Emissionsfreies Fliegen mit Wasserstoff

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Department of Hybrid Concepts

- Power Electronic Hardware, Controls and FC/Battery Power Management Systems

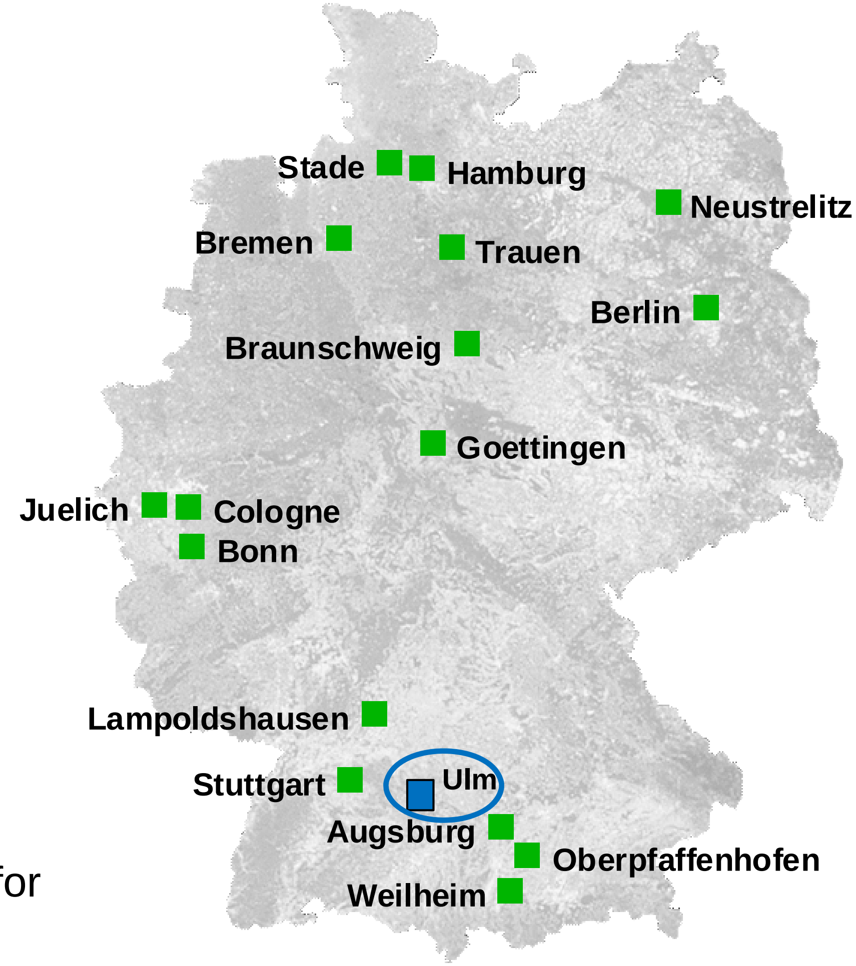
Department of Propulsion Research

- High power E-Machines, Generators

Applications: Aircraft applications, ….

Hardware/Test bench:

- ICE-Battery-E-Machine Hybrid up to MW
- Hydrogen infrastructure
- Low pressure and temperature chamber for components and complete systems



Aerospace Research Center and Space Agency of the Federal Republic of Germany (DLR)

- 7.700 employees
- 16 national facilities
- > 30 institutes and test facilities
- offices in Brüssel, Paris, Washington
- Test facilities in Almeria/Spain

- **ESI Energy System Integration, DLR**
  - Battery Systems and degradation
  - Fuel Cell Systems and degradation
  - Aircraft Applications MEA and AEA

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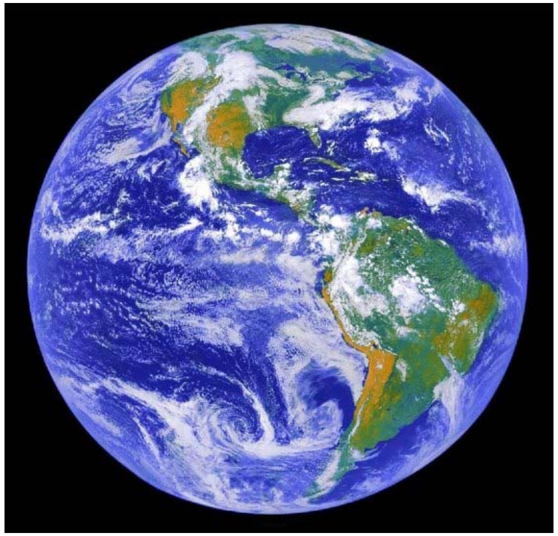
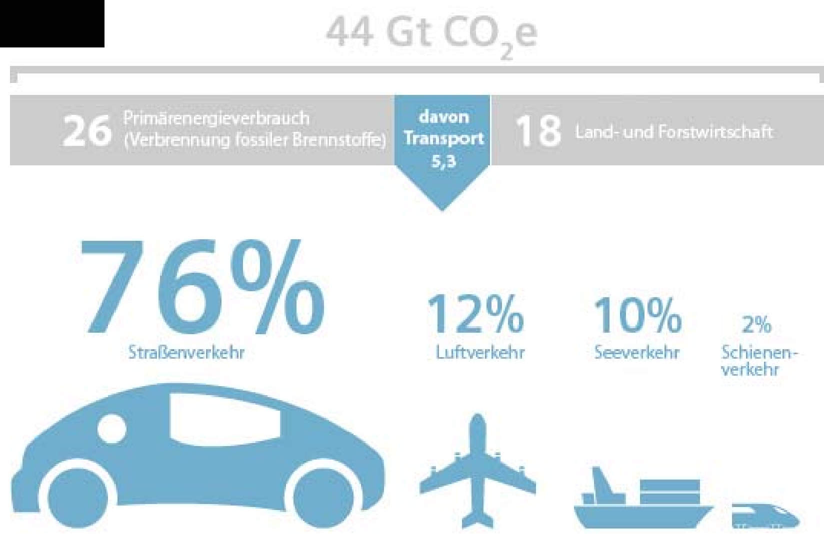
CO_2 – Emissionen verändern die Zusammensetzung der Luft in der Atmospäre





Quelle: IEA World Energy Outlook, Vattenfall, Siemens

CO_2-Emissionen in Deutschland

820Mt CO2/Jahr

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Auswirkungen Klimaveränderung

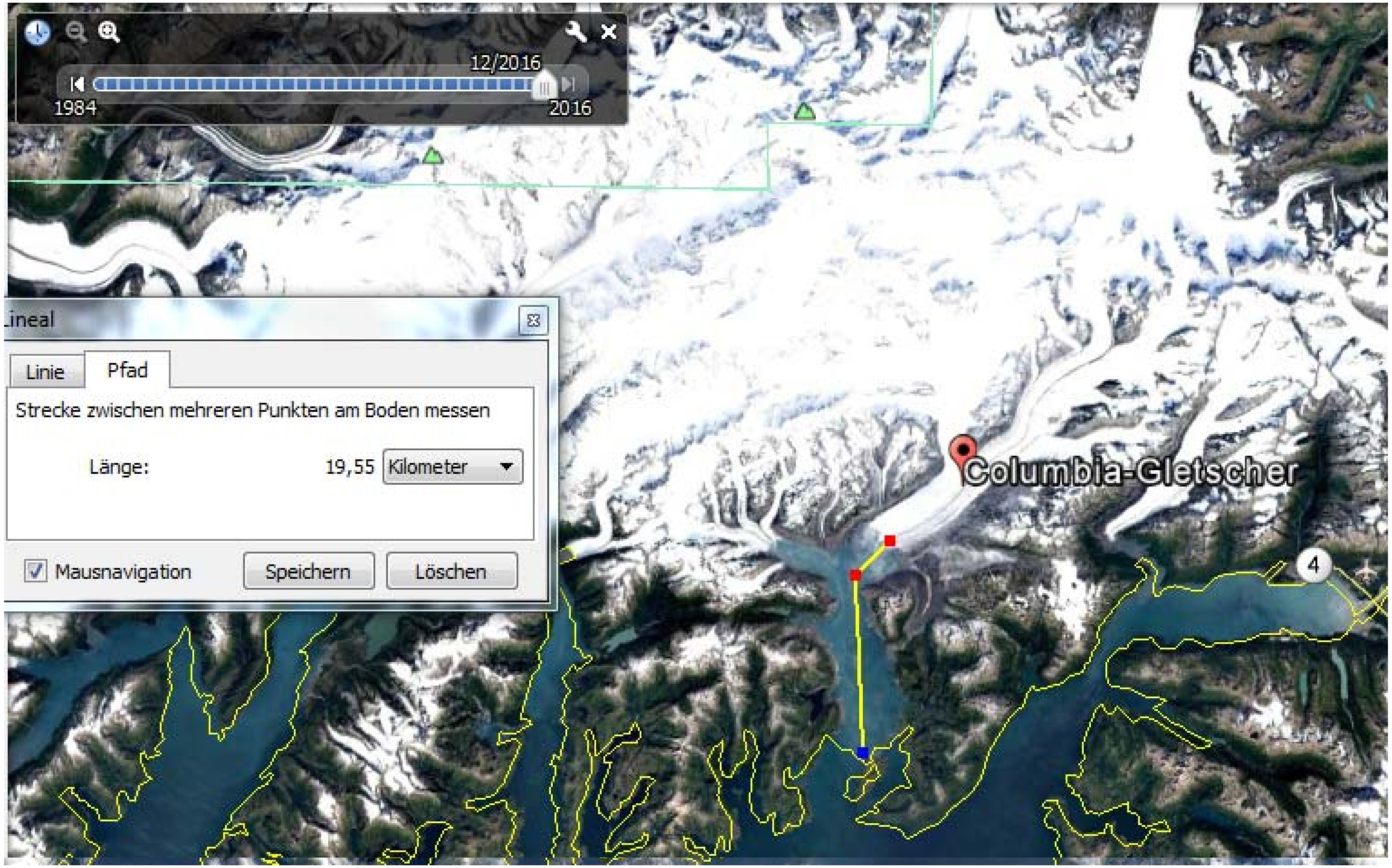
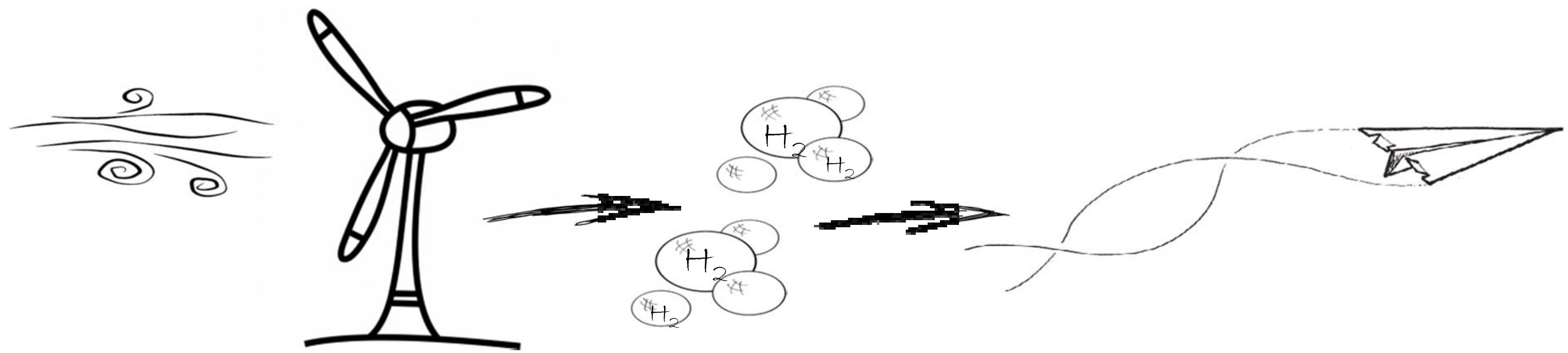


Bild: Google Earth

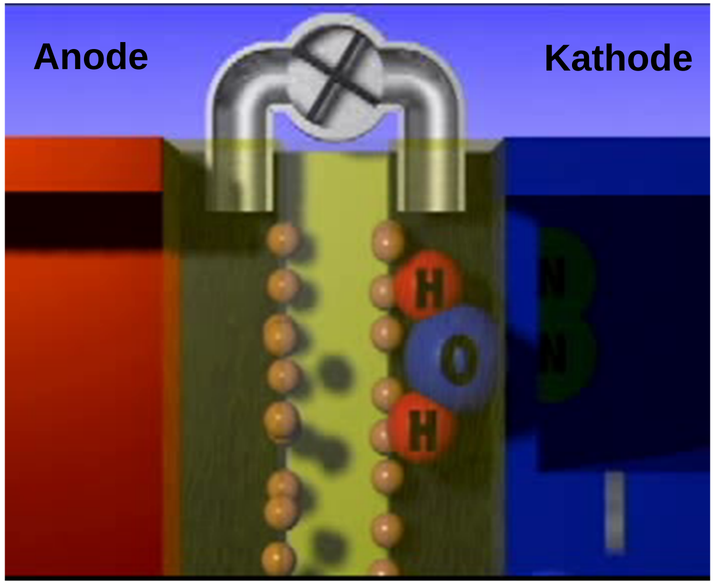
Wasserstoffantrieb für Flugzeuge

Ist es möglich mit regenerativ erzeugtem Wasserstoff ohne CO_2 Emissionen zu fliegen?



Potenziale der Brennstoffzelle in der Luftfahrt

→ *Elektrochemische Grundlagen der Brennstoffzelle (PEMFC basiert)*



Grundreaktion der Wasserstoff-Brennstoffzelle:

$2H_2 + O_2 \rightarrow$ **$2H_2O$** *(+ el. Energie / Arbeit + Wärme)*

Teilreaktion Anode:

$2H_2 \rightarrow 4\,H^+ + 4\,e^-$

Teilreaktion Kathode:

$4\,H^+ + 4\,e^- + O_2 \rightarrow 2\,H_2O$

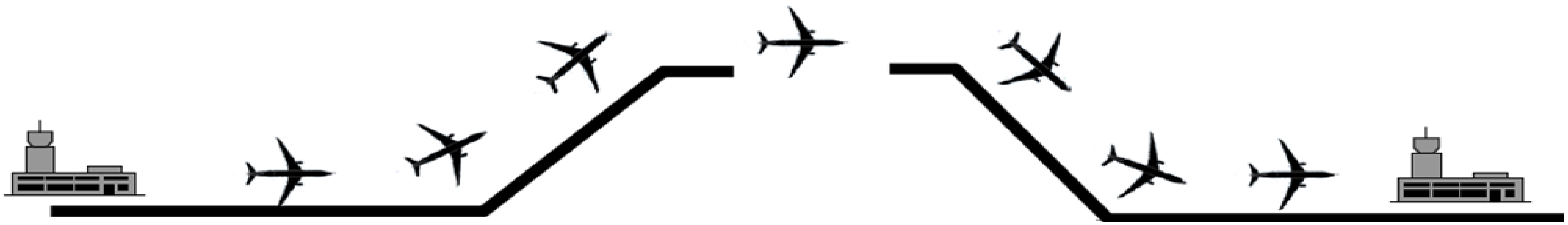
→ N_2 aus der Luft bleibt als Inertgas

→ Nutzung des produzierten Abwassers

→ Potential zur CO_2 Freiheit

→ kein Carnotprozess d.h. bei niedrigen Arbeitstemperaturen sind Wirkungsgrade in (kleinen) Systemen bis 55% möglich

Technische Randbedingungen und Phasen einer Flugmission



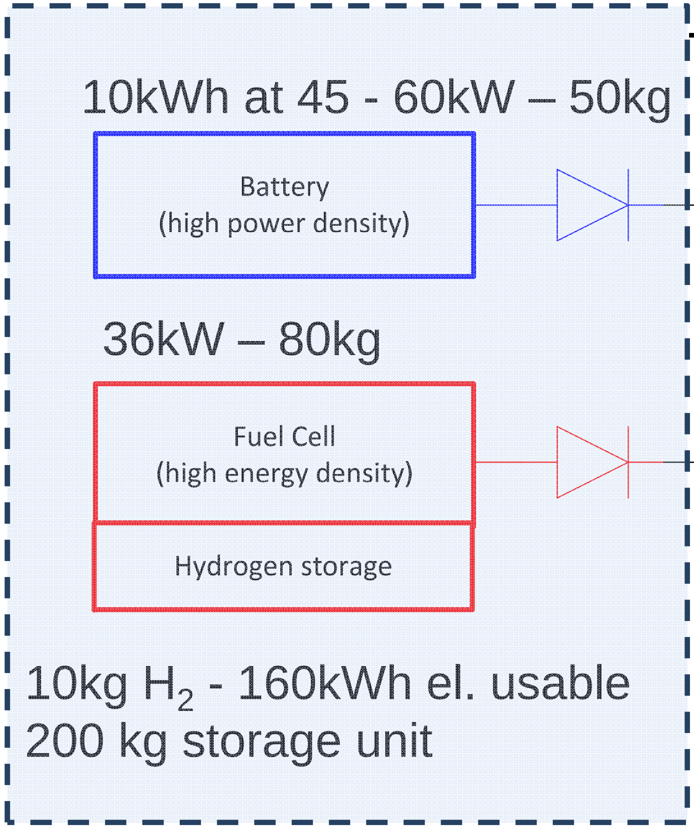
Taxiing & Takeoff → Departure → Cruise → Descent → Landing & Taxiing

P=1013mbar
$T_{ambient}$ = 14°C

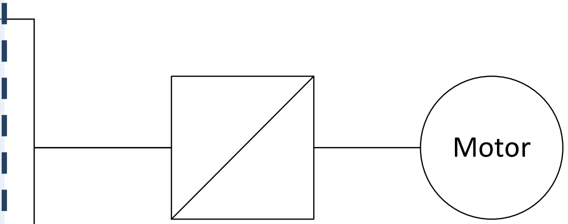
P=250 – 550mbar
$T_{ambient}$ = - 60°C   -15°C

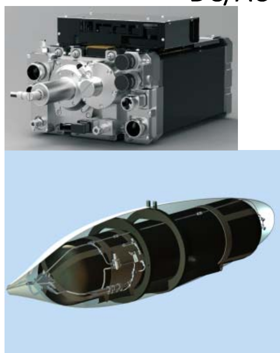
P=1013mbar
$T_{ambient}$ = 14°C

Hybrid electric hydrogen propulsion unit – Schematics, simple math for feasible energy capacity



→ 30 - 80 kW electric power at 350 - 270V





Bei Verwendung von Flüssigwasserstoff erhöht sich die Energiedichte im Quell-System auf bis zu 950Wh/kg

Mass balance 50kg + 80kg + 200kg = 330kg

Energy balance 170kWh usable (at 50%eff)

} 515Wh/kg (Druckwasserstoff)
(622Wh/kg at 20kgH_2)

History of emission-free aviation at UUlm and DLR

- Power source
- Electric power distribution
- Electric motors for aircraft application

„More Electric“ and „All Electric“ applications in aviation

2007-2015

- Replacement of the A320 Auxiliary Power Unit
- emission-free taxing Airbus A320

HY4

DLR-H2

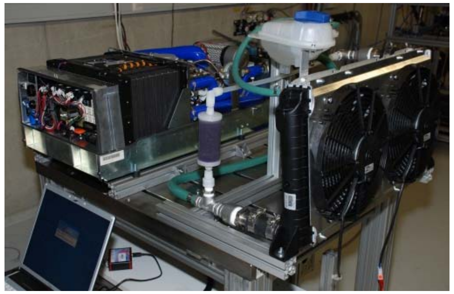
2008-2016

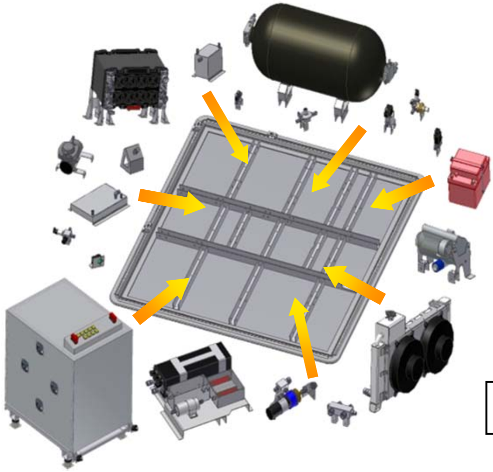
- DLR-H2 – first piloted emission-free hydrogen fuel cell aircraft
- ***HY4 – first 4 seater hydrogen - fuel cell aircraft***

Elektrochemischer Gasturbinen APU Ersatz mit Wasserstoff im A320

Aircraft Application
Functionality, Architecture, BOP

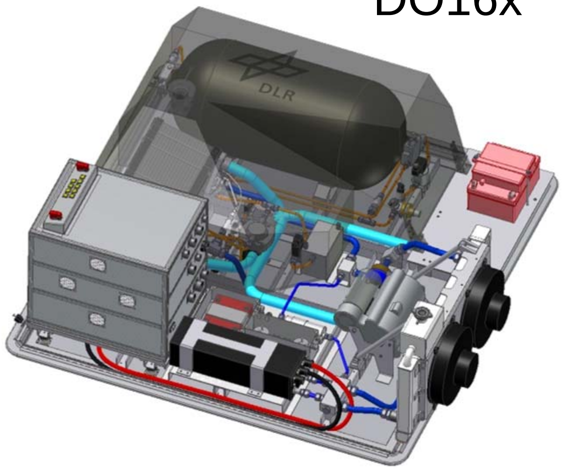
FC System from Transport Application

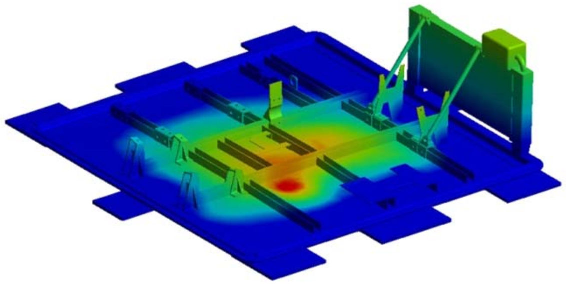




Airworthy technology development platform

DO16x





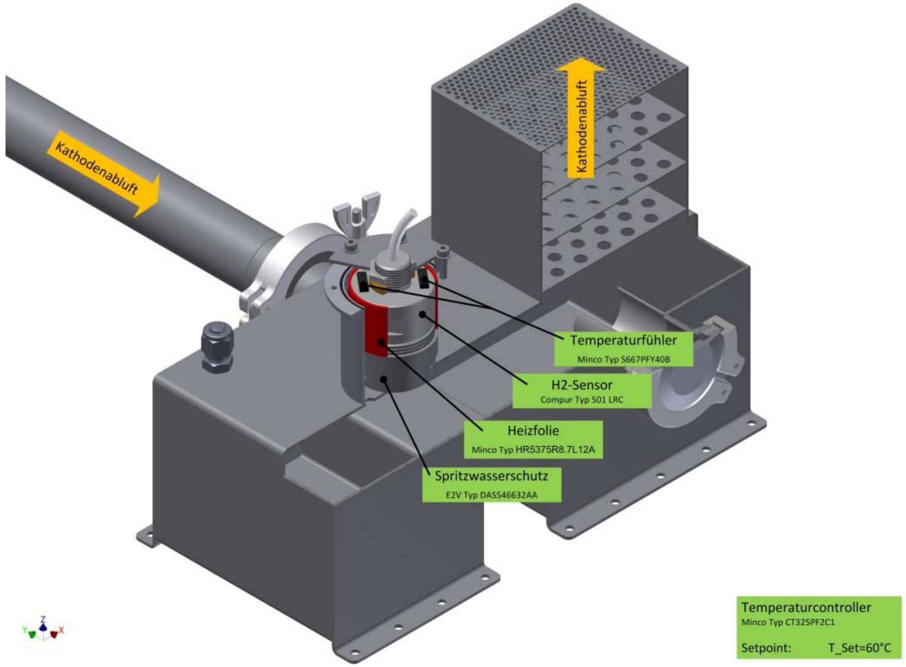
Mechanical Strenght Simulation

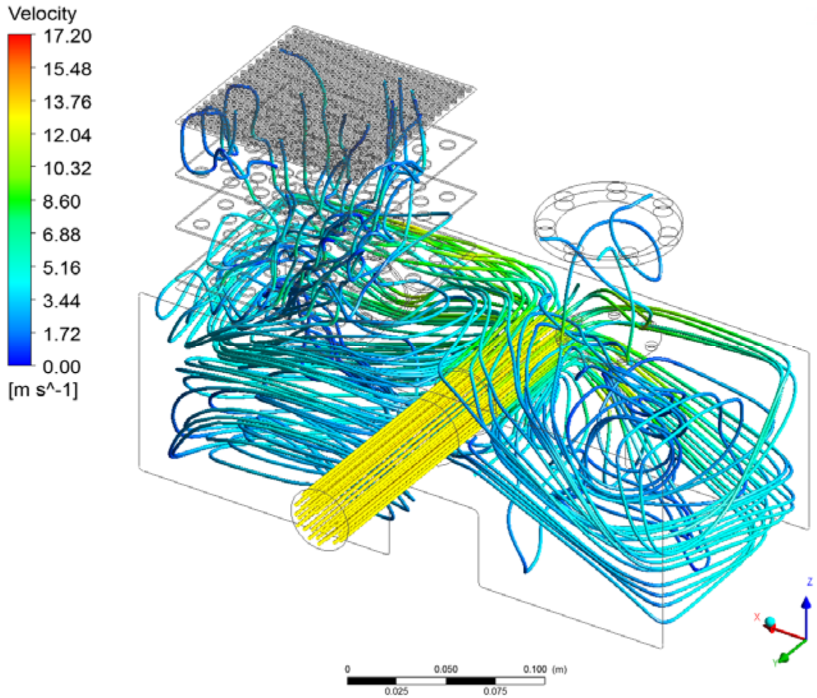
- **Fuel cell**
- **DC/DC**
- **hydrogen storage**

H2 Sensor humid environment

Design development for hydrogen detection in very humid environments (e.g. cathode exhaust)

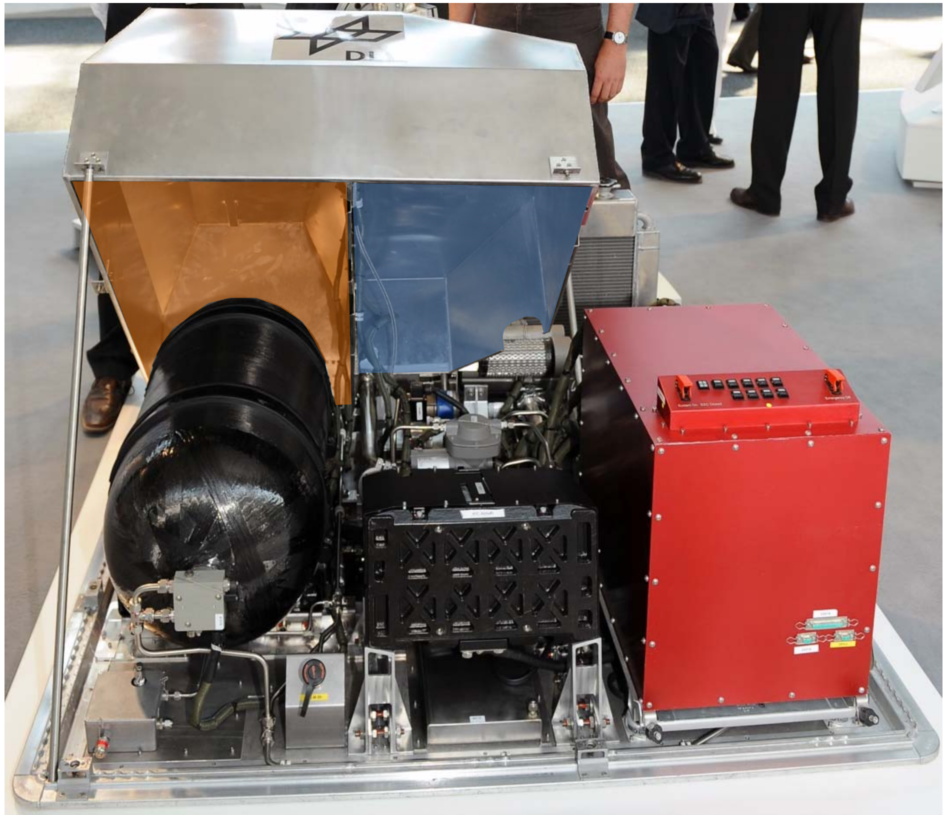
- Heated control volume to levels above monitored atmosphere
- Design validation using CFD tools → zusammen

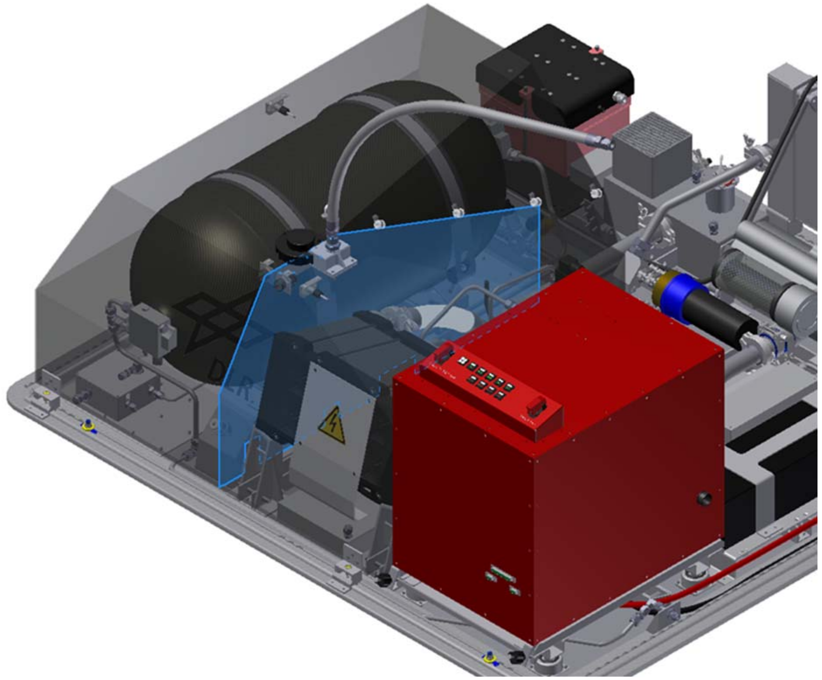




Hydrogen tank system integration

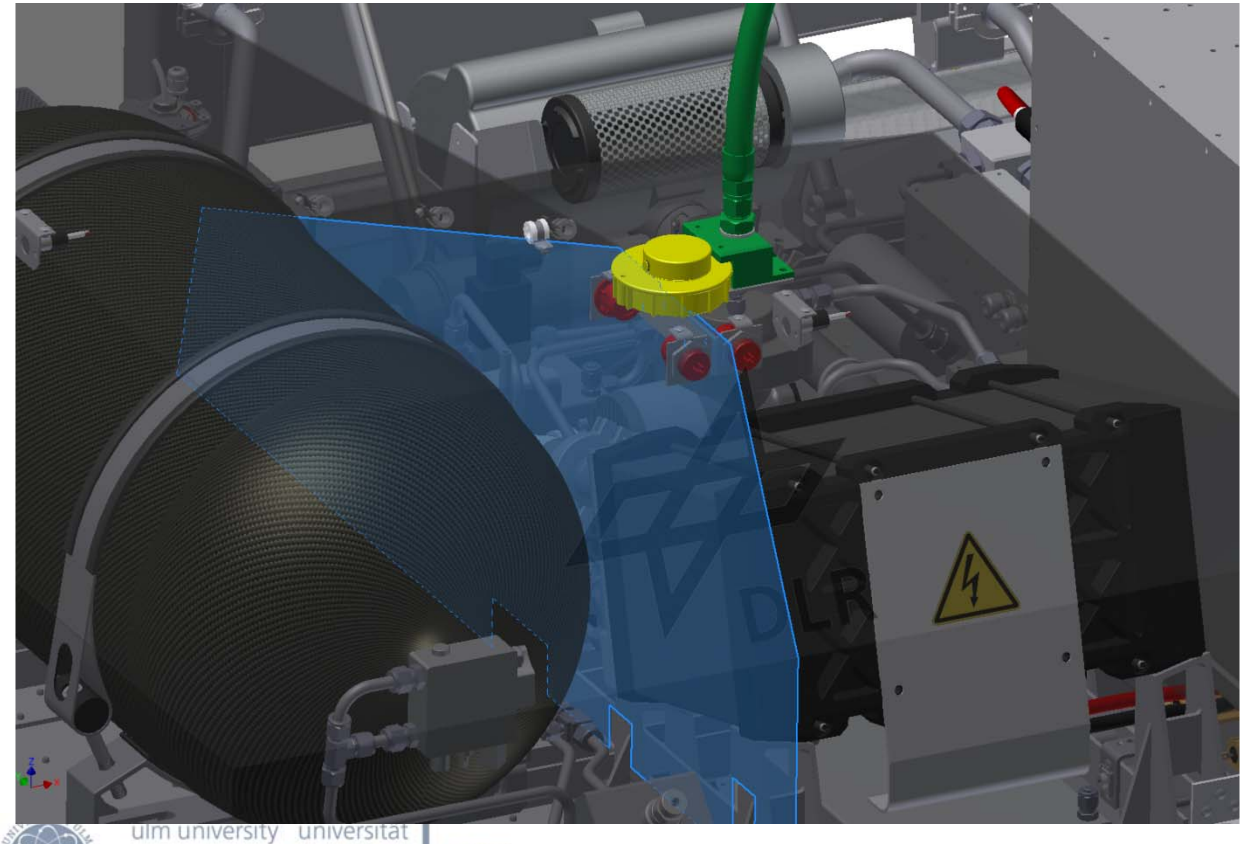
- Enclosure with high pressure (orange) and low pressure (blue) compartment
- Compartments are airtight separated by wall (blue)





Hydrogen tank system integration

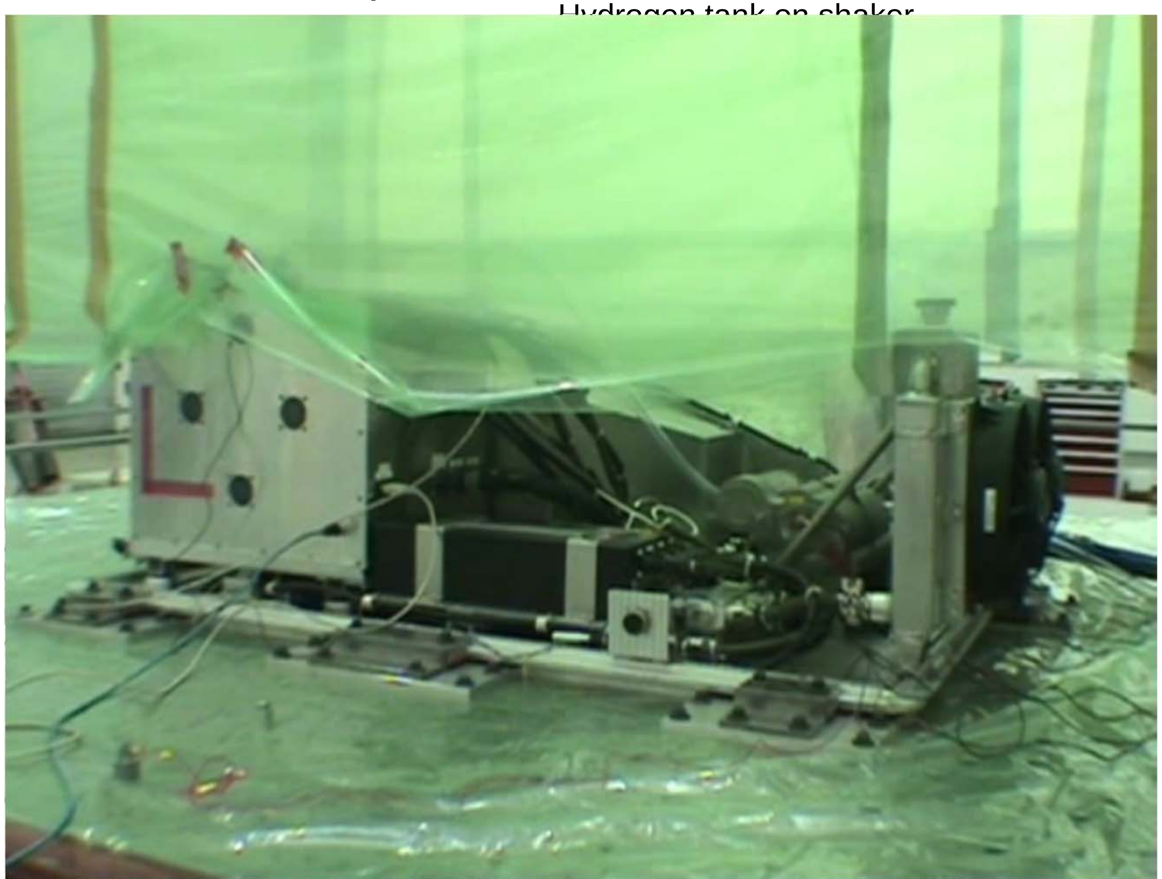
- Redundant hydrogen detection in each enclosure compartment with two sensors in each (red)
- Permanent enclosure ventilation (yellow) into discharge line (green)

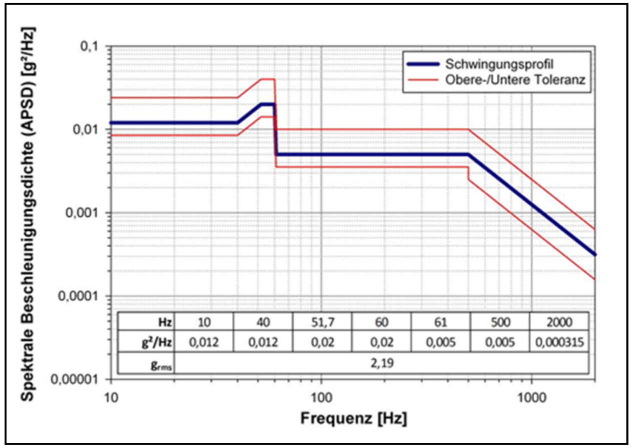


Hydrogen tank qualification tests

- Vibration test according to RTCA-DO160E (1h/direction)
- Bonfire test and pressure burst test according to ISO15869 (performed by manufacturer)

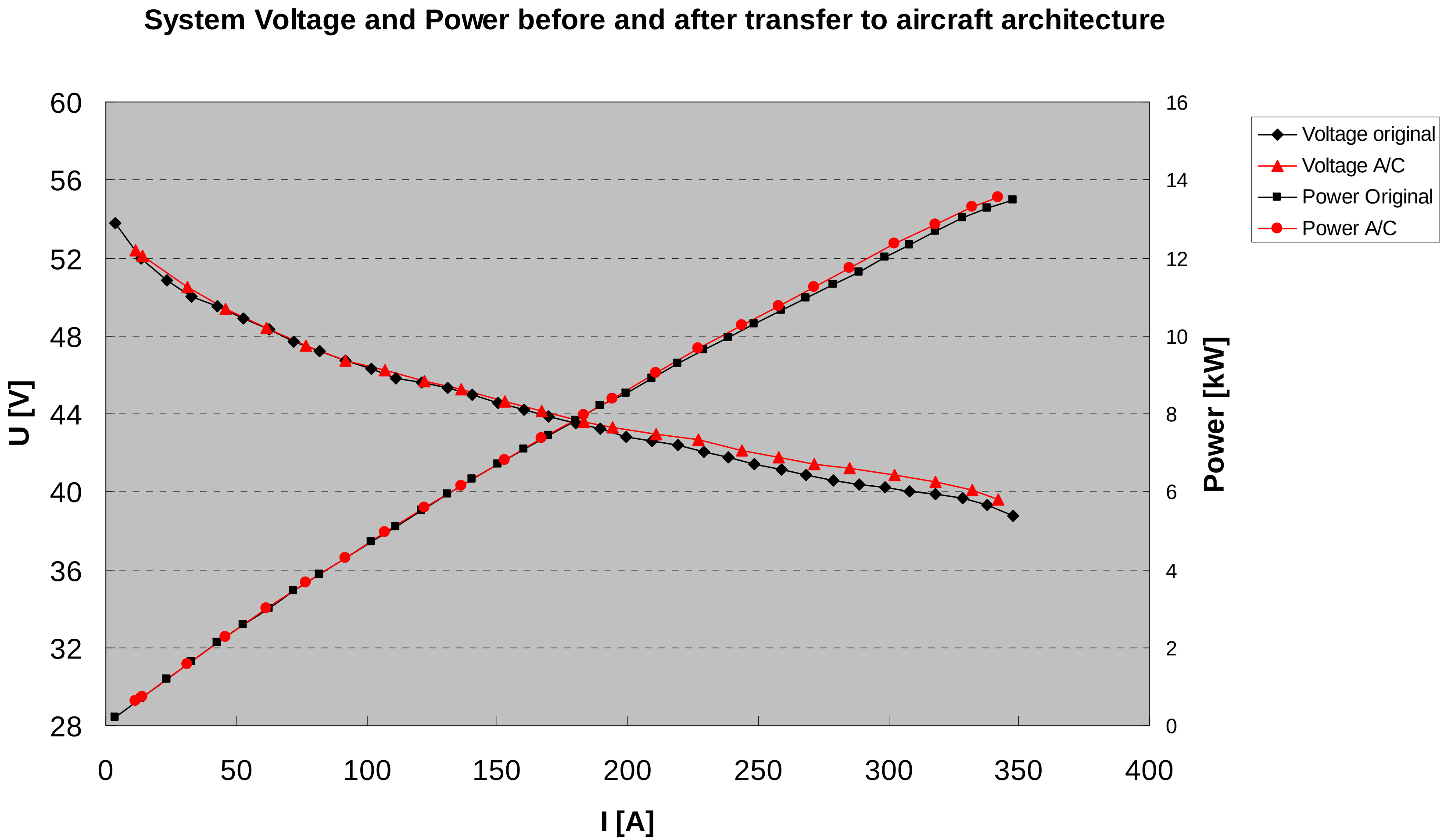
Hydrogen tank on shaker





RTCA-DO160E vibration profile

Fuel cell technology transfer to aircraft application



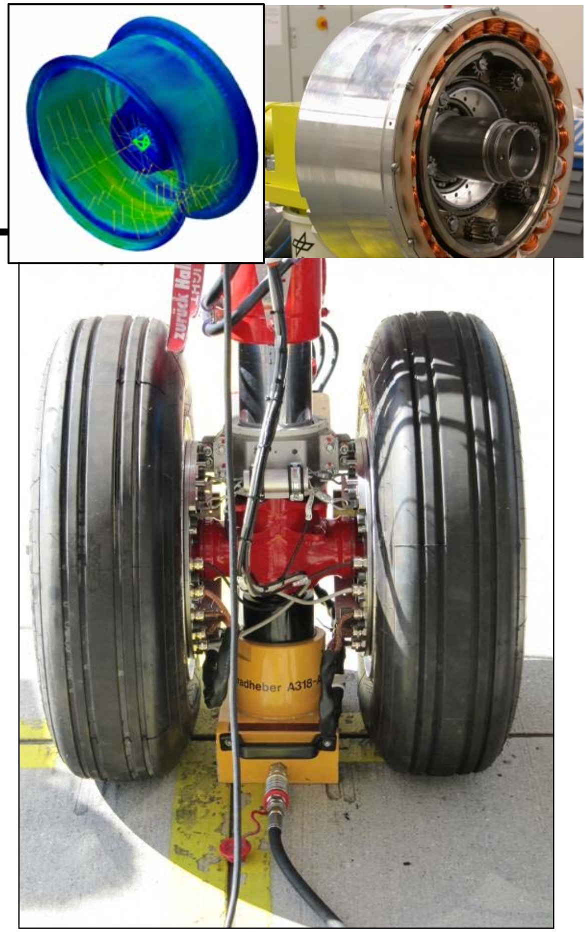
→ No power loss by transfer to airworthy architecture

Overview emission free taxi with ***fuel cell and e-NWD***

Multifunctional fuel cell system in cargo bay

Motor electronics

Control Box and Data Aquisition

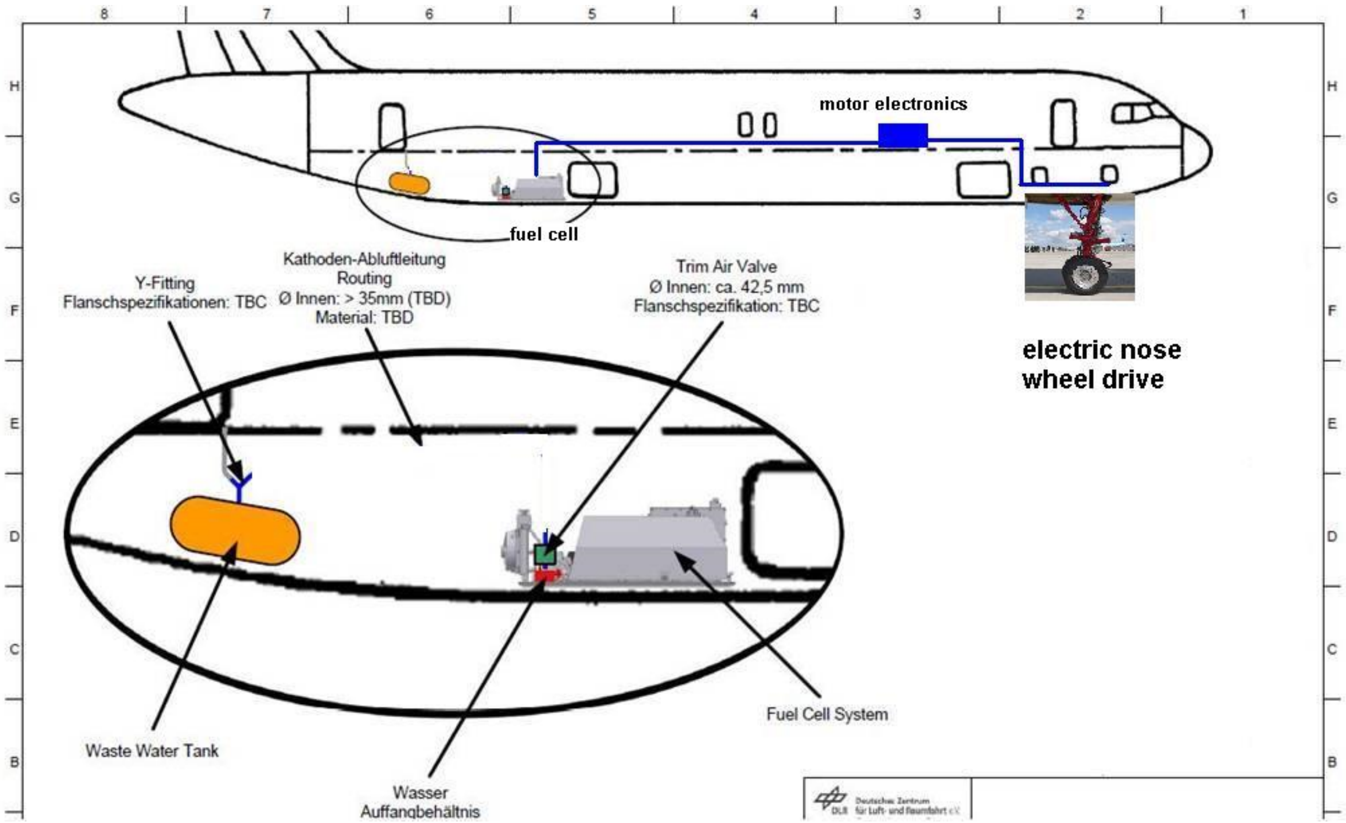


Fully integrated e-NWD

High Torque 11.000Nm

Emission free taxi - system installation in A320

**Fuel cell system and electrical nose wheel drive installation
in cooperation with Airbus (Hamburg/Toulouse/Lutton) and Lufthansa Technik**



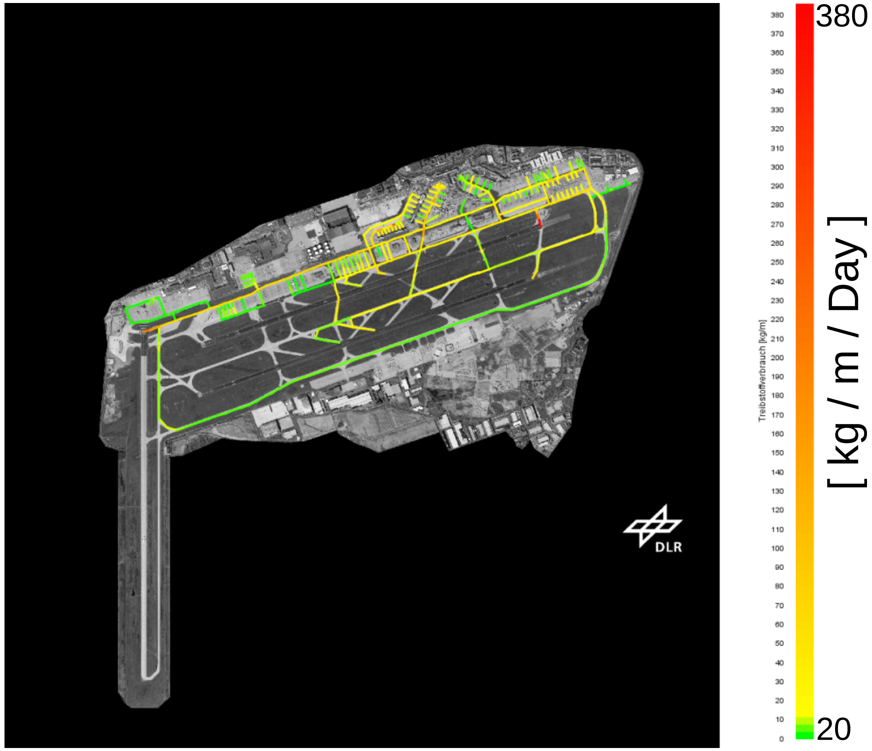
DLR

A320 emission free taxi with ***fuel cell and e-NWD***

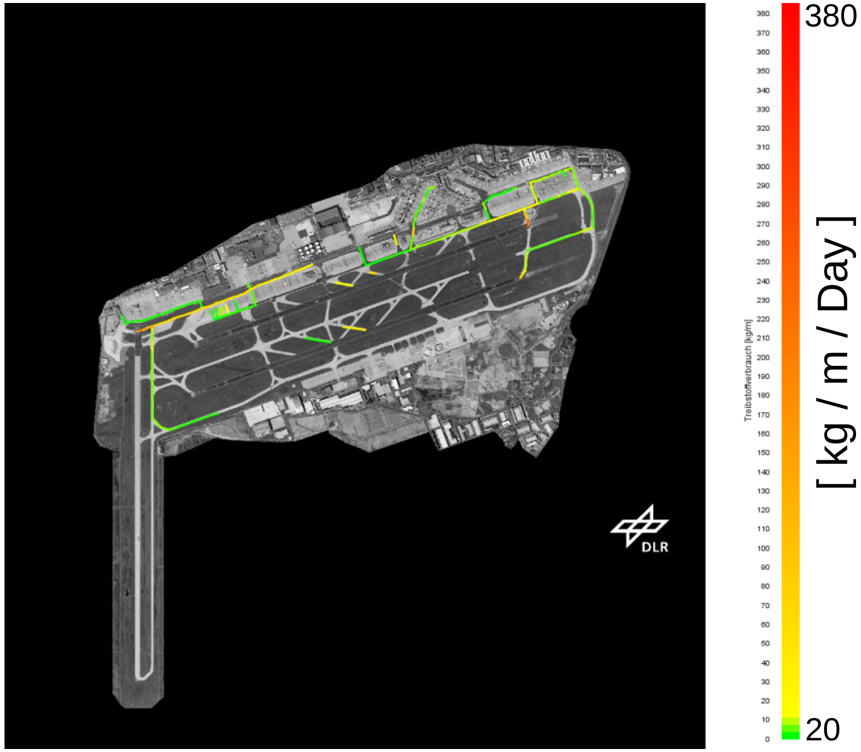
Test DLR + Airbus + LHT

Emission free taxi – fuel cell + el. drive (Frankfurt Airport)

Fuel Burn A320 + B737 conv.



Fuel Burn A320 + B737 el. FC Taxi

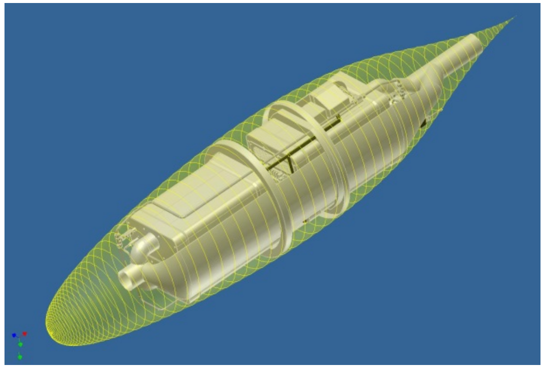


Savings A320 + B737 ca. 44t Kerosene/day = 136t CO_2/day

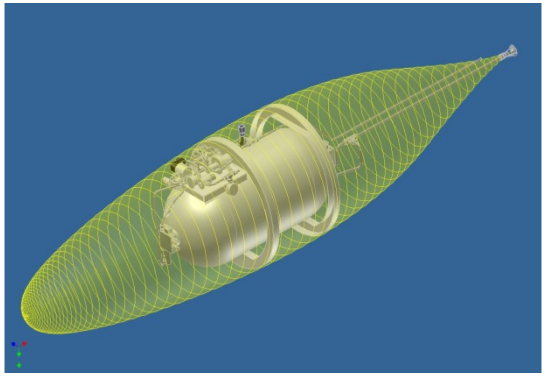
Aequivalent Hydrogen ca. 2,4 t (332 Landings, 334 Starts, 4.4.2009)

→ *700 -1000h Engine Saving Time/Year/Plane*

DLR-H2 – erstes Brennstoffzellenflugzeug



Brennstoffzellensystem



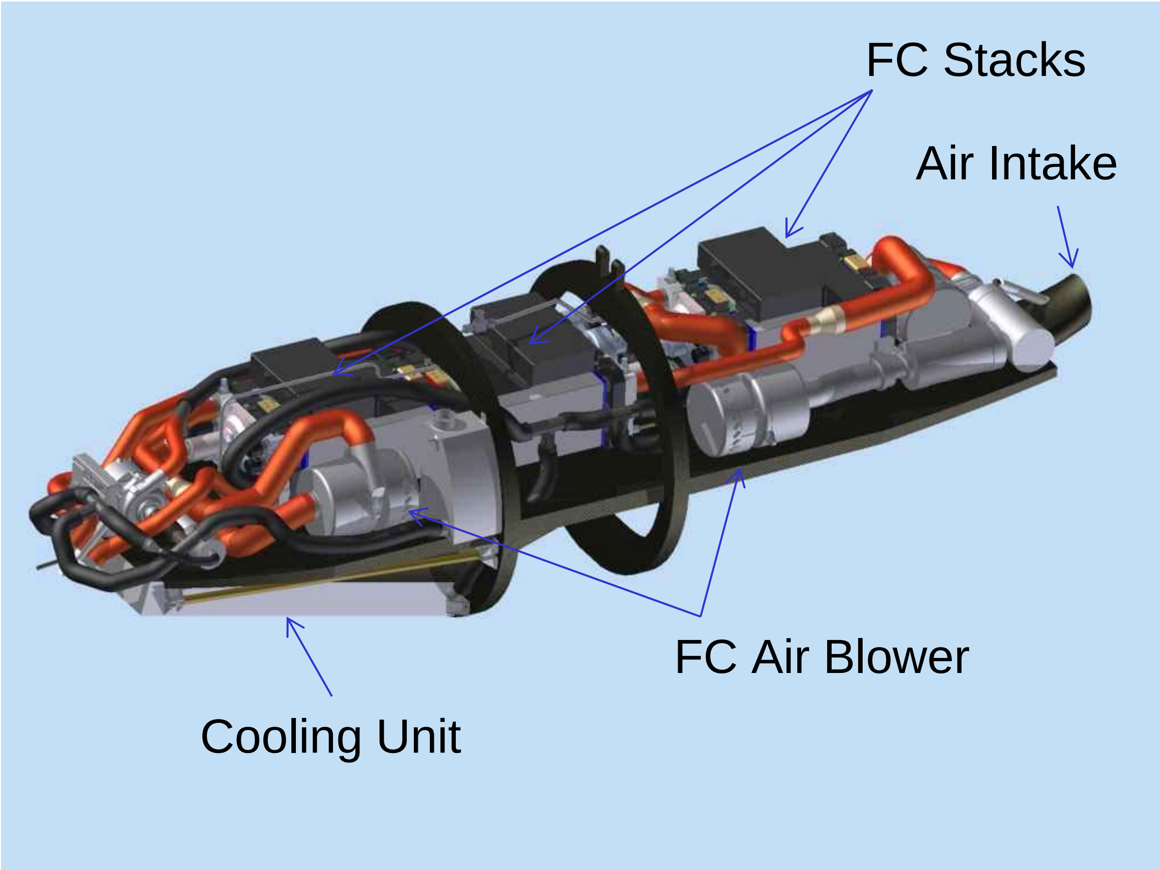
Wasserstoff-Speichersystem

Einsitziges Flugzeug mit elektrischem Propellerantrieb

Leistungsquelle:

Brennstoffzellen-Batterie Hybrid

Fuel Cell Technology Antares DLR H2 – Gen 2



Modular hybrid fuel cell system with cooling booster

Fuel Cell System Power
up to 33kW, Hybrid up to 55kW

→ modular system with high redundancy

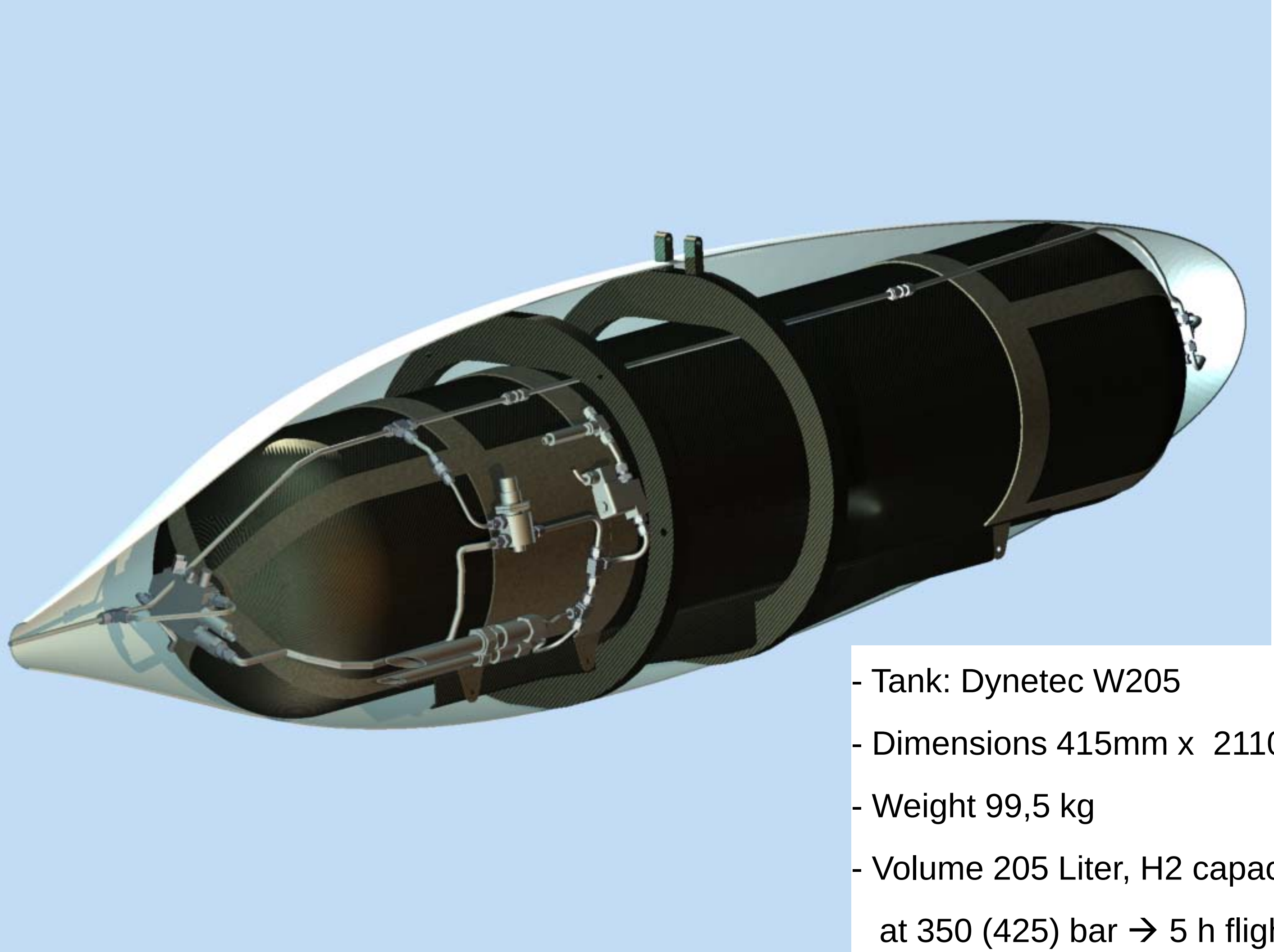
→ Medium active area (ca. 230cm^2)

→ High voltage auxiliary components

→ **System** efficiency up to 52%

→ **reliable, redundant, modular**

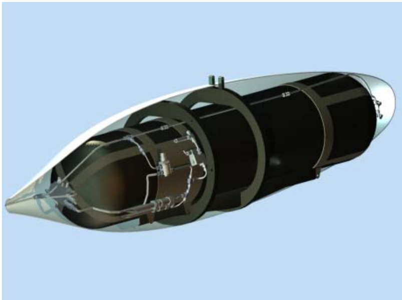
Hydrogen storage system Gen 2



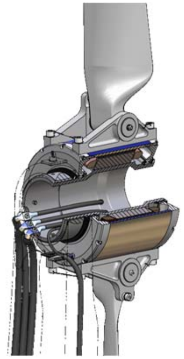
- Tank: Dynetec W205
- Dimensions 415mm x 2110 mm
- Weight 99,5 kg
- Volume 205 Liter, H2 capacity 4,89 kg
  at 350 (425) bar → 5 h flight time

Übersicht Antriebsstrang BZ- Antrieb

Wasserstoff - Speicher



Batterie 10kWh



Elektromotor

= ≈

Leistungsmanagement

Kompaktes Brennstoffzellensystem

- Technologische Herausforderung aufgrund **gravimetrischer** und **volumetrischer** Anforderungen
- **Systemzuverlässigkeit** hat stets erste Priorität

Integration Brennstoffzelle in DLR H2

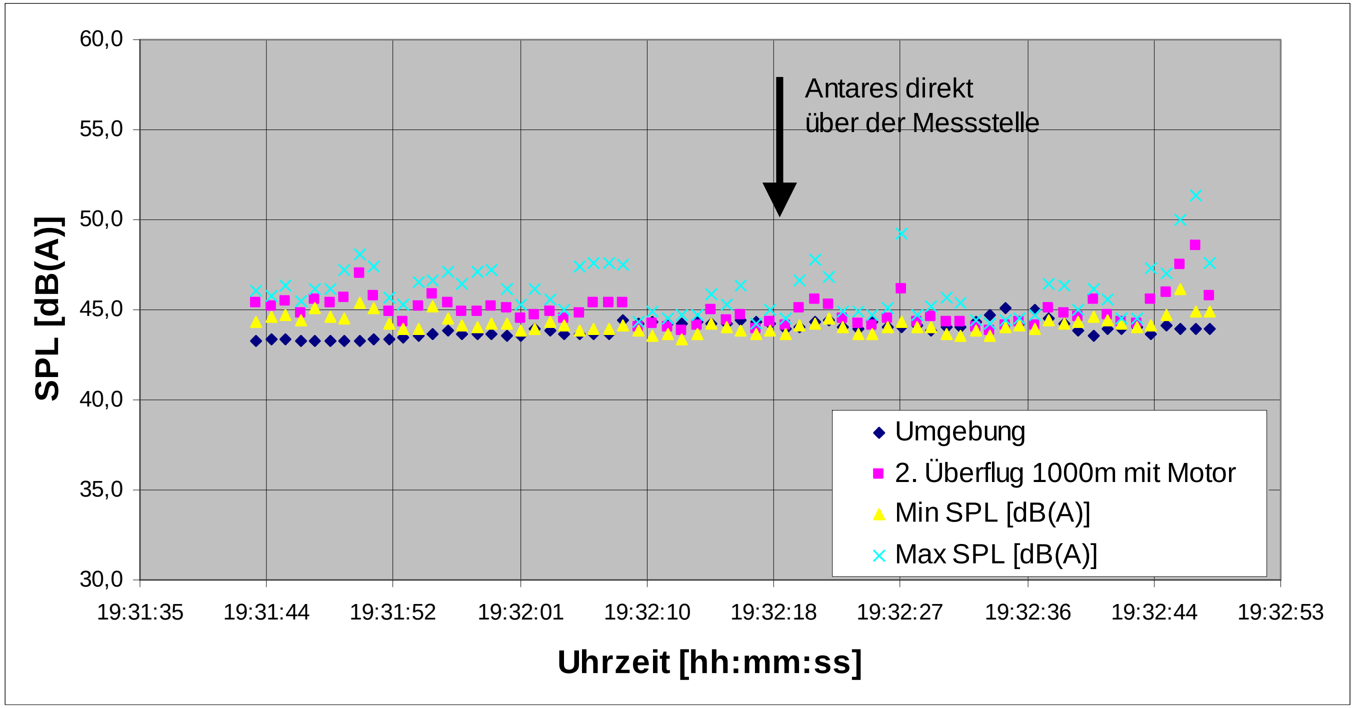
EASA – Permit to fly
nach CS 23

Systemeffizienz >50%

Erstflug DLR-H2 (25.05.2009)

Lärmemission DLR-H2

- Messung in Anlehnung an ICAO Annex 16 Vol.1



→ **Geringe bis keine Lärmwahrnehmung im Überflug**

Langstreckenversuch DLR- H2

Gesamt: 11 Stunden 42 Minuten, 1483,9 km

Hof - Stuttgart

2 Stunden 18 Minuten

295,5 km

ca. 2,2kg Wasserstoff

Herbst 2015: DLR-H2 Projekt beendet

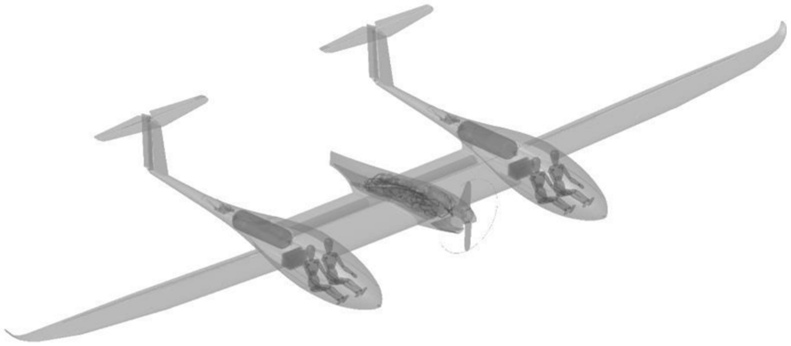
Wo ist die Grenze des Machbaren?

HY4 – Aircraft Integration overview

DLR · ulm university universität uulm · HYDROGENICS Advanced Hydrogen Solutions · Flughafen Stuttgart · H2FLY · PIPISTREL

General Aviation - Emission free passenger flight – HY4 as AIRTAXI

Emission free hydrogen fuel cell plane



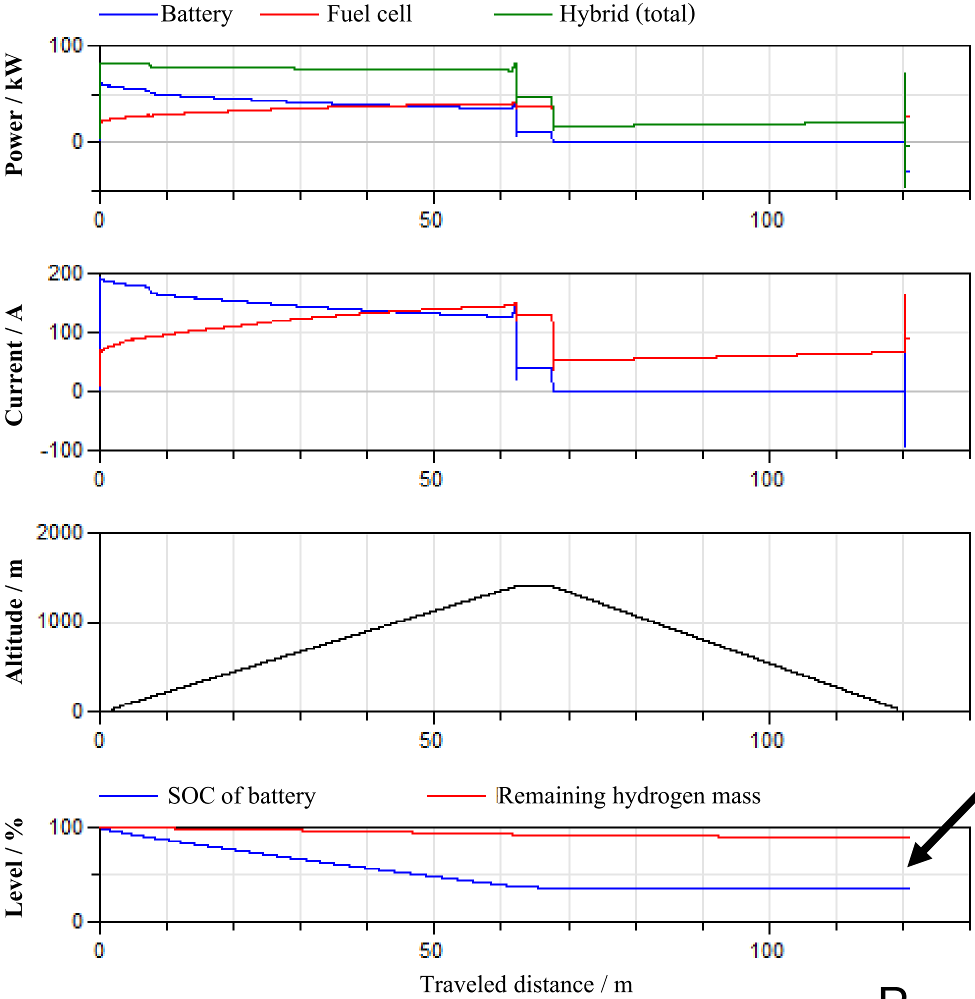
Cruising altitude	10000 ft (3000 m)
Cruising speed	140 km/h -200 km/h
Range	***750-1500km***
Souls on board	4
Maximum weight	1500 kg
Net weight	approx. 1100 kg
Engine power	80 kW (120 kW)
Fuel cell power	45 kW
Battery power	45 kW (80 kW)
Battery capacity	21 kWh@75 A
Hydrogen storage	300 kWh
Wingspan	21.36 m
Length	7.4 m

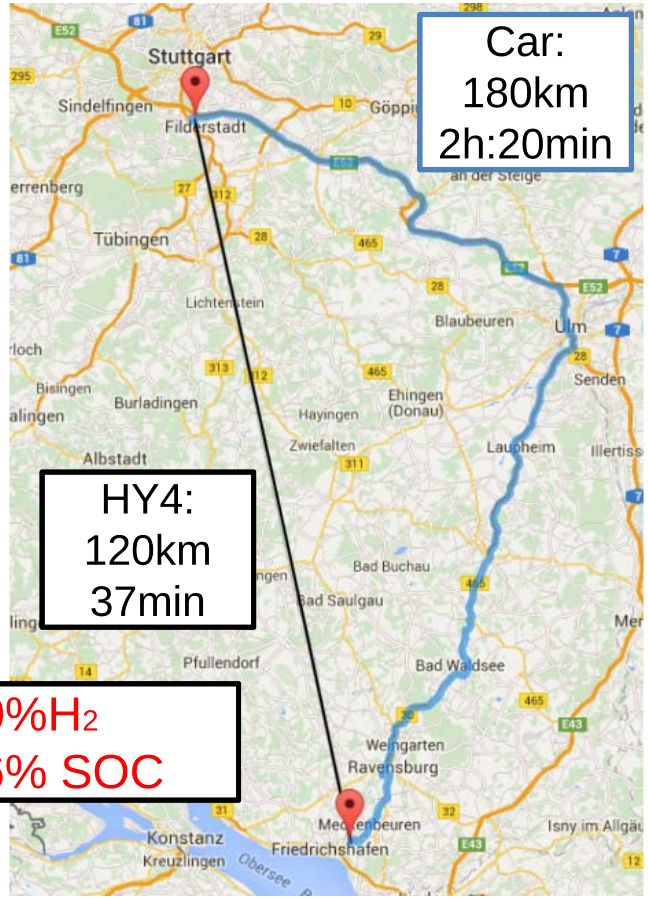
Show feasibility, demonstrate key features

DLR ulm university universität uulm HYDROGENICS Advanced Hydrogen Solutions Flughafen Stuttgart H2FLY PIPISTREL

Flight Friedrichshafen-Stuttgart

Simulation of a flight with 200km/h airspeed



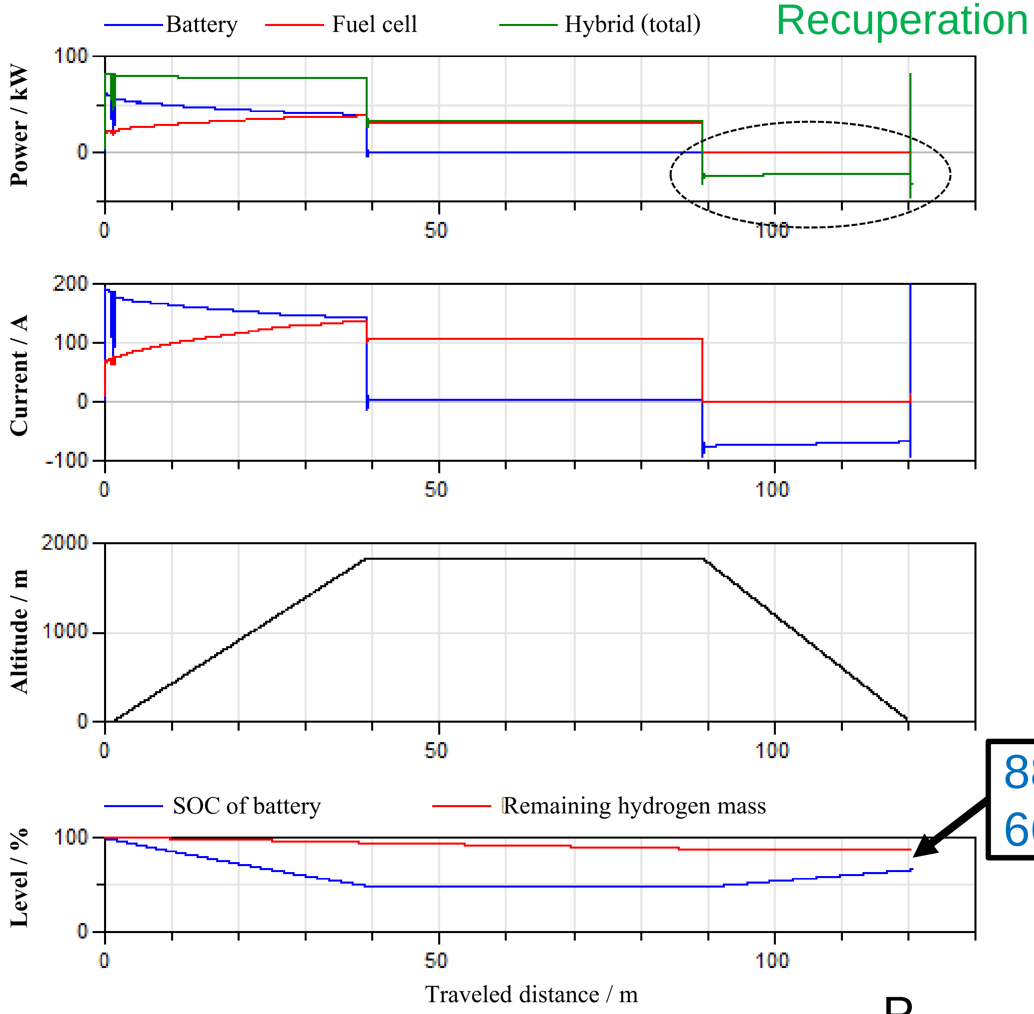


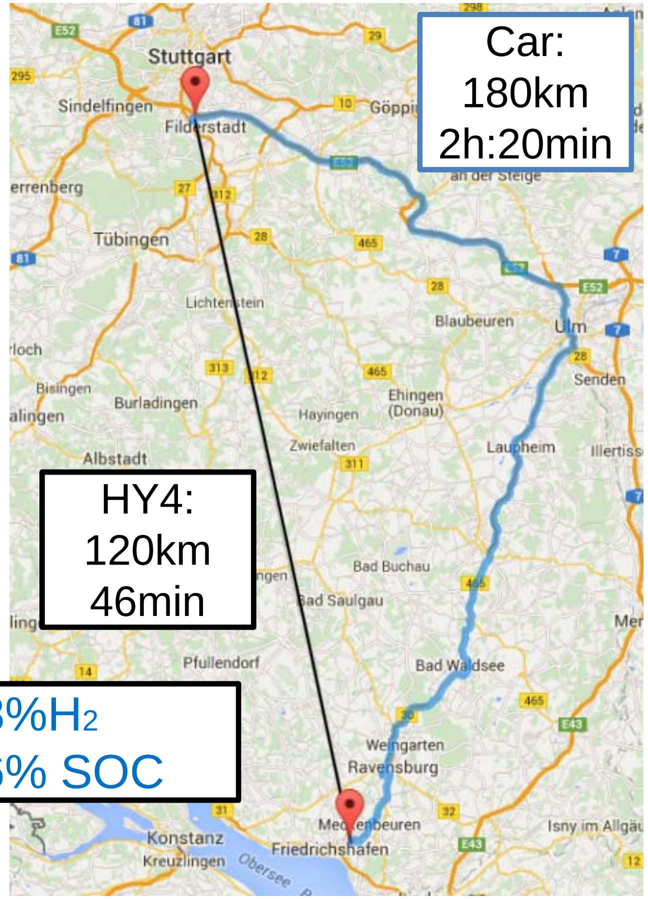
Source: Google Maps

$P_{drivetrain}$ approx. 48kW

Flight Friedrichshafen-Stuttgart

Simulation of a flight with 160km/h airspeed





Source: Google Maps

$P_{drivetrain}$ approx. 37kW

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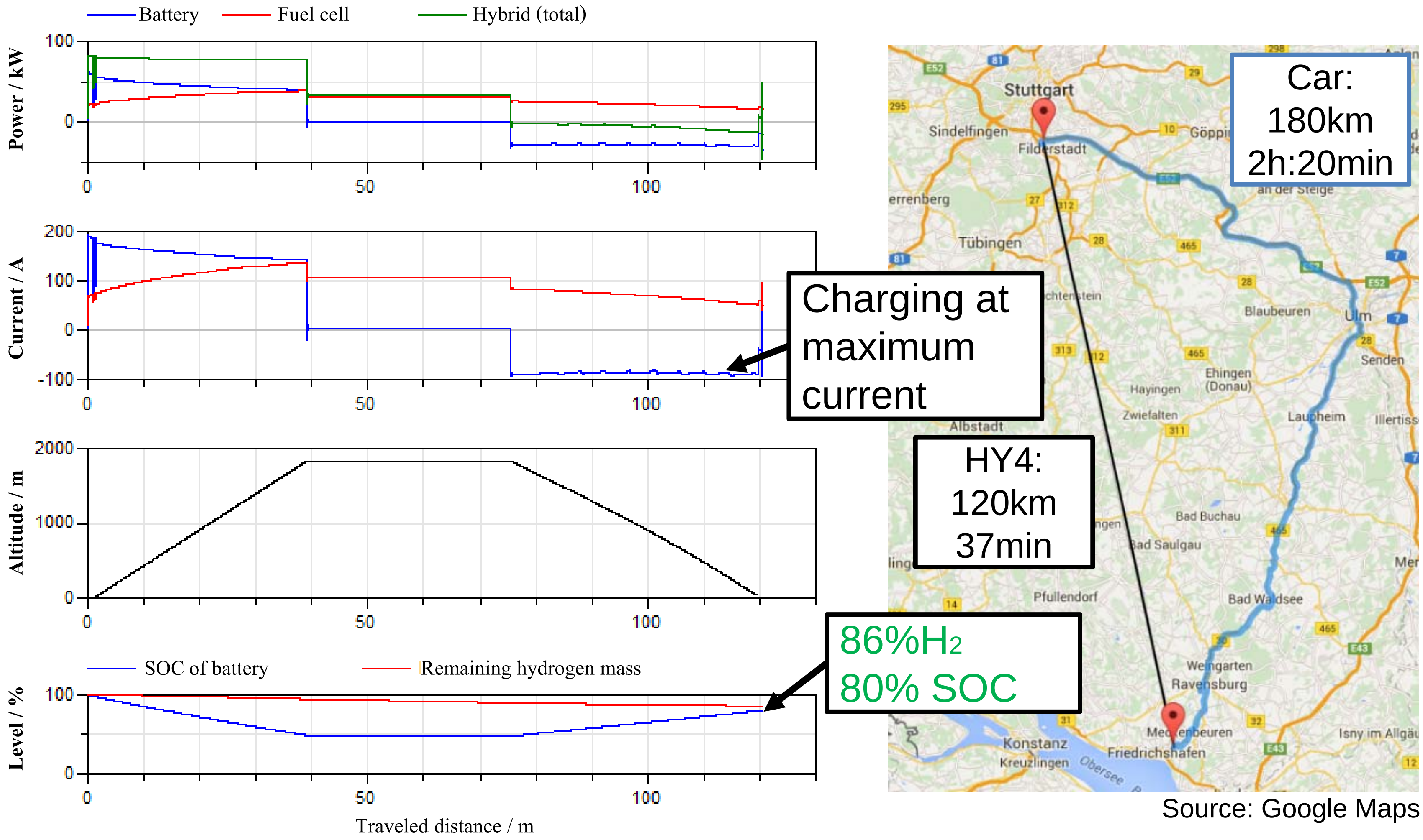
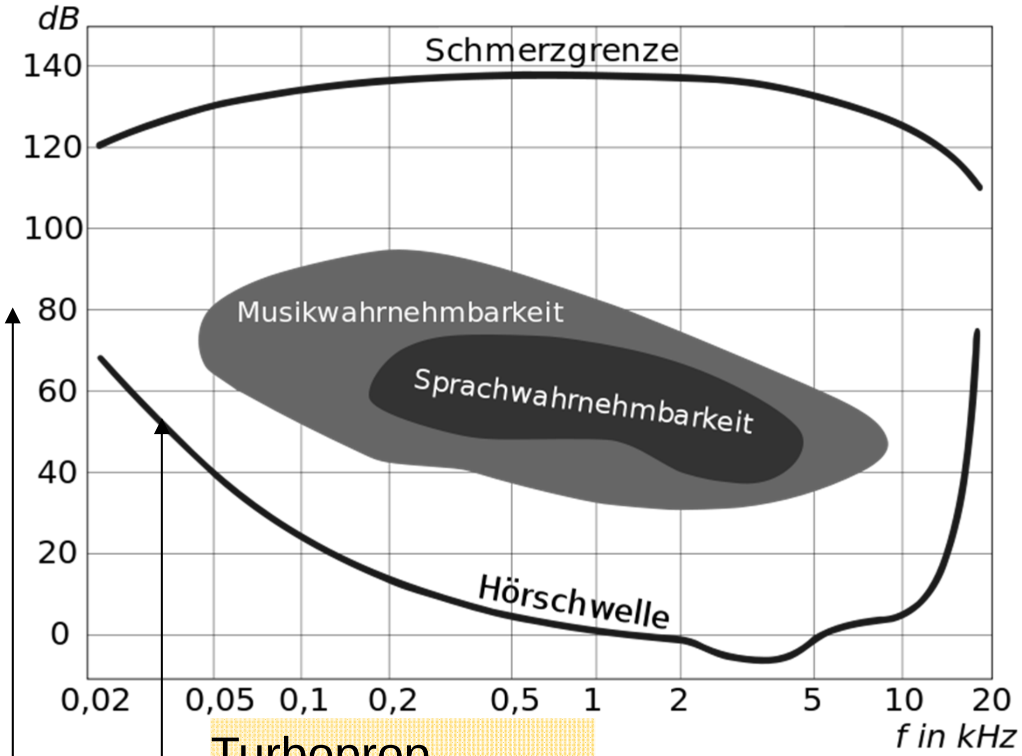
Flight Friedrichshafen-Stuttgart

Recharge battery from the fuel cells, 200km/h (including DC/DC Boost)



Source: Google Maps

Noise perception on electric propulsion for aircraft application



Turboprop

Noise production frequency for 2016 HY4

Noise production frequency for 2017 HY4

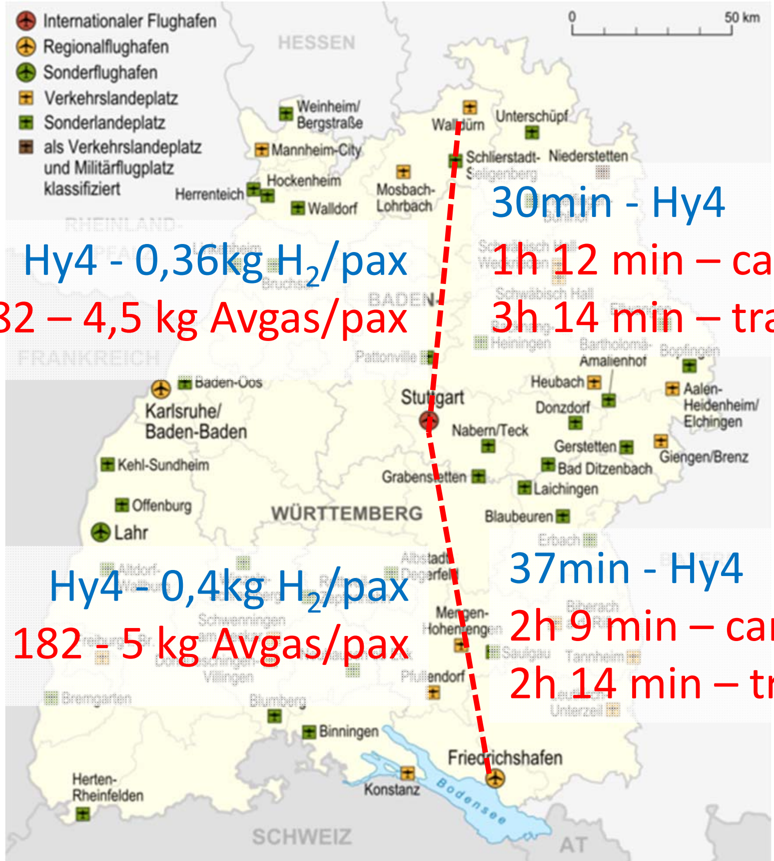
- Noise level perception better due to low frequencies

→ High torque electric motors require ***low rpm propeller*** at high speed!

DLR

Go4H2– Airtaxi Motivation, Potential

- **Demand:** Regional air traffic (60 Airports in BW,
  aprox. 300 in Germany and 1200 in Europe)



Example routes:

Walldürrn – Stuttgart Airport

Friedrichshafen – Stuttgart Airport

Go4H2 – Airtaxi Motivation, Potential, Infrastructure

- **Demand:** Regional air traffic (60 major airports in Germany,
  aprox. 300 adequate airfields in Germany and 1200 in Europe)

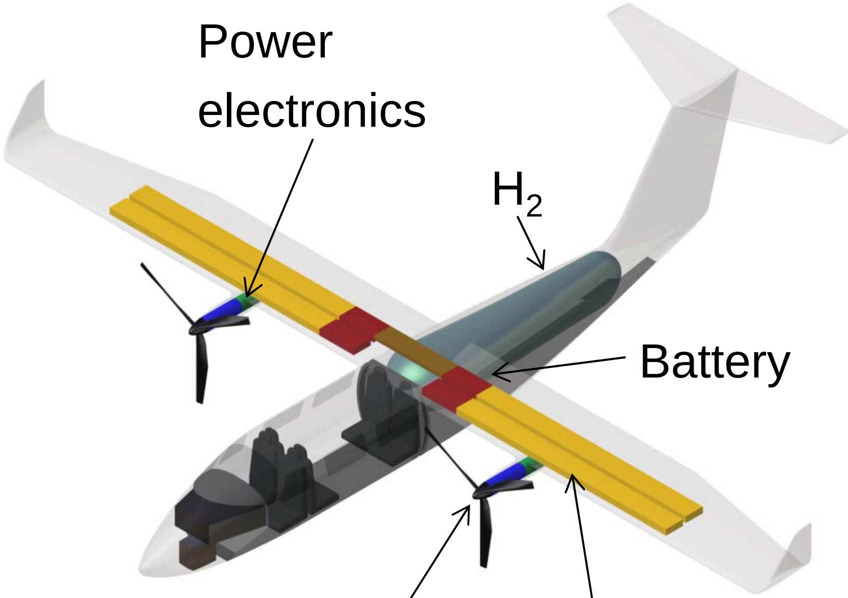
- Small investment for initial hydrogen infrastructure expected
- Synergies with automotive refueling stations should be used

- Technology development for worldwide market!

ACARE Goals:

4 hour „door to door“ inside Europe

Build up schematics and boundary conditions 6 seater FC-Hybrid



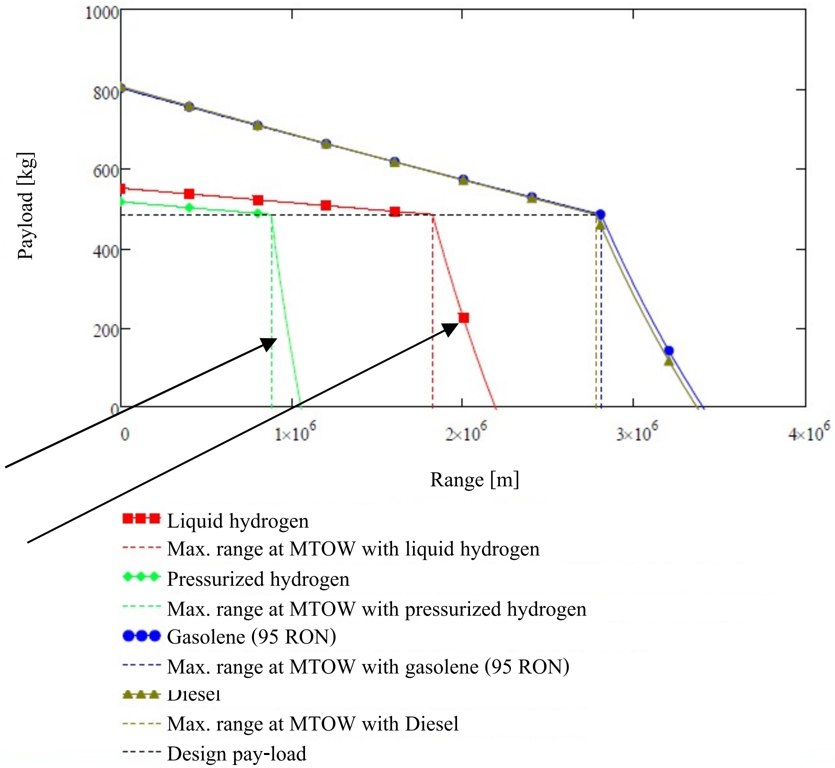
Parameter	Symbol	Größe
Abrissgeschwindigkeit	v_{S0}	$61kts/113\frac{km}{h}/31.4\frac{m}{s}$
Landestrecke	l_{Lande}	$600m$
Startstrecke	l_{Start}	$700m$
Steigrate	v_{Steig}	$984.3\frac{ft}{min}/5\frac{m}{s}$
Reisegeschwindigkeit	v_{Reise}	$148.5kts/275\frac{km}{h}/76.4\frac{m}{s}$

Tabelle 5.1.: Vorgegebene Mindestflugleistungen

Compact integration architecture with high redundancy

Vision: 6 seat fuel cell powered aircraft (DLR-TT+IFB Stuttgart)

Goal: Intermediate, financial atractive demonstration platform



-1000km range with pressurized hydrogen

-2000km range with liquid hydrogen

Felix Frey IFB, Josef Kallo DLR 2014

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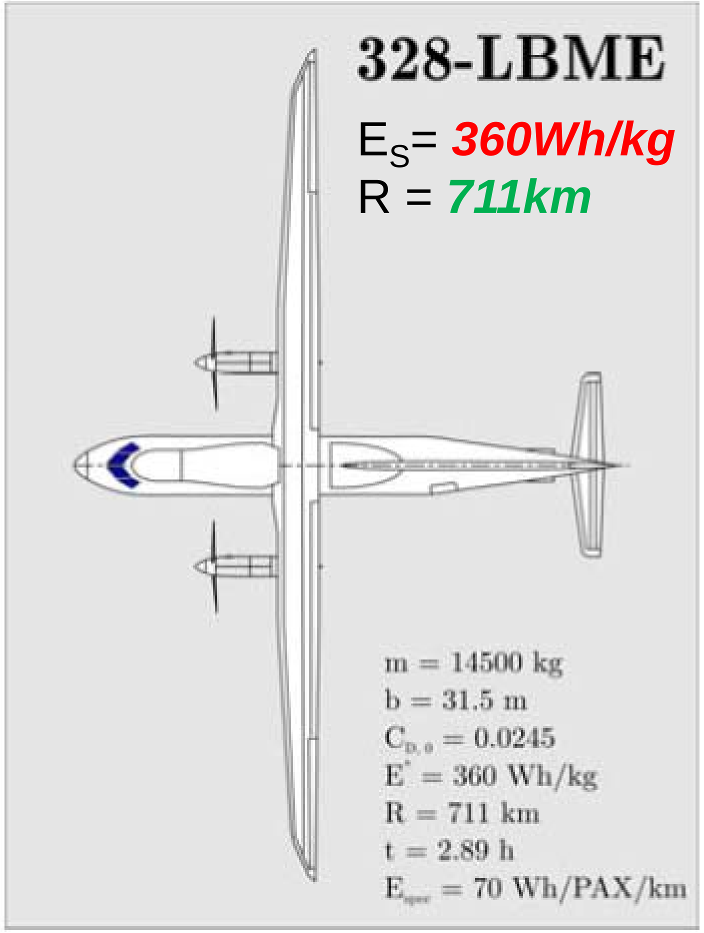
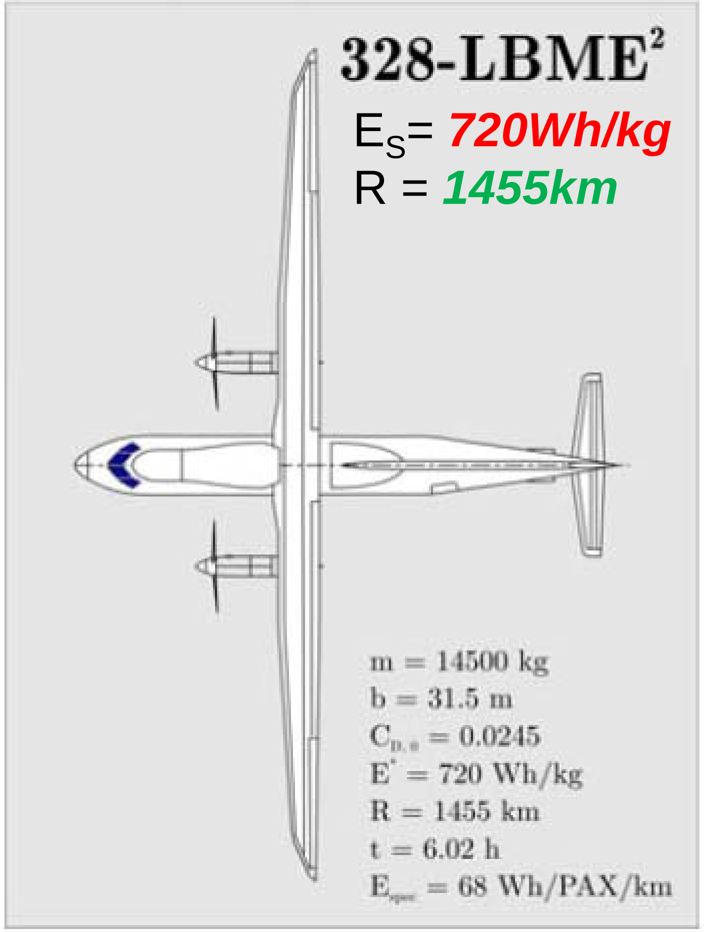
Electric plane study (M. Hepperle, DLR, 2012-2014)

28 seater





Vision: electric, emission-free flight
Passenger airplane (up to 40 Seats) FC+Battery+H2

Felix Frey, Josef Kallo 2015

Study is focused on

- Propulsion power,
- Weight distribution,
- Flight stability
- Aspects of integration

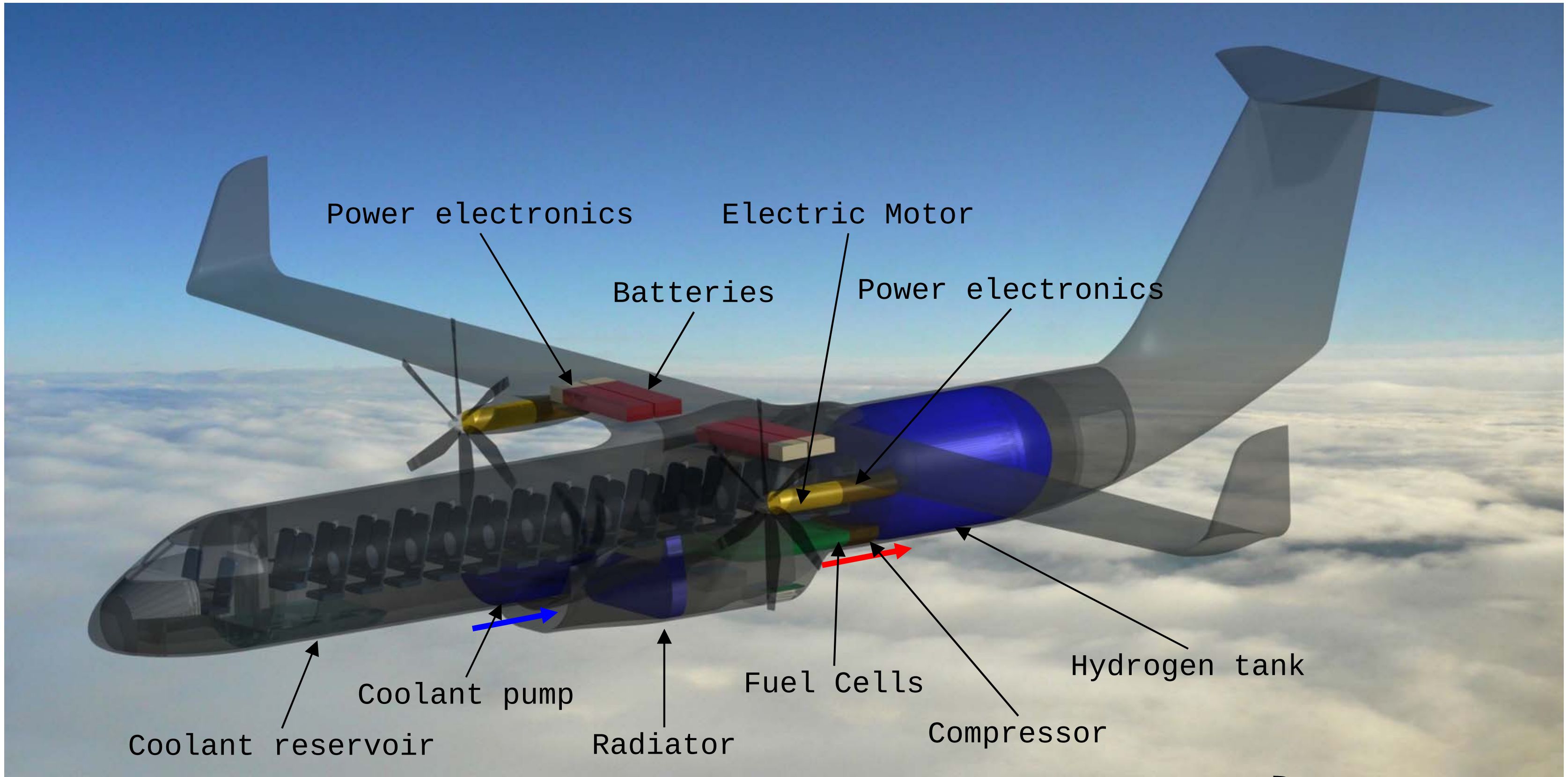
Rather on component integration and thermal managment, not on aerodynamic optimization! Further optimization of aircraft concept can be expected.

- 40 seat regional aircraft
- > 2 MW – combined hybrid propulsion power
- approx. 1.3 MW cruise
- 230-280kts
- 400-1000km range feasible

Goal: show feasibility: emission free flight is possible

Outline of an 40 seater regional aircraft with fuel cell propulsion system

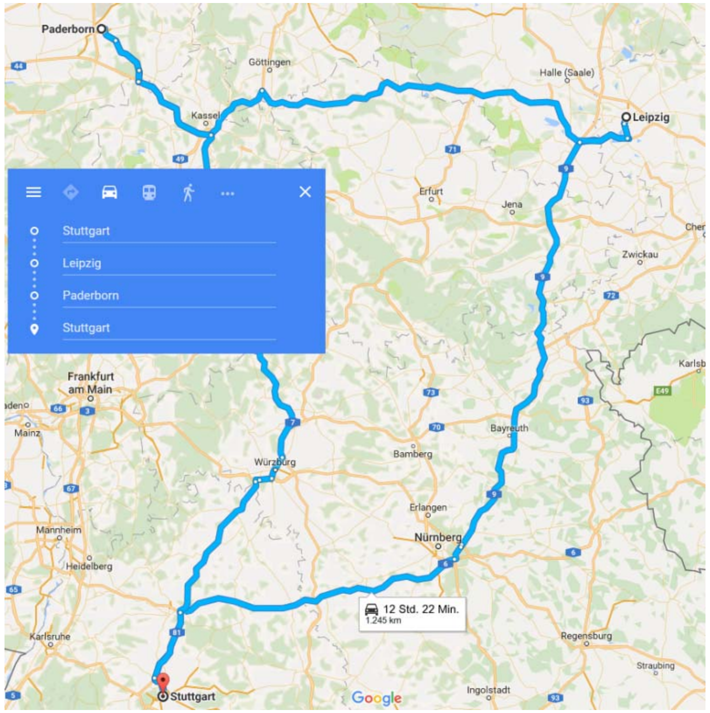
Felix Frey, Josef Kallo 2015



Fuel cell modules with 4 parallel strings, total power >1,3 MW_{el}
Fuel cell module string voltage ca. 900V

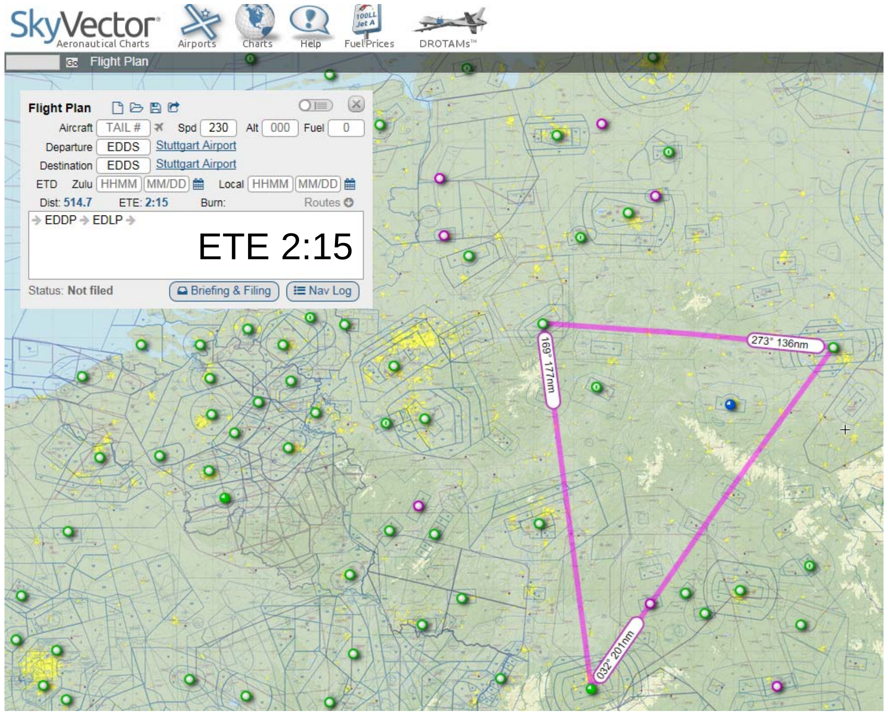
Thermal management crucial !

Electric regional aircraft scenario



Stuttgart – Leipzig – Paderborn – Stuttgart

ca. 1245 km round trip → 12h:22 min

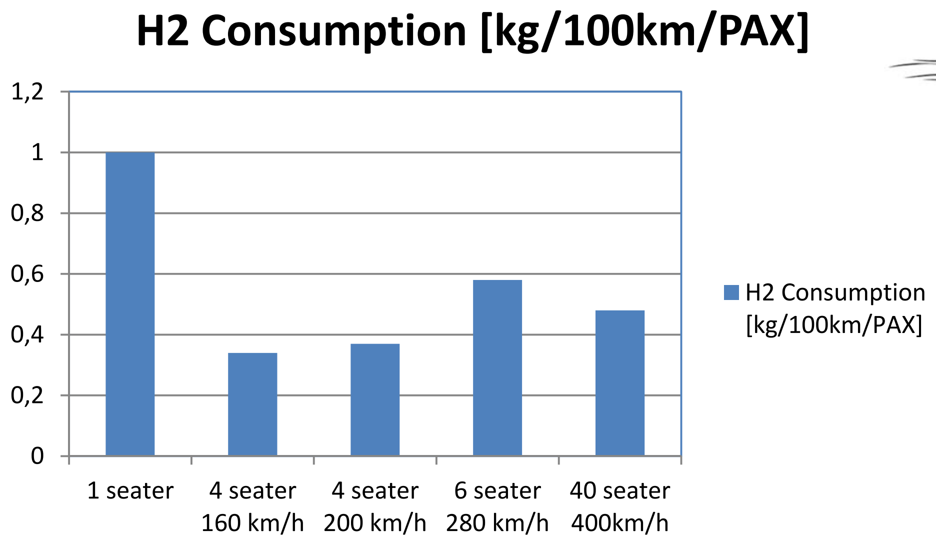


Stuttgart – Leipzig – Paderborn – Stuttgart

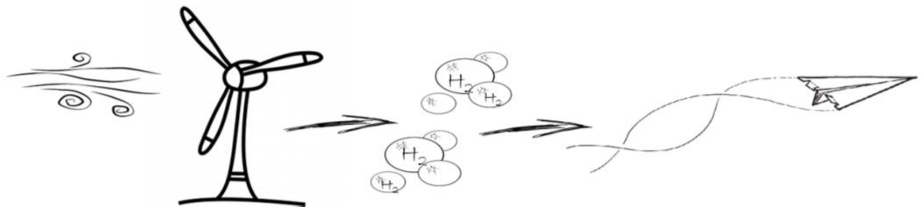
ca. 920 km round trip 2:15

(including takeoff and descent ca. 3:00 in plane)

Hydrogen consumption and fuel cost



→ Taking advantage of speed and seat capacity



EE- Hydrogen aprox. 5-7Euro/kg

Conventional Hydrogen produced by Methane processing → 2-4 Euro/kg

Energy amount used in Germany for kerosene fuels 2013

- 2013 – overall kerosene and equivalent energy amount used in Germany:

8,8 Mio. tons*

eq.

377 PJ (at 42,8MJ/kg) **

eq.

105 TWh

** http://www.mwv.de/index.php/daten/statistikeninfoportal*

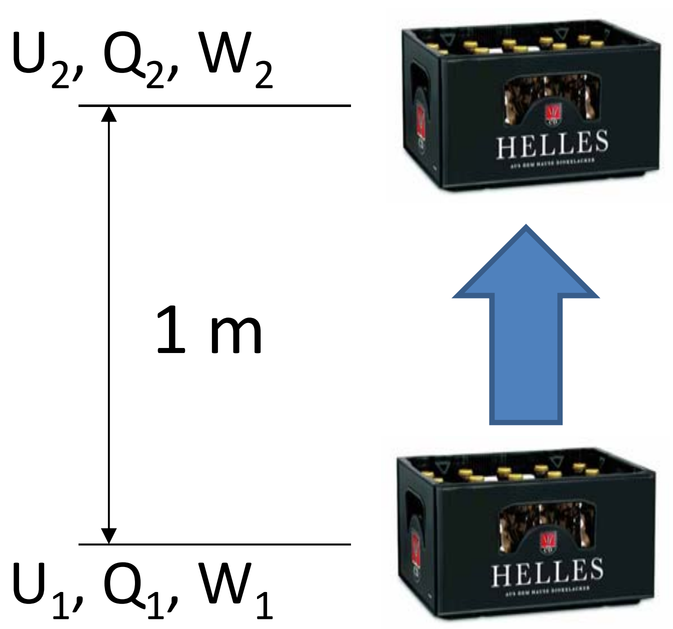
*** http://www.exxonmobil.com/AviationGlobal/Files/WorldJetFuelSpec2008_1.pdf*

Expected residual energy amount in Germany 2030 from renewable energy converters

- Based on the 2013 BEE e.V. paper a cumulative ***34,5 TWh/a*** surplus energy amount from renewables is expected in 2030 (total renewable electrical energy prospected in 2030 ca. 450TWh/a)

Energiewandlung

- Beispiele für Innere Energie und Arbeit
  - Potentielle Energie



$$\Delta U_{1\rightarrow 2} = \Delta Q_{1\rightarrow 2} + \Delta W_{1\rightarrow 2}$$

Innere Energie — Wärme — Mechanische Arbeit

Bierkisteneinheit (BKE) =

m(19,7kg) * g(9,81m/s2) * h(1m) = **193 Joule**

Ca. 2 900 000 BKE Stuttgart nach Berlin

Ca. 53 000 000 000 000 000 BKE Weltweit für Luftfahrt

Zusammenfassung elektrisches Fliegen mit H_2

HY4 - AIR TAXI Konzept technologisch realisiert

E6 – Konzept technologisch realisierbar

E40 – Konzept technologisch realisierbar jedoch finanzielle Herausforderungen

Stellenausschreibungen HY4 – Universität Ulm

Am **Institut für Energiewandlung und –speicherung** der Universität Ulm ist zum **nächstmöglichen Zeitpunkt** eine Stelle als

Akademischer Mitarbeiter/Akademische Mitarbeiterin/Postdoc (100% - Stelle)

befristet für zunächst 3 Jahre zu besetzen. Eine Verlängerung um weitere 2 Jahre ist ggf. möglich. Die Möglichkeit zur **Promotion** ist gegeben.

Die Hauptaufgaben umfassen Forschung und Lehre im Fach der elektrischen Energietechnik. Der Forschungsschwerpunkt liegt im Gebiet „Effiziente Leistungselektronik für die Elektromobilität“. Hierzu sollen in einem ersten Schritt für das elektrisch angetriebene Brennstoffzellenflugzeug „HY4“ leistungselektronische Konzepte für die Hybridisierung und Motoransteuerung entwickelt und validiert werden.

3 Stellen Wissenschaftlicher Mitarbeiter/Promotion/Postdoc
3 + 2 Jahre
Leistungselektronik, Hybridisierung, elektrische Antriebe

Kontakt: josef.kallo@uni-ulm.de oder josef.kallo@dlr.de

Danke für Ihre Aufmerksamkeit!