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Neue Wege.

Future of [More] Electrical Aircraft

Dr Askin T. Isikveren

Head, Visionary Aircraft Concepts

ICAS Biennial Workshop – 2013

The Lord Charles Hotel & Conference Centre

Cape Town, South Africa, 02 September 2013

Agenda

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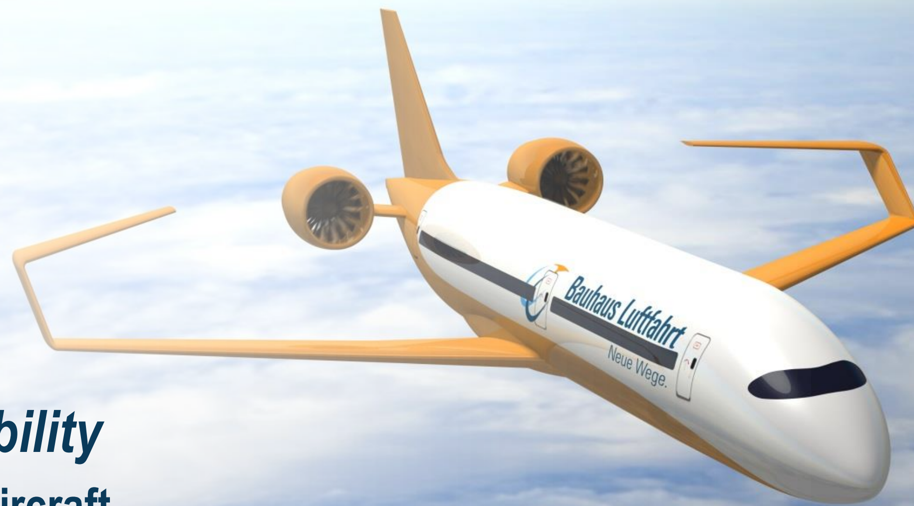
>> Bauhaus Luftfahrt – An Introduction

>> Socio-economic Drivers & Top Level Requirements

>> Advanced Electrical Technologies

> Electric Flight Feasibility Assessment
> Hybrid-Electric Architectures
> Typical Power Demand of Sub-systems



>> Design & Integration for Electro-mobility

> Evolution of More-Electric & All-Electric Aircraft
> Hybrid-Energy Engineering for Motive Power
> Ce-Liner: Zero Emissions Concept
> Interesting Engineering Trade-studies

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The Bauhaus Luftfahrt Approach

>> Founded in November 2005 by

- > The Bavarian Ministry of Economic Affairs, Infrastructure, Transport and Technology
- > EADS (inc. Airbus, Cassidian & Eurocopter)
- > IABG mbH
- > Liebherr Aerospace
- > MTU Aero Engines

>> A non-profit research institution with long-term time horizon

- > Strengthening the cooperation between industry, science and politics
- > Developing new approaches for the future of aviation with a high level of technical creativity
- > Optimizing through a holistic approach in science, economics, engineering and design

>> Going "New Ways" for the mobility of tomorrow

Emphasis on Inter-disciplinary Research

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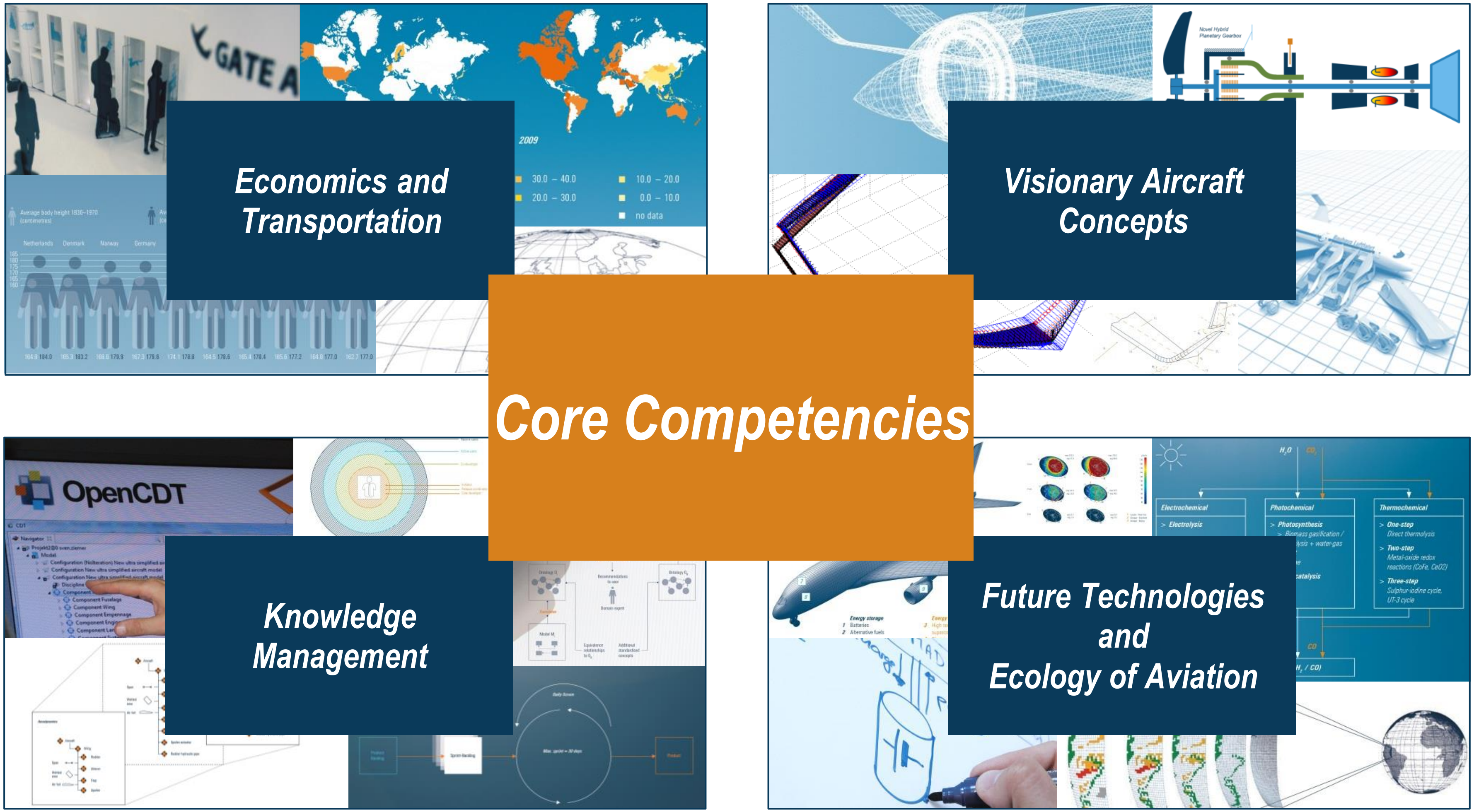

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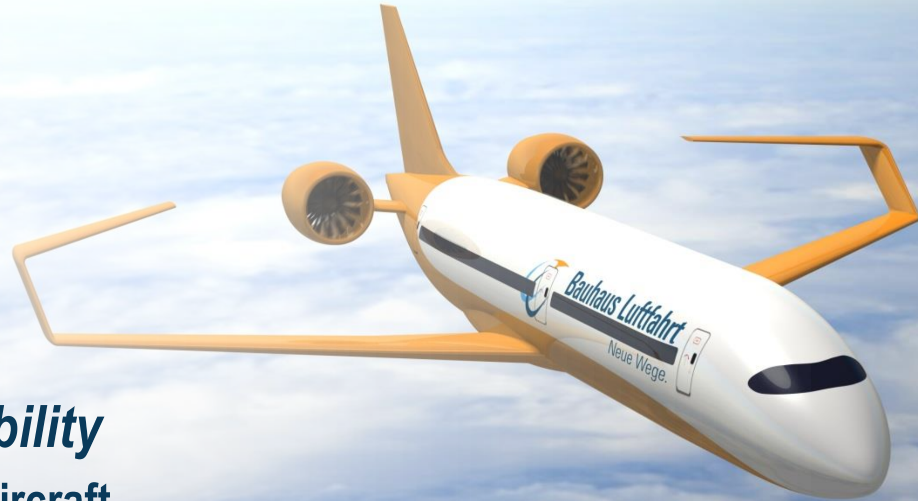

Socio-Economic Drivers

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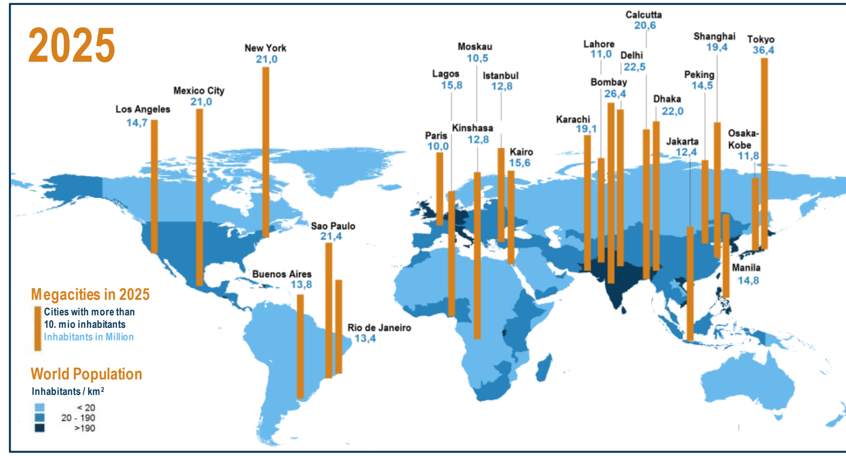
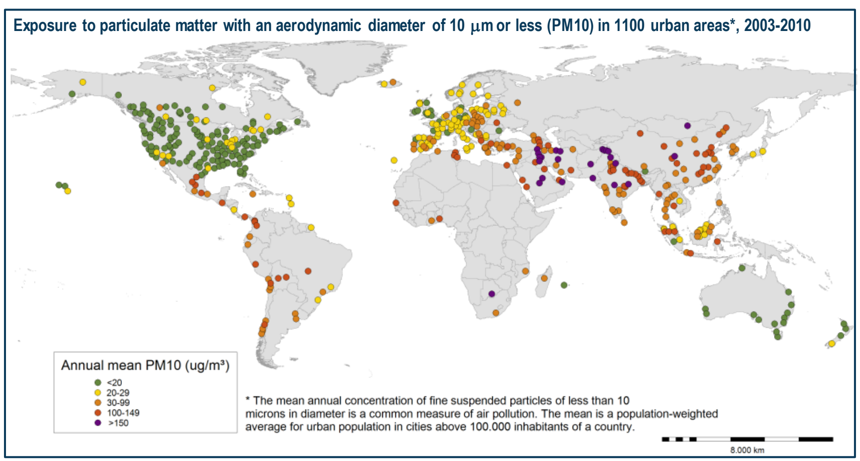
>> *Megacities*

- > Urban Living, growing middle-class

>> *Demographic & Anthropometric*

- > Increasing world-wide average age
- > Increasing passenger size and weight
- > Hybrid cultures, gender empowerment





>> *Environment*

- > Environmental degradation
- > Mass transportation vs. individual motorised transport
- > Socio-political pressure placed on reducing emissions and noise

Source: modified from Cole, BHL Symposium 2013

The Top-level Requirements

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>> Flightpath 2050

- > 75% less CO_2 emissions[a]
- > 90% less NO_x emissions[a]
- > 65% reduction in perceived noise[a]
- > Aircraft is designed and manufactured to be recyclable
- > Emission-free taxiing
- > 80% less accidents[b]
- > 90% of all journeys (door-to-door within the EU) within 4 hrs
- > Flights arrived within 1 min. of planned time regardless of weather
- > ATM should handle at least 25M flights

[a]based on a typical aircraft with 2000 technology
[b]based on 2000 traffic

>> Strategic Research & Innovation Agenda

Goals and Key contributions	2000 (Reference)	2020 (Vision)	2020 (AGAPE)	2020 (SRIA)	2035 (SRIA)	2050 (SRIA)
CO_2 objective vs 2000 ("HLG")		-50%**				-75%**
CO_2 vs 2000 (kg/pass km)*		-50%	-38%	-43%	-60%	-75%
Airframe energy need (Efficiency)	1	0,75	0,85	0,8	0,7	0,32
Propulsion & Power energy need (Efficiency)	1	0,8	0,8	0,8	0,7	
ATM and Infrastructure	1	0,88	0,95	0,93	0,88	0,88
Non Infrastructure-related Airlines Ops	1	0.96	0.96	0.96	0,93	0,88

* comparison with same transport capability aircraft and on a same mission in term on range and payload
** ACARE 2020 and ACARE 2050 High Level Goals for airframe, engine, systems and ATM/Operations

Granualising SRIA 2050 → Required Strategy

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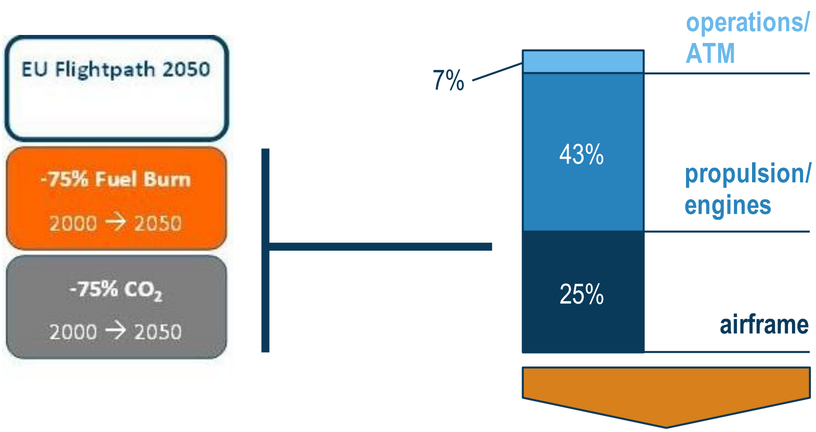
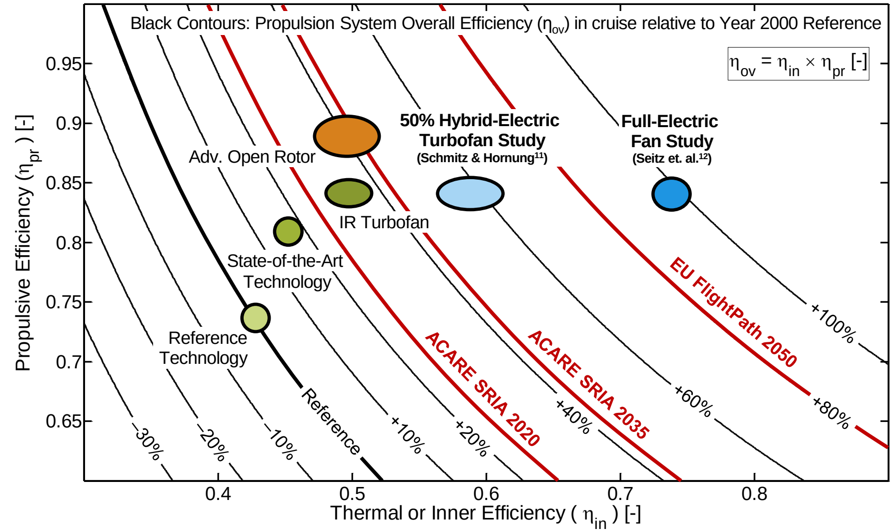
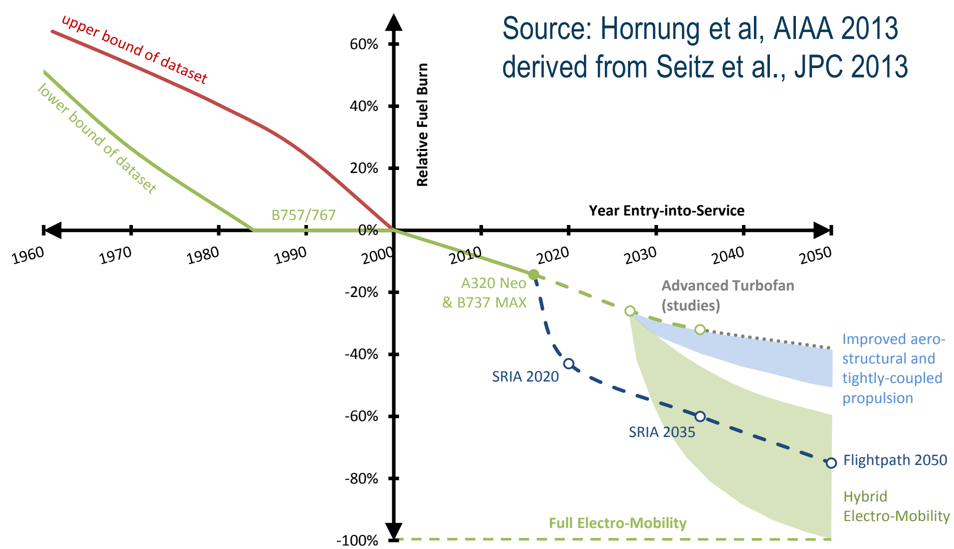


Hybrid-Energy approach in conjunction with:

> Distributed Propulsion

> Active very flexible polyhedral wings





Source: Hornung et al, AIAA 2013
derived from Seitz et al., JPC 2013

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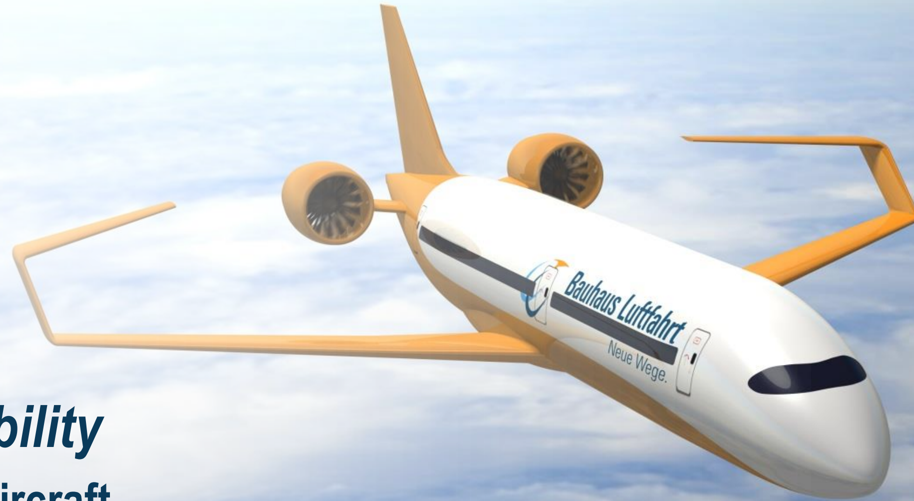

Electric Flight Feasibility Assessment

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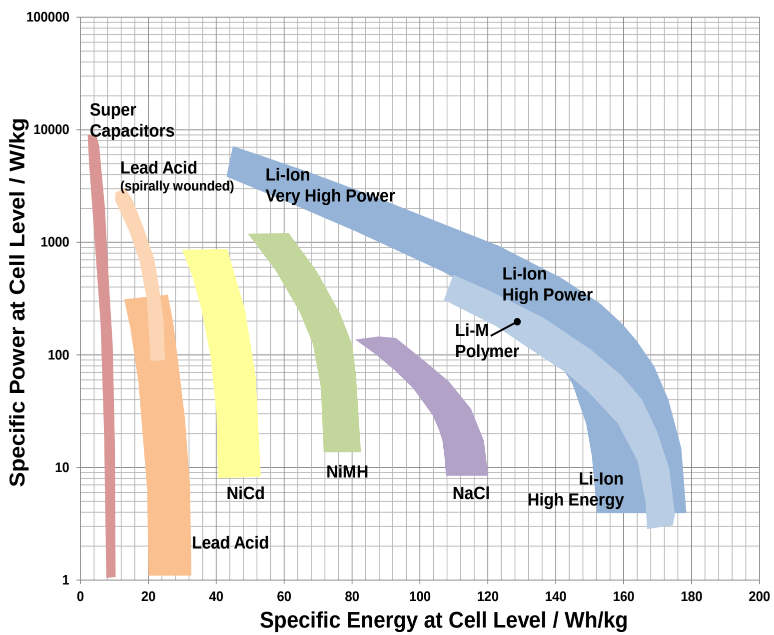


Source: Kuhn and Sizmann, DLRK 2012

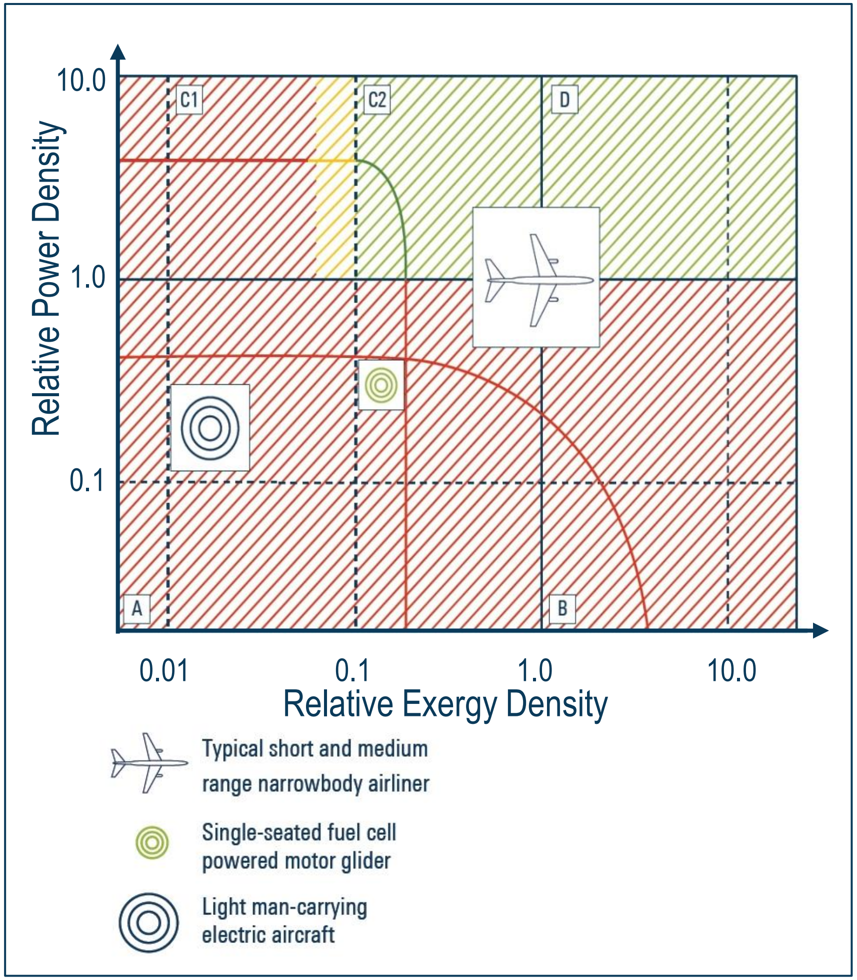
>> Exergy (useable energy):

The energy density is insufficient as feasibility assessment criterion

>> Ragone metrics:

Exergy and power densities are the key indicators for electric aircraft feasibility in the comparison of alternative power sources

Electric Flight Feasibility Assessment



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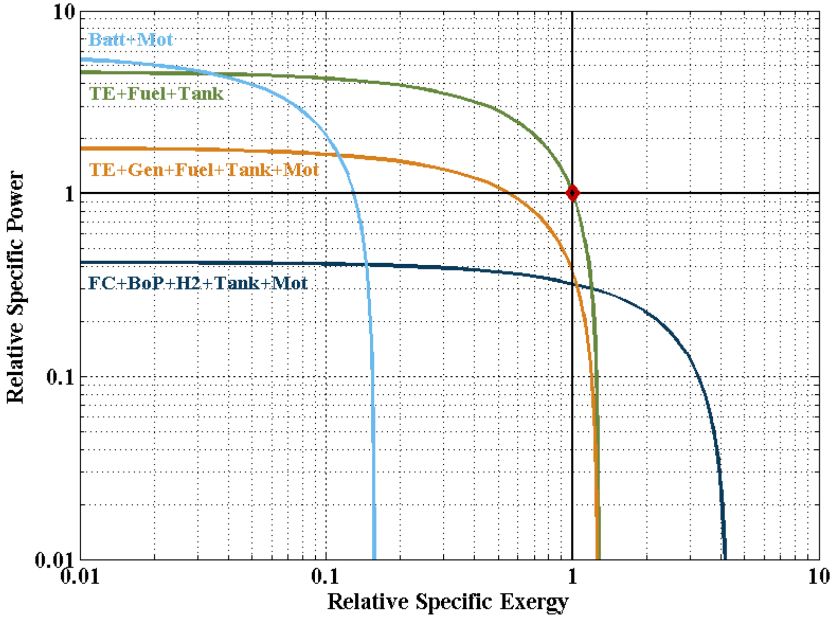

Sources:
Sizmann, 2010
Kuhn et al., CEAS 2011
H. Kuhn et al., ICAS 2012

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>> Hybridization:

energy storage devices each inadequate may be an enabling energy system in combination

Electric Flight Feasibility Assessment

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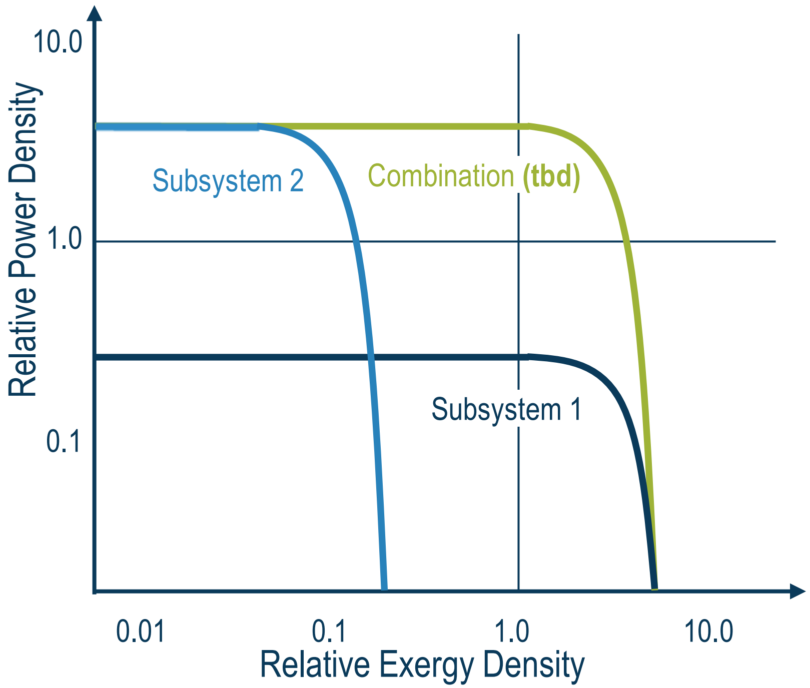

Sources:
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Hybrid-Electric Power System Architectures

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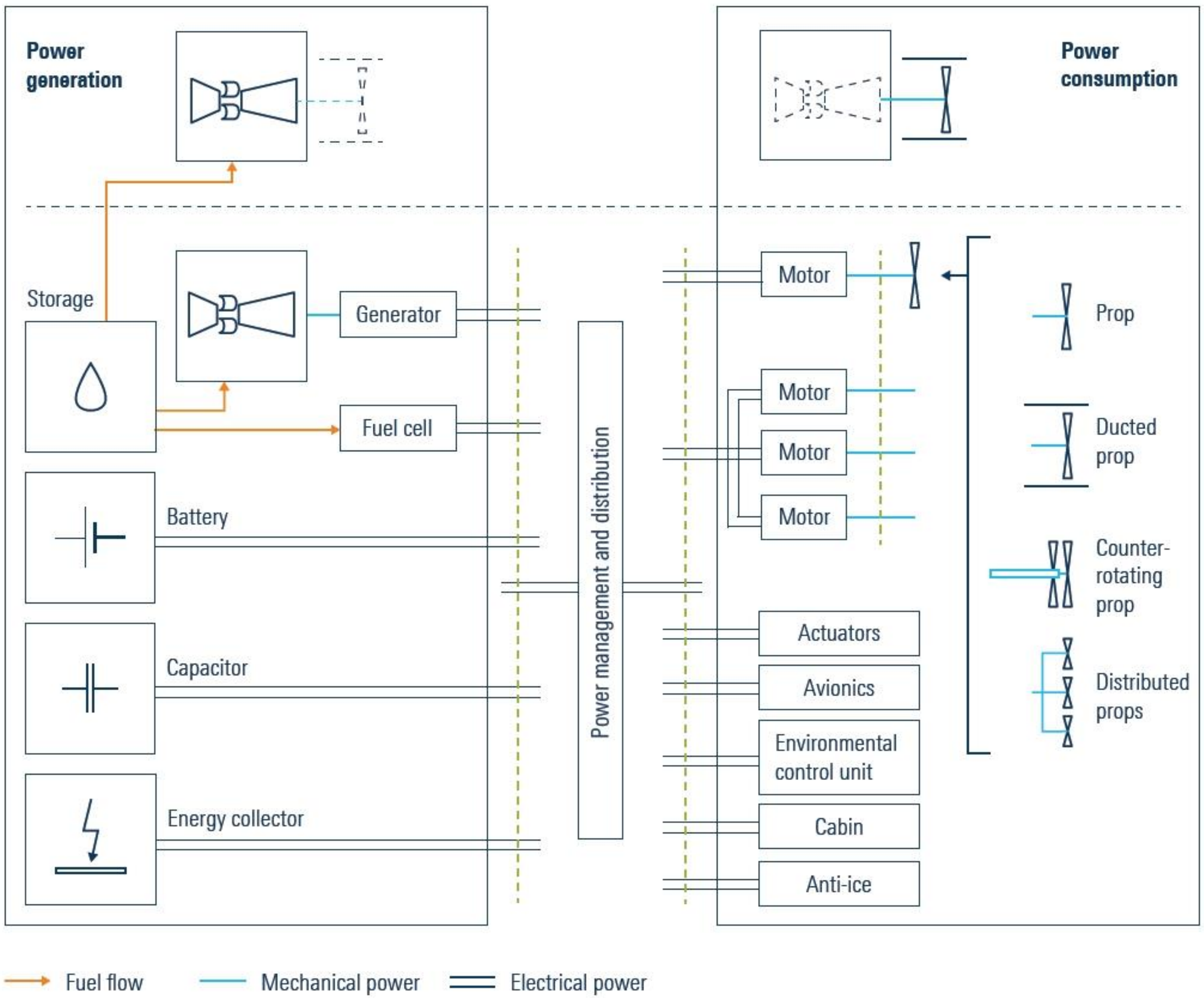

Typical Power Demand of Sub-systems

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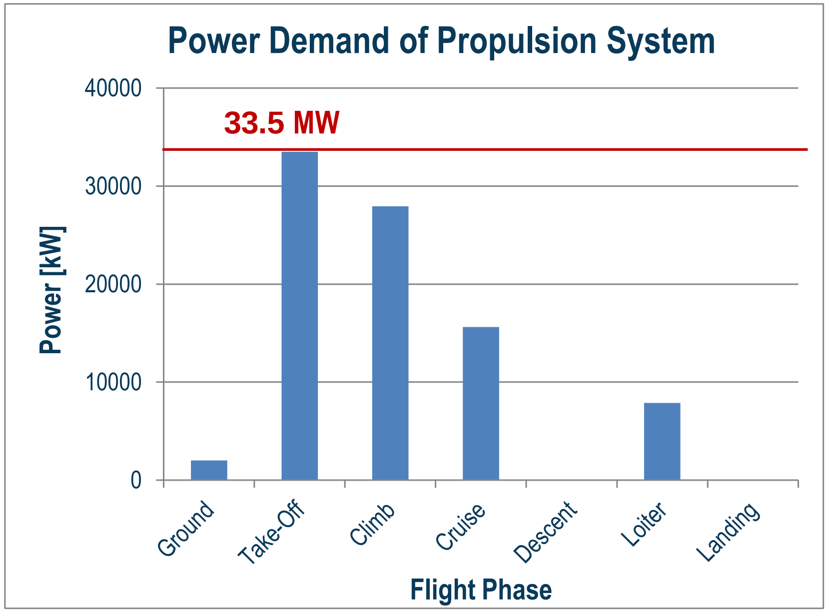
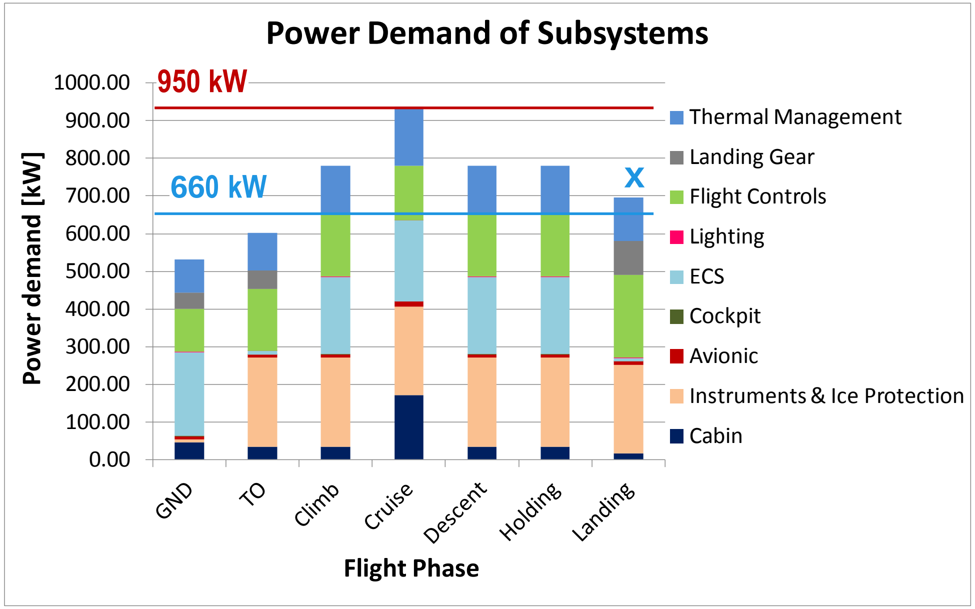
>> Maximum required power at different flight phases

>> Propulsion system = electric motor, motor controller, battery control unit





red line: normal operation

blue line: abnormal ops = excl. non-essential customers

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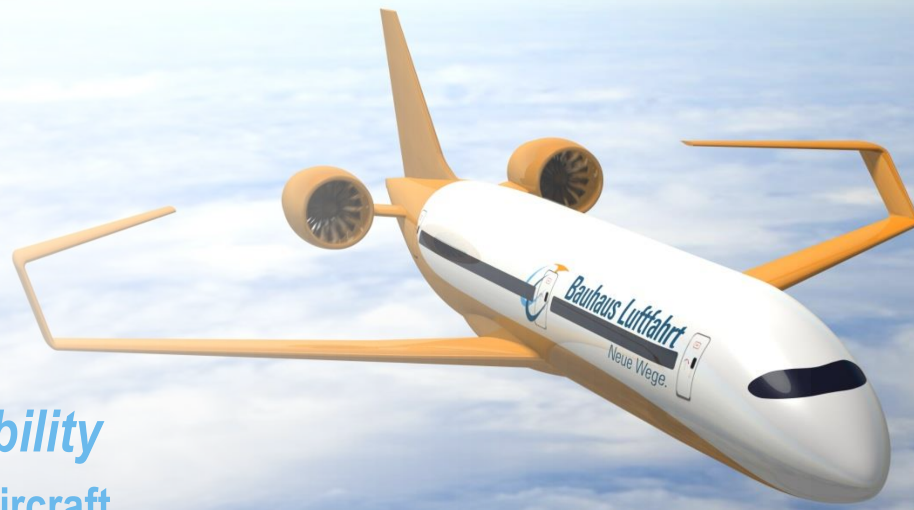
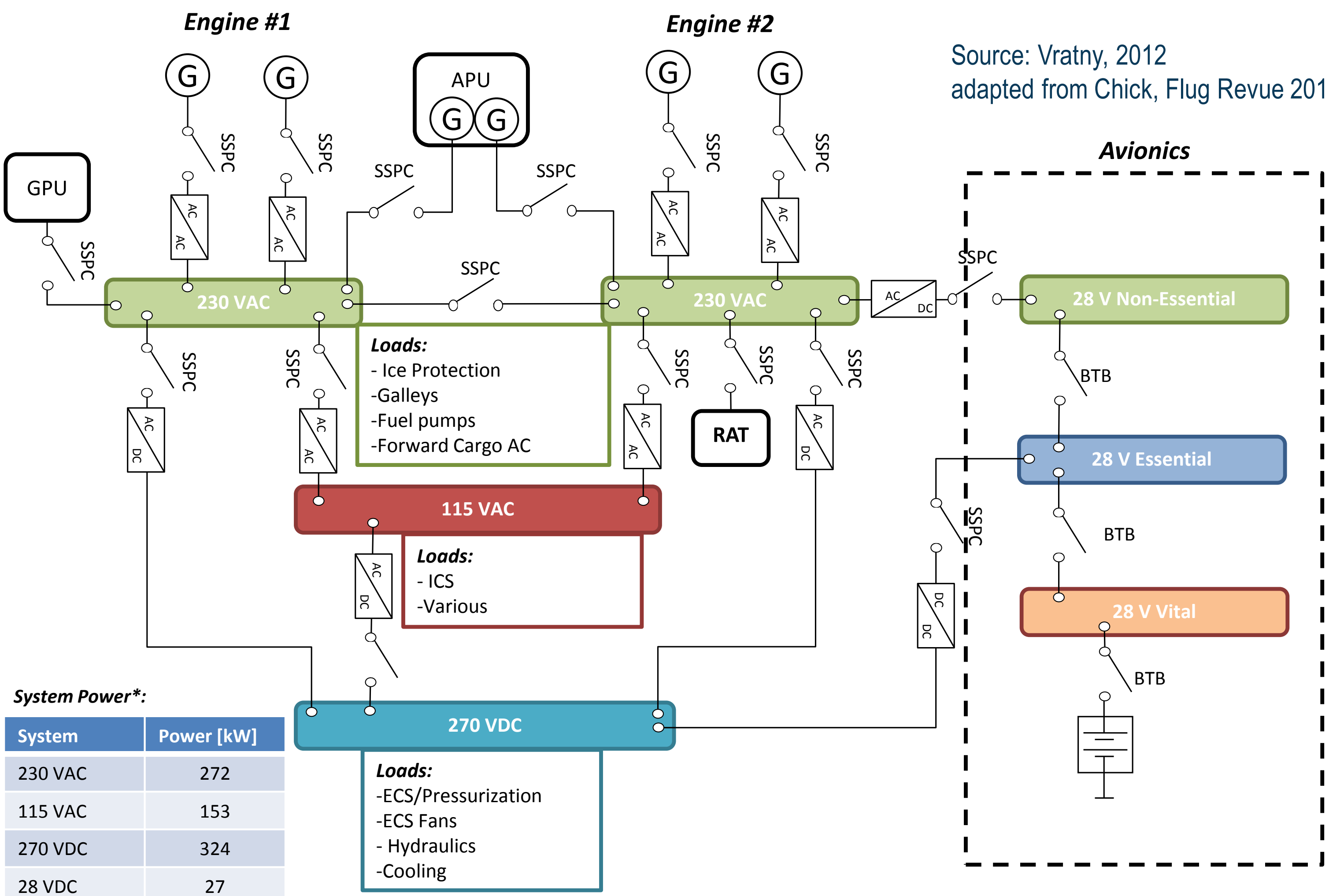


ATA 24 MEA State-of-the-Art

MEA System Architecture based on Boeing 787* (hybrid voltage system)

Source: Vratny, 2012
adapted from Chick, Flug Revue 2012



System Power*:

System	Power [kW]
230 VAC	272
115 VAC	153
270 VDC	324
28 VDC	27

ATA 24 AEA Evolution circa 2025 (mod. risk)

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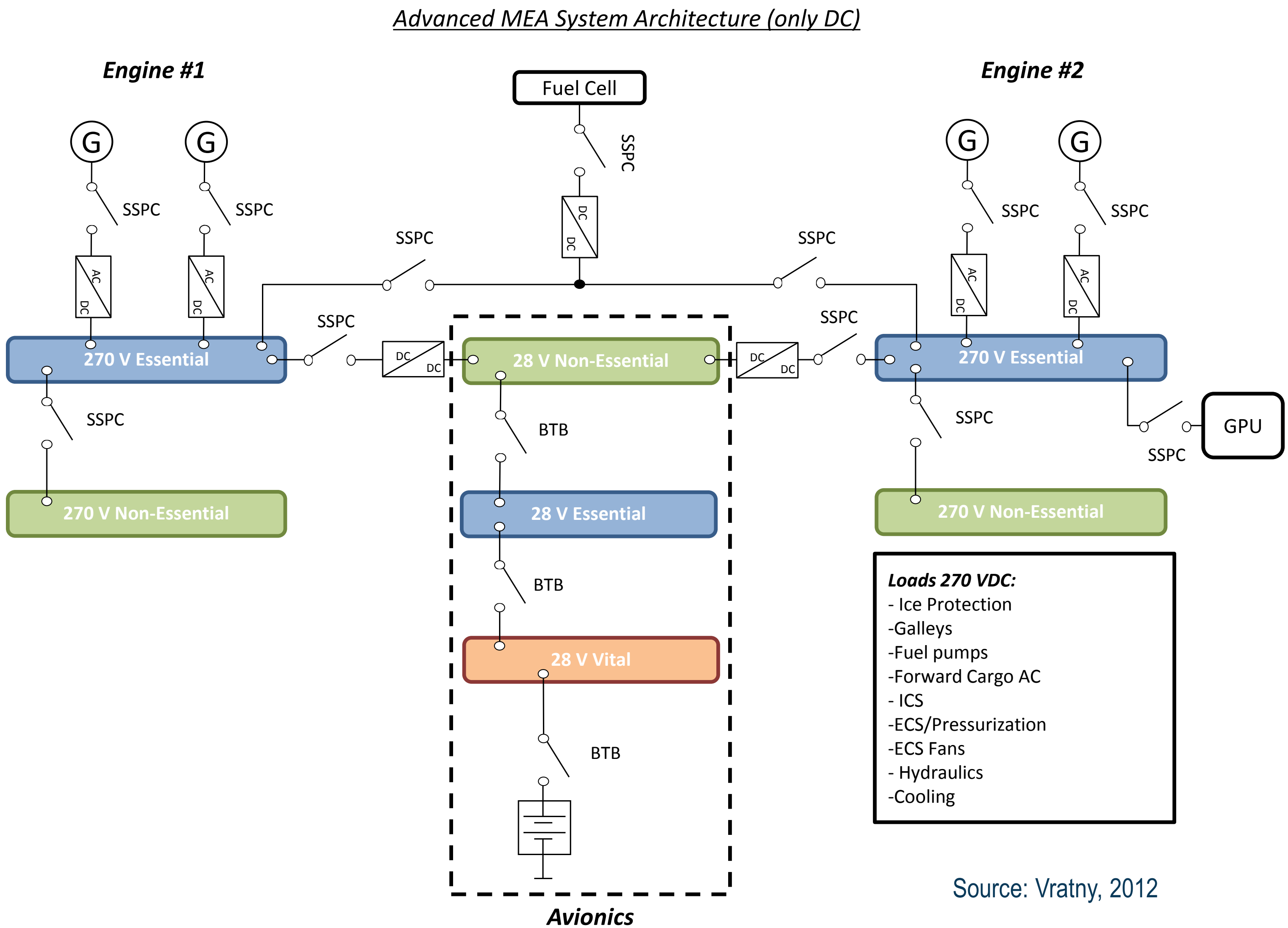

Source: Vratny, 2012

ATA 24 AEA Evolution circa 2035 (higher risk)

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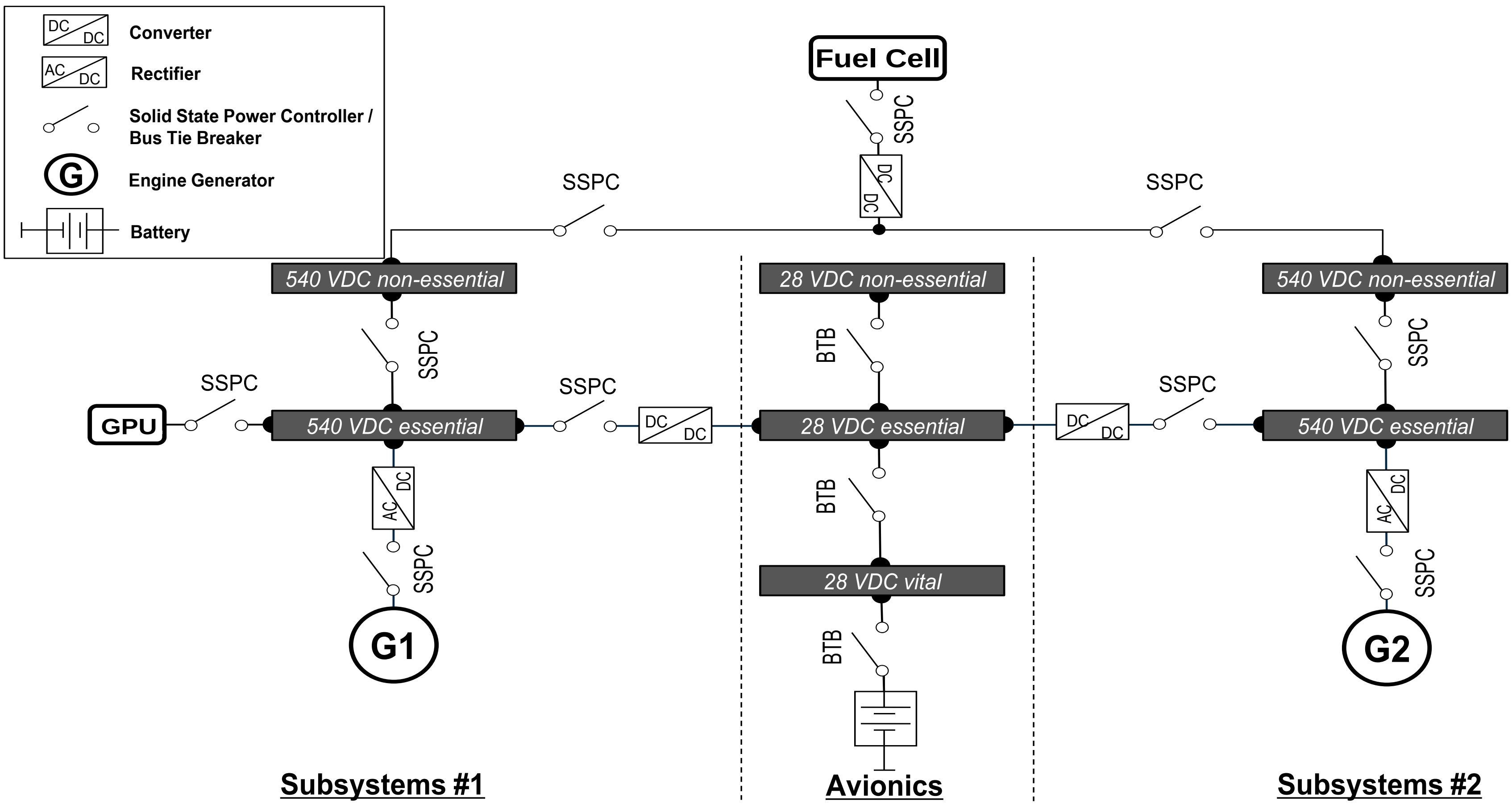

Source: Pornet et al., AIAA 2013

Combining Energy Sources for Motive Power

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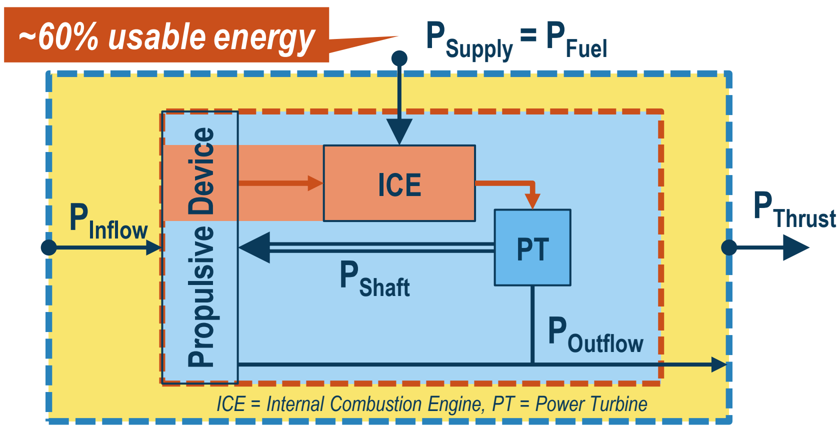
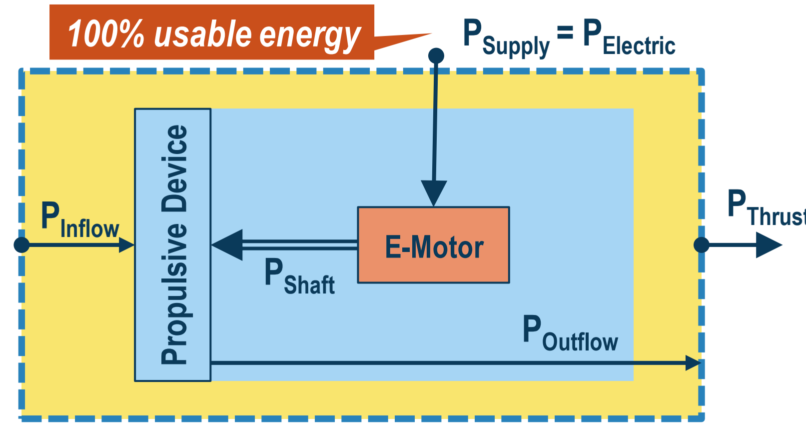
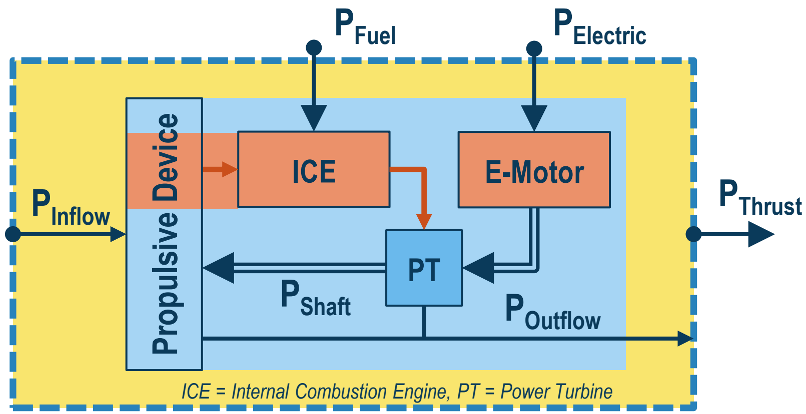


Gas Turbine Engine



Fully Electric Propulsion

Source: Schmitz, 2012 & Seitz et al., DLRK 2012



Hybrid Cycle Engine

>> Alternative Figures-of-Merit

> **Thrust Specific Power Consumption**

$$TSPC = \frac{P_{supply}}{F_0} = \frac{V_0}{\eta_{ov}} = \frac{V_0}{\eta_{ec} \cdot \eta_{tr} \cdot \eta_{pr}}$$

> **Energy Specific Air Range**

$$ESAR = \frac{dR}{dE} = \frac{V_0 \cdot L/D}{TSPC \cdot m_{A/C} \cdot g} = \frac{\eta_{ov} \cdot L/D}{m_{A/C} \cdot g}$$

Hybrid-Energy Engineering for Motive Power

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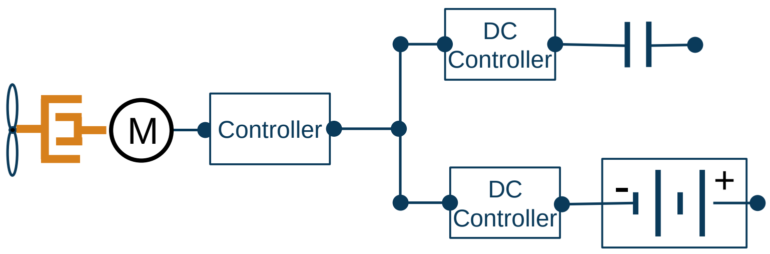
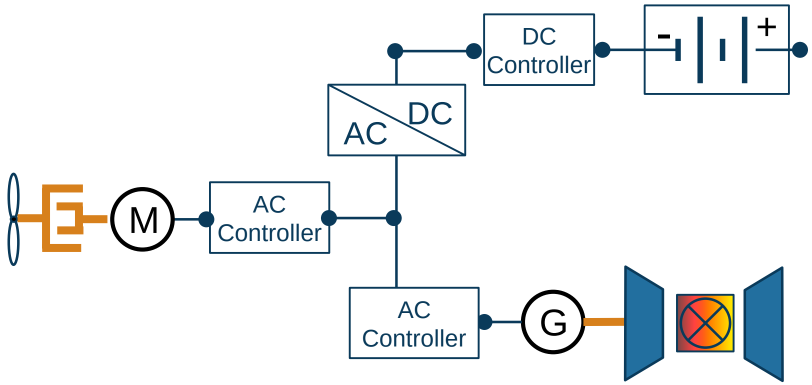
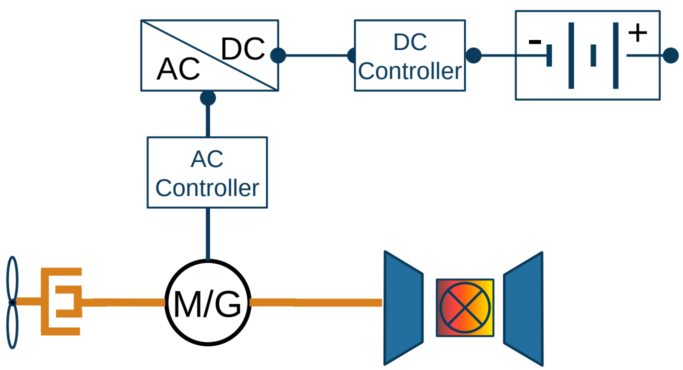
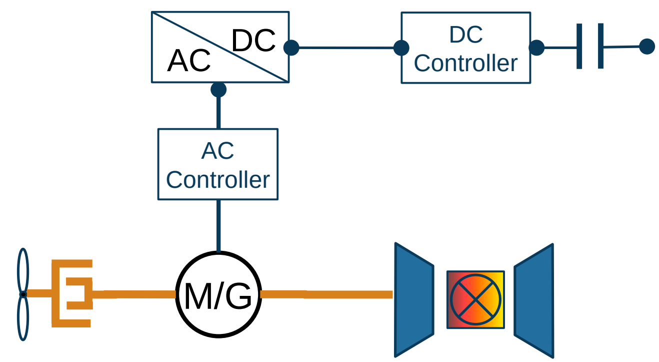
>> Serial Hybrid Solutions





>> Parallel Hybrid Solutions





Hybrid-Energy Aircraft Study

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>> Medium-range Single-Aisle

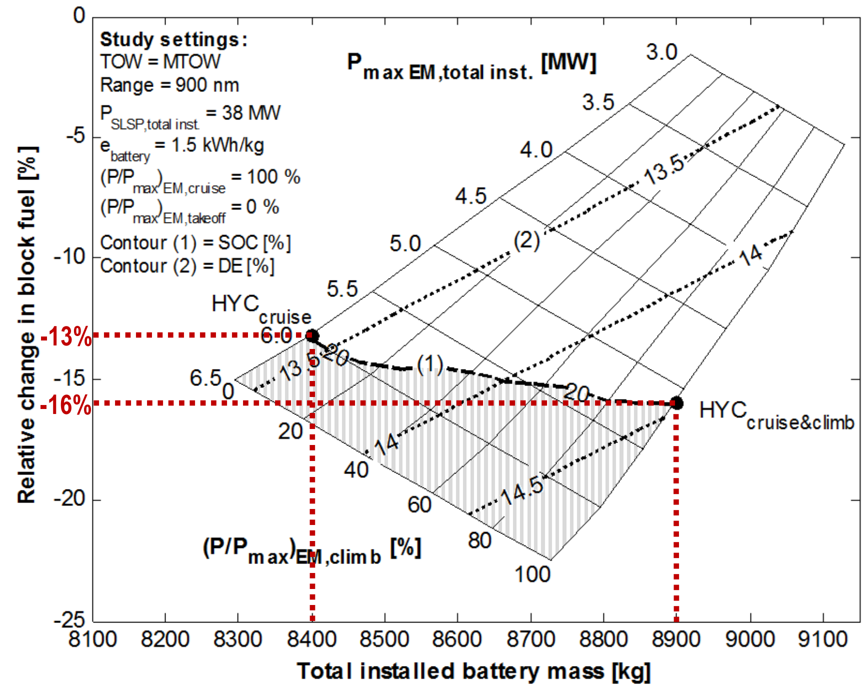
- > Reference aircraft EIS 2035
- > 180 PAX with max range of 3300 nm

>> Retrofit Hybrid Aircraft concept

- > Installation of advanced elec. system
- > Battery energy density 1500 Wh/kg
- > No-resizing of the combustion engines
- > MTOW and OMLs kept fixed

>> Performance outcomes

- > Max PAX Range → -530 nm (-16%)
- > 900 nm stage length
  - > Cruise-only: -13% block fuel
  - > Climb and Cruise: -16% block fuel
- > Up to -3% ESAR drop Ref. → Retrofit



Concept	*TOW/MTOW [%]*	*P EM,total inst. [MW]*	*m battery,total inst. [kg]*	*ΔFuel burn [%]*	*DE [%]*
HYCcruise	100	6	8400	-13	13.4
HYCcruise&climb	100	5.1	8900	-16	14.5

Source: Pornet et al., AIAA 2013

Zero-emissions Concept – The Ce-Liner

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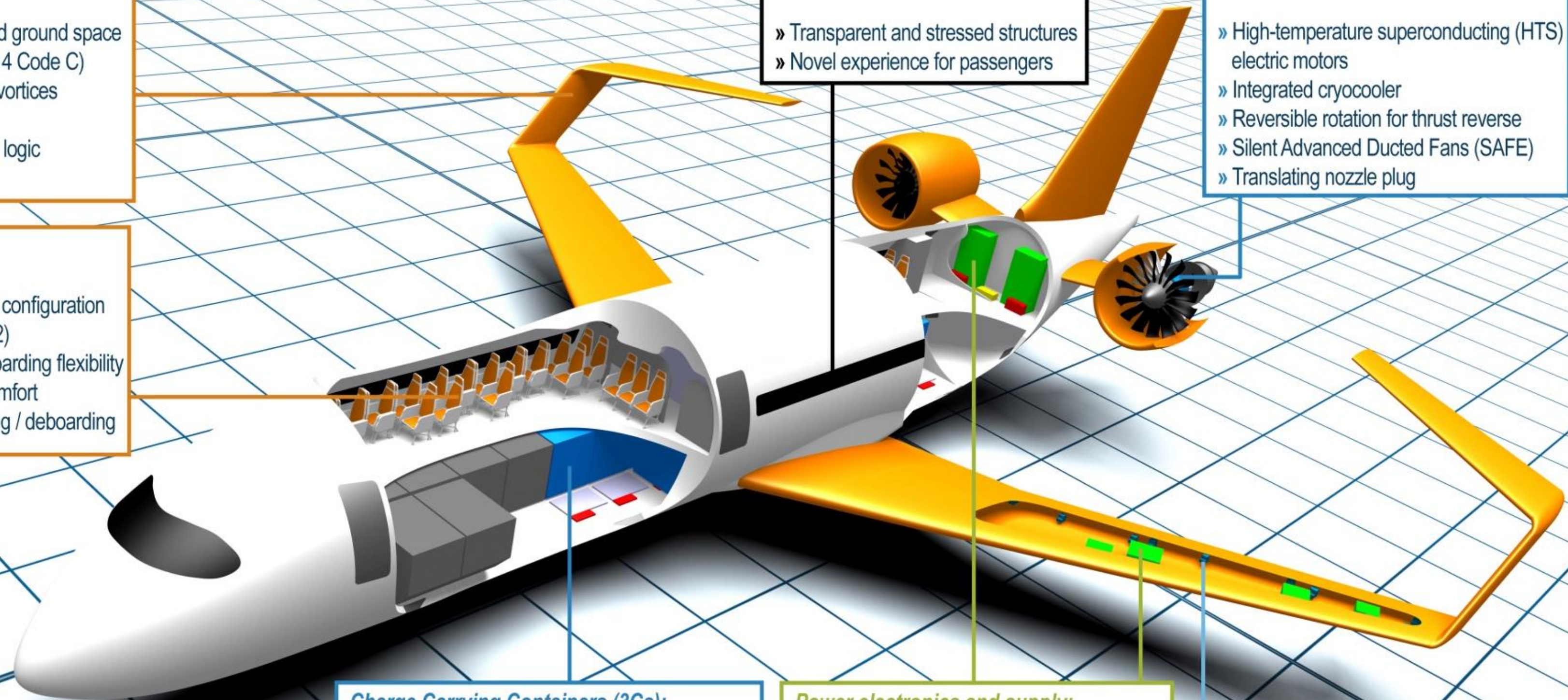

Self-trimming, non-planar C-wing:

- Designed according to limited ground space requirements (ICAO Annex 14 Code C)
- Reduced formation of wake vortices
- High lift-to-drag ratio
- Innovative flight controls and logic
- No horizontal tail required

Cabin layout:

- Widebody cabin in twin-aisle configuration
- Seven-abreast seating (2-3-2)
- Sideward folding seats for boarding flexibility and increased passenger comfort
- Center door for rapid boarding / deboarding

Continuous window belts:

- Transparent and stressed structures
- Novel experience for passengers

Electric propulsion system:

- High-temperature superconducting (HTS) electric motors
- Integrated cryocooler
- Reversible rotation for thrust reverse
- Silent Advanced Ducted Fans (SAFE)
- Translating nozzle plug

Charge Carrying Containers (3Cs):

- Specially modified containers, dimensions and handling like conventional LD3 cargo containers
- Advanced Lithium-Ion battery technology
- Capacity: 2000 Wh/kg
- Exchanged, not recharged during turnaround

Power electronics and supply:

- Direct current (DC) power supply systems
- Alternate current (AC) engine controllers
- Solid State Power Controller (SSPC)
- Converter 3000V-540V DC (subsystems)
- Direct current (DC) actuator controllers

Actuation systems:

- Electric mechanical actuators
- Redundancy according to ETOPS requirements

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Universally-Electric Systems Architecture

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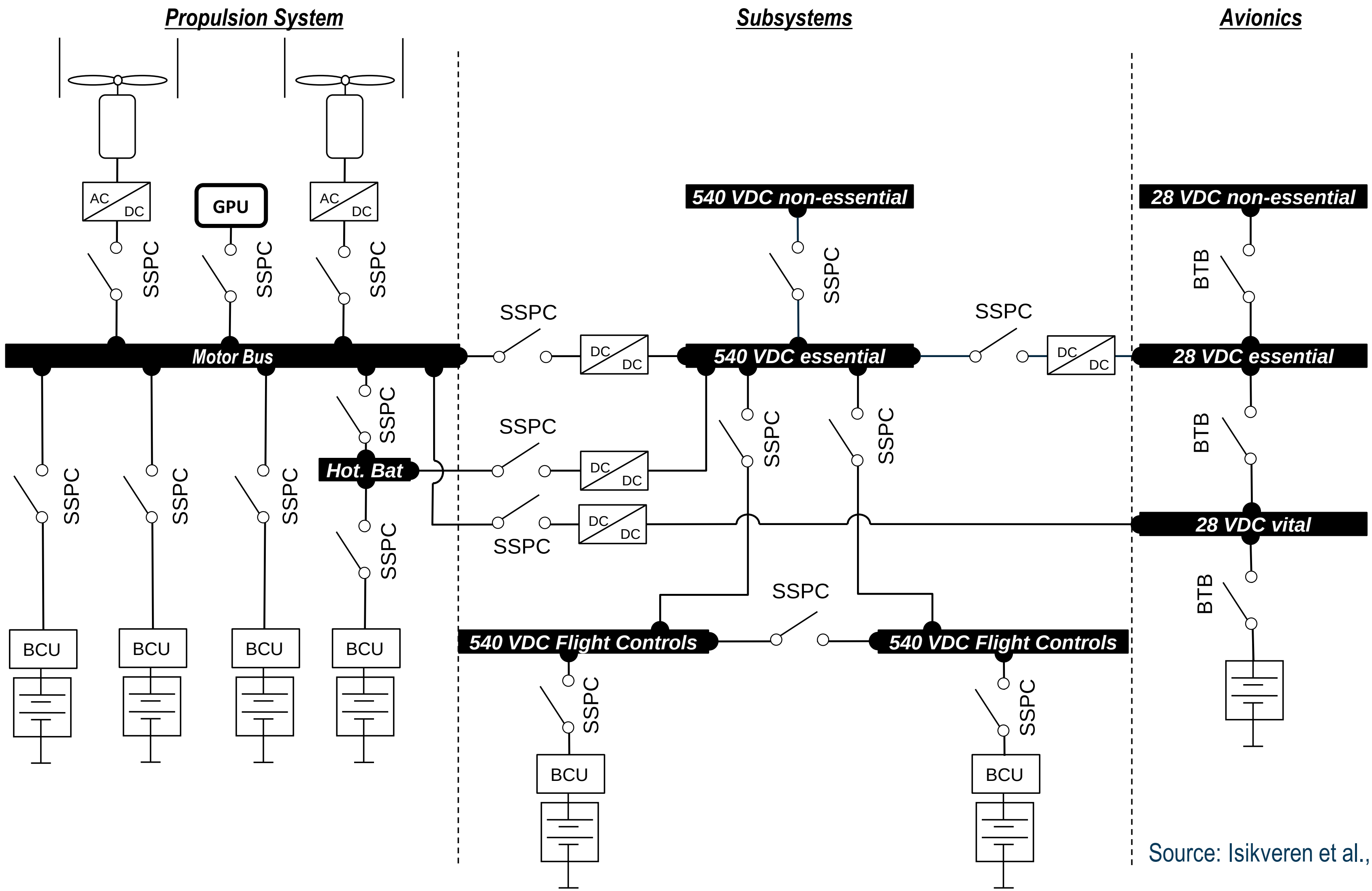

Source: Isikveren et al., 2013

Power and Battery Performance Profiles

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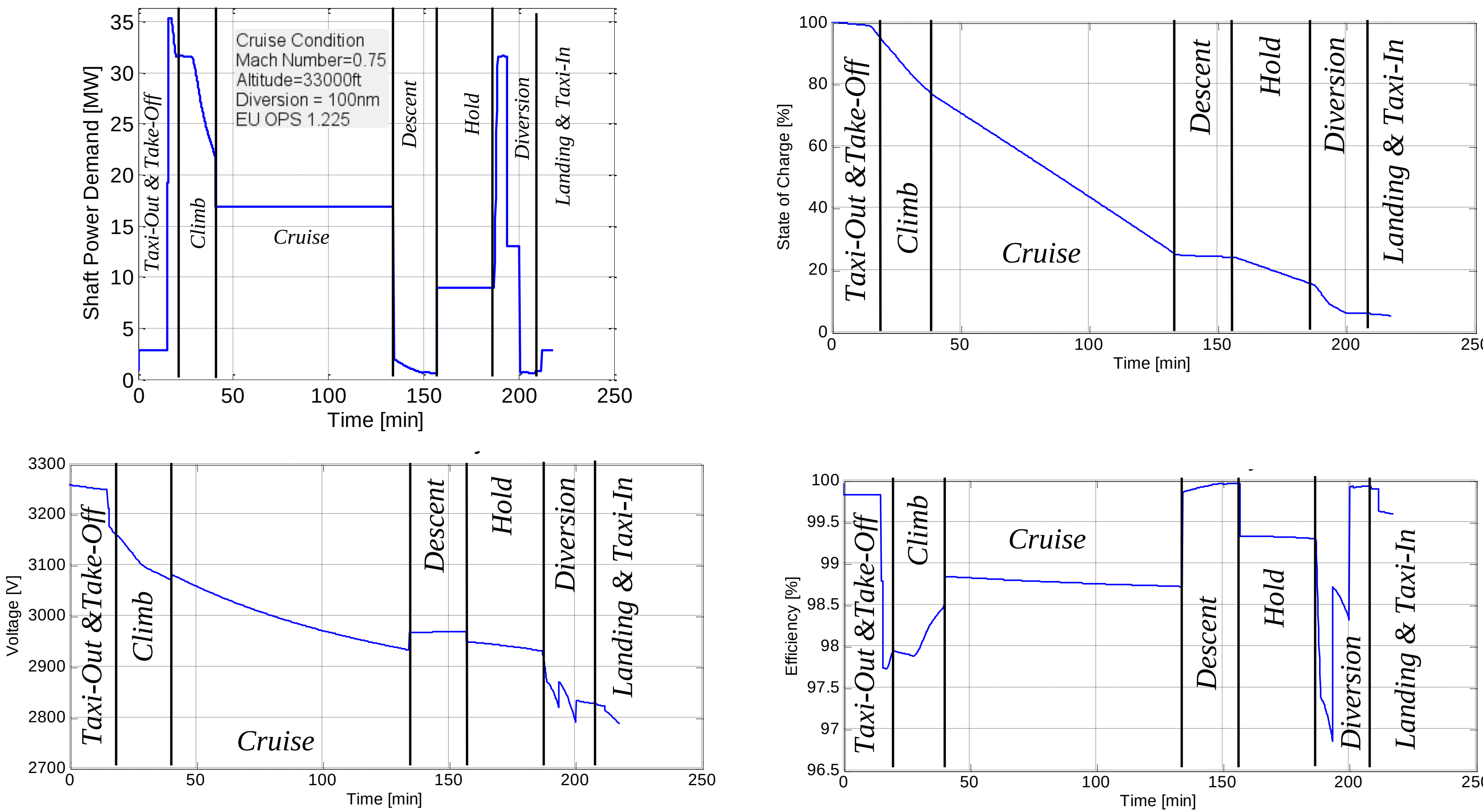

Source: Vratny et al., CEAS 2013

Benchmarking Ce-Liner

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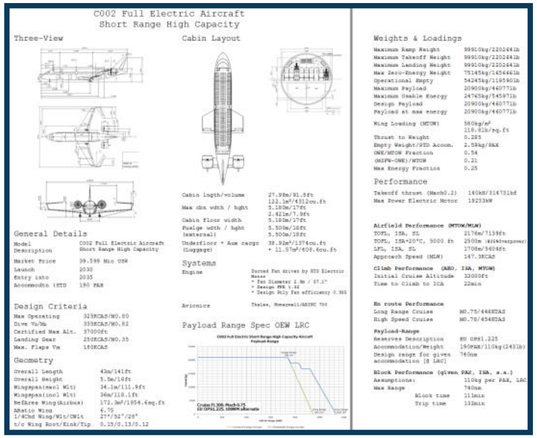
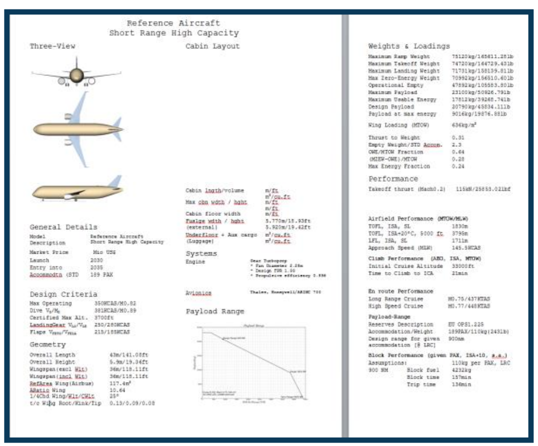

C002 Full Electric Aircraft
Short Range High Capacity
Three-View
Cabin Layout
Weights & Loadings
Performance
General Details
Systems
Design Criteria
Payload Range Spec OEW LRC
Geometry


Reference Aircraft
Short Range High Capacity
Three-View
Cabin Layout
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General Details
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Design Criteria
Payload Range
Geometry

Aircraft Properties	Units	Ce-Liner	B787-3+	Δ (B787-3+)
MTOW	[kg]	109300	73700	+49.1%
MLW	[kg]	109300	70360	N/A
OEW / MTOW	[%]	54.4	65.4	-16.8%
OWE / PAX	kg/PAX	314	253	+24.0%
Max Energy(Fuel) Weight / MTOW	[%]	27.5	24.3	+13.2%
Reference Area (Sref)	[m²]	172.3	115.2	+49.6%
Aspect Ratio (planar wing)	[-]	7.1	10.8	-34.2%
MTOW / Sref	[kg/m²]	635	636	~0.0%
Power / MTOW	[kW/kg]	0.407	N/A	N/A
Thrust / MTOW (M0.20, SL)	[-]	0.233	0.310	-24.8%
TOFL@ISA,SL	[m]	2245	1830	+22.7%
LFL@ISA,SL	[m]	1875	1770	+5.9%
Approach Speed (MLW)	KCAS	149	146	+2.1%
Des.Range, LRC, ICA, Max-PAX	[nm]	900 nm, M0.75, FL330		
(L/D) @ LRC, TOC, ISA+10°C	(-)	20.5	18.4	+11.4%
ESAR, 900 nm, LRC, ISA+10°C	[km/kWh]	0.0473	0.0374	+26.4%

Operational Aspects and Performance

>> Loadability and Turn-around

- > Little flexibility for manipulating loading loops
- > Specialised procedures for handling heavy 3Cs and high voltages
- > Less autonomy during turn-around

>> Servicing and Maintenance

- > Specialised procedures when handling power electronic systems
- > Greatly improved MTBF, MTBUR
- > Need to maximise component/sub-system DSGs

>> Normal Mode En route Perform.

- > Simpler flight planning, "low-and-slow" design is not inevitable
- > Fixed SEP, no step-cruise
- > "Stepped" payload-range trade
- > Lower noise attributes

>> Abnormal Mode Performance

- > PMAD system driven limitations
- > OEI during en route conditions – no change in SEP, buffet limitations
- > Impact of actual operating ambient conditions plus EMI/HIRF effects

Design and Integration of Adaptive Top-Wing

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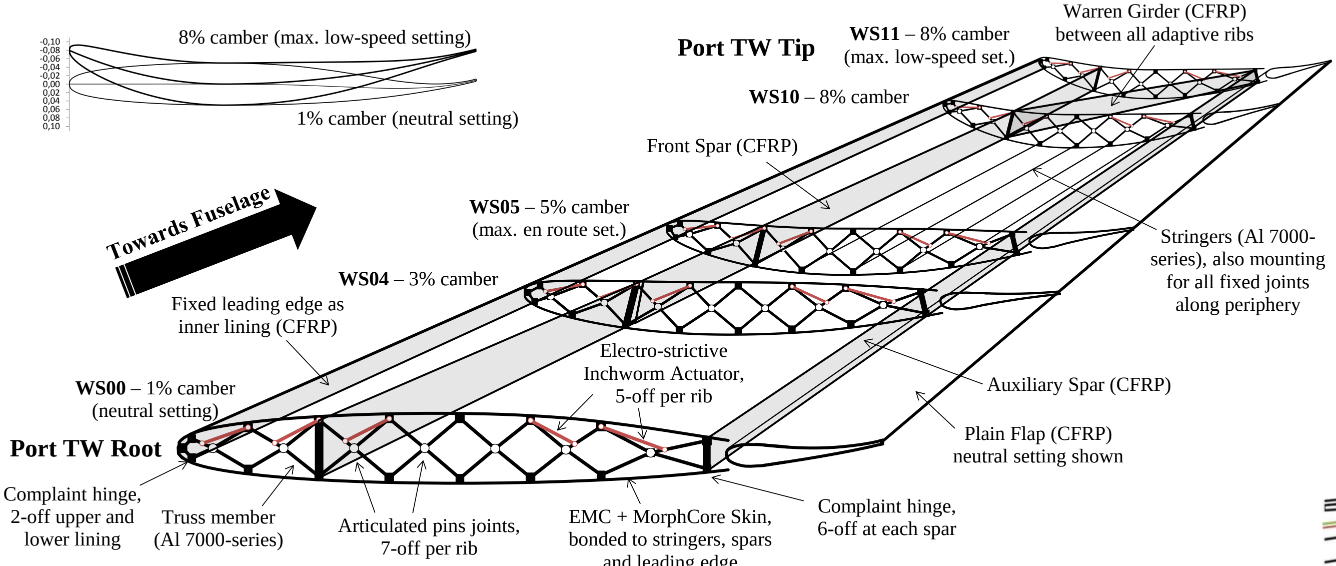
>> Critical trim/control cases

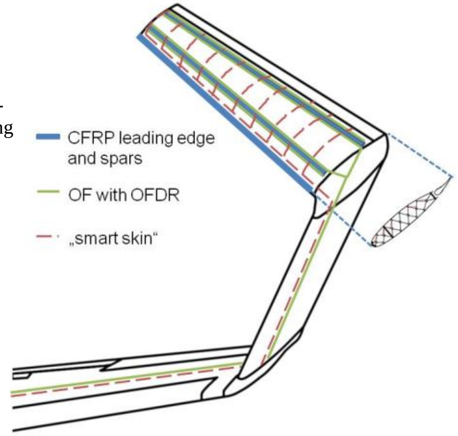
- > Cruise, take-off rotation, landing de-rotation and go-around

>> Variable stiffness, adaptive hybrid-compliant system

>> Structural Health Monitoring

- > Utilised for maintenance scheduling and actuation monitoring
- > Specially embedded OFDR and adoption of so-called „smart skin“





Source: Lorenz et al., IWSHM 2013

Engineering Trade-study: EF vs EOR

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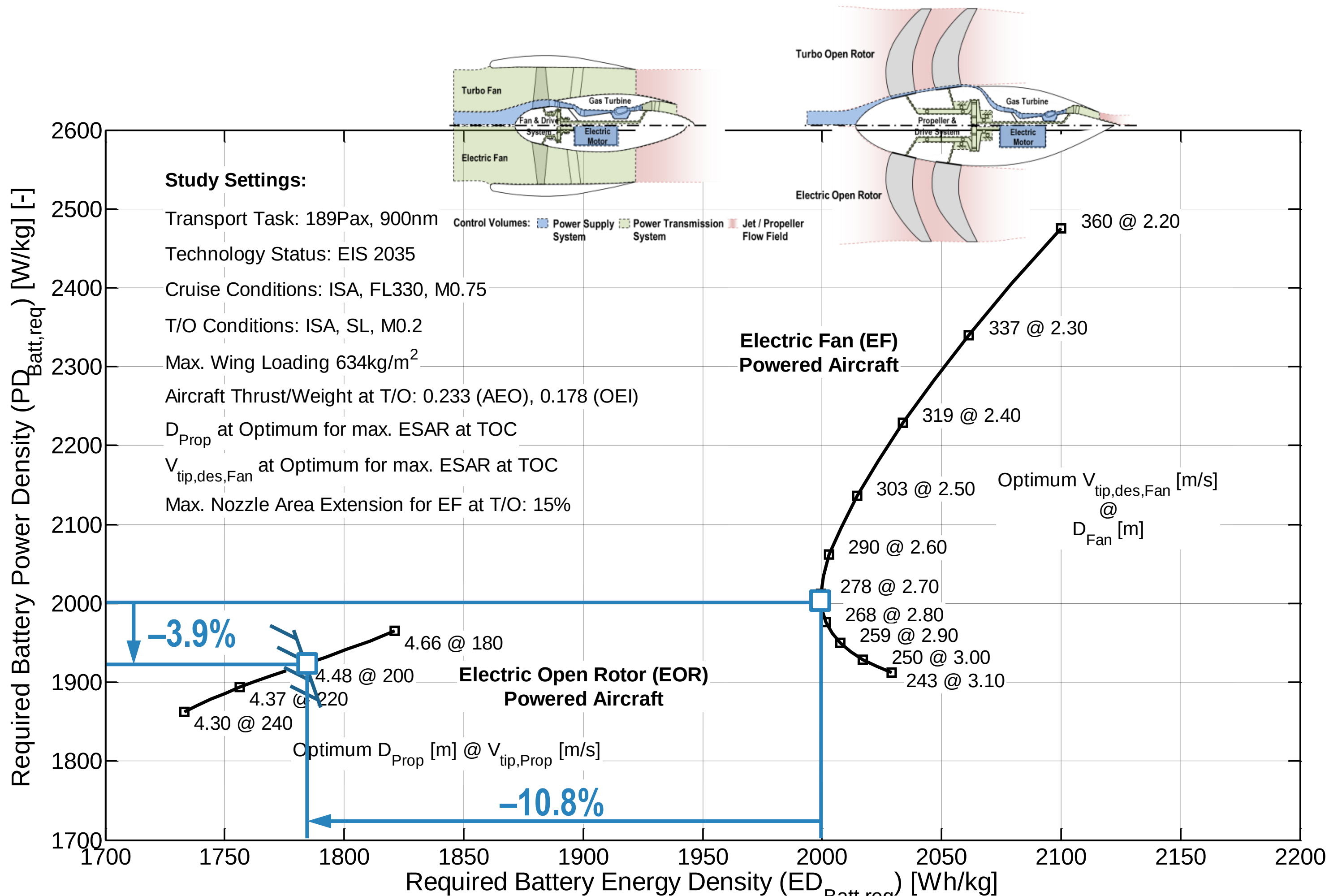

Source: Seitz et al., JPC 2013

Engineering Trade-study: Propulsive Fuselage

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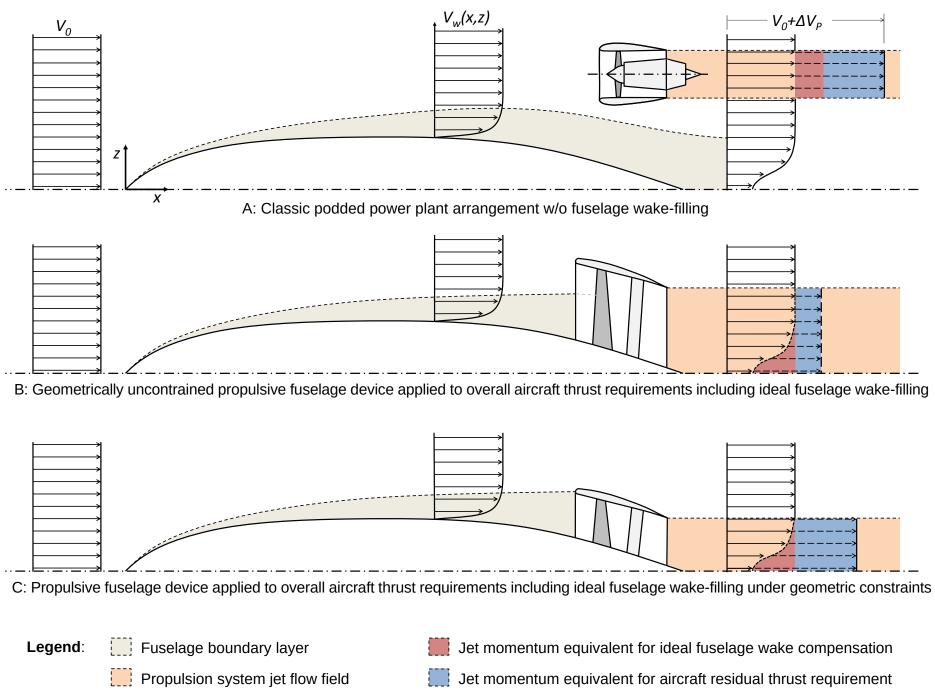
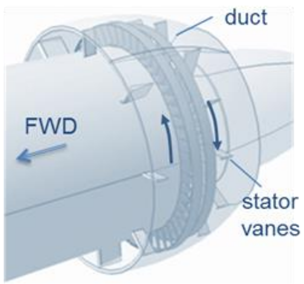
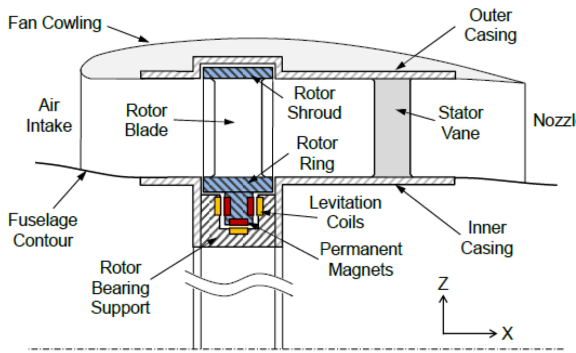
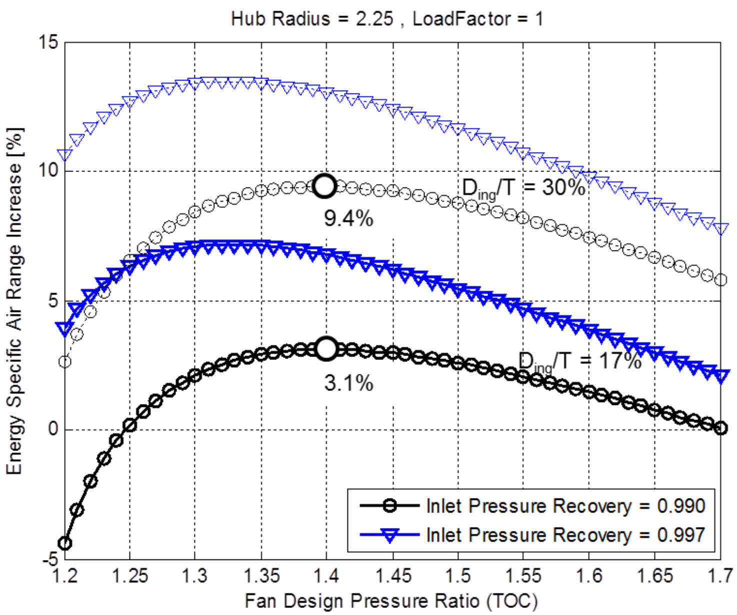
Neue Wege.

Source: adapted from Seitz & Gologan, CEAS 2013









Source: Steiner et al., ICAS 2012

Key Observations and Future Research Work

>> Key Observations

- **To realise Flightpath 2050 goals for emissions a hybrid-energy approach is necessary**
  - MEA-AEA evolution will not be sufficient → some means of electrical energy generation and/or storage for propulsion is key
  - Indications that single energy storage approach will be limiting for commercial transportation
  - Short-haul operations → Universally-Electric solution
  - Medium-to-long-haul operations → Hybrid-Electric solution
  - Even with relatively aggressive specifc weights, electrification yields significant degradation in vehicular efficiency → distributed propulsion and advanced, active wings could offset this

>> Future Research Work

- **Hybrid Electrical Power Systems – dual energy storage approach**
- **Integration schemes that accommodate retro-fit/upgrades between UESA and HE without extensive re-design**

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