves**
United States	399.1%	332.6%	3.8%
Australia	34.8%	35.0%	0.0%
Canada	59.7%	62.4%	0.9%
China	79.8%	86.8%	2.5%
Congo	2.0%	2.1%	0.1%
Cuba	52.5%	55.4%	0.4%
Madagascar	58.7%	285.1%	2.0%
Morocco	86.8%	105.0%	14.3%
New Guinea	68.6%	71.3%	3.9%
Philippines	39.1%	42.5%	0.8%
Russia	31.7%	31.7%	0.8%
South Africa	95.0%	110.9%	5.0%
Other countries	31.6%	31.2%	0.4%
World total (rounded)	1.4%	1.4%	0.0%

	Aviation absorption of nickel produced (%)		
	Production in 2019	**Production in 2020**	**Reserves**
United	77.8%	65.6%	10.5%
Australia	6.6%	6.2%	0.0%
Brazil	17.3%	14.4%	0.1%
Canada	5.8%	7.0%	0.4%
China	8.7%	8.7%	0.4%
Cuba	21.3%	21.4%	0.2%
Dominician Republic	18.5%	22.3%	0.0%
Indonesia	1.2%	1.4%	0.0%
New Caledonia	5.0%	5.2%	0.0%
Philippines	3.3%	3.3%	0.2%
Russia	3.8%	3.7%	0.2%
Other countries	3.4%	3.6%	0.1%
World total (rounded)	0.4%	0.4%	0.0%

IN QUALI PAESI ABBIAMO ABBONDANZA DI QUESTE RISORSE ?

IS THE ELECTRIC ENERGY GREEN ?

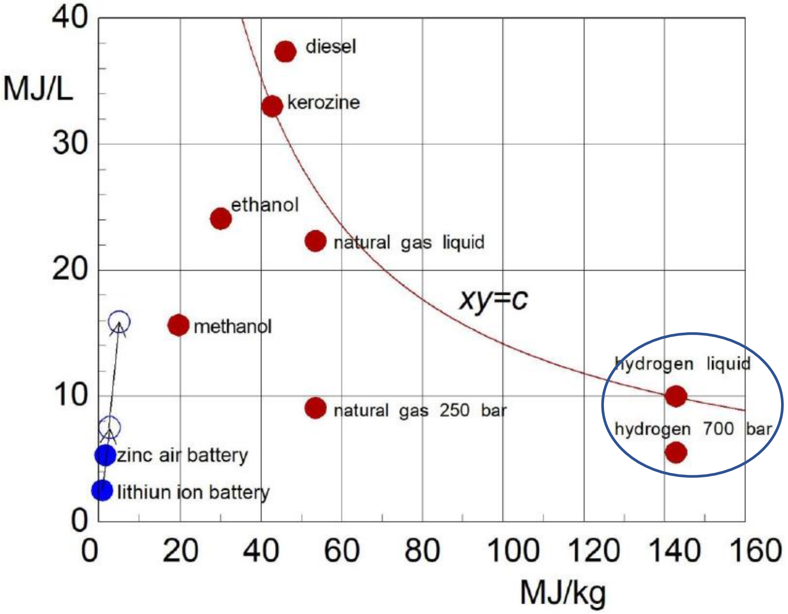




Media Unione Europea
CO2 per kWh di energia elettrica prodotta
2020 **280 g/kWh**

SVEZIA 2020 **10 g/kWh**

HYDROGEN: the promising alternative (Example CAR application)



HIGH Energy

1 kg of H2 => 33 kWh
(3 times 1Kg of gasoline or Gpl)
(2 times 1Kg of metano)
But the problem of H2 is the **volume** not the mass !

FAST Refueling

Toyota Mirai e la Hyundai Nexo, refueling H2 time of 3-5 minuti
=> 5-6 kg of H2 @ 700 bar.
It is about 5-6 times faster than to recharge the battery for electric cars
(Tesla Model 3 with supercharger V3, 250 kW max)

ANTI-KNOCK (as fuel)

Octane number H2 =130 Gpl=93 Gasoline=93 Methane=120
(It is possible to increase the compression ratio on a combustion engine (+ eff)

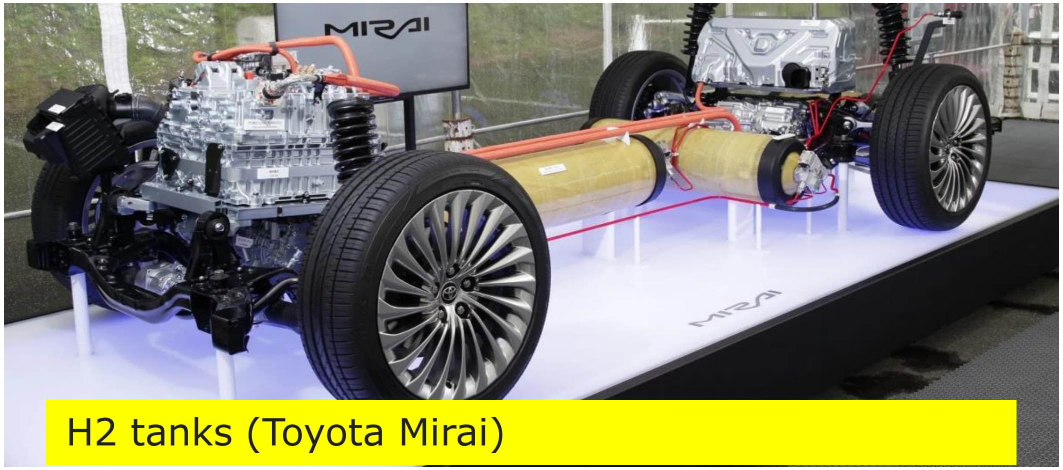
HYDROGEN: the promising alternative (CAR application)

REFUELING COST

13-14 €/Kg (about 80 € to fill the tank for a car) => 13 cents/Km
The battery is much cheaper (it is about 1/3 of FCEV car with H2)
Tesla Model 3 charged@ Supercharger (attualmente 33 cent/kWh) , 7,5 Km/KWh, => 4,5 cents/Km

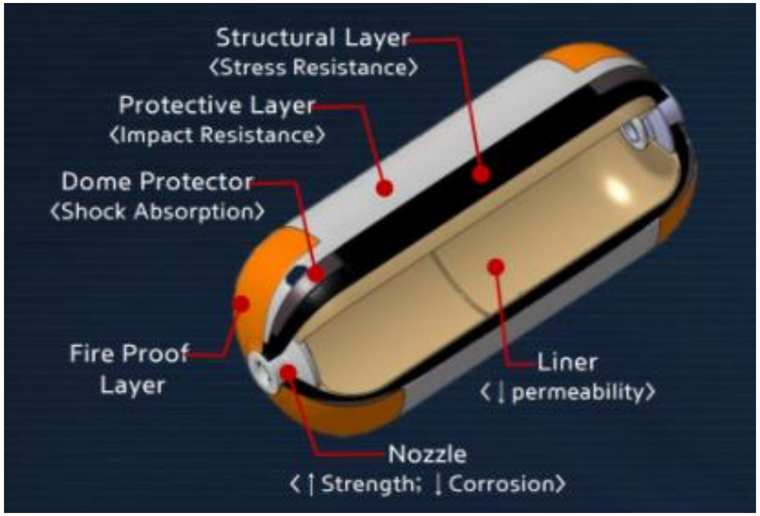
LOW VOLUMETRIC DENSITY

Low density => @1 atm and 25 °C, ro=0.089 Kg/m^3 (12 times lower than air)
For Methane (similar problem) => 200 bar
For H2 => 700 bar (to have similar energy of methane)
Problem with the TANK (For Mirai 5 Kg of H2 stored in several reinforced tank with carbon fiber and with a weight of about 100 Kg).
For Hyunday Nexo tank thickness is 25 mm.



H2 tanks (Toyota Mirai)

H2 ENERGY for storage



PRESSURIZED

The energy to store pressurized H2 @700 bar it is approximately 15% of the energy delivered by the amount of H2.

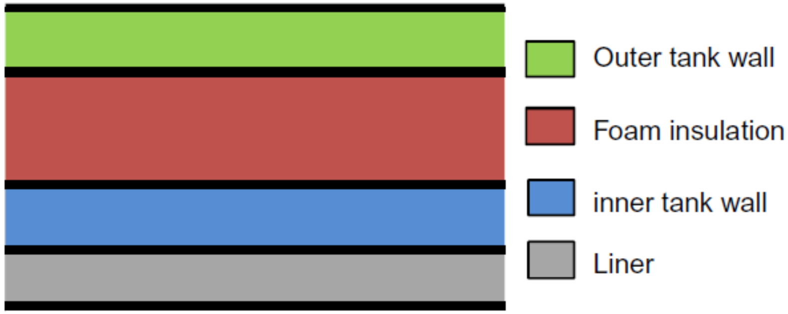
Pressurized H2, 600 bar , 0°-20°C => 70 Kg/m^3

10 times lower density

w.r.t. gasoline

CRYOGENIC

In case of extremely cooled (cryogenic) H2 (-260 °C) the tank is not highly structurally loaded (so it is light) but the energy to cool the H2 it is about 30% of the energy delivered and during operation it is difficult to mantain the low temperature.



Cryogenic H2, 1,5 bar , -260°C => 71 Kg/m^3

HYDROGEN:

ENERGY and carbon neutrality to produce H2

H2 is an energy vector (we do not find H2 in nature like methane or gasoline)
Usually if we spend some energy to extract H2, including all the energy disspated in the process, for storage, transport, etc, the remaining energy is about 30-40%.
The ideal condition is to use green energy to produce H2.

CARBON Neutrality

Energy used to produce H2 can be obtained by burning fossil fuels (CO2 emissions)
In USA 78% of the energy is produced by fossil sources (almost half of this DIRTY Carbon !!!)
In China 60% of the energy is produced by Carbon

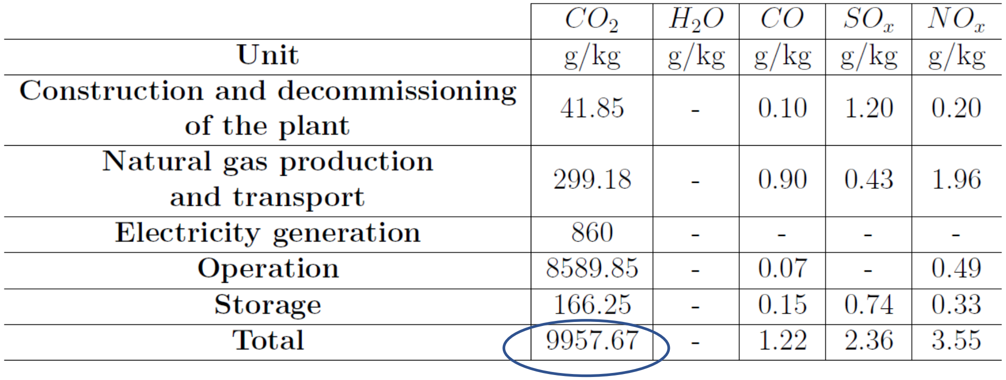
97% of H2 is produced by chemical operations (steam reforming of natural gas as Methane)
This process is producing CO2

WATER Electrolysis (70% efficiency)
To produce 1Kg of H2 (33 KWh of energy) we need 50-55 KWh of energy
To create compressed H2 and for storage and transport we need further 15 KWh/Kg.

IF WE BURN H2 we create Nox

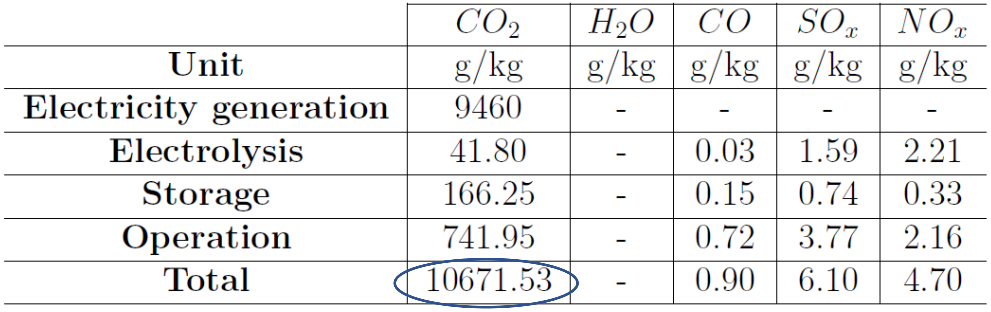
(Air contains Nitrogen)

Hydrogen production and related emissions



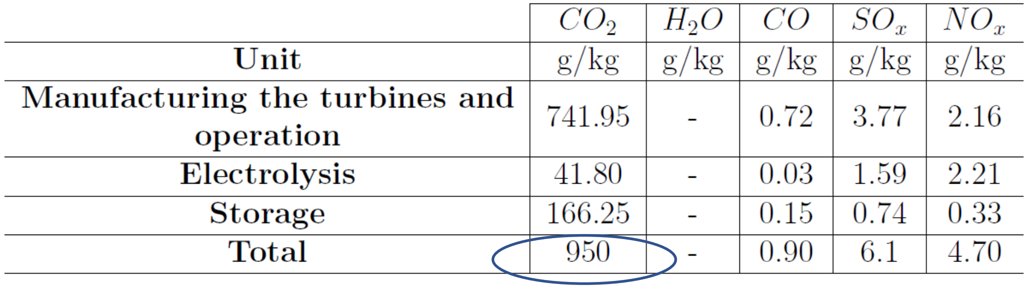
	CO_2	H_2O	CO	SO_x	NO_x
Unit	g/kg	g/kg	g/kg	g/kg	g/kg
Construction and decommissioning of the plant	41.85	-	0.10	1.20	0.20
Natural gas production and transport	299.18	-	0.90	0.43	1.96
Electricity generation	860	-	-	-	-
Operation	8589.85	-	0.07	-	0.49
Storage	166.25	-	0.15	0.74	0.33
Total	9957.67	-	1.22	2.36	3.55

Table 3.2: Emissions for NGSR via dirty energy technique



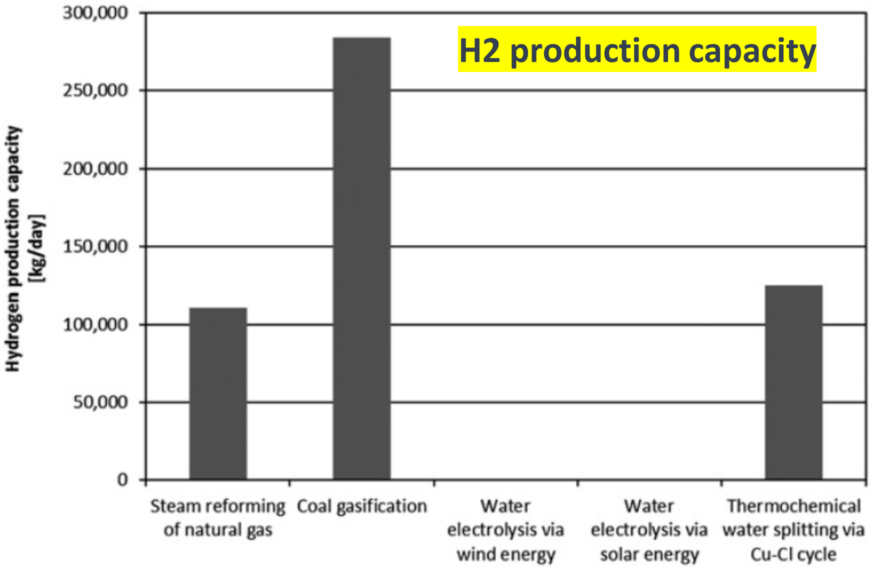
	CO_2	H_2O	CO	SO_x	NO_x
Unit	g/kg	g/kg	g/kg	g/kg	g/kg
Electricity generation	9460	-	-	-	-
Electrolysis	41.80	-	0.03	1.59	2.21
Storage	166.25	-	0.15	0.74	0.33
Operation	741.95	-	0.72	3.77	2.16
Total	10671.53	-	0.90	6.10	4.70

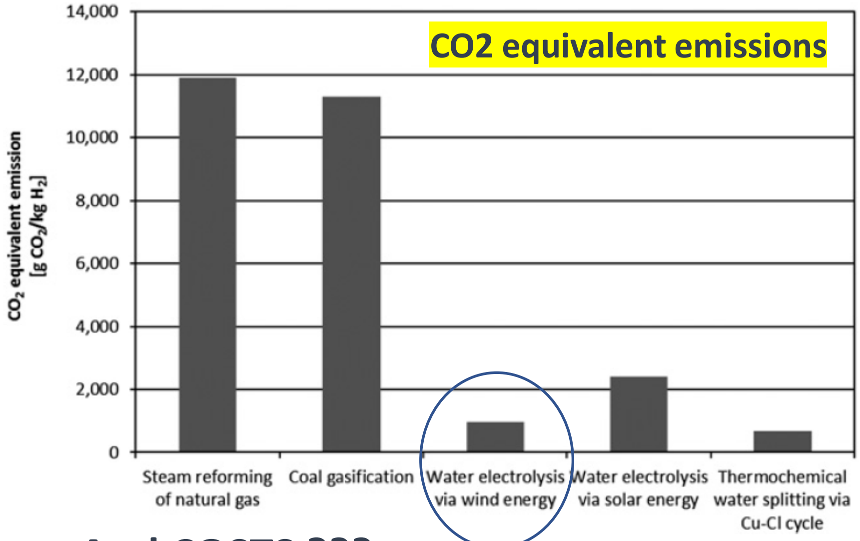
Table 3.4: Emissions for water electrolysis via dirty energy technique



	CO_2	H_2O	CO	SO_x	NO_x
Unit	g/kg	g/kg	g/kg	g/kg	g/kg
Manufacturing the turbines and operation	741.95	-	0.72	3.77	2.16
Electrolysis	41.80	-	0.03	1.59	2.21
Storage	166.25	-	0.15	0.74	0.33
Total	950	-	0.90	6.1	4.70

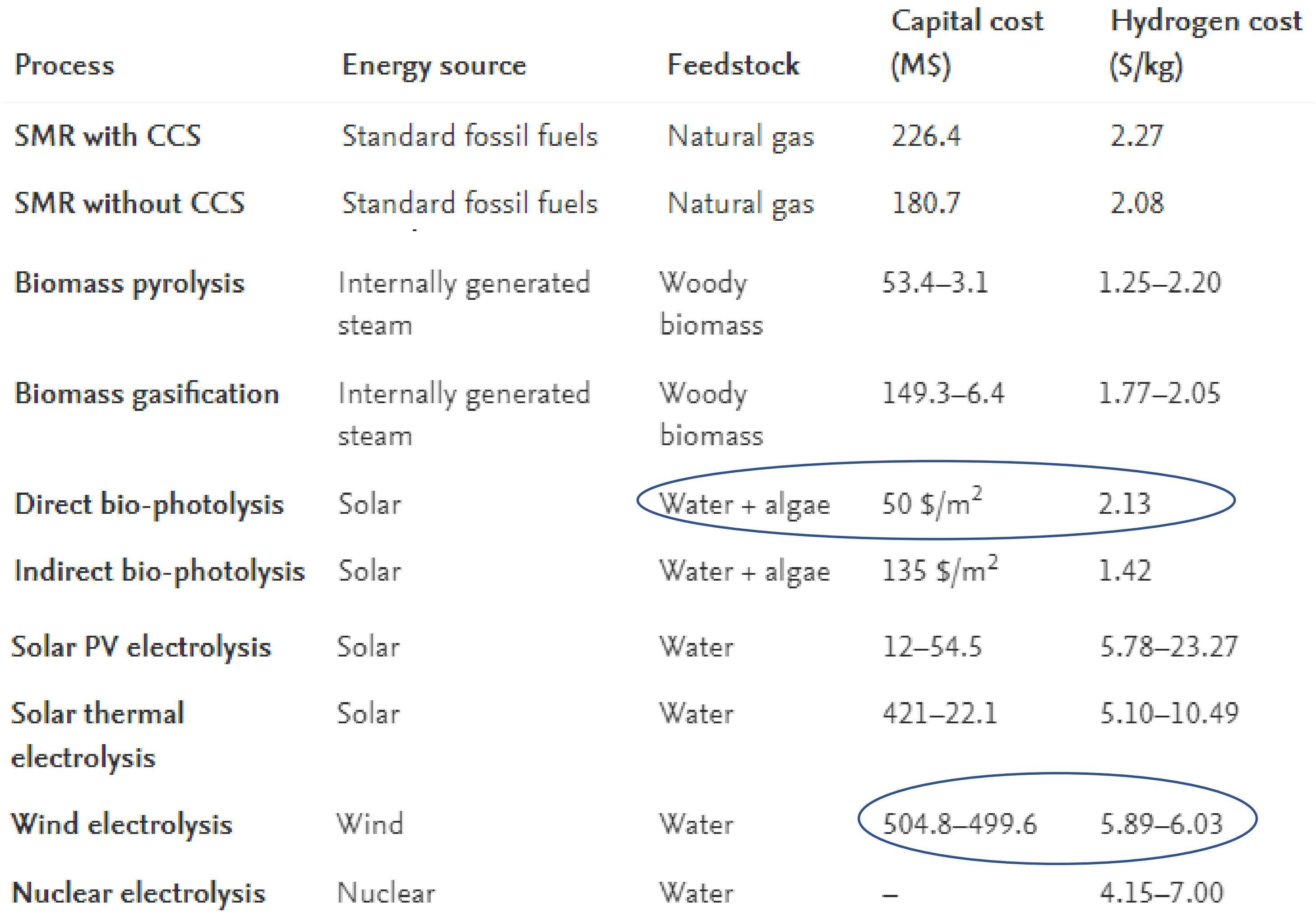
Table 3.3: Emissions for water electrolysis via wind energy technique





And COSTS ???

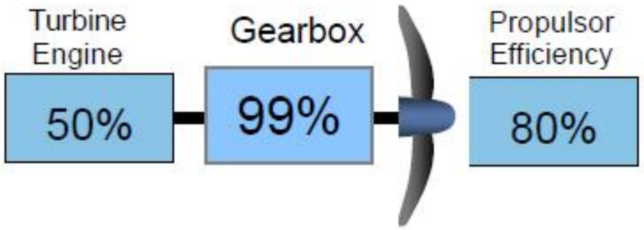
Hydrogen production costs



Process	Energy source	Feedstock	Capital cost (M$)	Hydrogen cost ($/kg)
SMR with CCS	Standard fossil fuels	Natural gas	226.4	2.27
SMR without CCS	Standard fossil fuels	Natural gas	180.7	2.08
Biomass pyrolysis	Internally generated steam	Woody biomass	53.4–3.1	1.25–2.20
Biomass gasification	Internally generated steam	Woody biomass	149.3–6.4	1.77–2.05
Direct bio-photolysis	Solar	Water + algae	50 $/m^2	2.13
Indirect bio-photolysis	Solar	Water + algae	135 $/m^2	1.42
Solar PV electrolysis	Solar	Water	12–54.5	5.78–23.27
Solar thermal electrolysis	Solar	Water	421–22.1	5.10–10.49
Wind electrolysis	Wind	Water	504.8–499.6	5.89–6.03
Nuclear electrolysis	Nuclear	Water	–	4.15–7.00

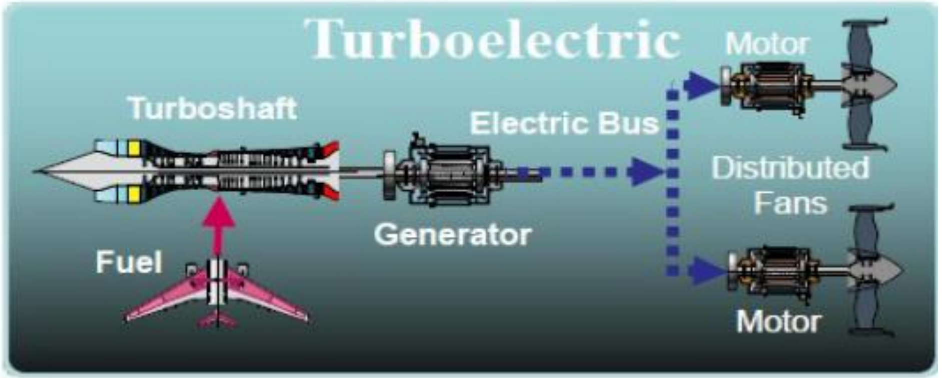
ELECTRIC/HYBRID AIRPLANES

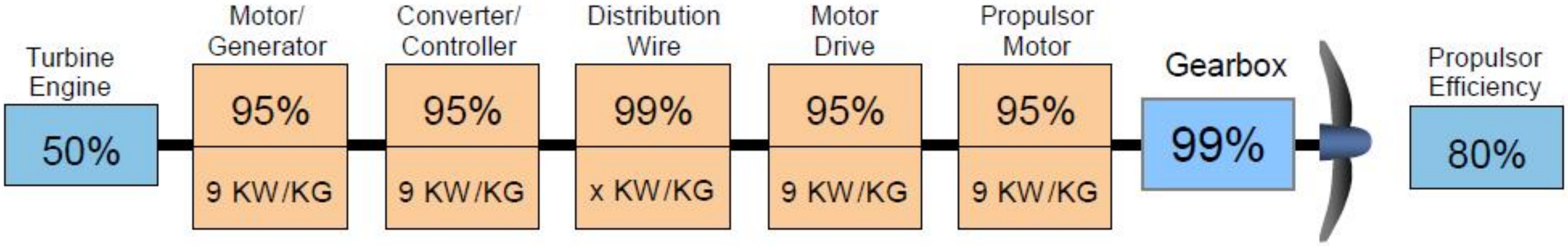
Propulsive Efficiency



Turbine Engine	Gearbox	Propulsor Efficiency
50%	99%	80%

=39.6%





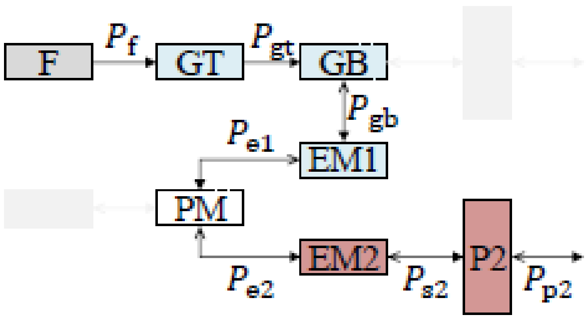
Turbine Engine	Motor/ Generator	Converter/ Controller	Distribution Wire	Motor Drive	Propulsor Motor	Gearbox	Propulsor Efficiency
50%	95%	95%	99%	95%	95%	99%	80%
	9 KW/KG	9 KW/KG	x KW/KG	9 KW/KG	9 KW/KG		

=32%

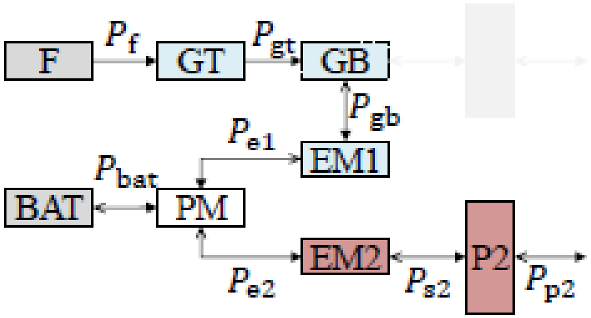
ELECTRIC/HYBRID AIRPLANES

Powertrain architecture

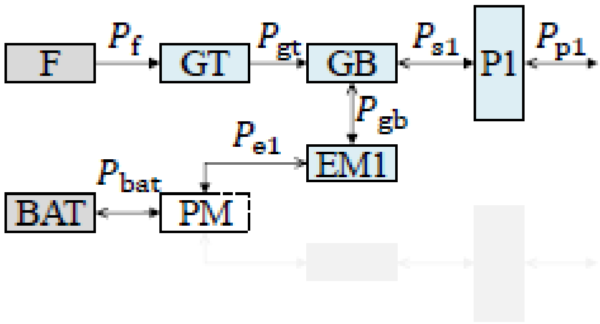
2. Turboelectric

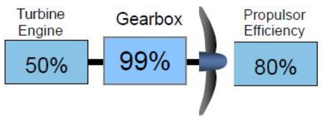


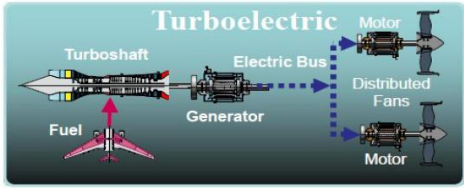
3. Serial

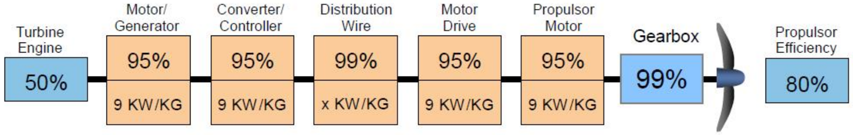


4. Parallel

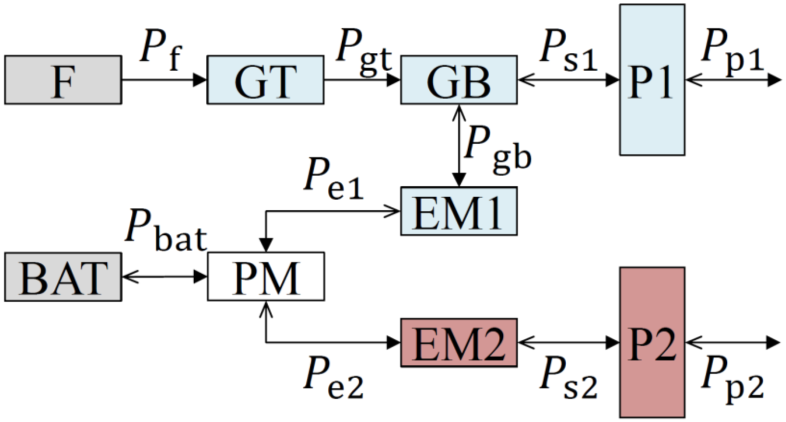








Serial/parallel partial hybrid (SPPH)



ELECTRIC/HYBRID COMMUTER AIRCRAFT
ELICA PROJECT

AIR S.PACE

SIEMENS

Parameter	Value
Max. MTOM	8,618 kg
Payload	2,000 kg
Take-off distance total	700 m
Take-off field length	1,000 m
Long range cruise speed	375 km/h
High speed cruise	430 km/h
Noise	75 dB(A)
Design range	435 km
Max. range	1,400 km

Flightpath 2050

The project aligns with the environmental expectations of the European Commission

Door-to-door

90% of european travellers should reach their destination within 4 hours

Reducing emissions

Carbon, nitrogen oxides, and noise emissions will be reduced by 50%

Strengthening

Safeguard european high-quality jobs in the aerospace sectors

Market Research

Powertrain Architecture

Aircraft Design

Scientific Challenge

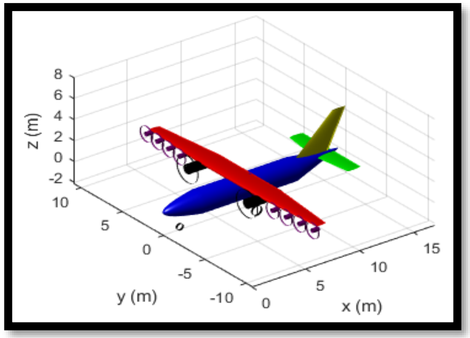
ELICA PROJECT

The project divided a roadmap to clean aviation in two different steps:

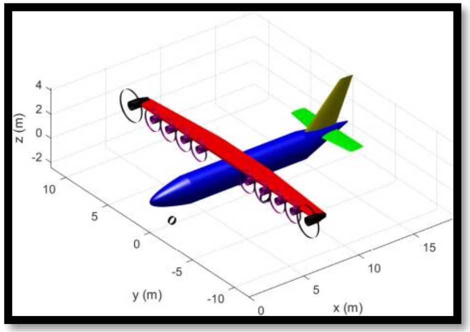
2025: the use of battery provide a ready to market technology that can support the electrification of existing platforms;

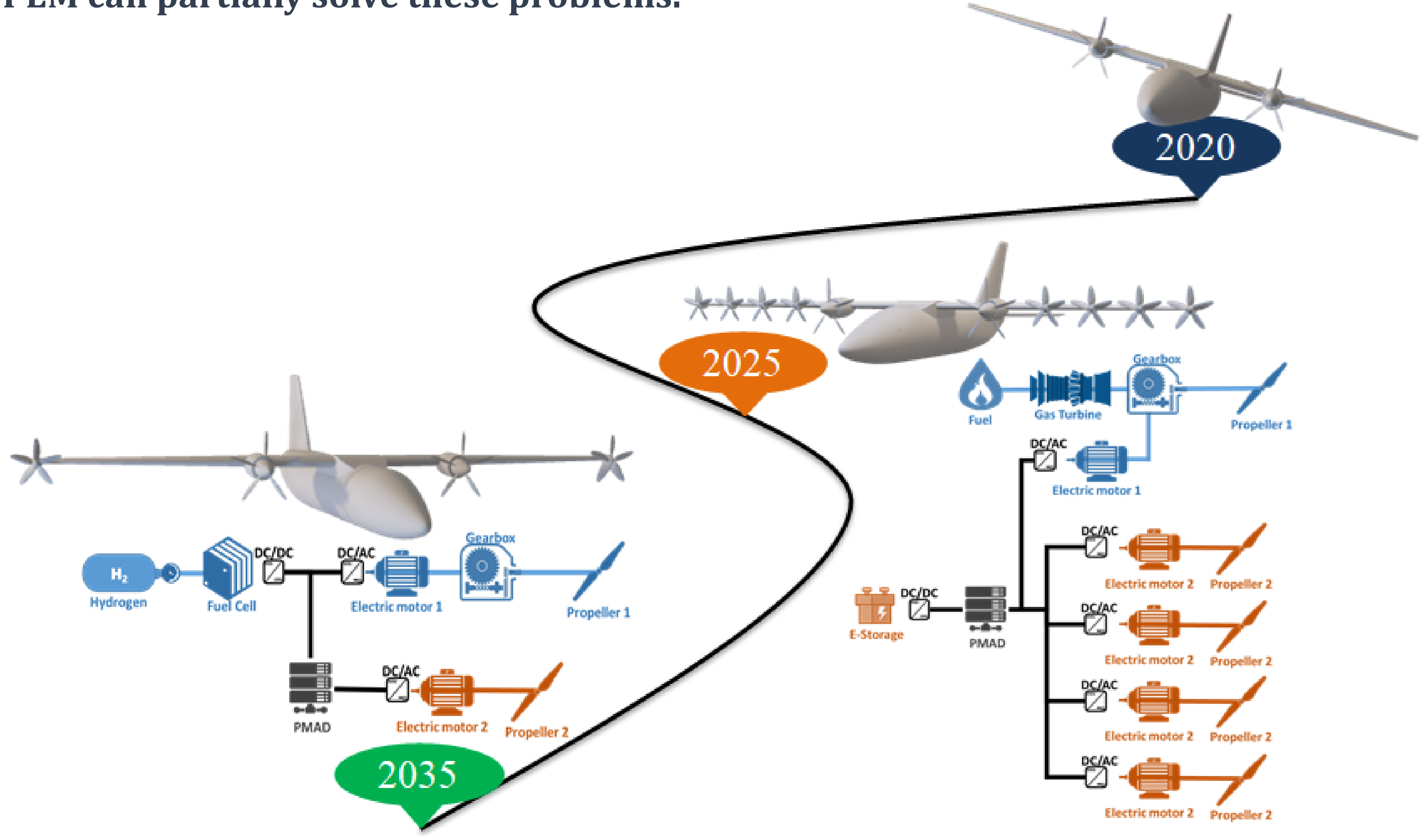
2035: hydrogen is not ready to be implemented on the market due to some safety issues and technological challenges associated to the thermal management system. However, by 2035, the introduction of HT-PEM can partially solve these problems.

2025: HE Version



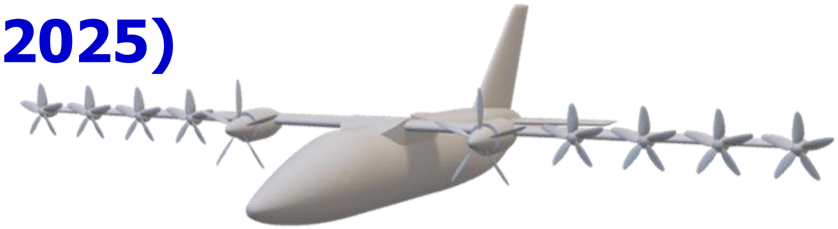
2035: H2 Version

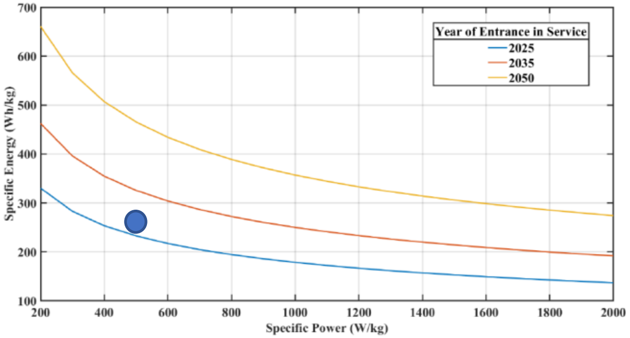




ELICA PROJECT – Hybrid concept (2025)

A **serial-parallel architecture** was selected in order to be able to split the power on two separated propulsive lines.





S_w	33.944
b_w	21.006
AR_w	13.000

BATTERY			
Name	**Symbol**	**Value**	**Unit**
Specific energy	e_{BAT}	270.000	Wh/kg
Specific power	p_{BAT}	500.000	W/kg
Energy density	v_{BAT}	600.000	Wh/l

Battery mass limited to 700 kg due to the CS-23 limitation on the max. take-off weight!

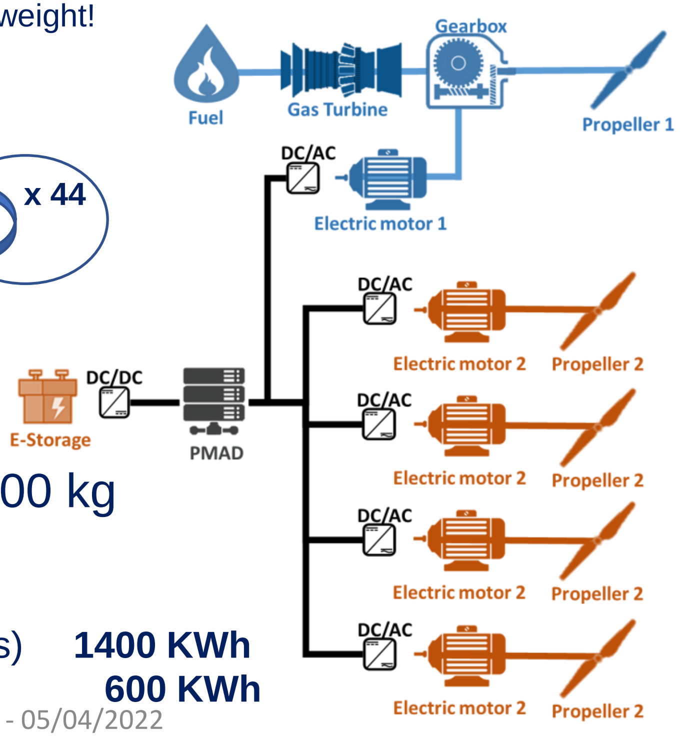
WEIGHTS (DESIGN MISSION)			
Name	**Symbol**	**Value**	**Unit**
Maximum Take Off Weight	W_{MTO}	8608.3	kg
Maximum Operative Weight	W_{OE}	6226.6	kg
Powerplant Weight	$W_{Powerplant}$	2550.0	kg
Fuel Weight	W_{Fuel}	615.0	kg
Hydrogen Weight	W_{H2}	0.0	kg
Battery Weight	$W_{Battery}$	700.0	kg

WEIGHTS (TYPICAL MISSION 1)			
Name	**Symbol**	**Value**	**Unit**
Maximum Take Off Weight	W_{MTO}	8325.2	kg
Fuel Weight	W_{Fuel}	331.8	kg
Hydrogen Weight	W_{H2}	0.0	kg
Battery Weight	$W_{Battery}$	700.0	kg

ENERGY DENSITY

FUEL	**12000 Wh/Kg**
BATTERY	**270 Wh/Kg**

x 44



700 kg

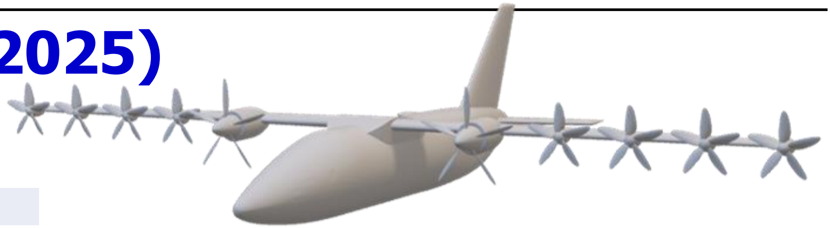
BATT energy =180 KWh

Whole mission required energy:

Design Mission (500 nm) (without reserves) **1400 KWh**

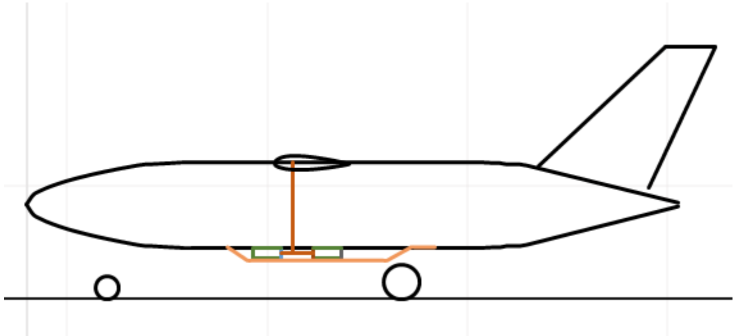
Typical Mission (200 nm) “ **600 KWh**

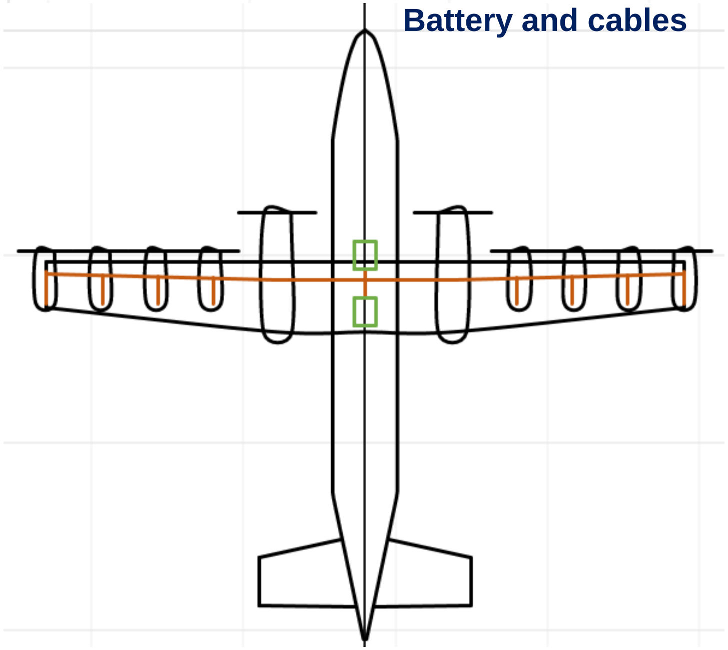
ELICA PROJECT – Hybrid concept (2025)



DETAILED WEIGHT ESTIMATION
(Interaction with RR)

		Global weight
Tank Kerosene, Pipelines, TMS, etc.	1	197.96
Battery Pack	2 x 350	700.00 kg
E-Generator/Motor	2	59.34
E-Motor Drive	8 x 30.5	244.08
DC/DC E-Storage	2	13.21
DC/AC e-motor drive	8 x 6.6	52.83
DC/AC generator	2	32.63
Cabling	1	148.17
Gearboxes	2	99.00
PMAD	2	3.77
Propeller DEP	8 x 53.8	430.21
Propeller Main	2	213.36
Gasturbine	2	360.00
Powertrain		**2554.56 Kg**



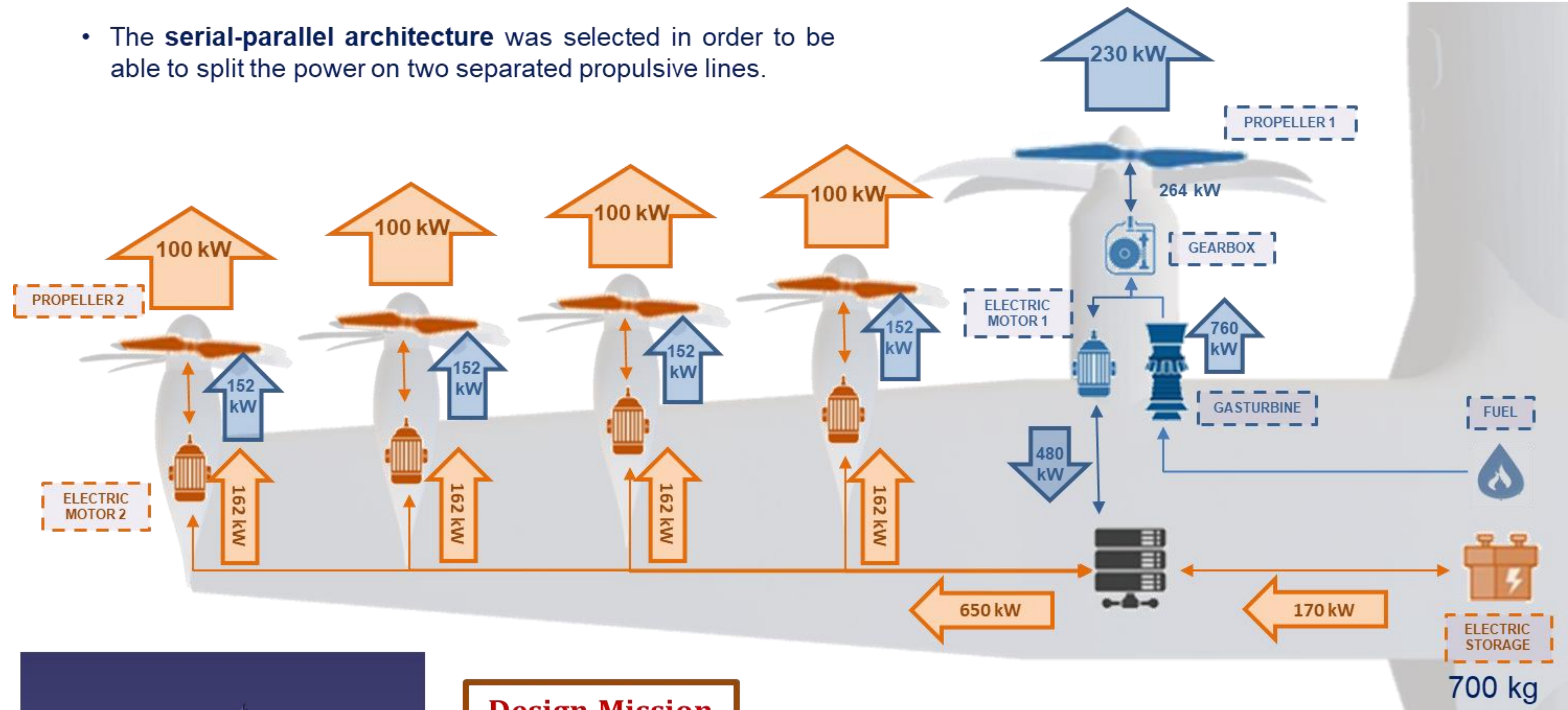


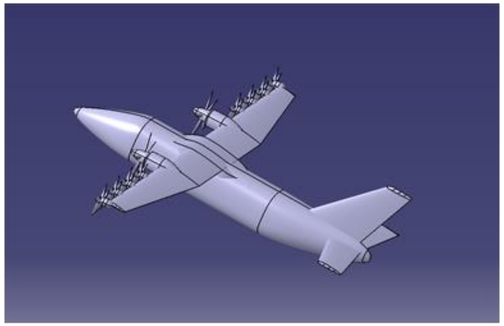
ALSO BATTERY TMS has been included

ELICA PROJECT – Hybrid concept (2025)

HYBRID PROPULSIVE SYSTEM MODELLING

- The **serial-parallel architecture** was selected in order to be able to split the power on two separated propulsive lines.





Design Mission

Target EIS: 2025

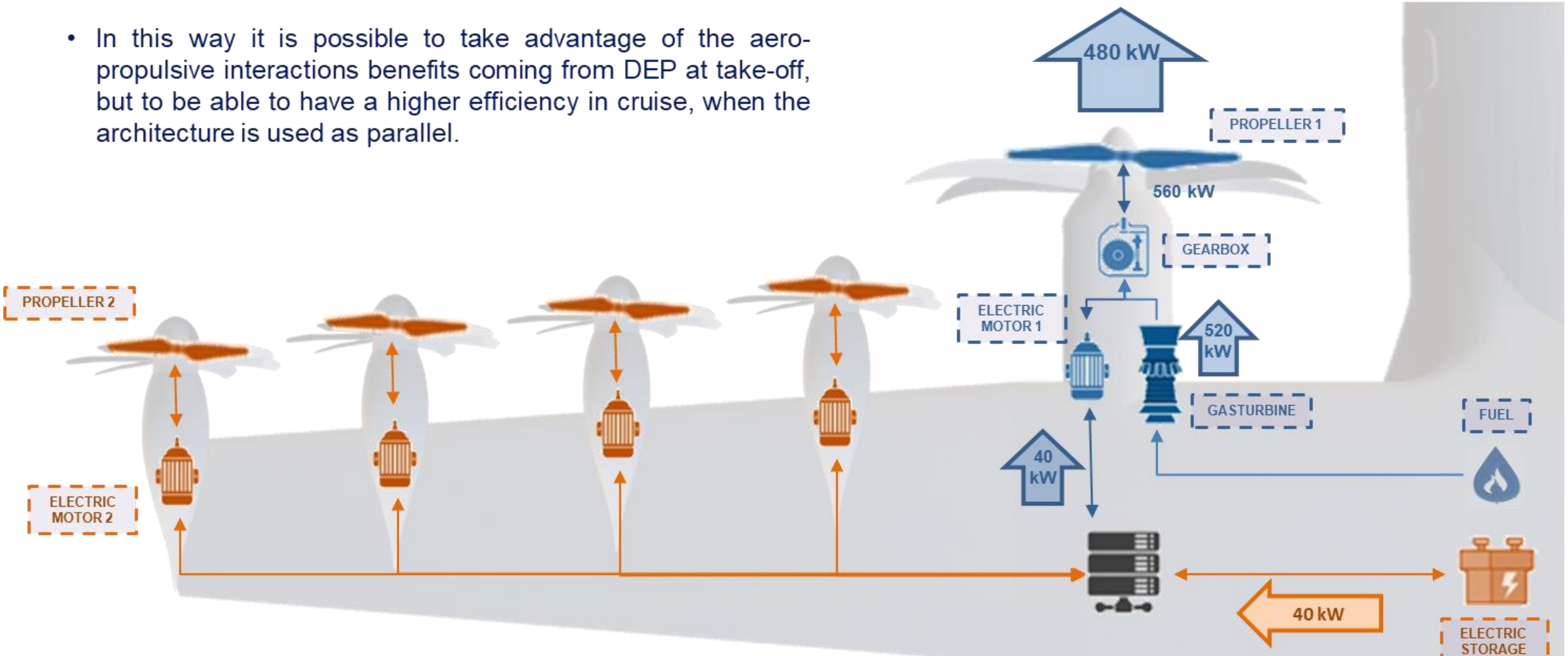
Take-Off Phase

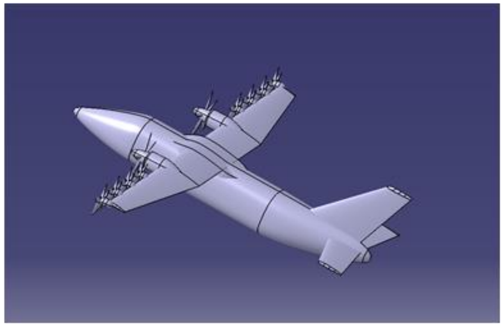
Installed primary engine (GT) power:	760 kW (x2)
Installed primary e-drive power:	500 kW (x2)
Installed secondary e-drive power:	175 kW (x8)
Installed battery power:	175 kW (x2)

ELICA PROJECT – Hybrid concept (2025)

HYBRID PROPULSIVE SYSTEM MODELLING

- In this way it is possible to take advantage of the aero-propulsive interactions benefits coming from DEP at take-off, but to be able to have a higher efficiency in cruise, when the architecture is used as parallel.





Design Mission

Target EIS: 2025

Cruise Phase

Installed primary engine (GT) power:	760 kW (x2)
Installed primary e-drive power:	500 kW (x2)
Installed secondary e-drive power:	175 kW (x8)
Installed battery power:	175 kW (x2)

ELICA PROJECT – Hybrid concept (2025)

DESIGN MISSION (500 nm)

CONVENTIONAL

Phase	Time (min)	Range (km)	Altitude (m)	Fuel Burned (kg)	Required Energy (kW*h)
TakeOff	0.34	0.523	15	2.47	4.75
Climb	6.76	37.824	3048	38.47	61.02
Cruise	135.51	846.363	3048	473.55	1244.82
Descent	7.19	41.898	457	12.26	62.80
Descent2Landing	1.86	5.829	15	3.61	11.39
Landing	0.33	0.594	0	0.49	0.50
		933.031	6583.680	530.860	1385.280

Block Fuel (kg)	530.9	Block Fuel Energy (kW*h)	6370.3	Flight Required Energy (kW*h)	1385.3
Total mission Fuel (incl diversion+loiter)(kg)	707.1	Total Fuel Energy (kW*h)	8484.8	Total Mission Flight Required Energy (kW*h)	1807.8

HYBRID

Phase	Time (min)	Range (km)	Altitude (m)	Fuel Burned (kg)	Battery Energy Consumed (kW*h)	Required Energy (kW*h)
TakeOff	0.29	0.510	15	1.83	1.66	5.63
Climb	6.20	34.731	3048	31.45	28.29	63.31
Cruise	134.03	837.164	3048	372.00	115.16	1362.47
Descent	9.30	54.148	457	14.23	0.01	89.13
Descent2Landing	1.78	6.291	15	3.12	0.00	14.27
Landing	0.40	0.835	0	0.54	0.00	0.42
		933.678	6583.680	423.173	145.118	1535.225

Block Fuel (kg)	423 (-20%)	Block Fuel Energy (kW*h)	5078 (-20%)	Flight Required Energy (kW*h)	1535 (+11%)
Total mission Fuel (incl diversion+loiter)(kg)	581 (-18%)	Total Fuel Energy (kW*h)	6973 (-18%)	Total Mission Flight Required Energy (kW*h)	2015 (+11%)
		Total Battery Energy (kW*h)	145.000		

TYPICAL MISSION (200 nm)

CONVENTIONAL

Phase	Time (min)	Range (km)	Altitude (m)	Fuel Burned (kg)	Required Energy (kW*h)
TakeOff	0.33	0.505	15	2.37	4.57
Climb	6.35	35.513	3048	36.17	56.49
Cruise	46.93	293.131	3048	162.79	428.84
Descent	7.18	41.840	457	12.24	62.66
Descent2Landing	1.86	5.828	15	3.61	11.37
Landing	0.33	0.594	0	0.49	0.50
		377.412	6583.680	217.665	564.437

Block Fuel (kg)	217.6	Block Fuel Energy (kW*h)	2612.0	Flight Required Energy (kW*h)	564.0
Total mission Fuel (incl diversion+loiter)(kg)	393.7	Total Fuel Energy (kW*h)	4725.0	Total Mission Flight Required Energy (kW*h)	986.0

HYBRID

Phase	Time (min)	Range (km)	Altitude (m)	Fuel Burned (kg)	Battery Energy Consumed (kW*h)	Required Energy (kW*h)
TakeOff	0.28	0.498	15	1.78	1.61	5.49
Climb	5.91	33.096	3048	30.00	26.99	59.65
Cruise	45.35	283.226	3048	108.62	130.43	458.32
Descent	9.29	54.115	457	14.22	0.01	88.99
Descent2Landing	1.79	6.292	15	3.12	0.00	14.25
Landing	0.40	0.835	0	0.54	0.00	0.42
		378.062	6583.680	158.288	159.030	627.107

Block Fuel (kg)	158 (-27%)	Block Fuel Energy (kW*h)	1899 (-27%)	Flight Required Energy (kW*h)	627 (+11%)
Total mission Fuel (incl diversion+loiter)(kg)	316 (-20%)	Total Fuel Energy (kW*h)	3793 (-20%)	Total Mission Flight Required Energy (kW*h)	1106 (+12%)
		Total Battery Energy (kW*h)	159.000		

Battery mass limited to 700 kg due to the CS-23 limitation on the max. take-off weight

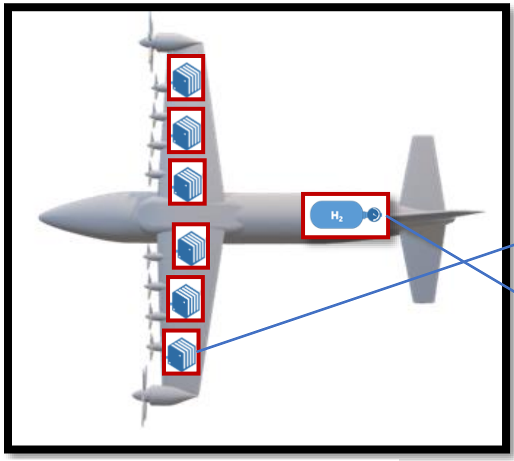
DESIGN MISSION -20% FUEL REDUCTION
TYPICAL MISSION -27% FUEL REDUCTION
W.R.T. CONVENTIONAL GREEN 2025

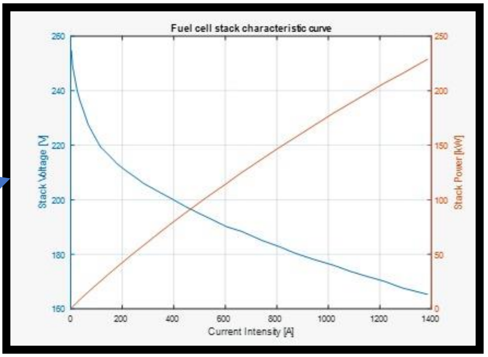
AVERAGE +11% ENERGY REQUIRED

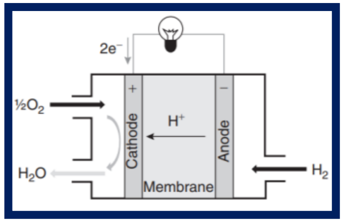
ENERGY DENSITY		
	FUEL	**12000 Wh/Kg**
	BATTERY	**270 Wh/Kg**

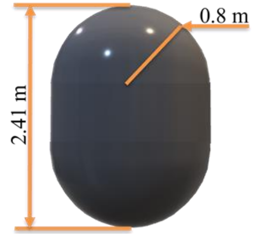
ELICA PROJECT – FULL ELECTRIC (Fuel CELL) concept (2035)

PROTON EXCHANGE MEMBRANE FUEL CELLS (PEMFC)




Fuel cell stack characteristic curve

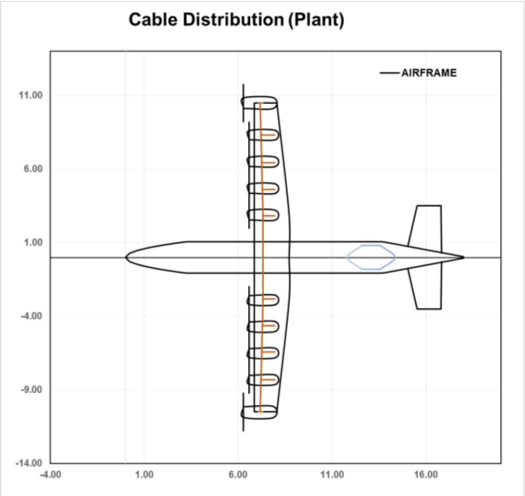


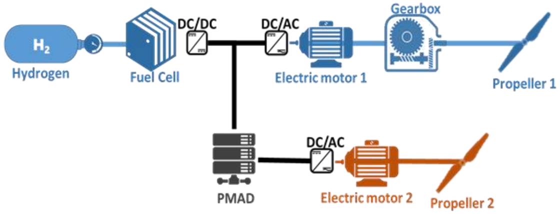


H2 tank : 3.7 m^3
H2 mass 350 Kg

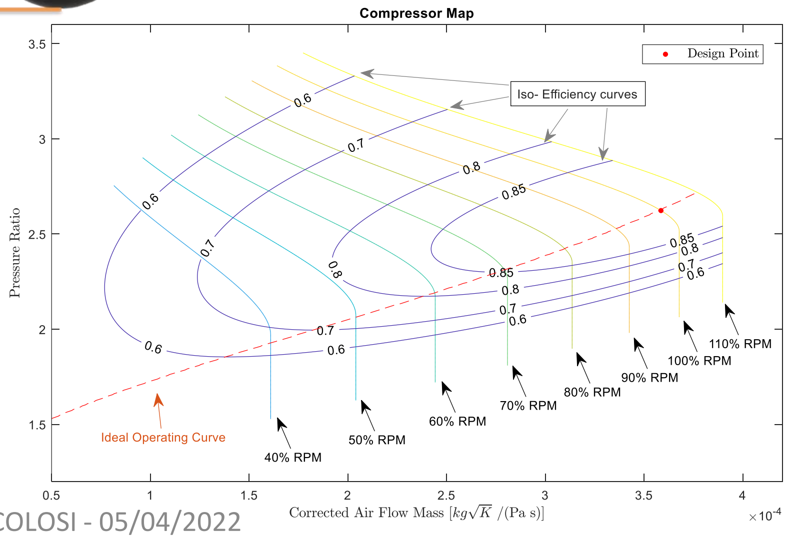
The main challenge of liquid hydrogen tanks is keeping temperature and pressure constant while facing the tensile stress acting on the tank wall.

PEM Fuel Cells	2025	2035
Specific Power [kW/kg]	1.6	2.5


Cable Distribution (Plant)



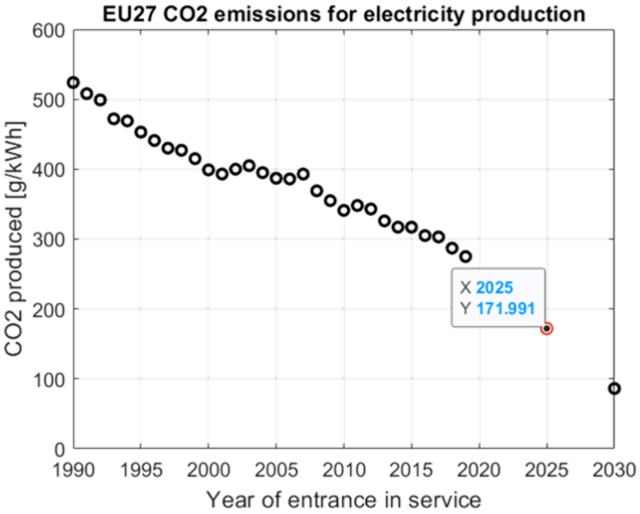
-100% FUEL REDUCTION

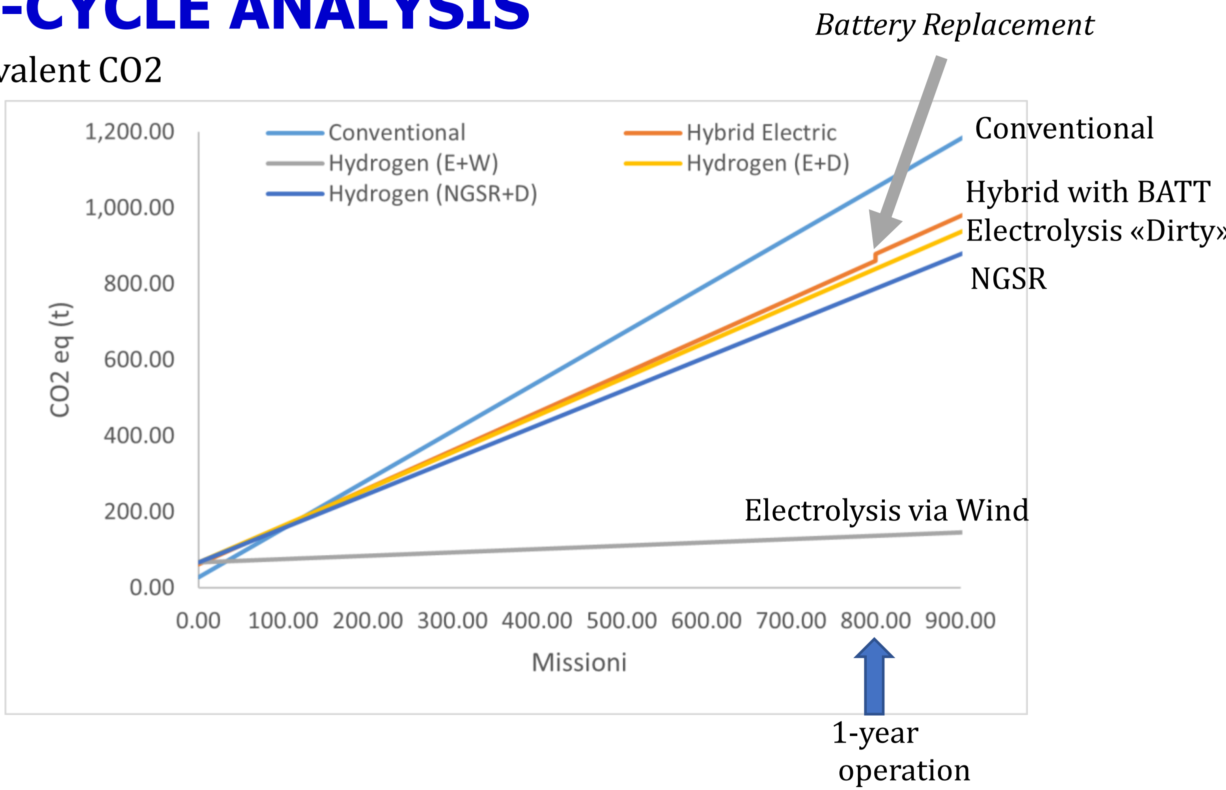

Compressor Map

ELICA PROJECT – LIFE-CYCLE ANALYSIS

GWP (Global Warming Potential => Equivalent CO2

Emissioni per la produzione energia elettrica:





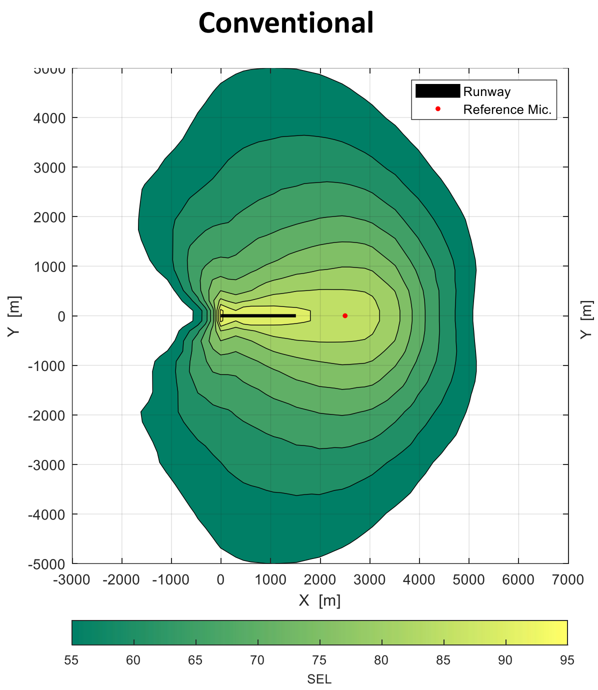
Alcune tecniche di produzione dell'idrogeno:

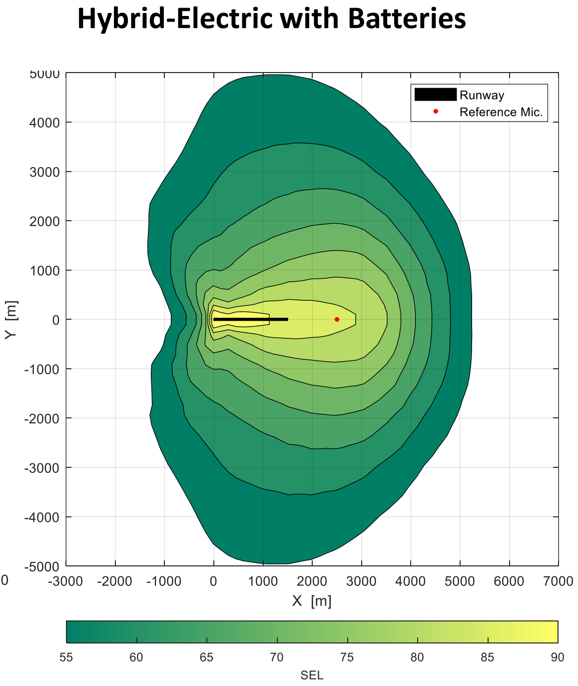
- Natural Gas Steam Reforming (NGSR)
- Coal Gasification
- Water electrolysis via wind energy
- Water electrolysis via solar energy
- Thermochemical water splitting

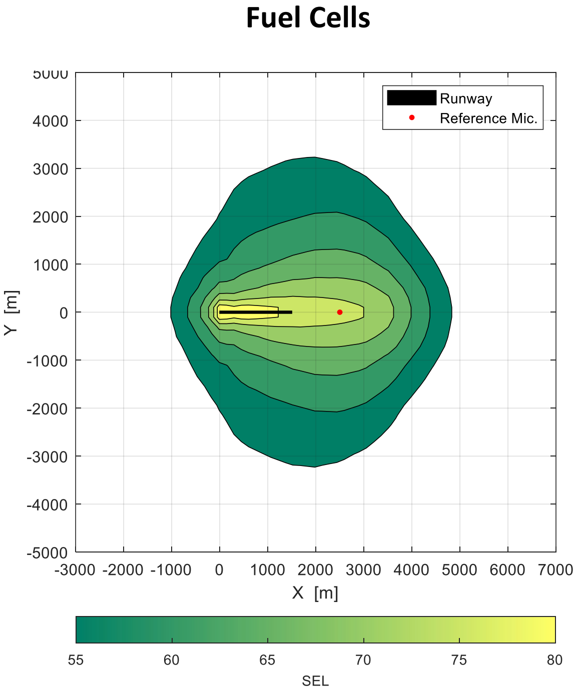
La configurazione ibrido elettrica consente di ridurre le emissioni di **CO2-eq. - 20%** rispetto alla convenzionale
CONVENTIONAL (1 Y operation) 1040 tonn CO2 eq
HYBRID (1 Y operation) 830 tonn CO2 eq
FUEL CELL (Hydrogen Electrolisi via WIND) 110 tonn CO2 eq

Le configurazioni a idrogeno risultano le migliori come emissioni totali, in particolare quella in cui l'idrogeno è prodotto tramite **elettrolisi con energia eolica (-85-90%)**

ELICA PROJECT – NOISE


Conventional


Hybrid-Electric with Batteries


Fuel Cells

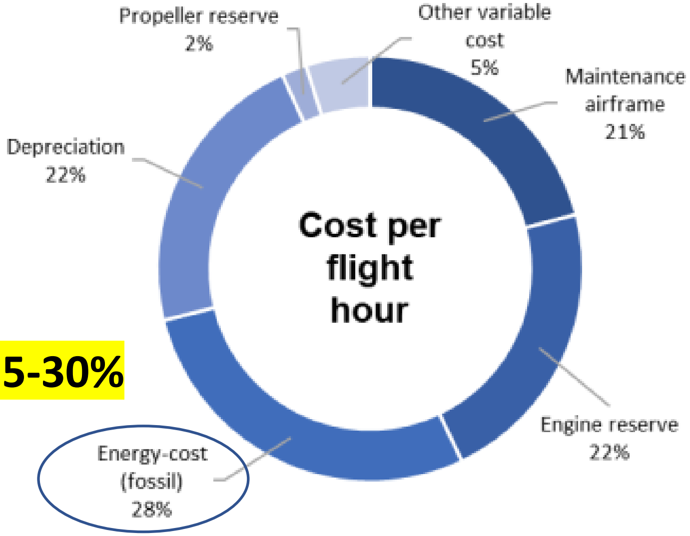
	Conventional	Hybrid-Electric with Batteries	Fuel Cells
Noise footprint Aera (km²)	15.40	14.60	6.30
Reduction (%)	-	-5.19	-59.09

ELICA PROJECT – COSTS

Net Price 19 Pax Electric Aircraft: 6,000,000 €
Depreciation period: 21 years

JET-A1 consumption per flight hour: 240 l/h
Net price JET-A1 for CAT: 0.99 €/l
JET-A1 cost per flight: 285.12 €

FUEL only 25-30%



E-energy consumption per mission: 385 kWh/mission
Net price per kWh: 0.22 €/kWh
E-energy cost per flight: 84.7 €

Fuel energy calculation:
240 l/h*1.2 h=288 l /mission=216 Kg/mission
216*12000 Wh/Kg=2600 kWh/mission

Maintenance per flight hour: 176.00 €/h
Engine reserve per flight hour: 185.30 €/h
Propeller reserve per flight hour: 16.00 €/h
Other variable cost per flight hour: 41.00 €/h
Total reserve cost per flight: 501.96 €

Passenger fees per mission: 168.72 €/mission
Air traffic fees per mission: 169.20 €/mission

Variable cost per mission: 871.78 €/mission
Variable cost per flight km: 2.24 €/km

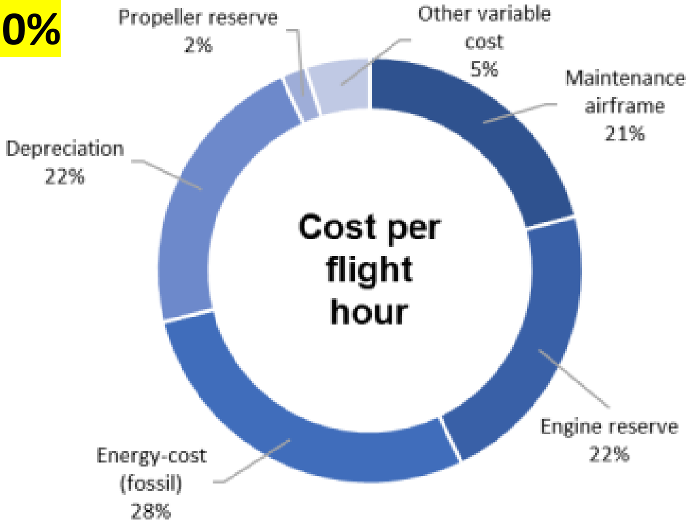
AIR TRAFFIC FEES CAN IN THE FUTURE HAVE A GREAT IMPACT IN PUSHING ELECTRIC FLIGHT

ELICA PROJECT – COSTS

Variable cost per mission: 871.78 €/mission
Variable cost per flight km: 2.24 €/km

Passenger fees per mission: 168.72 €/mission
Air traffic fees per mission: 169.20 €/mission
Other mission cost: 22.00 €/mission
Cost per revenue mission: 475.08 €/mission

FUEL only 25-30%



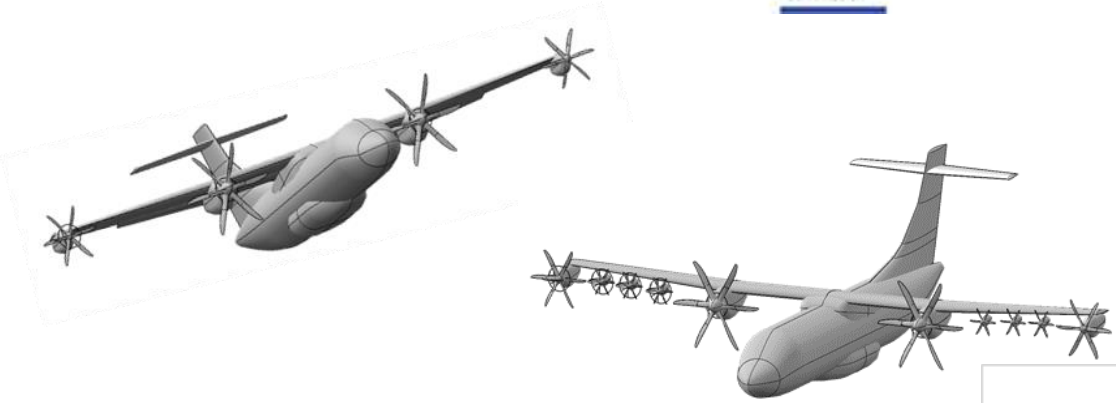
AIR TRAFFIC FEES CAN IN THE FUTURE HAVE A GREAT IMPACT IN PUSHING ELECTRIC FLIGHT

The energy cost is only a small fraction. The impact of hybridization on operational cost in really marginal (high cost of maintenance and fees).

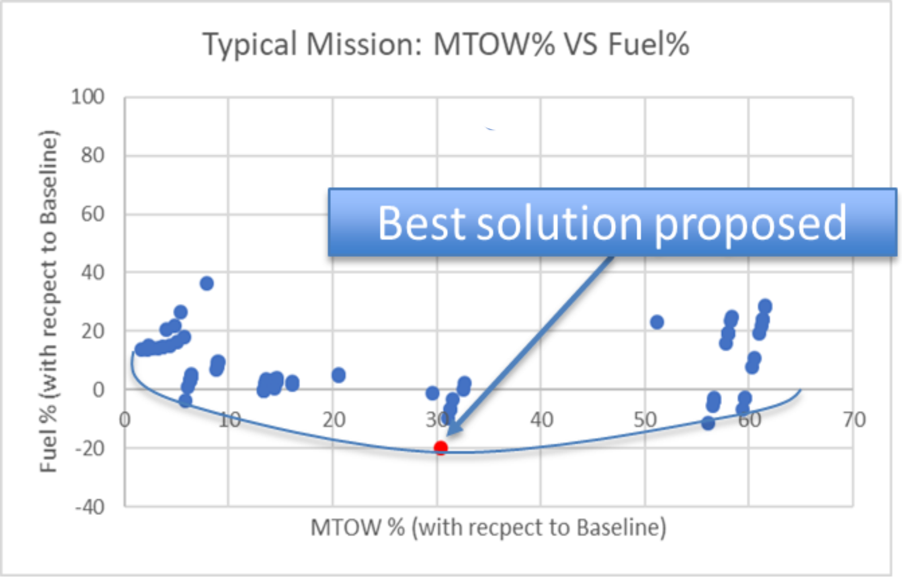
OF COURSE ALSO FUEL COST CAN BE A DRIVER !

ELECTRIC/HYBRID REGIONAL AIRPLANES
IRON PROJECT

CS2 Project – Coordinator CIRA,
Topic Leader LEONARDO Aircraft



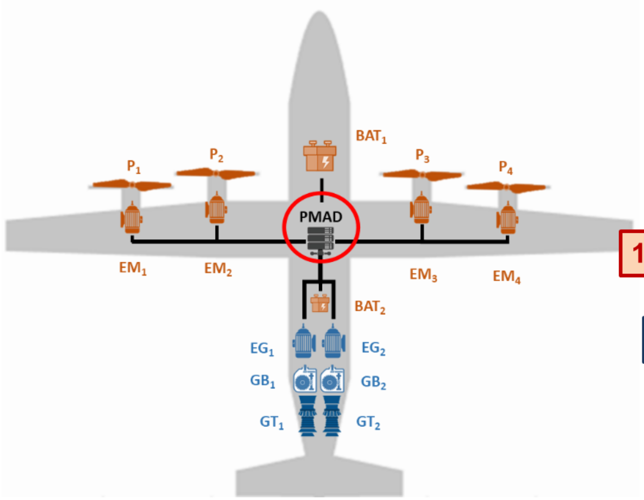
HYBRID REGIONAL AIRCRAFT
Fuel saving -20-30% w.r.t. Baseline
(efficient modern turboprop)

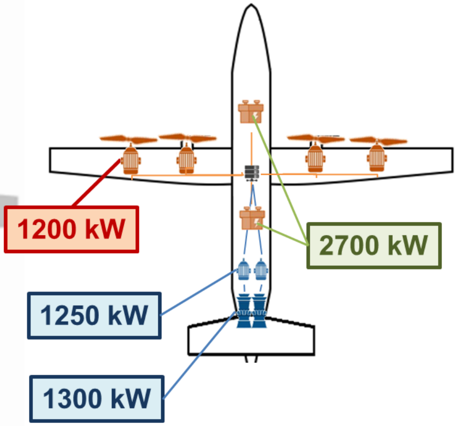


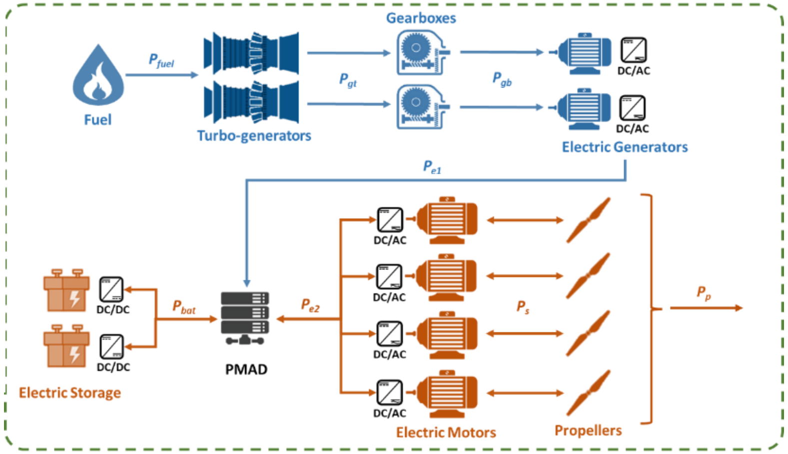
BATTERY WEIGHT at certain value can give negative effects on possible fuel savings.
Snow-ball effects are leading to an increase of fuel needed due to the high increase in weight.

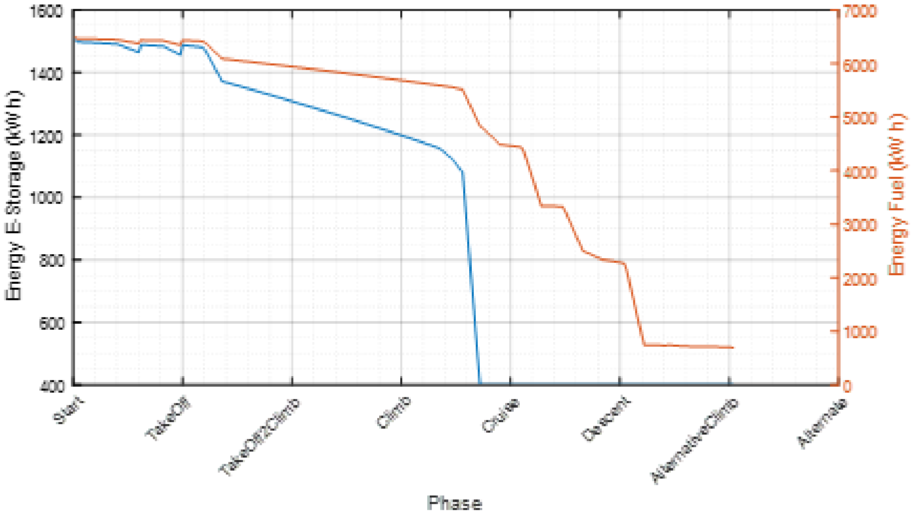
ELECTRIC/HYBRID REGIONAL AIRPLANES IRON D

Al fine di aumentare l’efficienza del motore termico (turbogeneratore) facendolo lavorare vicino al punto fisso, si è preferita una configurazione **seriale**. La batteria fornisce i picchi di potenza.

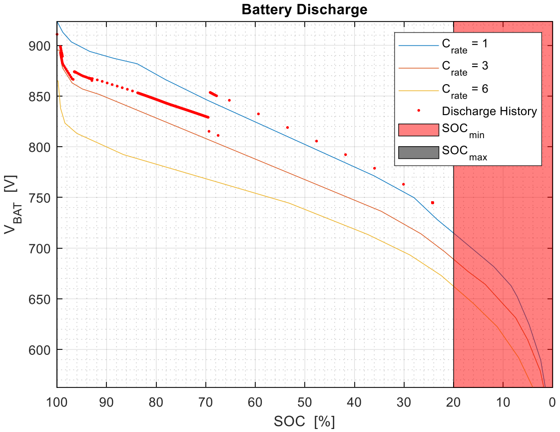






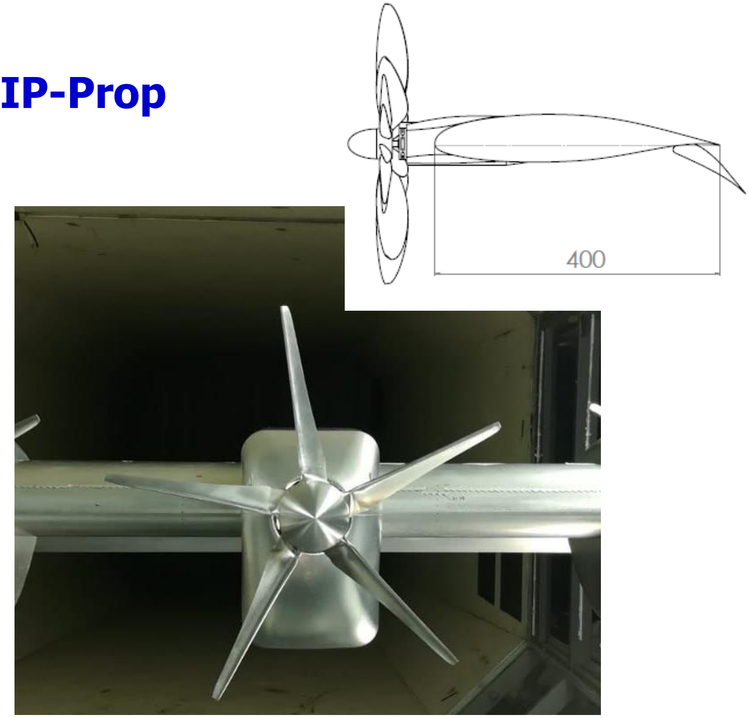


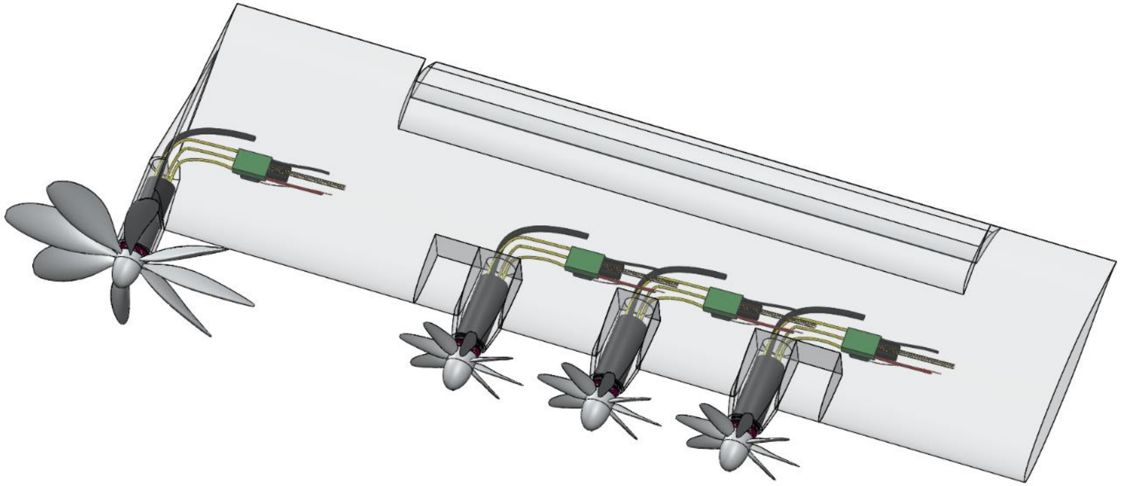
Fuel saving -40% on typical mission (200 nm) w.r.t. Baseline



PON PROSIB

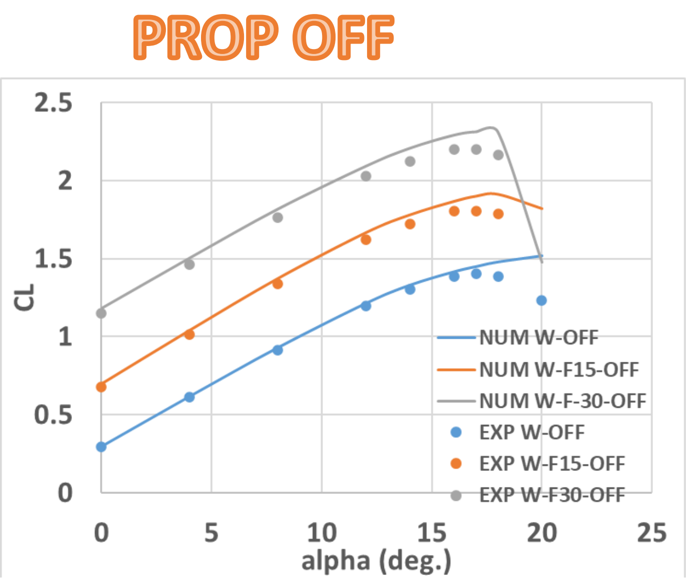
Wind-Tunnel Tests on a wing model with DEP and TIP-Prop

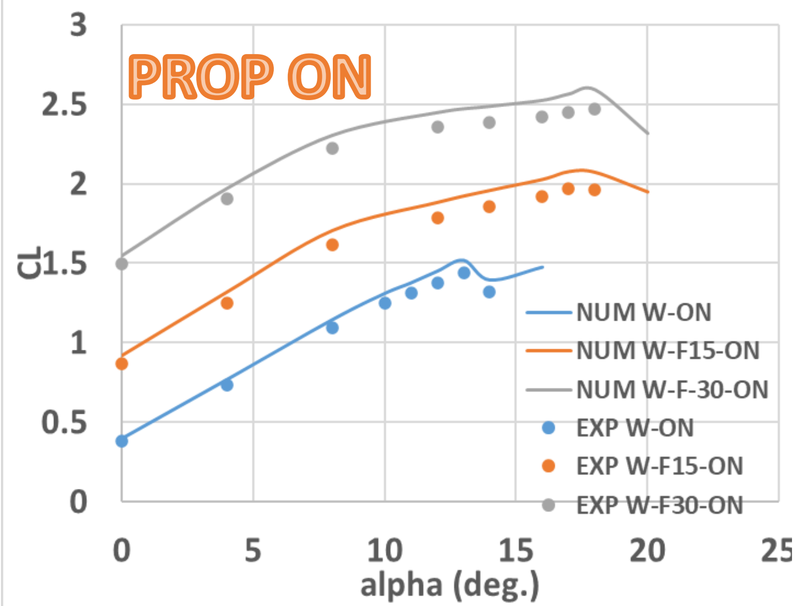


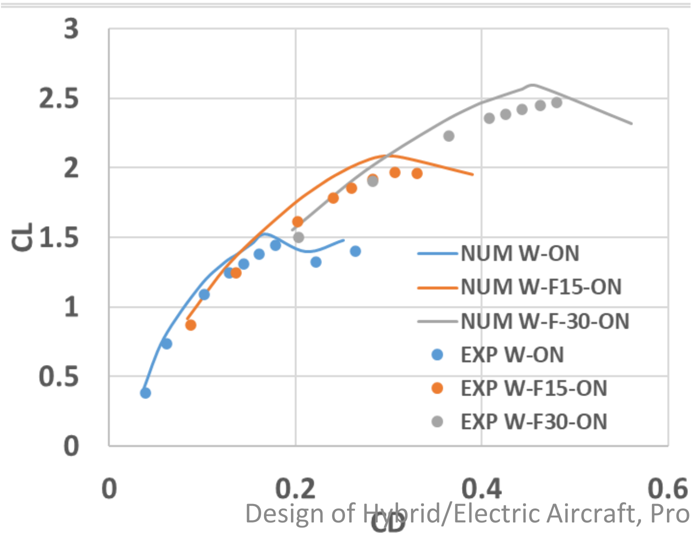


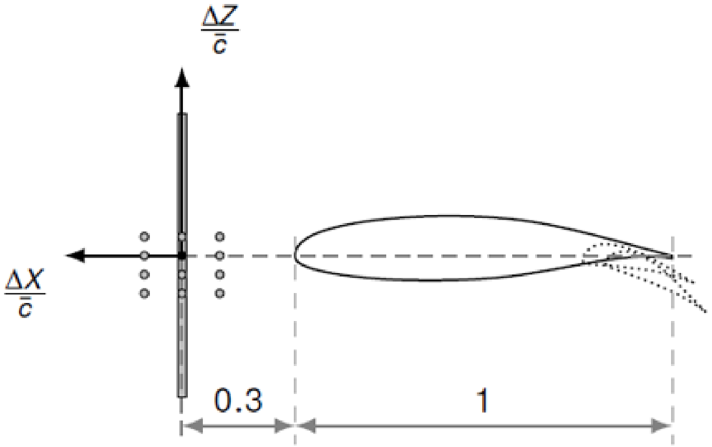
PON PROSIB

Wind-Tunnel Tests on a wing model with DEP and TIP-Prop









QUESTIONS