HTS-Technology for hybrid electric aircraft

ECD-IWCHTS 2017

Dr. Mykhaylo Filipenko, KIT - 13.09.2017

Siemens eAircraft part of Coorporate Technology

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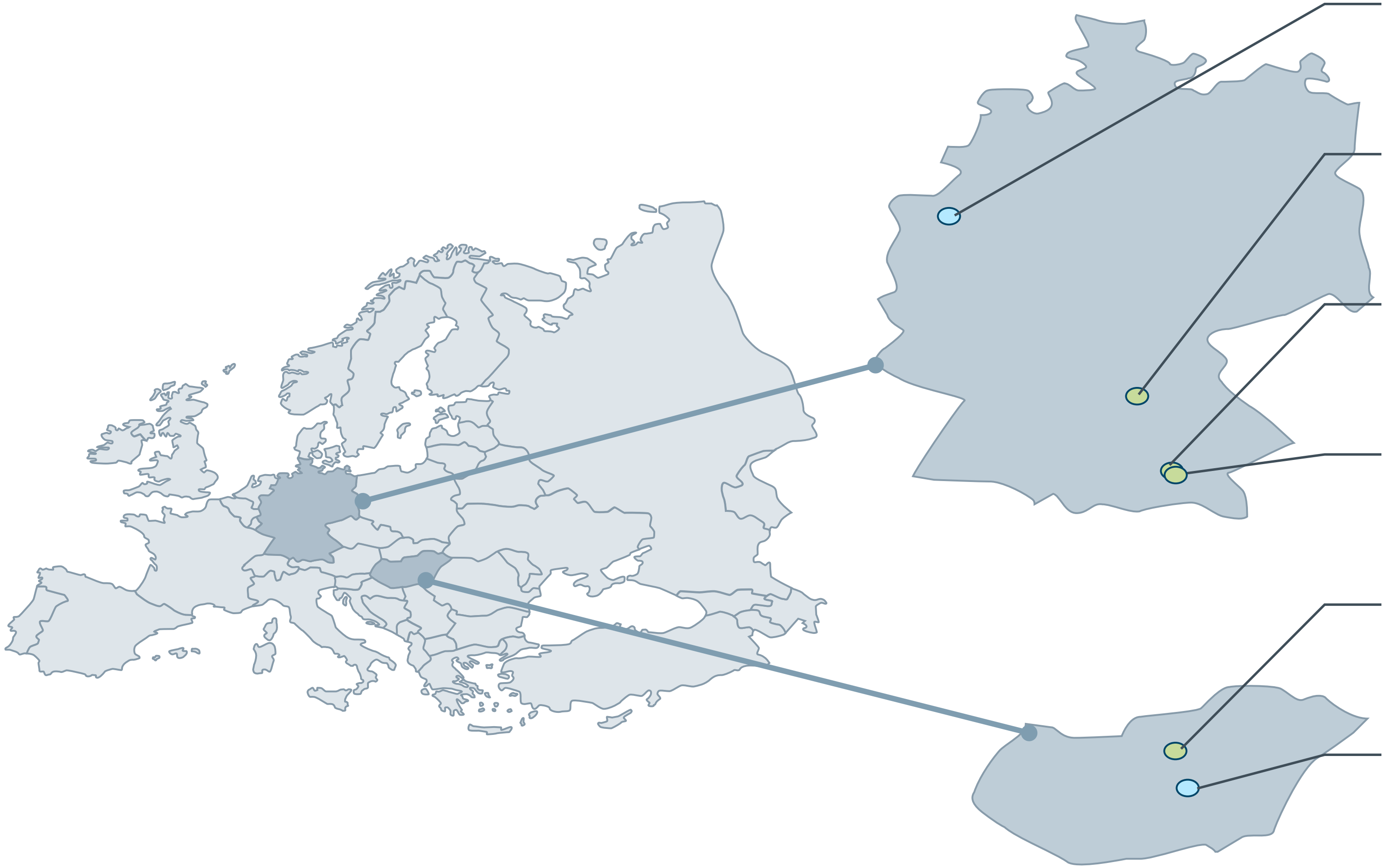
Overview of Siemens eAircraft locations



Dinslaken, Germany

Airfield for Extra 330LE flying testbed

Erlangen, Germany

Headquarters and design organization for certified applications

Munich, Germany

Testing labs

Taufkirchen, Germany

Airbus-Siemens collaboration

Budapest, Hungary

Design organization for general aviation

Matkópusztai airfield, Kecskemét, Hungary

Airfield for eFusion flying testbed

Airfield   Office location

Electric Aircraft – Why?

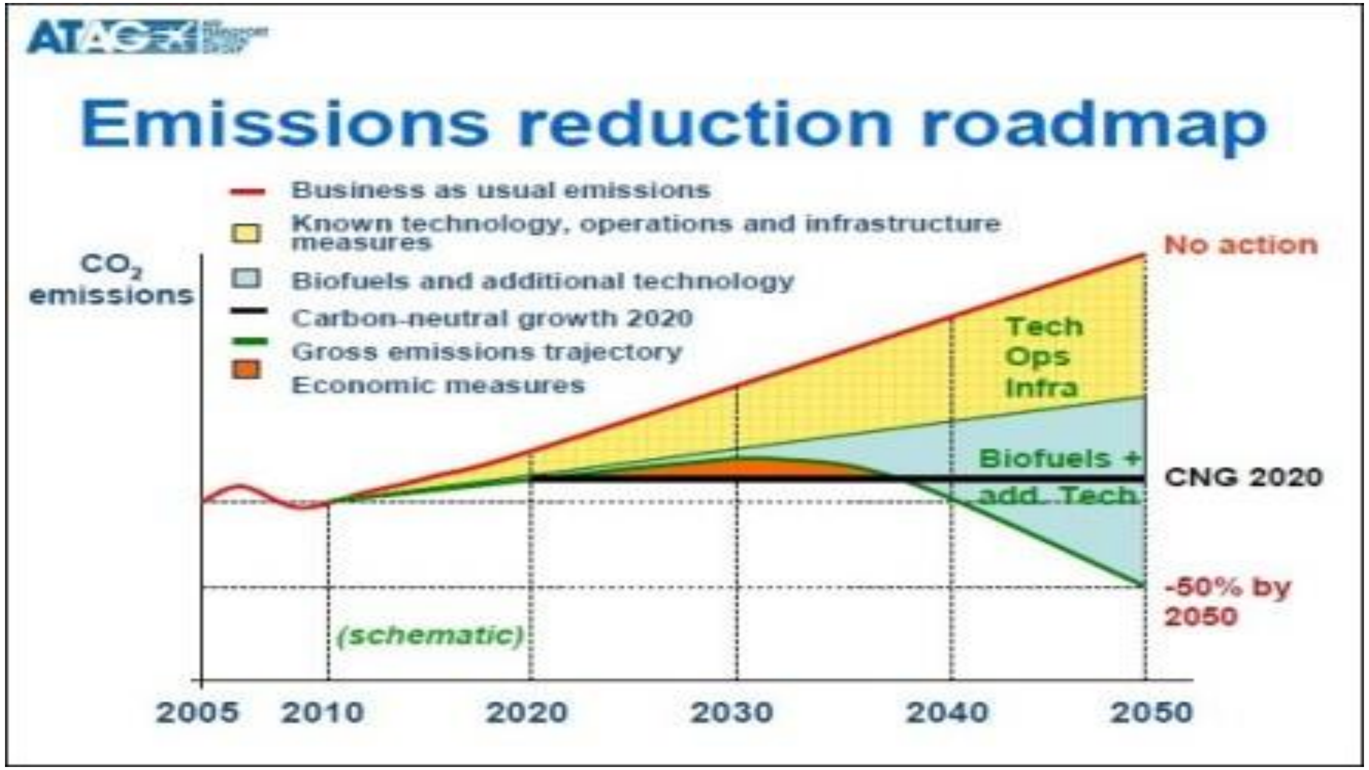
Save the Planet!

Flightpath 2050 Goals:

75 % CO_2 emission reduction

90 % NO_x emission reduction

65 % noise reduction



Electric Aircraft – Why?

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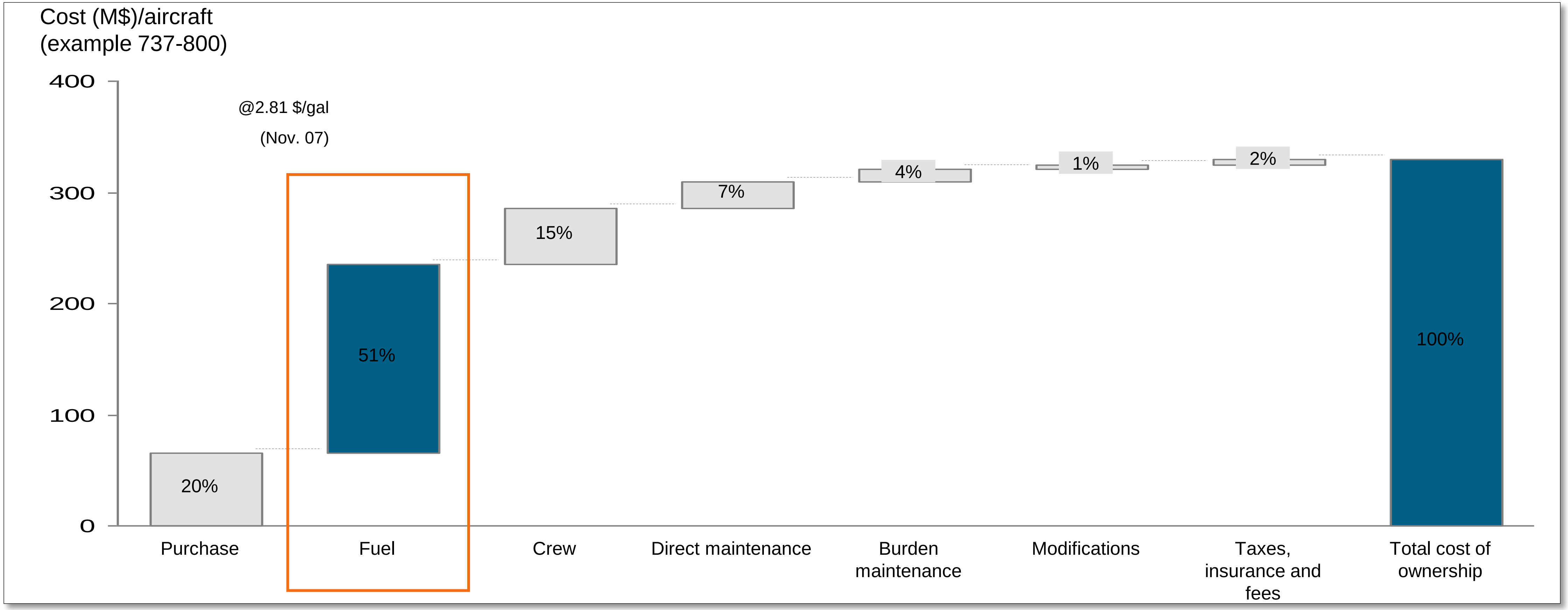
Also a business case !



Reduction of fuel consumption is main lever to reduce aircraft TCO

Note: Calculated using hourly operational costs from September 2007 Form 41 data for all US carriers currently operating 737-800s (Continental, American, Delta, Sun Country, ATA, Alaska). Assumes uptime avg. 10.3 block hrs/day, 20-year lifecycle, and 8-10 year modification cycle.

Source: Carrier Form 41 reports, IATA, airfinancejournal.com, TeamSai, Aerostrategy; BCG

Short History of Electric Aircraft

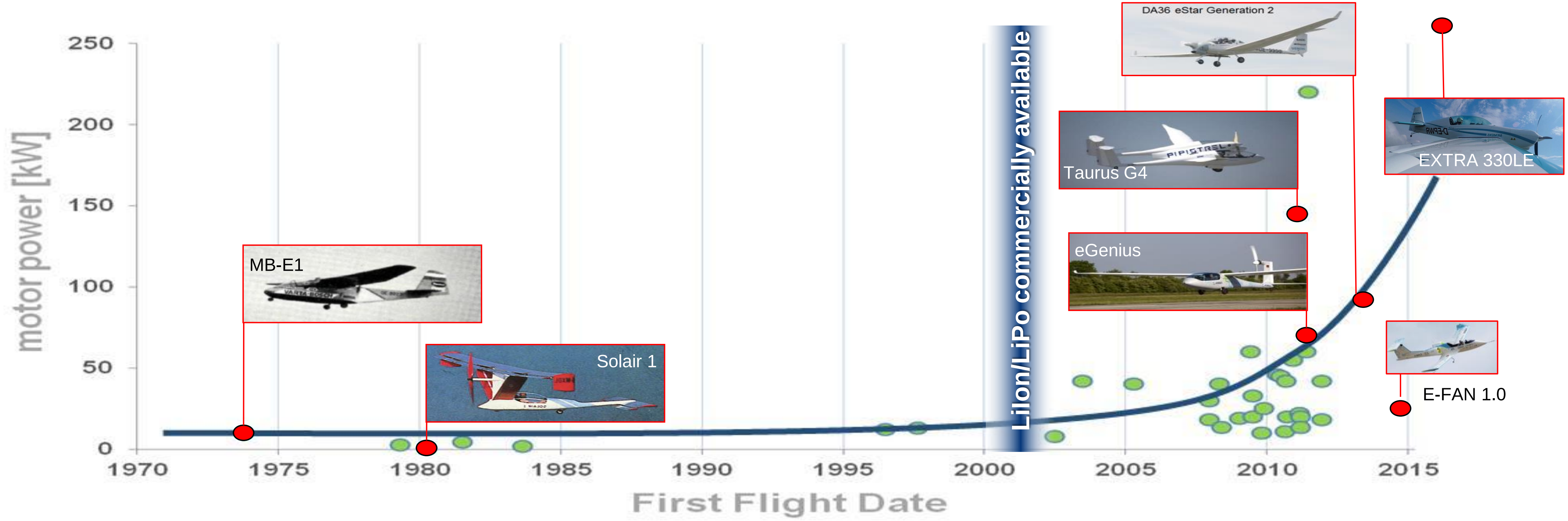


Image Courtesy of Airbus Group

Siemens eAicraft flight test history

2011 2013

Hybrid electric Diamond Aircraft eStar 1 and eStar 2

2014

Fully electric Pipistrel WattsUp trainer

2016

Fully electric Magnus eFusion

2016

Record motor SP260D in the Extra 330LE

Magnus eFusion - fully electric aircraft propulsion system installed firewall-forward

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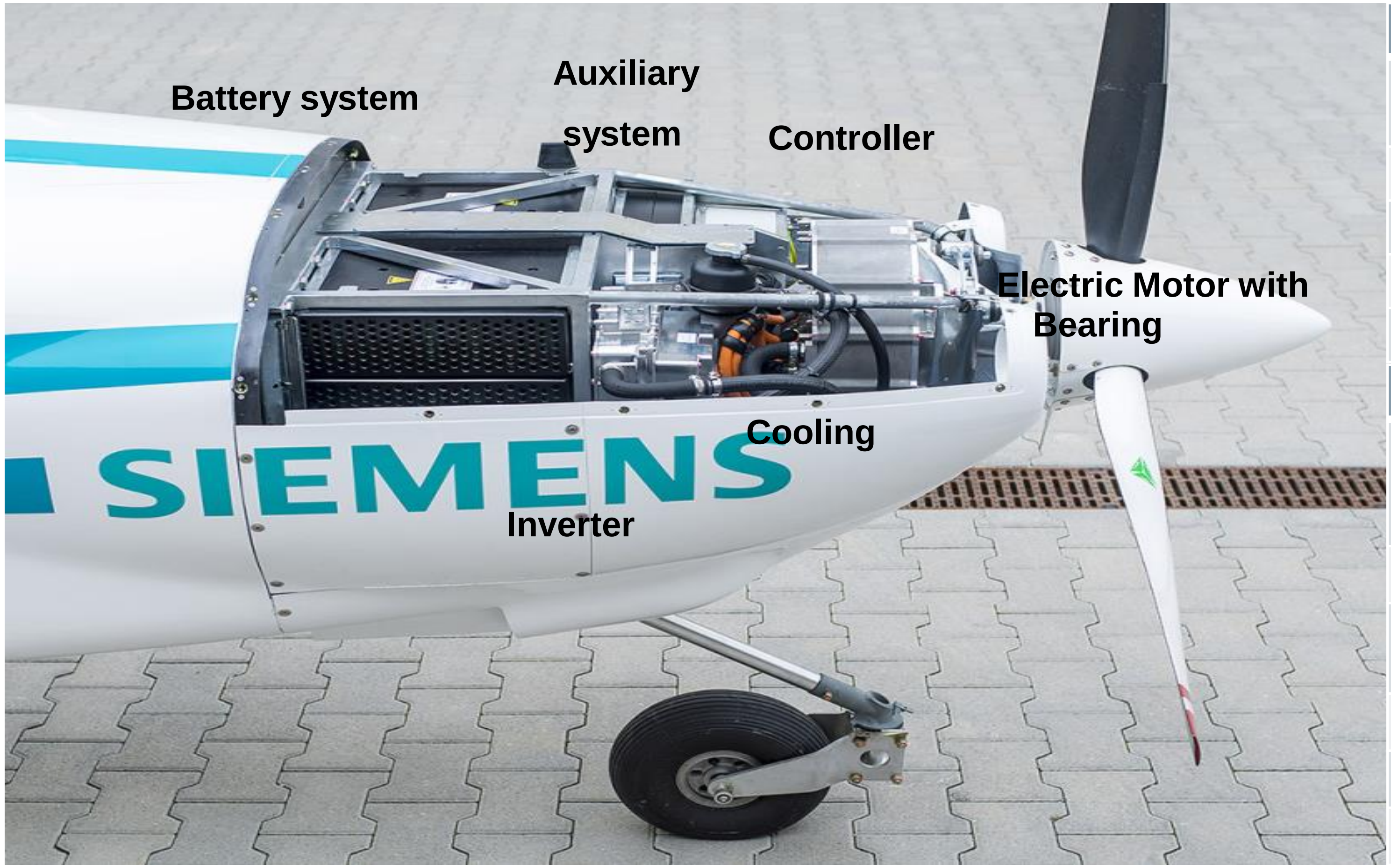
Magnus eFusion – maiden flight Summer 2016



Aircraft Data	
Empty weight including batteries and parachute	410 kg
MTOW	600 kg
Wingspan	8.4 m
Length	6.6 m
Height	2.4 m
Propulsion System Data	
Power	45 kW MCP 60 kW MTOP 85 kW max.
N_{max}	2500 rpm
DC-link voltage (nominal)	350 VDC (300 …450 V)
Torque M_{Boost}	324 Nm
Battery	10.1 kWh
Max. airspeed	97 KIAS

Flying testbed for ¼-MW class electric propulsion systems

Extra 330LE - maiden flight summer 2016

Aircraft Data	
MTOW	1000 kg
Wingspan	8.0 m
Height	2.6 m
Length	7.5 m
Wing area	10.7 m^2
Propulsion System Data⁺	
P_{max}	260 kW
P_{cont}	230 kW
N_{cont}	2250 rpm
M_{cont}	1000 Nm
η_{Mot}	max. 95%
$m_{Mot,\ including\ propeller\ bearing}$	50 kg

* As rated in the Extra 330LE

We expect electric propulsion to be the standard solution by 2050

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Outlook for electric propulsion market

Increasing dominance of electric propulsion

Today
Experimental flight with small aircraft demonstrated

2018
Market entry for ultra-light and military due to less strict certification rules

2022
Market **ramp-up for certified systems**, e.g., two- and four-seaters

2025
Fully electric flying for medium range (**energy storage capacity** sufficient)

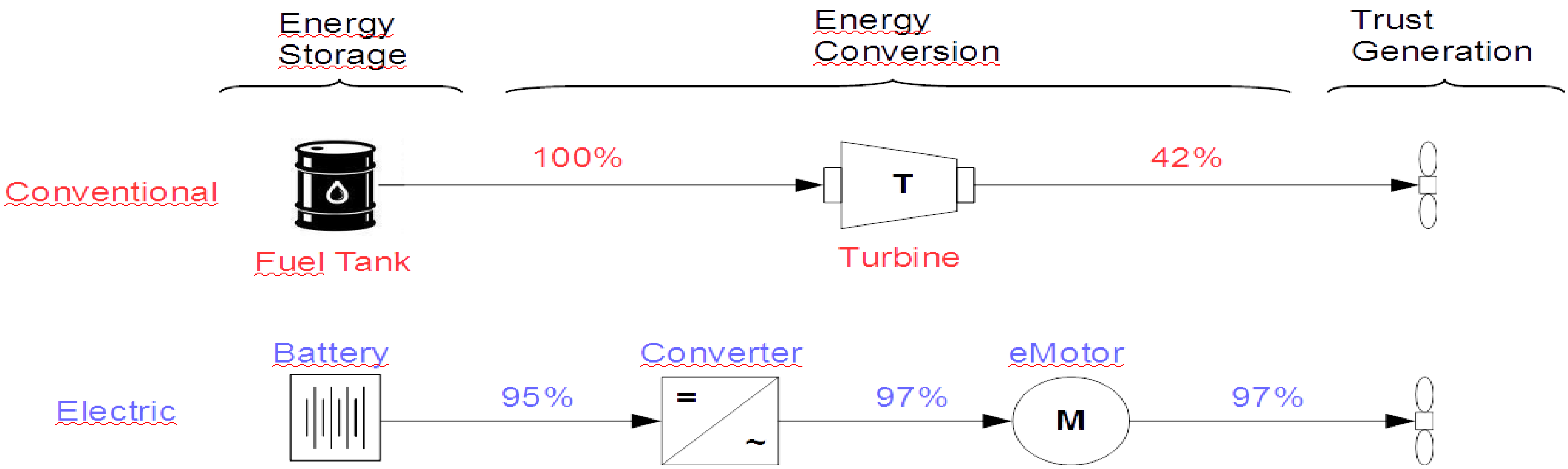
2030
Airlines offering **scheduled flights** based on hybrid-driven aircraft

2050
E-propulsion is the standard solution for all aircraft segments

Today → **2050**

Source: eAircraft market evaluation

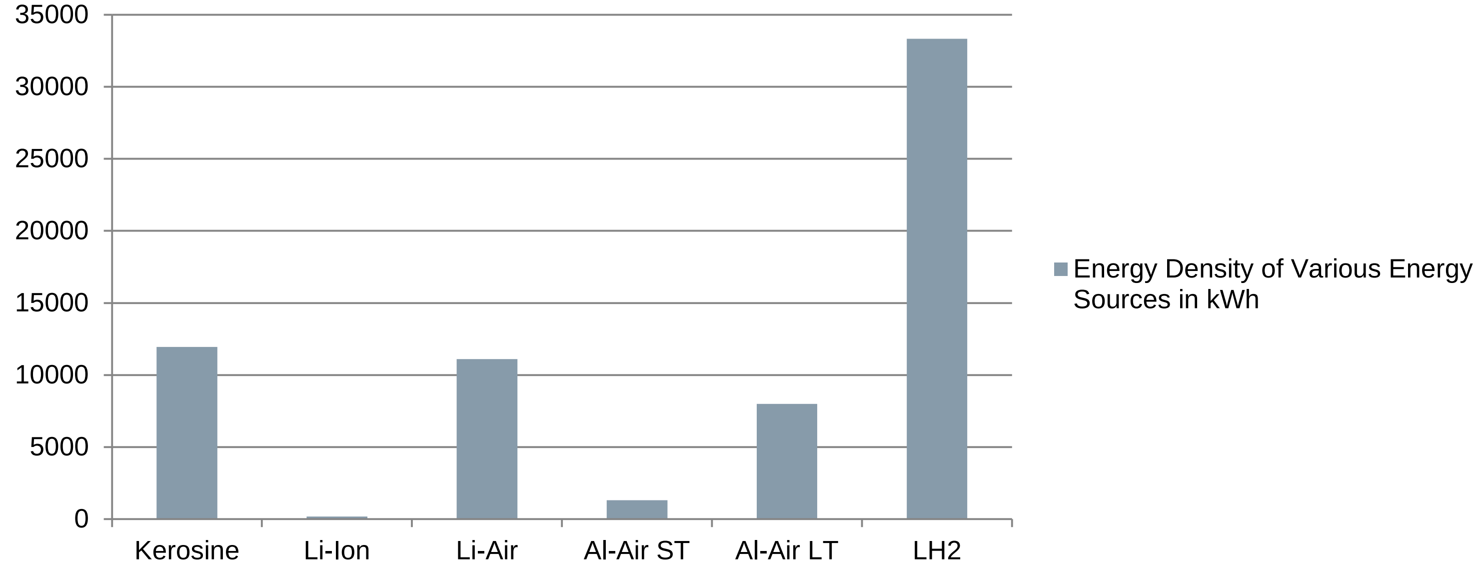
Comparison of Drive Trains



→ High Gains in Efficiency Possible !

Challenge One – Energy Storage

Energy Density of Various Energy Sources in kWh



1. Batteries could provide sufficient storage capacity in the far future

2 .Commercial development ongoing but it is still a long way

3. In the meantime hybrid electric concepts could be used for electric aircraft

Challenge Number Two – Weight of Drivetrain Equipment

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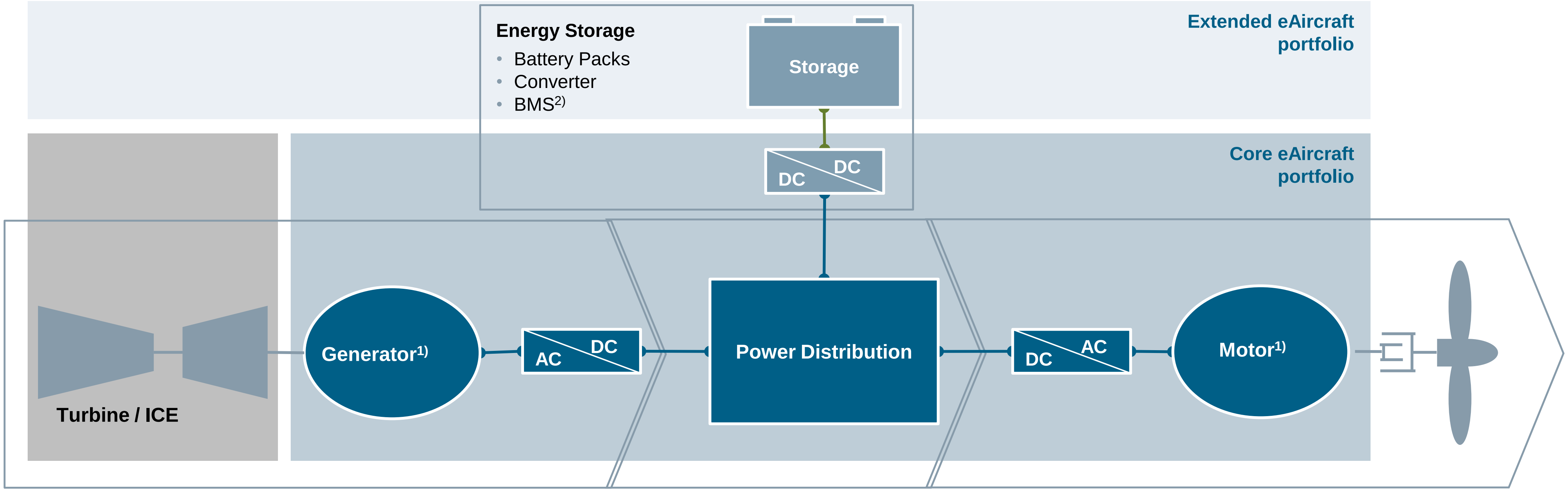

Power Generation
- Generator
- Inverter
- Controller
- Turbine/ICE[3]

Power Distribution
- Circuit Breaker
- Switches
- Cables
- Connectors

Propulsion Unit
- Motor
- Inverter
- Propeller
- Gearbox

Propulsion System

1) E-machines are capable to fulfill “power generation” and/or “propulsion” depending on e.g. mission profile, requirements and/or mode of operation, 2) Battery Management System (BMS), 3) Internal Combustion Engine (ICE)

Challenge Number Two – Weight of Drivetrain Equipment

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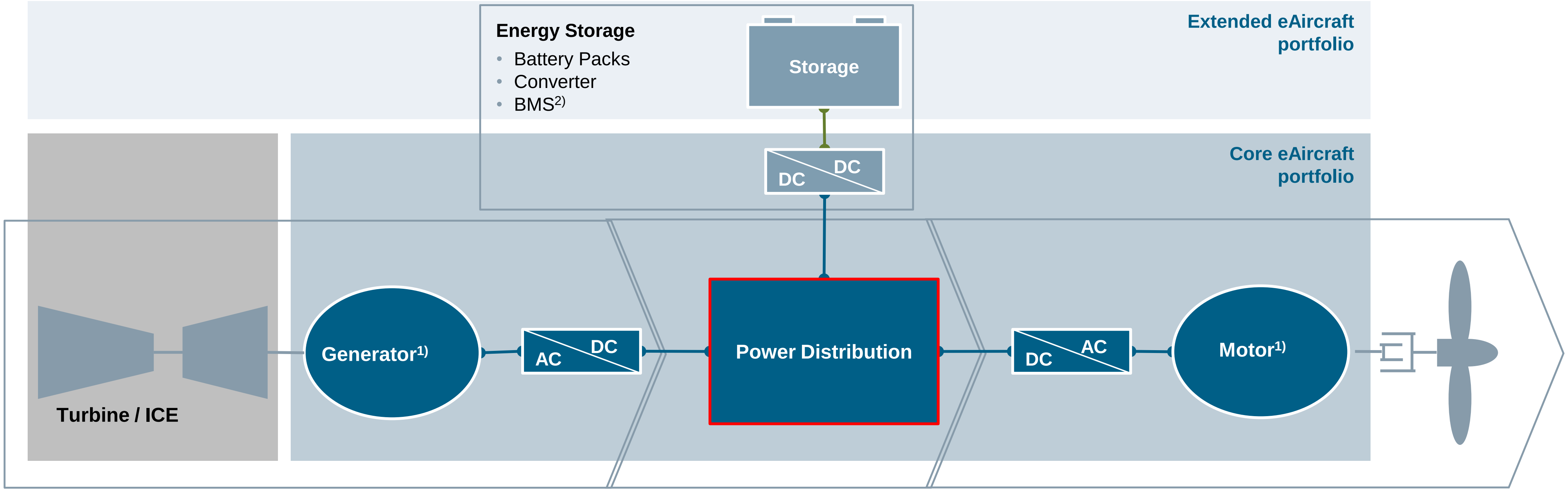

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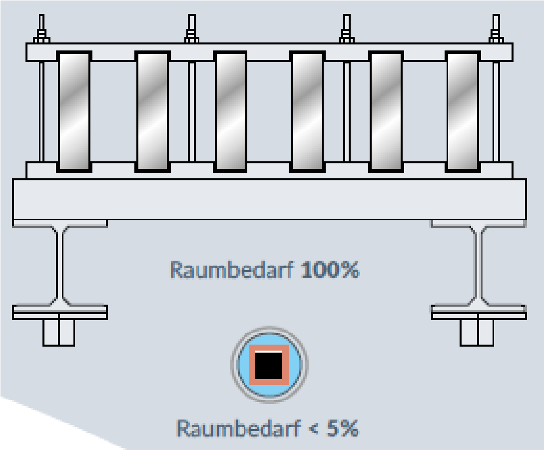
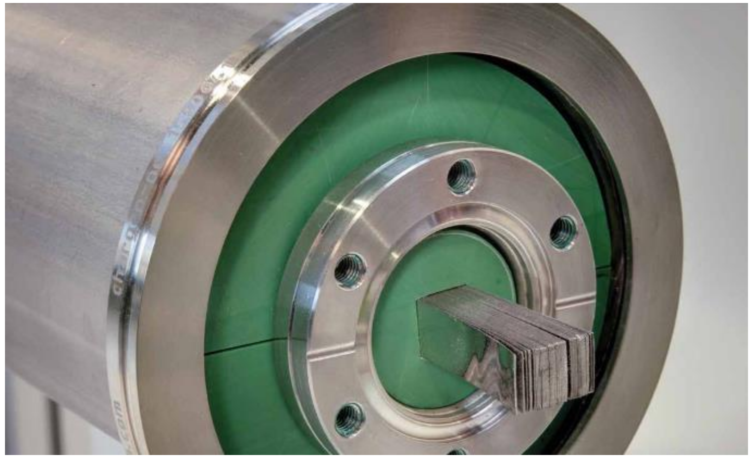
Cold Power Cables





Examples from Vision Electric and Nexans

Weight reduction of up to an order of magnitude for multi-MW systems (~ 2-10 t to 0.2t to 1t)

Voltage independency => high flexibilty for motor, PE design and switch design

Almost „of-the-shelf“ technology

Challenge Number Two – Weight of Drivetrain Equipment

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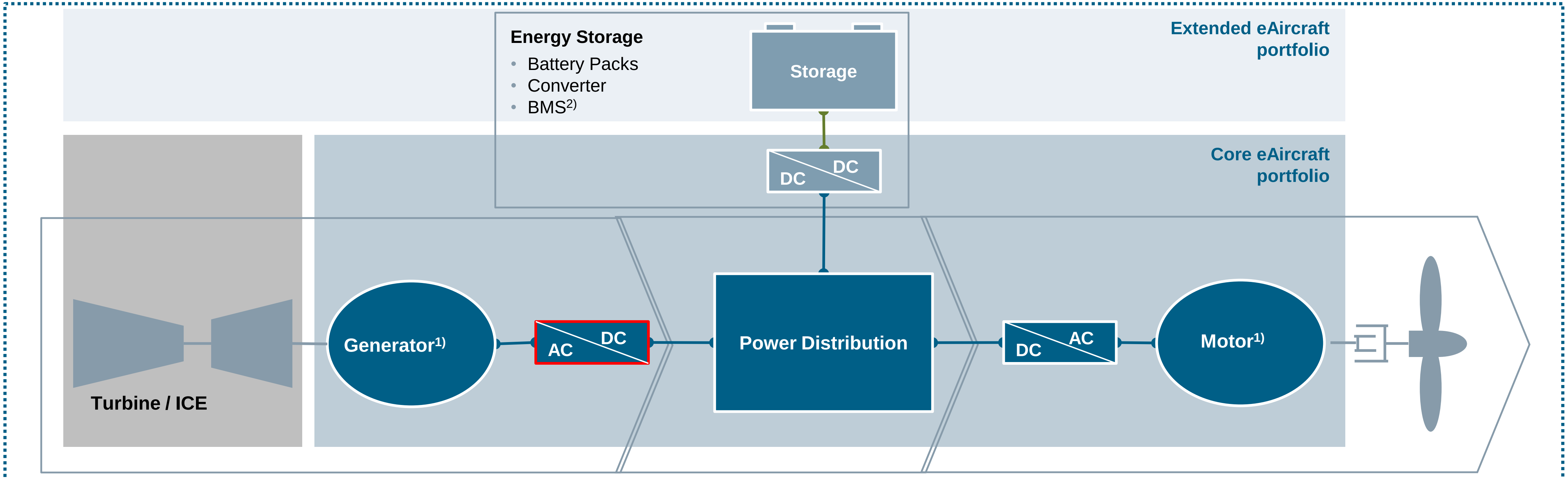

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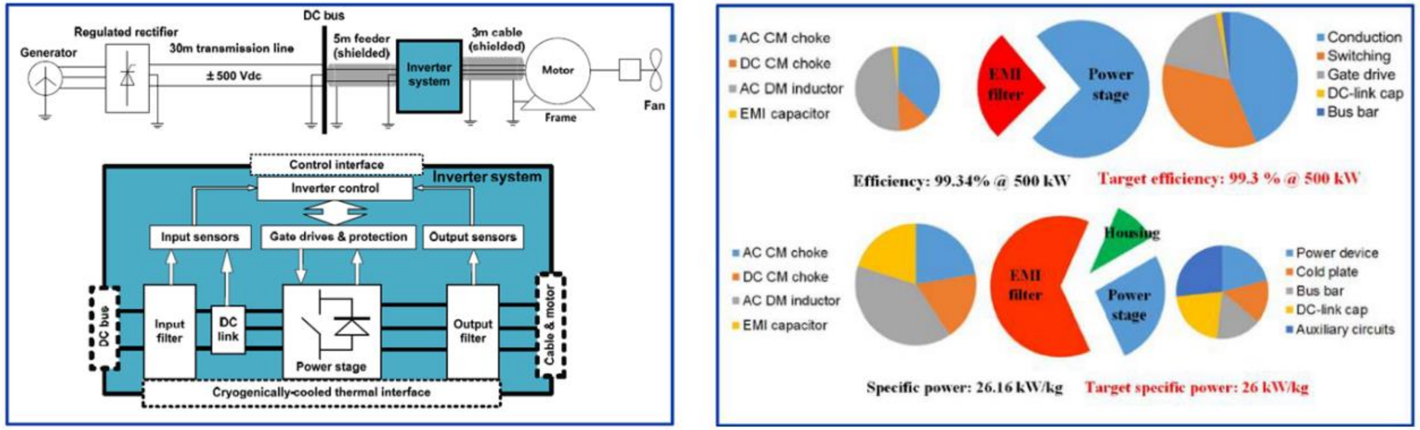
Least mature field concerning application at cryogenic temperatures

Increasing efforts in particular in USA:

- Development of 200 kW multi-level inverter for cryogenic application at University of Illinois with GaN modules
- Boeing 1 MW inverter
  Efficiency: 99.3 %
  Power-to-Weight: 26 kVA/kg

On-state behaviour		
Temperature range	20 K – 50 K	50 K – 100 K
Si n-channel MOSFETs/SJ MOSFETs	Little degradation in the on-state OR Non-ohmic behaviour and negative temperature dependence	Optimum range
Si p-channel MOSFETs	Negative temperature dependence / Non-ohmic behaviour	Optimum range
SiC MOSFETs	Positive temperature dependence / No improvements compared to higher temperatures	Negative temperature dependence / No improvements compared to higher temperatures
GaN HEMTs	Almost temperature independent / Improvements	Small positive temperature dependence / Improvements
Si/SiC Schottky diodes	No improvements compared to higher temperatures	No improvements compared to higher temperatures
GaAs Schottky diodes	Improvements at high current levels	Improvements at high current levels

Overview from PhD Thesis
Leong, University of Warwick, 2011

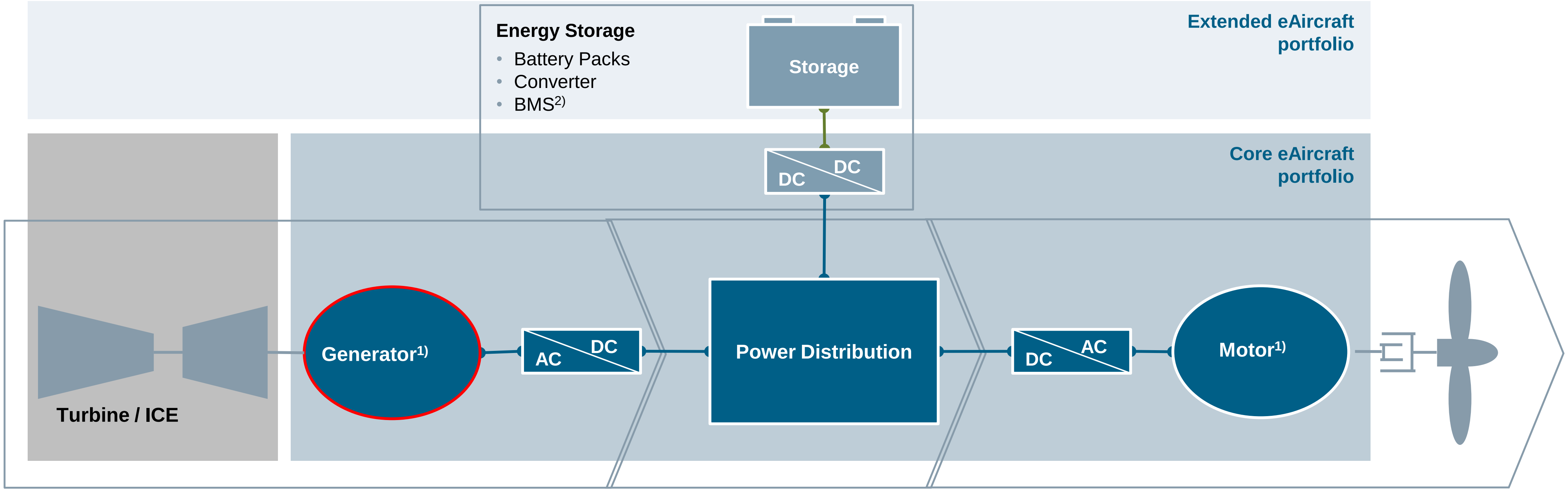


(a) System architecture (b) Efficiency and weight breakdown

Figure 13. Boeing cryogenic silicon megawatt inverter.

R. H. Jansen et al.: Overview of NASA Electrified Aircraft Propulsion Research for Large Subsonic Transports (AIAA Conference '17)

Challenge Number Two – Weight of Drivetrain Equipment



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Motor Weight – Today

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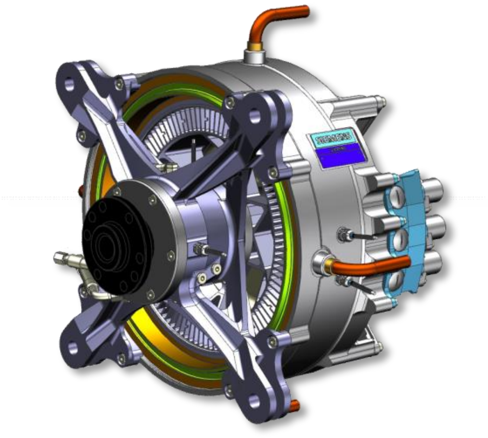
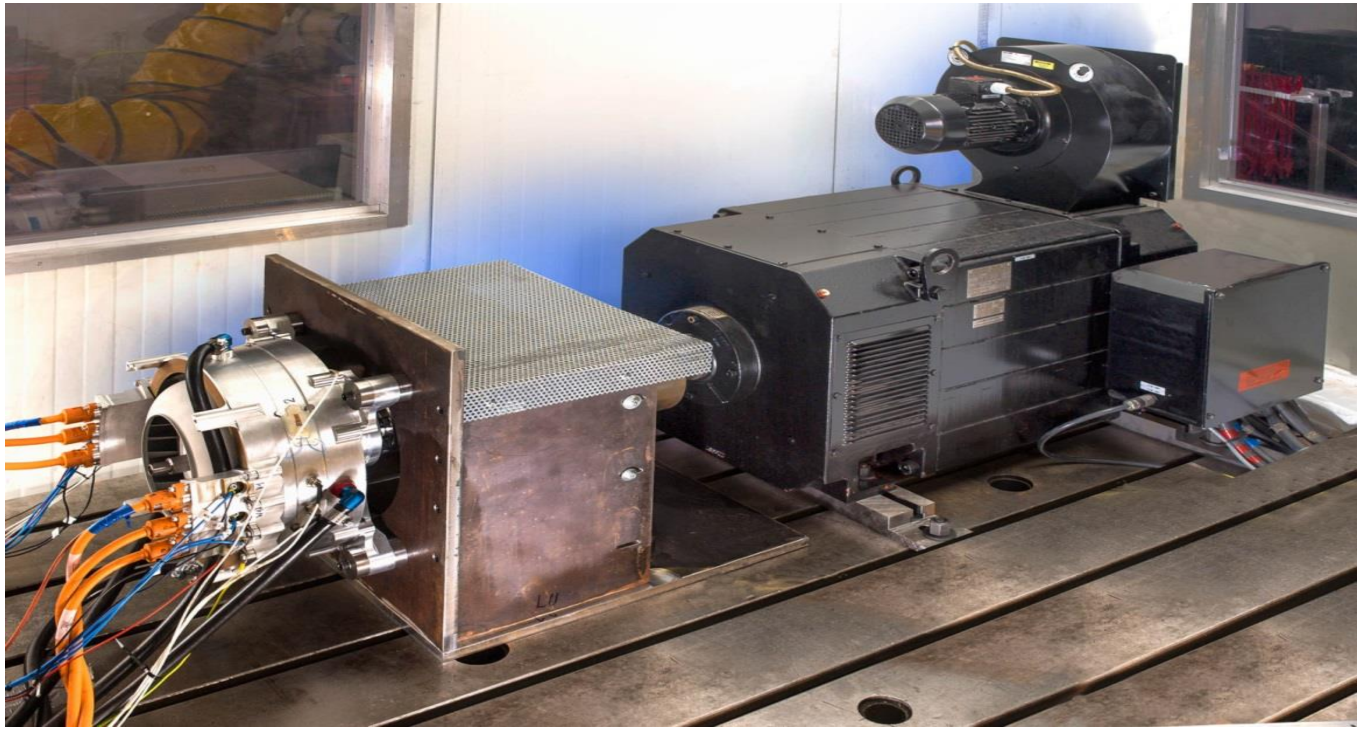


Motor Data

P_{cont} = 261 kW
n_{max} = 2500 rpm
M_{cont} = 1000 Nm
η_{260kW} = 95 %
D = 416 mm
L = 300 mm
P/M ~ 5.2 kW/kg



The best we can do up to now is the world record but we can‘t stop there!

Motor Weight – Future

$$\frac{P}{M} = \underbrace{\frac{1}{1+K_{\Phi}} \frac{m}{m_1} \frac{\pi}{2} K_e K_i K_p \lambda_0^2}_{\text{Topology}} \underbrace{B_g A}_{\text{Superconducting Materials}} f \eta$$

Topology

Superconducting Materials

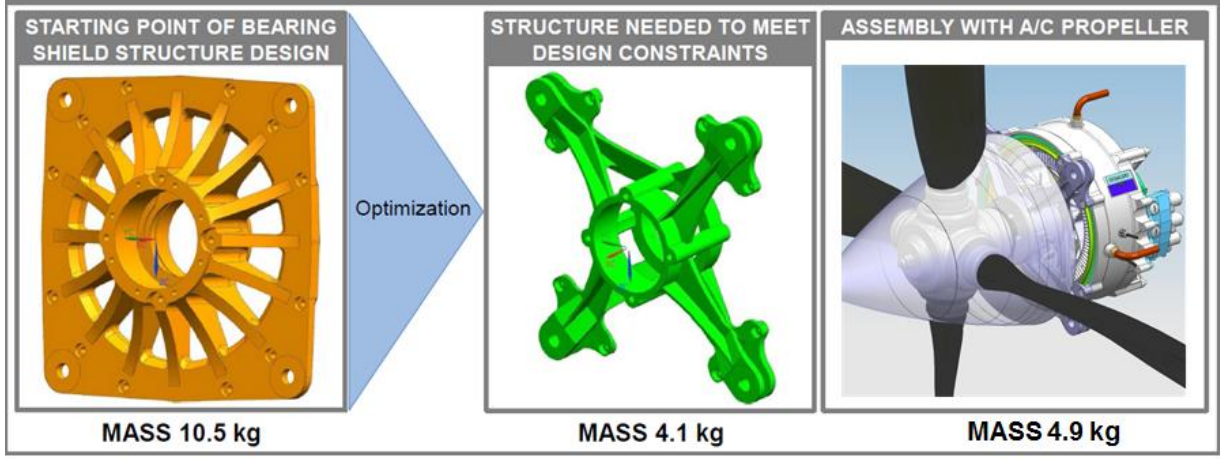
Motor Weight – Future

$$\frac{P}{M} = \frac{1}{1+K_\Phi} \frac{m}{m_1} \frac{\pi}{2} K_e K_i K_p \lambda_0^2 B_g A f \eta$$

Topology

Superconducting Materials

Example: Topology optimization using NX Nastran



Motor Weight – Future

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CFK Bearing Shield – 2.3 kg

$$\frac{P}{M}=\underbrace{\frac{1}{1+K_{\Phi}}\frac{m}{m_1}\frac{\pi}{2}K_e K_i K_p \lambda_0^2}_{\text{Topology}}\underbrace{B_g A}_{\text{Superconducting Materials}} f\,\eta$$

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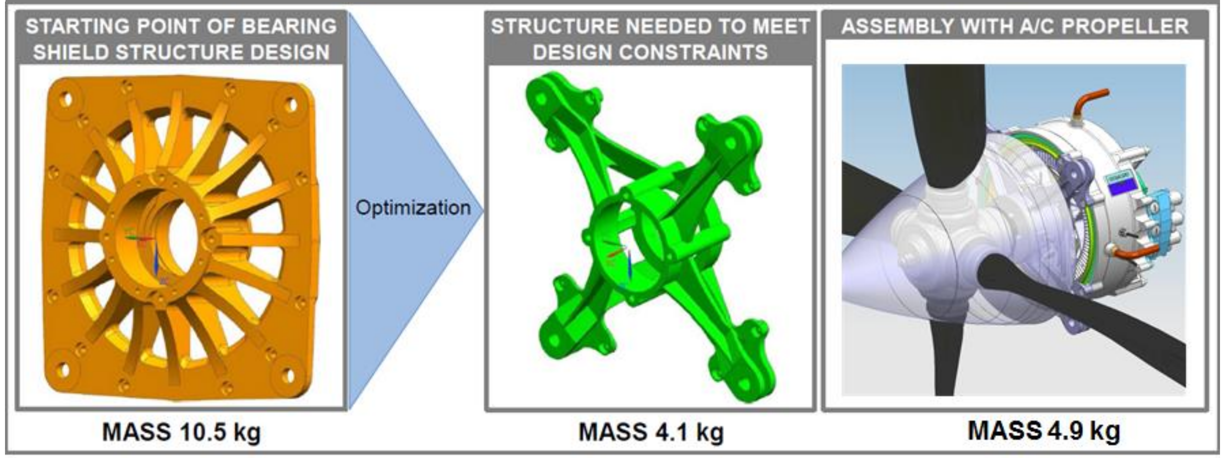

Motor Weight – Future

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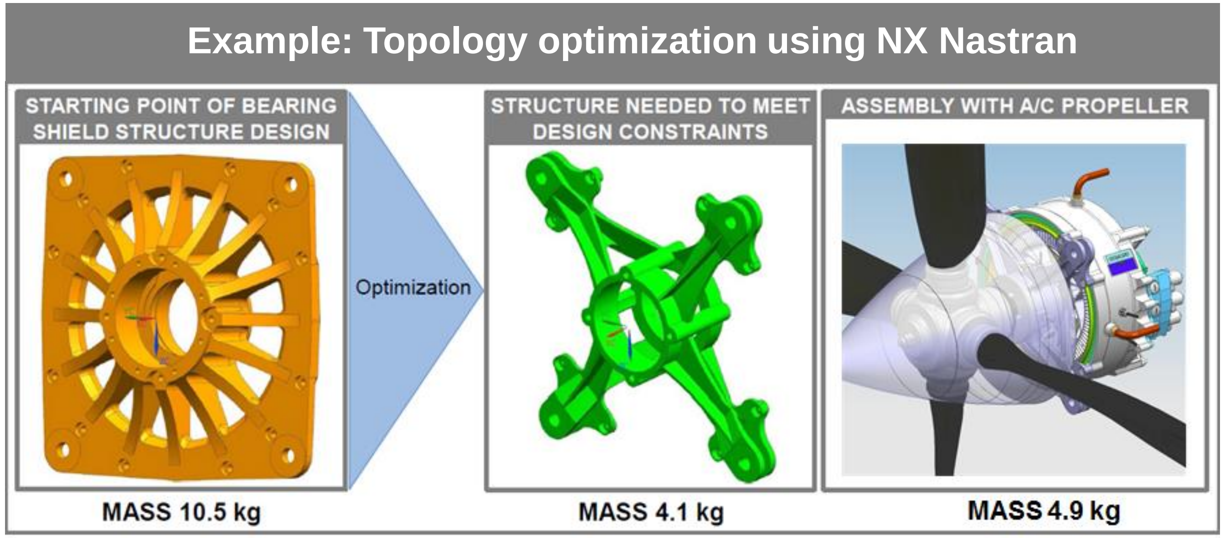
Topology

Superconducting Materials



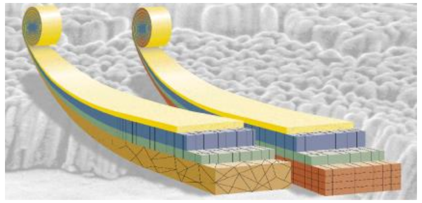
Siemens HTS-III Machine

4 MW @ 120 rpm

Cryogenic propulsion system

Biggest leverage – Advanced Cryogenic Materials

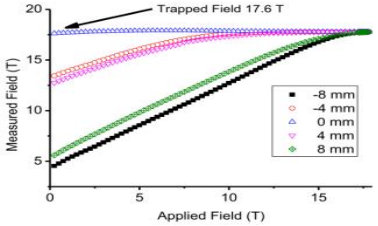
HTS Tapes & Wires



MgB2, YBCO

Allows very high current densities in the stator or high fields in the rotor

HTS-Bulks

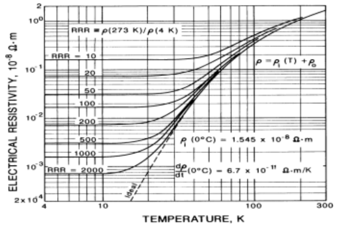


YBCO, GdBCO

allows very high

magnetic fields in the rotor

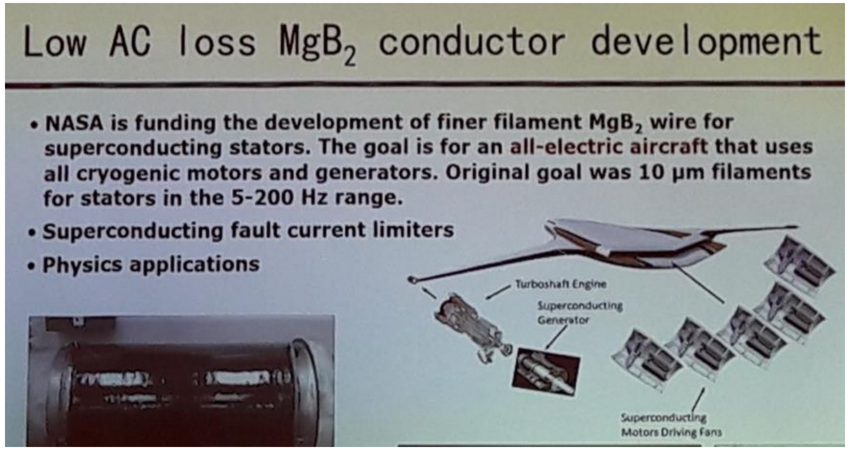
Filamented Wires

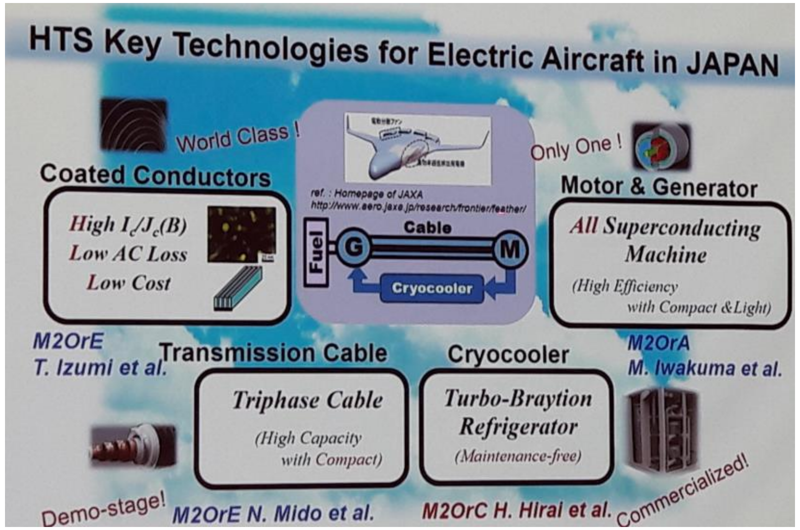


MgB2, 5N-Cu, 5N-Al

allows very high current densities in the stator with high frequencies

R&D all around the globe





The case for superconctivity

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IEEE/CSC & ESAS European Superconductivity News Forum (ESNF), No. 6, October 2008
(ASC Preprint 2AP01 conforming to IEEE Policy on Electronic Dissemination, Section 8.1.9)

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Next Generation More-Electric Aircraft: A Potential Application for HTS Superconductors

Cesar A. Luongo, *Senior Member, IEEE*, Philippe J. Masson, *Senior Member, IEEE*, Taewoo Nam,
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„.. Develop [..] rotating machines in the range of 25-40 kW/kg for motors and 40-80 kW/kg for high rotation speed generators ..“

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Hardly possible with superconducting technology

Expensive and complex technology

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Aircraft industry has used very expensive and complex technologies for decades

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Hardly possible with superconducting technology

Potential killer application

Expensive and complex technology

Aircraft industry has used very expensive and complex technologies for decades

Major reason for hybrid electric propulsion: Radically New Aircraft Design

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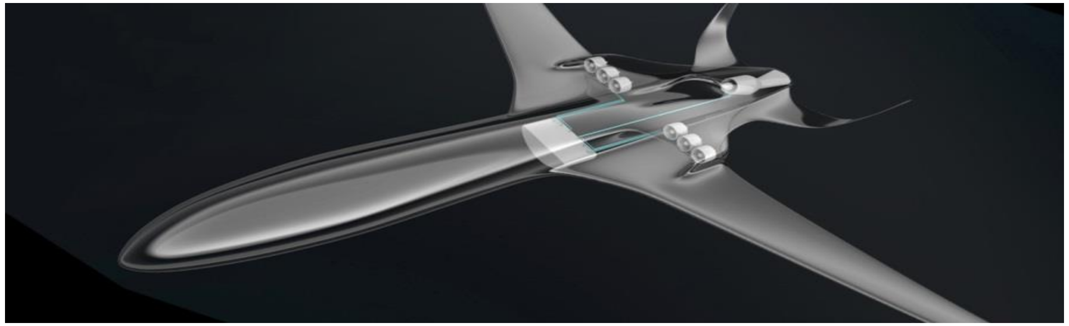

Last slide

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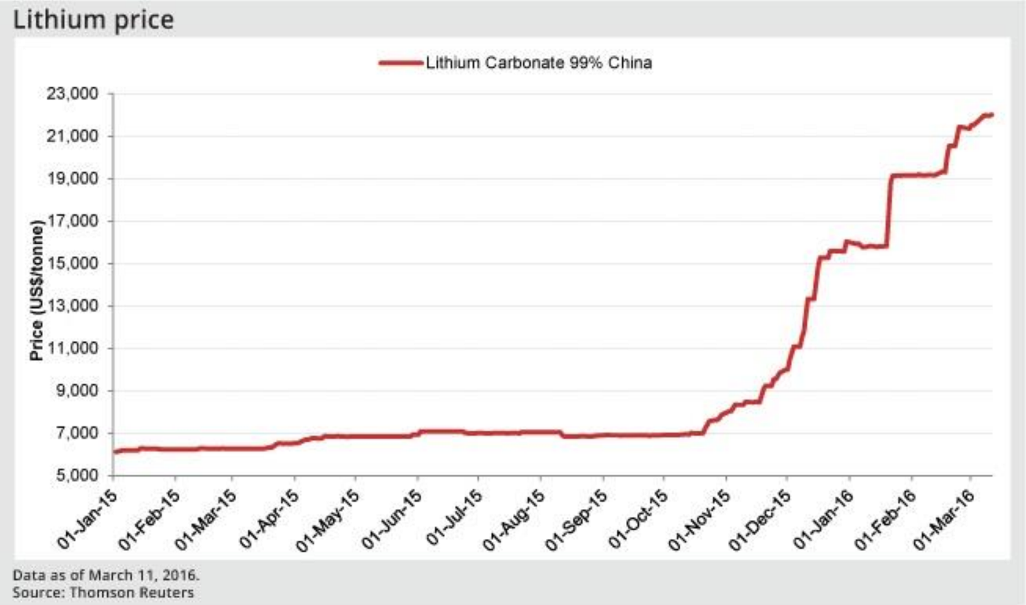
Rohstoff	2010	2011	2012	2013	2014	2015
Gold in US-Dollar pro Unze	1.225,46	1.569,52	1.666,54	1.410,8	1.266,34	1.160,59
Graphit in US-Dollar pro Tonne	1.514,58	2.511,46	2.487,5	1.400	1.325	1.175
Indium in US-Dollar pro Kilogramm	567,26	735,31	625	613,33	718,2	412,33
Kadmium in US-Dollar pro Kilogramm	4,09	2,95	1,92	2,02	1,8	1,1
Kobalt in US-Dollar pro Kilogramm	45,33	38,6	30,75	29,01	31,81	29,11
Kupfer in US-Dollar pro Tonne	7.534,18	8.820,53	7.949,44	7.332,19	6.859,2	5.501,12
Lithium-Minerale in US-Dollar pro short t*	676,94	745	821,22	821,22	6.526,59	6.375,03
Magnesit in Euro pro Tonne	70	91,83	90,54	70	70	71,67
Magnesium (Magnesium) in US-Dollar pro Tonne	2.920	3.127,7	3.134,72	2.726,04	2.481,14	2.146,91
Mangan in US-Dollar pro Tonne	2.549,17	3.316,46	2.786,67	2.319,71	2.225,42	1.818,75



Invest in Lithium, because the future is (hybrid) electric!

Thank you

Dr. Mykhaylo Filipenko

Head of center of competence electrical machines 1

eAircraft

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