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

>>> 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

Economics and Transportation

Visionary Aircraft Concepts

Core Competencies

Knowledge Management

Future Technologies and Ecology of Aviation
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Socio-Economic Drivers

>> **Megacities**
- Urban Living, growing middle-class

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

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**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

**Flightpath 2050**

- 75% less CO₂ 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**

<table>
<thead>
<tr>
<th>Goals and Key contributions</th>
<th>2000 (Reference)</th>
<th>2020 (Vision)</th>
<th>2020 (AGAPE)</th>
<th>2020 (SRIA)</th>
<th>2025 (SRIA)</th>
<th>2030 (SRIA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ objective vs 2000 (&quot;HLG&quot;)</td>
<td>-50%**</td>
<td>-50%</td>
<td>-38%</td>
<td>-43%</td>
<td>-60%</td>
<td>-75%</td>
</tr>
<tr>
<td>CO₂ vs 2000 (kg/pass km)*</td>
<td>-50%</td>
<td>-38%</td>
<td>-43%</td>
<td>-60%</td>
<td>-75%</td>
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<tr>
<td>Airframe energy need (Efficiency)</td>
<td>1</td>
<td>0.75</td>
<td>0.85</td>
<td>0.8</td>
<td>0.7</td>
<td>0.32</td>
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<tr>
<td>Propulsion &amp; Power energy need (Efficiency)</td>
<td>1</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>ATM and Infrastructure</td>
<td>1</td>
<td>0.88</td>
<td>0.95</td>
<td>0.93</td>
<td>0.88</td>
<td>0.88</td>
</tr>
<tr>
<td>Non Infrastructure-related Airlines Ops</td>
<td>1</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
<td>0.93</td>
<td>0.88</td>
</tr>
</tbody>
</table>

* 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

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**

**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.

Source: Kuhn and Sizmann, DLRK 2012
Electric Flight Feasibility Assessment

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>> Hybridization:

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

Sources:
Sizmann, 2010
Kuhn et al., CEAS 2011
H. Kuhn et al., ICAS 2012
Electric Flight Feasibility Assessment

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Sources:
- Sizmann, 2010
- Kuhn et al., CEAS 2011
- H. Kuhn et al., ICAS 2012
Hybrid-Electric Power System Architectures

Power generation
- Storage
- Battery
- Capacitor
- Energy collector

Power management and distribution
- Generator
- Fuel cell

Power consumption
- Motor
- Prop
- Ducted prop
- Counter-rotating prop
- Distributed props
- Actuators
- Avionics
- Environmental control unit
- Cabin
- Anti-ice

Fuel flow
- Mechanical power
- Electrical power

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Typical Power Demand of Sub-systems

Maximum required power at different flight phases

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

Power Demand of Propulsion System

- Ground: 33.5 MW

Power Demand of Subsystems

- Thermal Management
- Landing Gear
- Flight Controls
- Lighting
- ECS
- Cockpit
- Avionic
- Instruments & Ice Protection
- Cabin

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)

<table>
<thead>
<tr>
<th>System</th>
<th>Power [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>230 VAC</td>
<td>272</td>
</tr>
<tr>
<td>115 VAC</td>
<td>153</td>
</tr>
<tr>
<td>270 VDC</td>
<td>324</td>
</tr>
<tr>
<td>28 VDC</td>
<td>27</td>
</tr>
</tbody>
</table>

Loads:
- ECS/Pressurization
- ECS Fans
- Hydraulics
- Cooling

Engine #1
- 230 VAC
- 115 VAC
- 270 VDC
- 28 V Essential
- 28 V Vital
- 28 V Non-Essential

Engine #2
- APU
- RAT

Avionics
- 28 V Essential
- 28 V Vital

Source: Vratny, 2012 adapted from Chick, Flug Revue 2012
Advanced MEA System Architecture (only DC)

**Engine #1**

- 270 V Essential
- 270 V Non-Essential
- 28 V Non-Essential
- 28 V Vital
- 28 V Essential

**Fuel Cell**

**Engine #2**

- 270 V Essential
- 270 V Non-Essential

**Loads 270 VDC:**
- Ice Protection
- Galleys
- Fuel pumps
- Forward Cargo AC
- ICS
- ECS/Pressurization
- ECS Fans
- Hydraulics
- Cooling

**Source:** Vratny, 2012
ATA 24 AEA Evolution circa 2035 (higher risk)


Source: Pornet et al., AIAA 2013
Combining Energy Sources for Motive Power

~60% usable energy

\[ P_{\text{Supply}} = P_{\text{Fuel}} \]

\[ P_{\text{Inflow}} \quad \text{ICE} \quad P_{\text{Shaft}} \quad P_{\text{Thrust}} \quad P_{\text{Outflow}} \]

Gas Turbine Engine

\[ \text{ICE} = \text{Internal Combustion Engine, PT = Power Turbine} \]

100% usable energy

\[ P_{\text{Supply}} = P_{\text{Electric}} \]

\[ P_{\text{Inflow}} \quad \text{E-Motor} \quad P_{\text{Shaft}} \quad P_{\text{Thrust}} \quad P_{\text{Outflow}} \]

Fully Electric Propulsion

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

\[ \text{Hybrid Cycle Engine} \]

\[ \text{ICE} = \text{Internal Combustion Engine, PT = Power Turbine} \]

Alternative Figures-of-Merit

> Thrust Specific Power Consumption

\[ TSPC = \frac{P_{\text{supply}}}{F_0} = \frac{V_0}{\eta_{ov} \cdot \eta_{tr} \cdot \eta_{pr}} \]

> Energy Specific Air Range

\[ ESAR = \frac{dR}{dE} = \frac{V_0 \cdot \frac{L}{D}}{TSPC \cdot m_{A/C} \cdot g} = \frac{\eta_{ov} \cdot \frac{L}{D}}{m_{A/C} \cdot g} \]
Hybrid-Energy Engineering for Motive Power

Serial Hybrid Solutions

Parallel Hybrid Solutions
Hybrid-Energy Aircraft Study

>> 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

<table>
<thead>
<tr>
<th>Concept</th>
<th>TOW/MTOW [%]</th>
<th>$P_{EM,\text{total inst.}}$ [MW]</th>
<th>$m_{\text{battery, total inst.}}$ [kg]</th>
<th>$\Delta F_{\text{fuel burn}}$ [%]</th>
<th>DE [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HYCruise</td>
<td>100</td>
<td>6</td>
<td>8400</td>
<td>-13</td>
<td>13.4</td>
</tr>
<tr>
<td>HYCruise&amp;climb</td>
<td>100</td>
<td>5.1</td>
<td>8900</td>
<td>-16</td>
<td>14.5</td>
</tr>
</tbody>
</table>

Source: Pornet et al., AIAA 2013
Zero-emissions Concept – The Ce-Liner

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

<table>
<thead>
<tr>
<th>Continuous window belts:</th>
</tr>
</thead>
</table>
| » Transparent and stressed structures
| » Novel experience for passengers

<table>
<thead>
<tr>
<th>Electric propulsion system:</th>
</tr>
</thead>
</table>
| » High-temperature superconducting (HTS) electric motors
| » Integrated cryocooler
| » Reversible rotation for thrust reverse
| » Silent Advanced Ducted Fans (SAFE)
| » Translating nozzle plug

<table>
<thead>
<tr>
<th>Charge Carrying Containers (3Cs):</th>
</tr>
</thead>
</table>
| » 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

<table>
<thead>
<tr>
<th>Power electronics and supply:</th>
</tr>
</thead>
</table>
| » 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

<table>
<thead>
<tr>
<th>Actuation systems:</th>
</tr>
</thead>
</table>
| » Electric mechanical actuators
| » Redundancy according to ETOPS requirements

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Power and Battery Performance Profiles

Source: Vratny et al., CEAS 2013
## Benchmarking Ce-Liner

### Aircraft Properties

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

**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**

**Study Settings:**
- Transport Task: 189 Pax, 900 nm
- Technology Status: EIS 2035
- Cruise Conditions: ISA, FL330, M0.75
- T/O Conditions: ISA, SL, M0.2
- Max. Wing Loading: 634 kg/m$^2$
- Aircraft Thrust/Weight at T/O: 0.233 (AEO), 0.178 (OEI)
- $D_{\text{Prop}}$ at Optimum for max. ESAR at TOC
- $V_{\text{tip,des,Fan}}$ at Optimum for max. ESAR at TOC
- Max. Nozzle Area Extension for EF at T/O: 15%

**Electric Fan (EF) Powered Aircraft**
- $360 \, @ \, 2.20$
- $337 \, @ \, 2.30$
- $319 \, @ \, 2.40$
- $303 \, @ \, 2.50$
- $290 \, @ \, 2.60$
- $278 \, @ \, 2.70$
- $268 \, @ \, 2.80$
- $259 \, @ \, 2.90$
- $250 \, @ \, 3.00$
- $243 \, @ \, 3.10$

**Electric Open Rotor (EOR) Powered Aircraft**
- $4.66 \, @ \, 180$
- $4.48 \, @ \, 200$
- $4.37 \, @ \, 220$
- $4.30 \, @ \, 240$

**Source:** Seitz et al., JPC 2013
Engineering Trade-study: Propulsive Fuselage

A: Classic podded power plant arrangement w/o fuselage wake-filling

B: Geometrically uncontrained propulsive fuselage device applied to overall aircraft thrust requirements including ideal fuselage wake-filling

C: Propulsive fuselage device applied to overall aircraft thrust requirements including ideal fuselage wake-filling under geometric constraints

Legend:
- Fuselage boundary layer
- Jet momentum equivalent for ideal fuselage wake compensation
- Propulsion system jet flow field
- Jet momentum equivalent for aircraft residual thrust requirement

Source: adapted from Seitz & Gologan, CEAS 2013

Source: Van Dyck, 2012

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 specific 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
Contact

Bauhaus Luftfahrt e.V.
Lyonel-Feininger-Strasse 28
80807 Munich
Germany

Tel.: +49 (0) 89 3 07 48 49 - 0
Fax: +49 (0) 89 3 07 48 49 - 20
info@bauhaus-luftfahrt.net

http://www.bauhaus-luftfahrt.net