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IPEMC 2024 Chengdu, China | May 17-20 ECCE ASIA

e-VTOL Aircraft
The Future of Urban Air Mobility

Johann W. Kolar et al.

Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
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The Future of Urban Air Mobility

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Outline

- *Once Upon a Time ...*

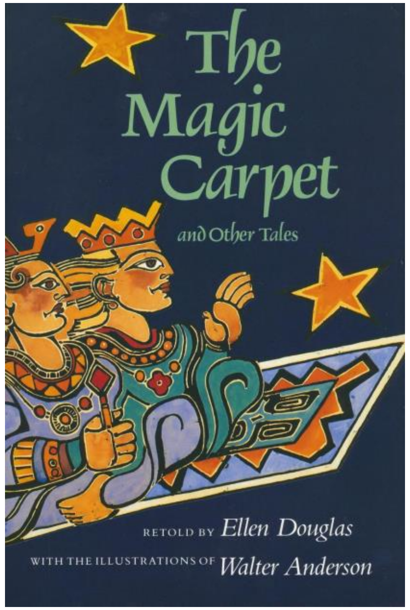
- *eVTOL Aircraft Concepts*
- *Energy / Power Sources*
- *El. Motor Technologies*
- *On-Board Power Electronics*
- *Ultra-Fast Battery Charging*

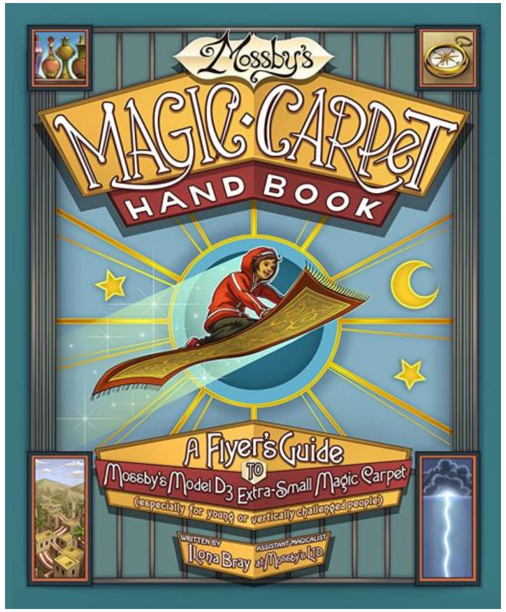
- *Sustainability*

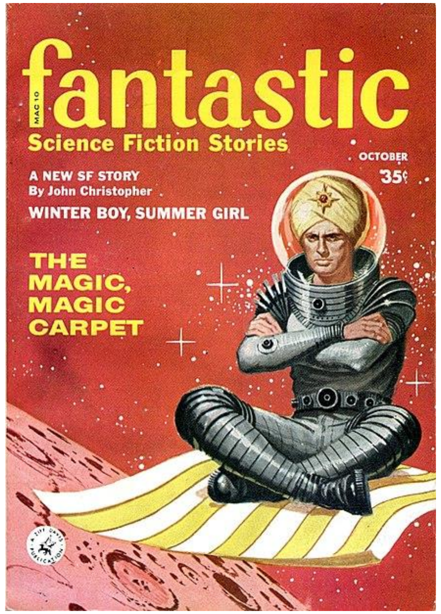
Acknowledgment
Martin Ulmer

Once Upon a Time ...

- "Magic Carpets" — Featured in the "1001 Nights" and Modern Literature
- Quietly and Swiftly / Instantaneously Carrying their Users to Desired Destinations







- Handbook on *How to Operate a Magic Carpet* for *"Young or Vertically Challenged People"*

Today´s Motivation

- 2015 — Typ. San Francisco Resident Spent 230 h / Year Commuting btw. Work & Home
- 500´000 Hours of Productivity Lost / Single Day

Source: http://billoodevelopment.com

- Use 3D-Airspace to Alleviate Transportation Congestion on the Ground — "Flying Cars"

Today´s Motivation

- 2015 — Typ. San Francisco Resident Spent 230 h / Year Commuting btw. Work & Home
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Source: https://www.youtube.com/watch?v=44bSw-wPW4c

- Use 3D-Airspace to Alleviate Transportation Congestion on the Ground — "Flying Cars"

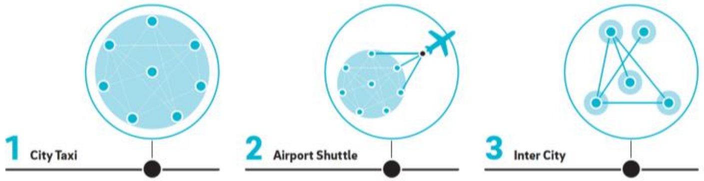
Urban Air Mobility

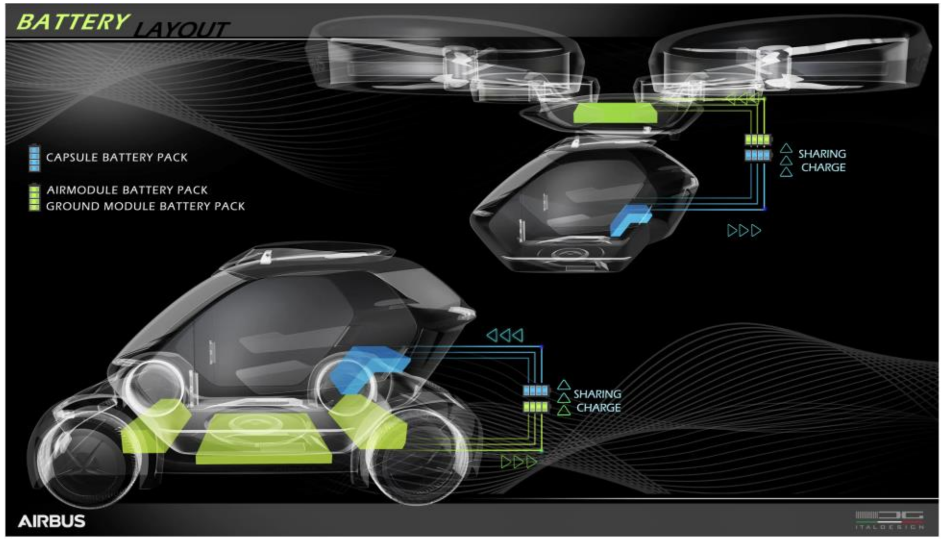
Operation Characteristic
eVTOL Aircraft Types

Urban Air Mobility (UAM)

- "On-Demand" UAM
- City Taxi / Intra-City / Inter-City Transport as Main Use Cases
- Distributed Electric Propulsion — Quiet / Efficient / Clean / Safe
- Vertical Take-Off & Landing (VTOL) Aircraft — "Vertiports" / No Runways

Source: Roland Berger 2020

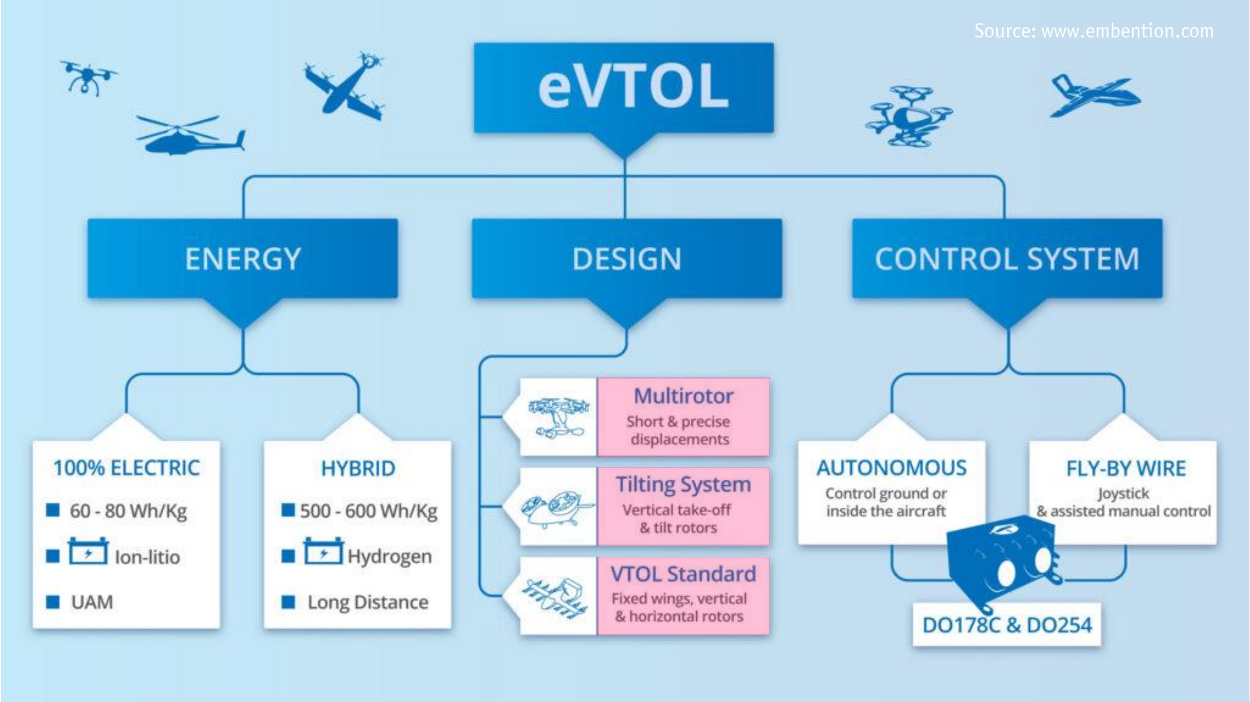




- "Pop.Up Next"— Modular All-Electric Drone — 4x2 Rotors | People-Pod | EV Chassis (Airbus & Audi until 2019)

Types of eVTOL Aircraft

- **Multicopter** — Wingless / Distributes Thrust to Fly / Short Distances
- **Lift-Thrust** — Wings / Independent Lift & Thrust Units / Low Complexity
- **Vectored Thrust** — Wings / Propulsion Units Rotate to Provide Lift & Thrust



eVTOL vs. Helicopter IDTechEx

- 15dB Lower Noise
- Maintenance $ 110,-/Hour (25%)
- OPEX $ 35...70,-/Hour (20%)
- Zero Emissions
- Future Full Automation — No Pilot
- Catastr. Failure $1/10^9$ Hours (10^{-4})
- Small Take-Off/Lndg Footprint

- **All-Electric Energy Supply** — Battery or Hybrid Battery/Fuel-Cell Combination

eVTOL Aircraft Concepts (1)

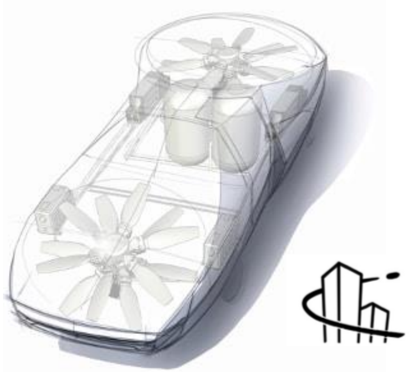
- Volocopter (Germany) — VoloCity
- 18 El. Rotors | Vert. Lift & Hover Flight | 900 kg Max. Take-Off Weight
- 2 Passengers | 110 km/h Cruise Speed | 36 km Range

VOLOCOPTER

- EASA Certification Process On-Going (Target: 2024)
- Freight-Carrying *VoloDrone* Announced

eVTOL Aircraft Concepts (2)

- Metro Skyways (former Urban Aeronautics Ltd., Israel) — CityHawk
- 2 Slow-Turing Ducted Fans | Vert. Lift & Horiz. Flight | 2000 kg Max. Take-Off Weight
- 4 Passengers | 280 km/h Cruise Speed | 280 km Range



METRO SKYWAYS

- Initially Powered with Fossil Fuel | Transition to Fuel-Cell Power Supply
- Small Operating Space | Intended for Urban Areas / In Service 2028 - 2030

eVTOL Aircraft Concepts (3)

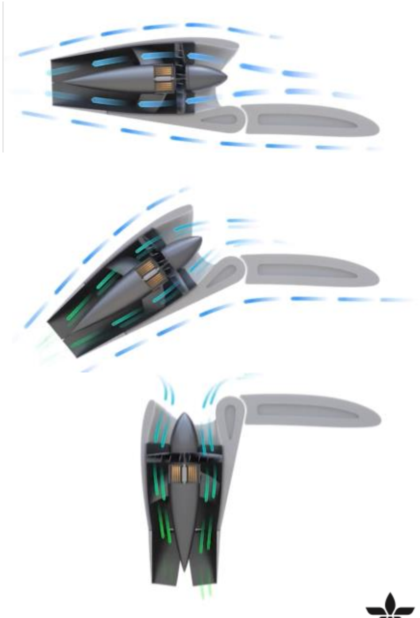
- Joby Aviation (USA) — Joby S4 2.0
- 6 Tilt-Propellers | Vert. Lift & Horiz. Flight | 2200 kg Max. Take-Off Weight
- 4 Passengers | 320 km/h Cruise Speed | 240 km Range

JOBY AVIATION

- *Uber Elevate* Acquired by Joby Aviation in 2020 / Commercial Operation Planned for 2024
- Battery Powered | Range Extension w/ Hybrid Fuel-Cell/Battery Architecture Announced

eVTOL Aircraft Concepts (4)

- Lilium (Germany) — Lilium Jet
- 36 Ducted El. Fans | Vectored Thrust — Vert. Lift & Horiz. Flight | 3100 kg Max. Take-Off Weight
- 6 Passengers | 280 km/h Cruise Speed | 250 km Range



LILIUM

- Partnership w/ Lufthansa Aviation / Commercial Operation Planned for 2025
- Extreme Requirements on Battery Technology / 320 kW Total Propulsion Power (Horiz. Flight)

eVTOL Aircraft Concepts (5)

- Skydrive Inc. (Japan) — SkyDrive SD-03
- 4x2 El. Rotors | Vert. Lift & Hover Flight | 400 kg Max. Take-Off Weight
- 1 Passenger | 50 km/h Cruise Speed | < 10 km Range

SKYDRIVE

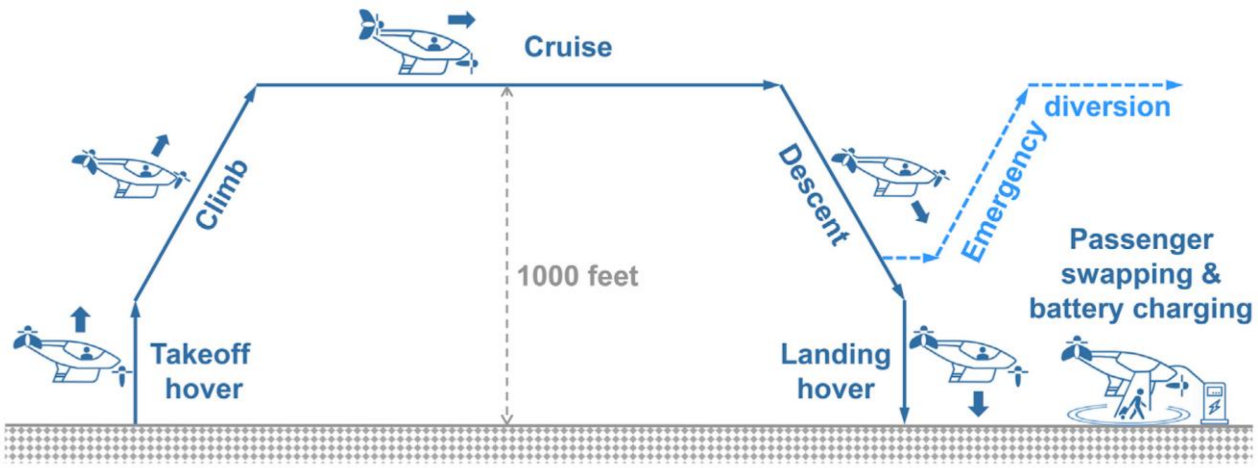
- Successful Manned Test Flight in 2020 / Type Certification Planned for 2025
- Mass Production of 30 kg Payload Cargo Drones Planned

eVTOL Mission Profile

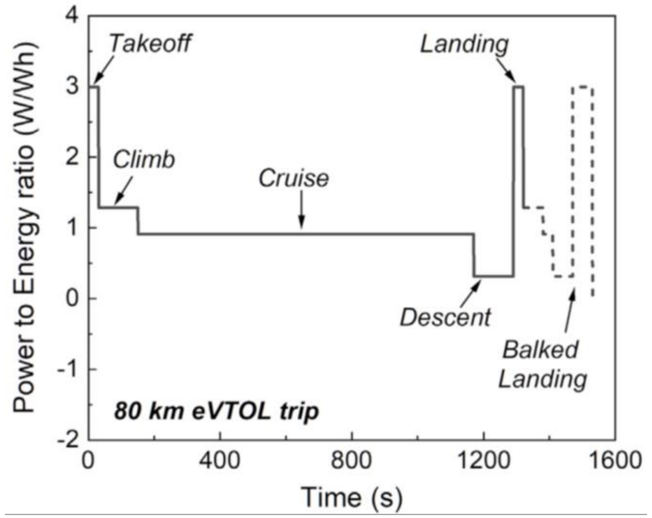
Operational Requirements
Power / Energy Sources

Urban Air Mobility — Mission Profile

- *Multirotor eVTOL* — Large Disk Actuator → Low Disk Loading σ → High Eff. Hover / Low L|D → Low Cruise Eff.
- *Vectored Thrust eVTOL* — Wings → High L|D → Eff. Cruise / Low Hover Efficiency



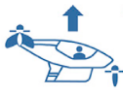
L|D ... Lift-to-Drag Ratio



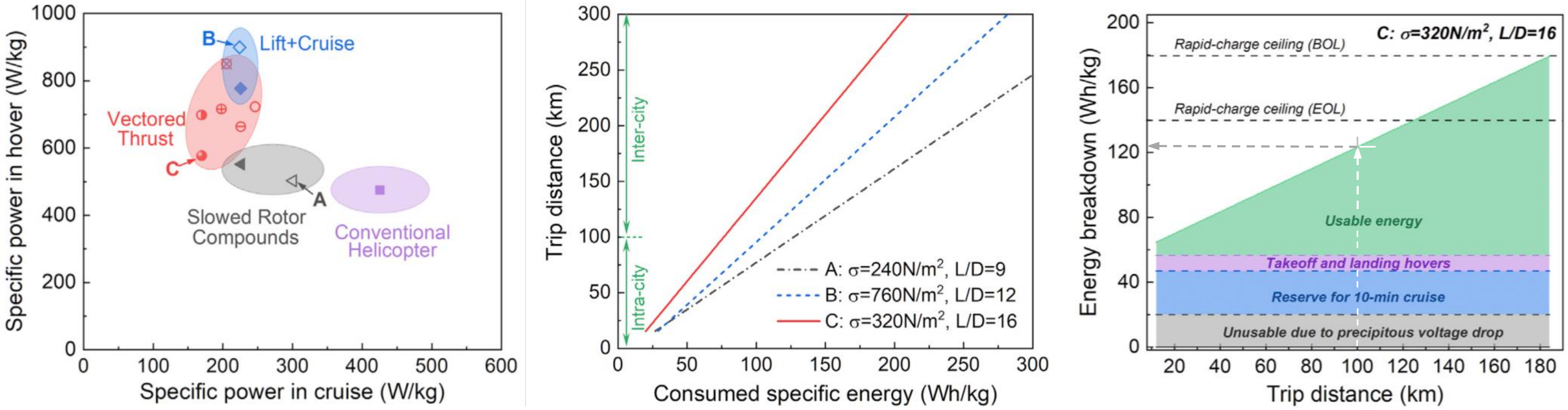
- Large Range — High Spec. Energy Battery
- High Payload — High Spec. Power / High C-Rate Battery
- High Vehicle Utiliz. | Low Batt. $$$ / Small Batt. — Fast High-Power Charging / High C-Rate / High # Cycles

Battery — Operational Requirements

- ***Multirotor eVTOL*** **— Large Disk Actuator → Low Disk Loading σ → High Eff. Hover / Low L|D → Low Cruise Eff.**
- ***Vectored Thrust eVTOL*** **— Wings → High L|D → Eff. Cruise / Low Hover Efficiency**



$$R_{trip} = SE_{trip}\frac{L}{D}\frac{\eta_c}{g}\omega_{bat}$$



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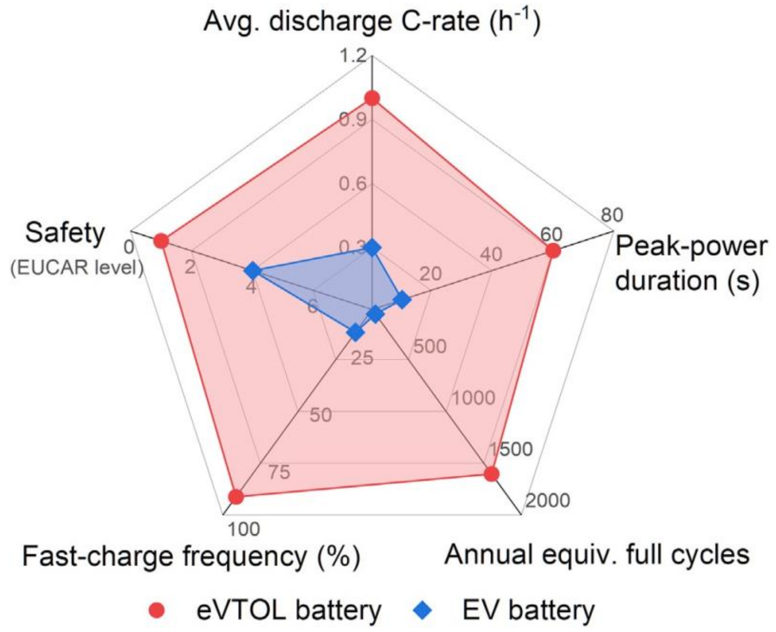
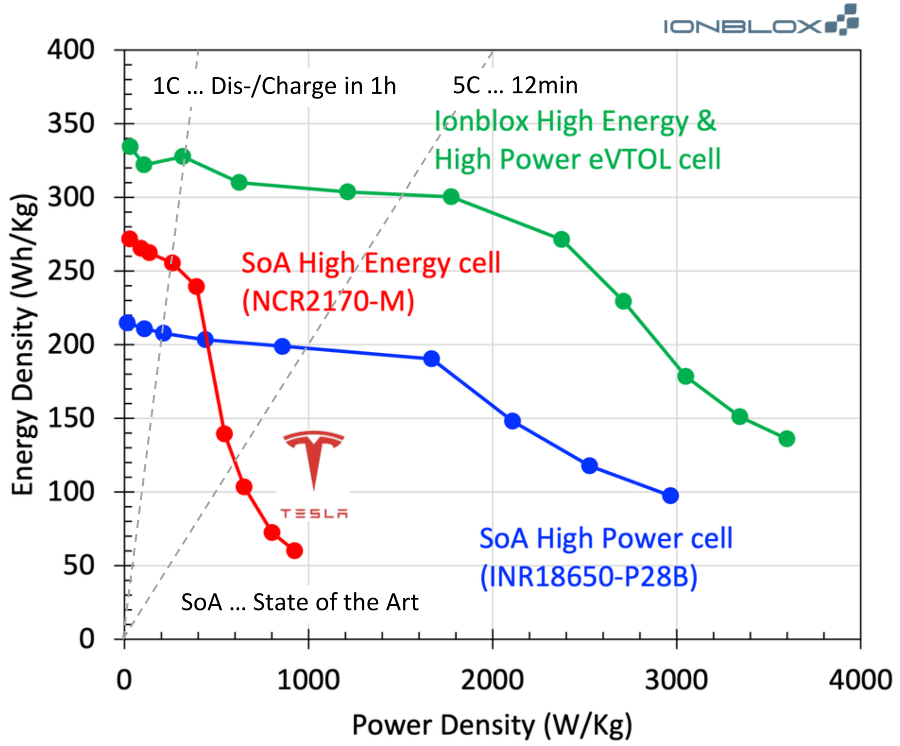
- **High Payload — High Spec. Power / High C-Rate Battery**
- **High Vehicle Utiliz. | Low Batt. $$$ / Small Batt. — Fast High-Power Charging / High C-Rate / High # Cycles**

$$t_{char} = \frac{SE_{trip}}{SP_{char}} = \frac{R_{trip}}{SP_{char}}\frac{g}{\eta_c \omega_{bat} L/D}$$

Battery Technology

- The "AND"-Challenge — High Specific Power & High Spec. Energy & High C-Rate & High Cycle Life
- Technology Interrelationships btw. Spec. Power / Spec. Energy / C-Rate (typ. 5C) / Cycle Life (typ. >2000)
- Battery Pack Wh/kg — typ. 80...90% of Cell





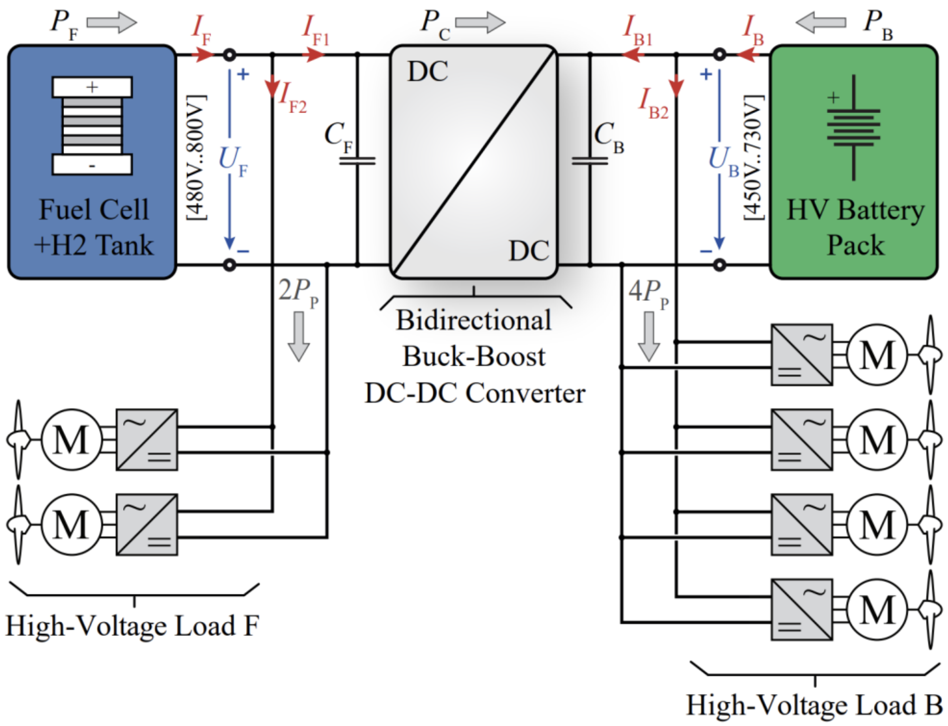
- Energy/Power Density Affects Payload & Range — Far Higher Requirements Compared to EV
- H_2 Fuel-Cells — typ. 500...1500 Wh/kg | 400...600 W/kg - Dependent on Payload & Range

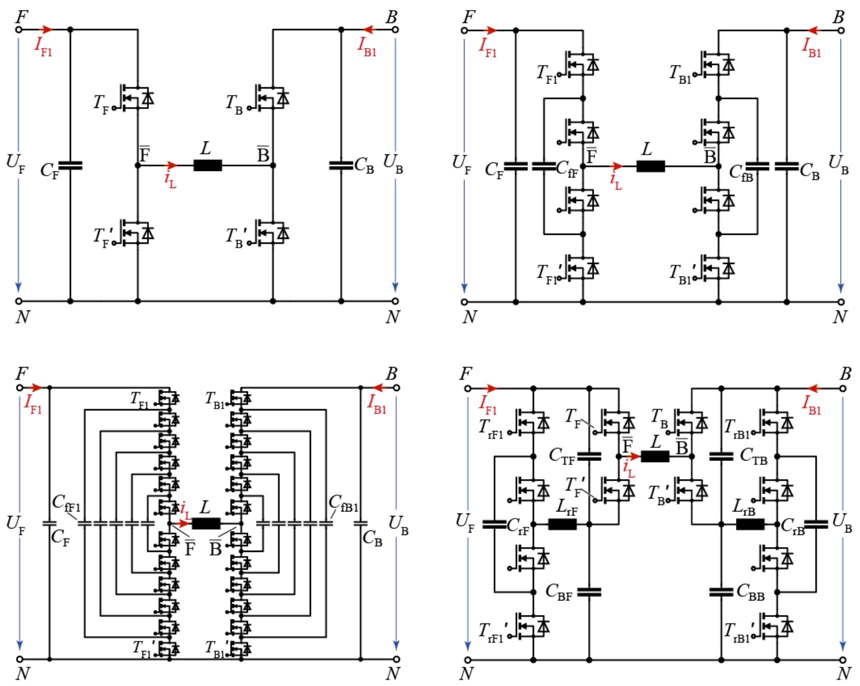
Ultra-Light Weight Power Electronics

Electric Power System
Buck-Boost DC/DC Conversion

Fuel-Cell/Battery Power Electronics Interface

- Overlapping Input / Output Voltage Ranges — Buck-Boost DC/DC Converter
- Design Example — Modular 150 kW System — 15 kW Module | U_{FC} = 480…800V | U_{Batt} = 450…720V

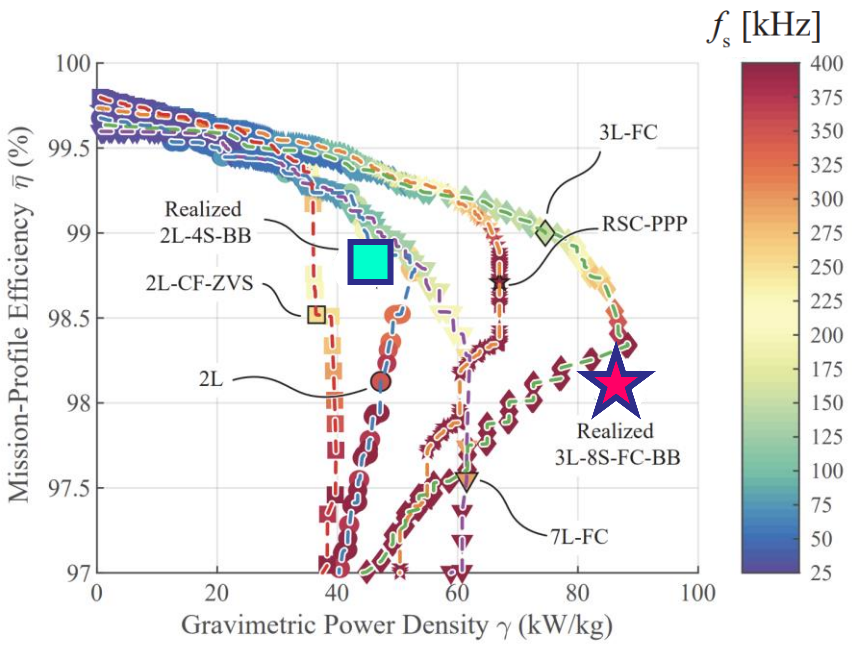


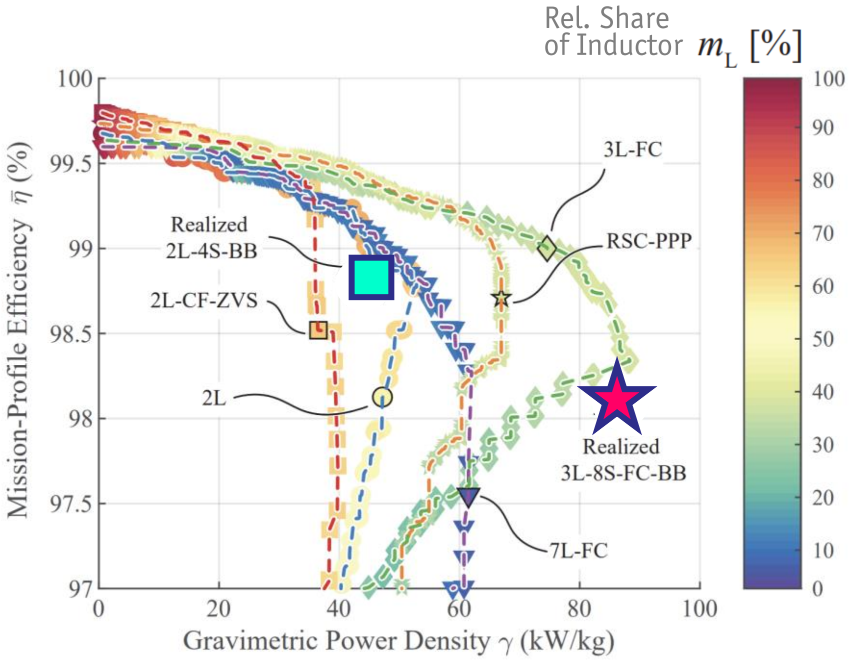


- Multi-Objective Comparative Analysis — 2-Level (ZVS) | Multi-Level | Partial Power Processing Topology

Fuel-Cell/Battery Power Electronics Interface

- Overlapping Input / Output Voltage Ranges — Buck-Boost DC/DC Converter
- Module — 15 kW | U_{FC} = 480...800 V | U_{Batt} = 450...720 V | T_C = 80°C, T_j < 150°C

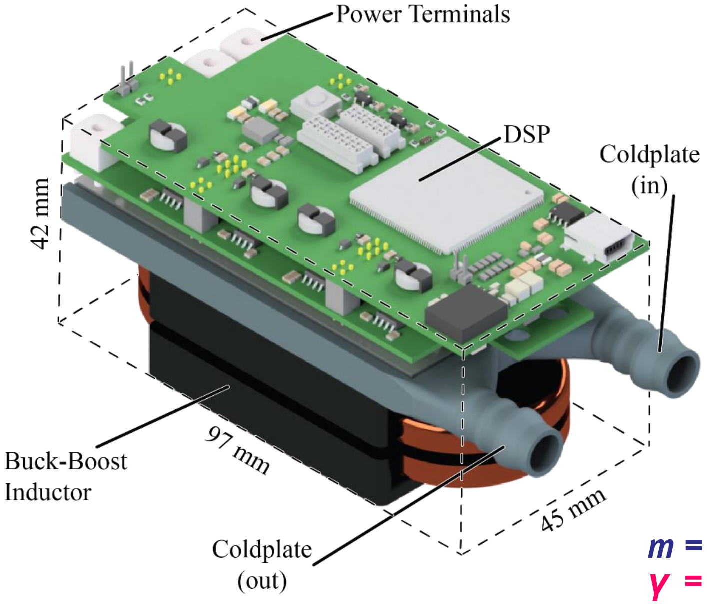




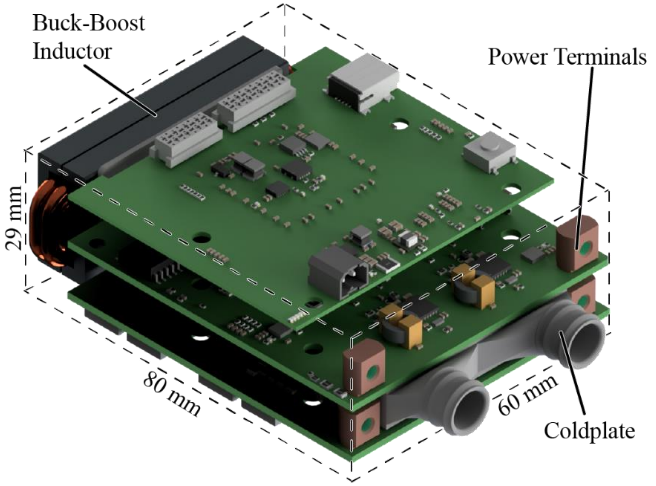
- Multi-Objective Comp. Analysis — 2-Level (SiC) f_{sw} = 275 kHz | 3-Level (GaN) f_{sw} = 400 kHz ($f_{sw,eff}$ = 800 kHz)
- Mission Efficiency — 50% Climbing / 50% Cruising / No Fuel-Cell Power During Descent – DC/DC Conv. Off
- System Considerations — Battery & Fuel-Cell Weight vs. Converter Weight – Adv. of High Eff. Converter

Comparative Evaluation — *2L vs. 3L Converter*

- Overlapping Input / Output Voltage Ranges — Buck-Boost DC/DC Converter
- Module — 15 kW | U_{FC} = 480...800 V | U_{Batt} = 450...720 V



2x



2-Level Converter

m = 346 g
γ = 44 kW/kg
ρ = 82 kW/dm³ → ρ = 82 kW/dm^3
η = 98.8 % (Mission)

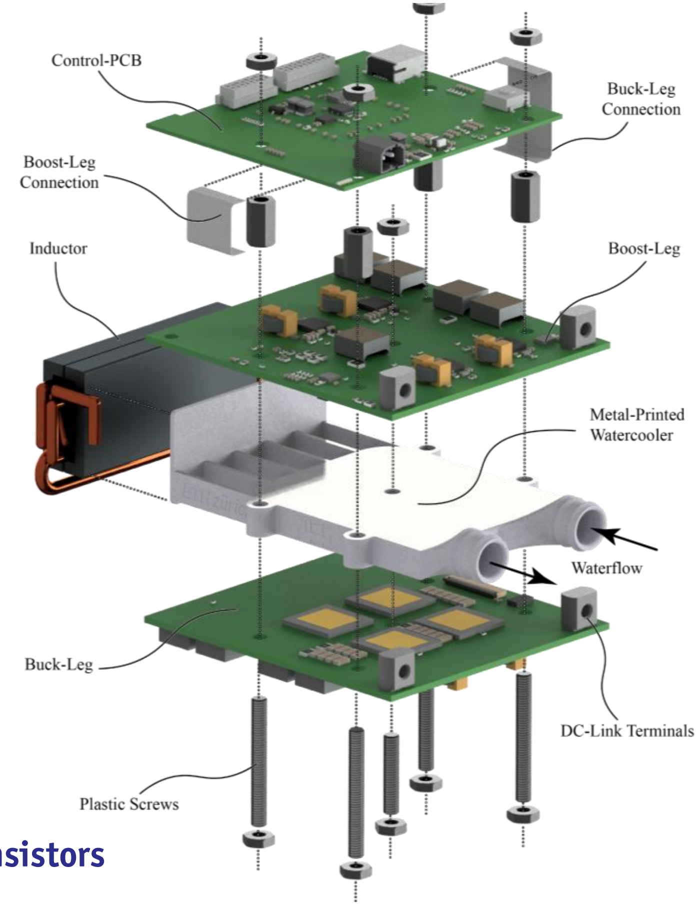
m = 175 g
γ = 86 kW/kg
ρ = 108 kW/dm^3
η = 98.1 % (Mission)

3-Level Converter

- Exp. System Power Density Higher than Calculated due to 3D-Printed Cold Plate & Sandwich Structure
- Ultra-High Power Density — Design Target of 20 kW/kg Achievable w/ Low-Complexity 2-Level Approach

3-Level Converter — Hardware Demonstrator

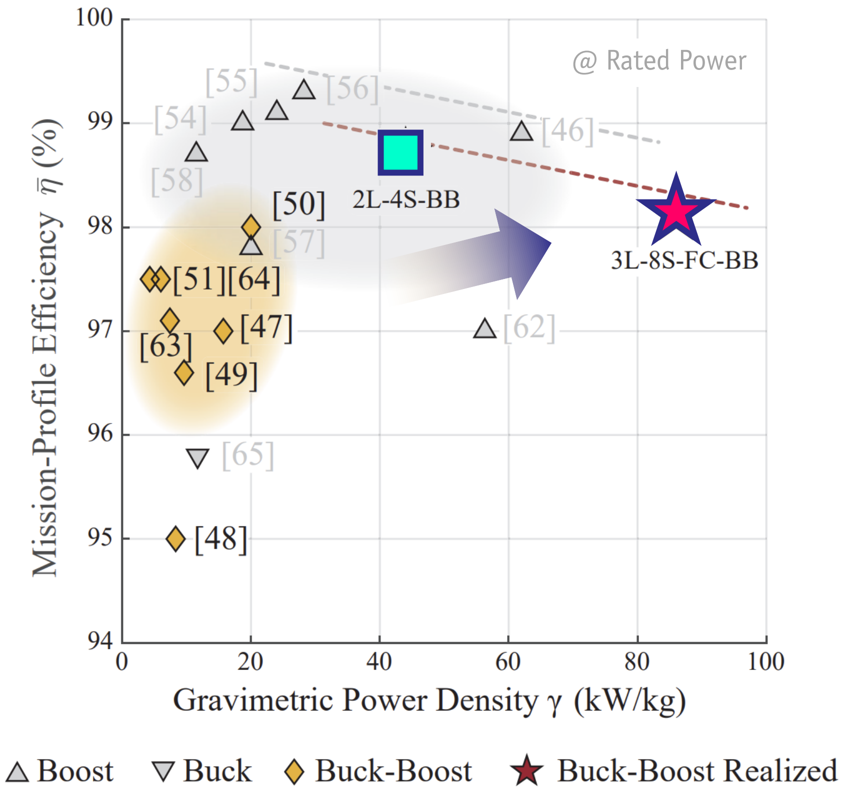
- Overlapping Input / Output Voltage Ranges — Buck-Boost DC/DC Converter
- Module — 15 kW | U_{FC} = 480...800V | U_{Batt} = 450...720V



- 3D-Printed Alumina H_2O-Cooler / 600V GaN Power Transistors

3-Level Converter — Experimental Results

- Overlapping Input / Output Voltage Ranges — Buck-Boost DC/DC Converter
- Module — 15 kW | U_{FC} = 480...800V | U_{Batt} = 450...720V

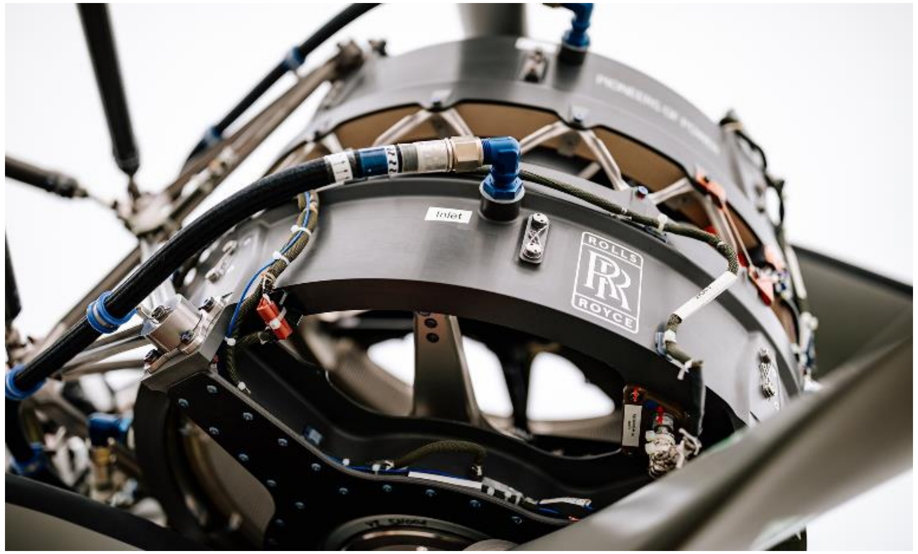


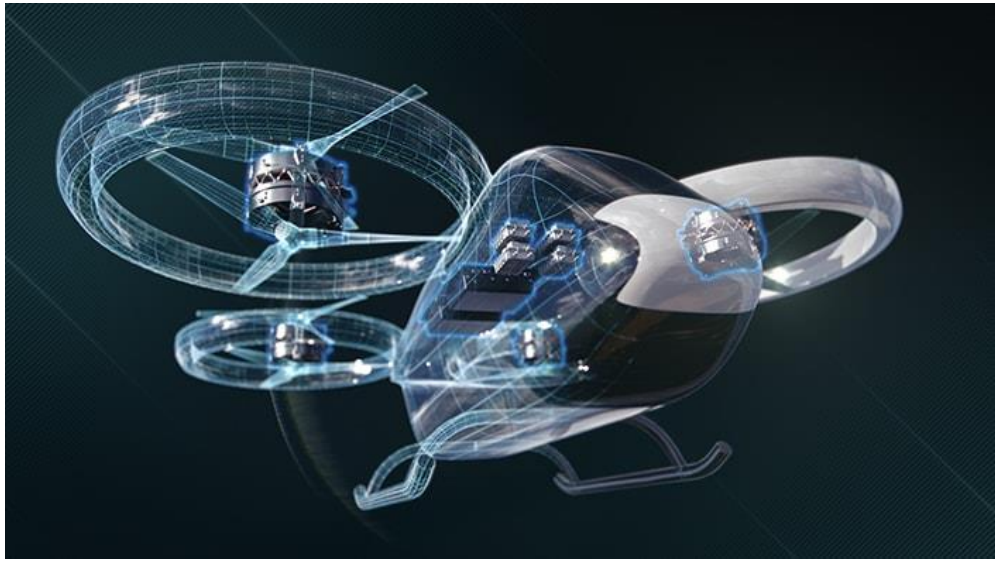
★ γ = 86 kW/kg @ $\eta_{Mission}$ = 98.1 %

eVTOL Aircraft Electric Motor Technology

- Best-in-Class — 30 Nm/kg | 15 kW/kg
- *Motor Scaling Acc. to Torque M (!) | P = M.ω – High Speed/Power Density & Gearbox OR Direct-Drive*
- Adv. / Low-Weight Radial- or Axial-Flux Motors incl. Concepts w/ Integr. Magnetic Gear — 20 kW/kg Target

Source: AIRBUS





- *CityAirbus* Demonstrator (2020) — 8x 100 kW Direct-Drive Rolls-Royce (SIEMENS) Adv. Motor Technology
- 4x2 Ducted Co-Axial Propellers – Low Noise | 400 kg Trust / Duct | 250 kg Payload | 120 km/h for 15 min

High-Power Battery Charging

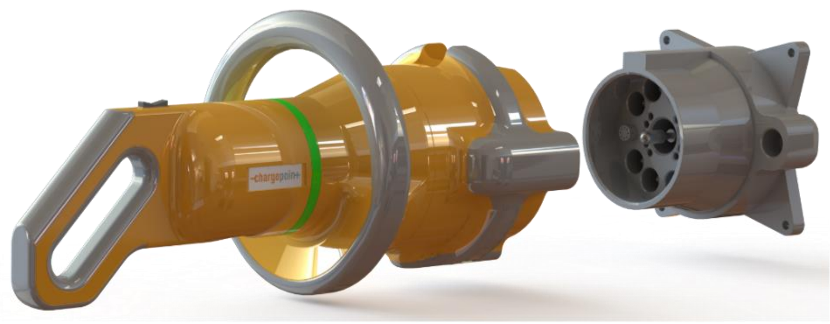
Solid-State Transformers

Ultra-Fast Battery Charging

- 20% → 100% Charging of typ. 200...400 kWh Battery in 15...20 min — Mandatory for High eVTOL Utilization
- MegaWatt Charging System (MCS) — For Heavy-Duty Trucks | Buses — Basis for eVTOL Aircraft AIR7357 Std

Source: NEW ATLAS

chargepoint

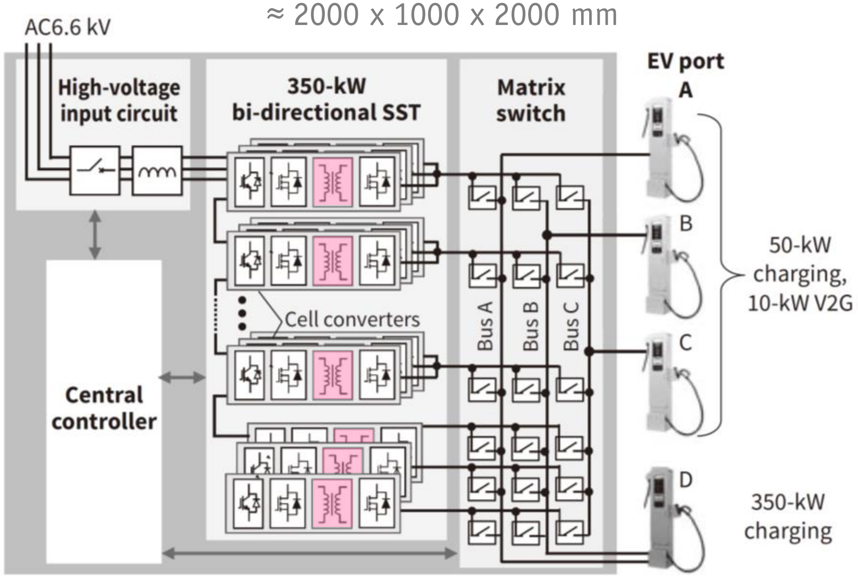


- ChargePoint 2-MW Charge Connector (max. 1000 V/4 x 500 A) incl. Liquid Cooling & High-Speed Data Transfer

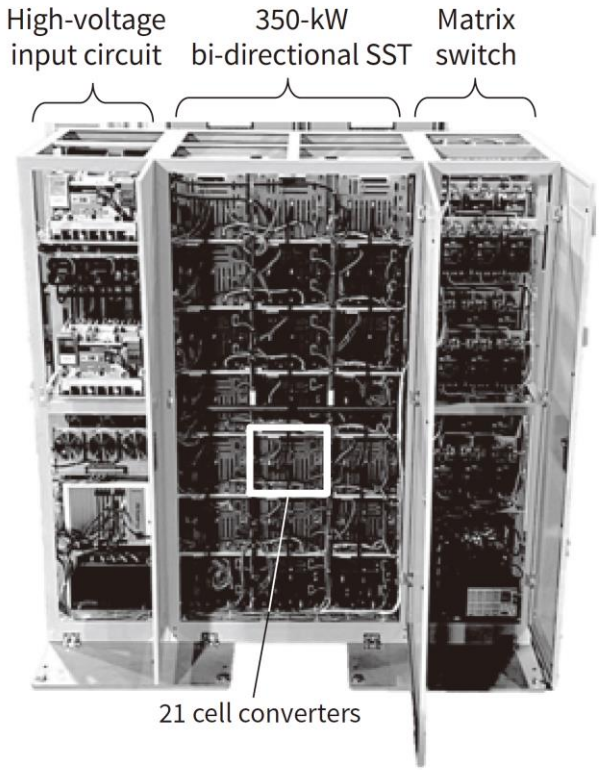
3-Φ 6.6kV Input / 350kW SST-Based EV Charger (1)

- 3x7 = 21 Cells | 5 kHz 1.7 kV Si-IGBT AC/DC Stage | 50 kHz 1.7 kV SiC 1050 V/400 V DC/DC Converter
- Matrix Switch Output for 21x 17 kW → 1x 350 kW Charging Port Config. & Cascaded Cell Balancing
- Forced Air Cooling

≈ 2000 x 1000 x 2000 mm



Source: HITACHI



- Power Density → 0.09 kW/dm³ (System) | ≈ 0.18 kW/dm³ (SST/Cells incl. Isol.)
- -40% Footprint / -70% Weight vs. LFT-Based Solution / 83% Lower Transf. Volume

3-Φ 6.6kV Input / 350kW SST-Based EV Charger (2)

- 3x7 = 21 Cells | 5 kHz 1.7 kV Si-IGBT AC/DC Stage | 50 kHz 1.7 kV SiC 1050 V/400 V DC/DC Converter
- Matrix Switch Output for 21x 17 kW → 1x 350 kW Charging Port Config. & Cascaded Cell Balancing
- Forced Air Cooling

Source: HITACHI

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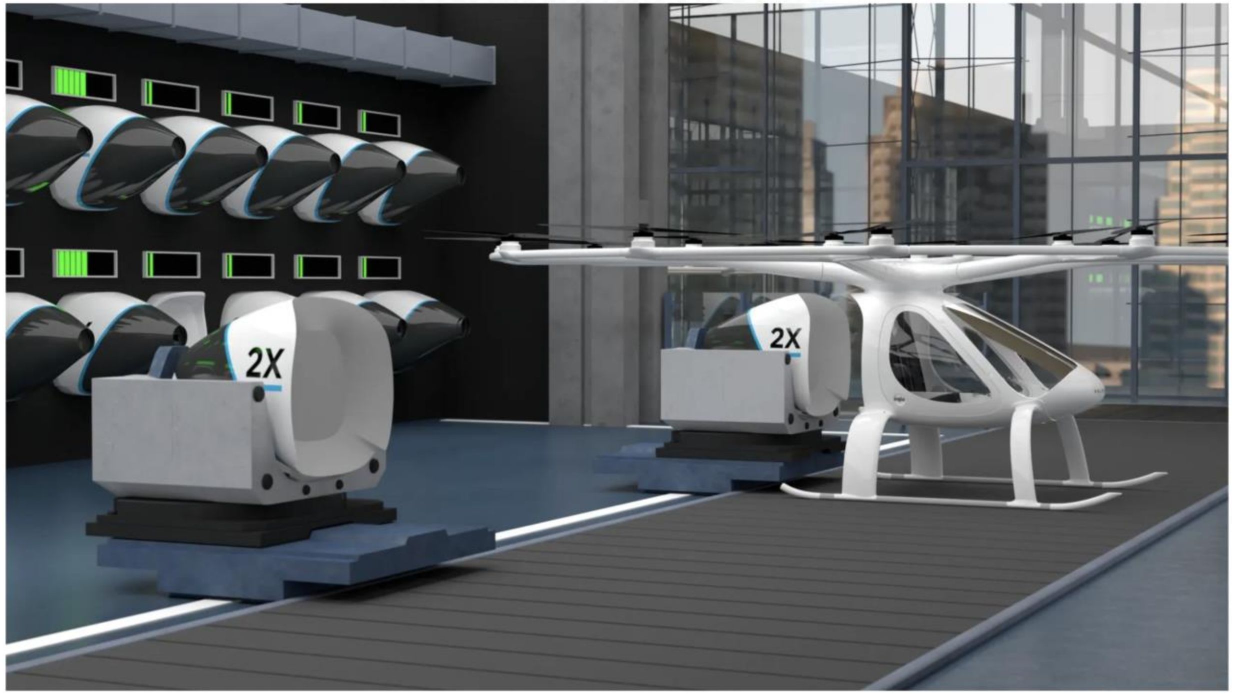
- -40% Footprint / -70% Weight vs. LFT-Based Solution / 83% Lower Transf. Volume

Remark — Battery Swapping

- Exchange of Drained Battery in Only 5min (!)
- Re-Charging of Batteries in Controlled Environment @ Low Energy $$$ Time Periods

Source: https://wassafss.medium.com



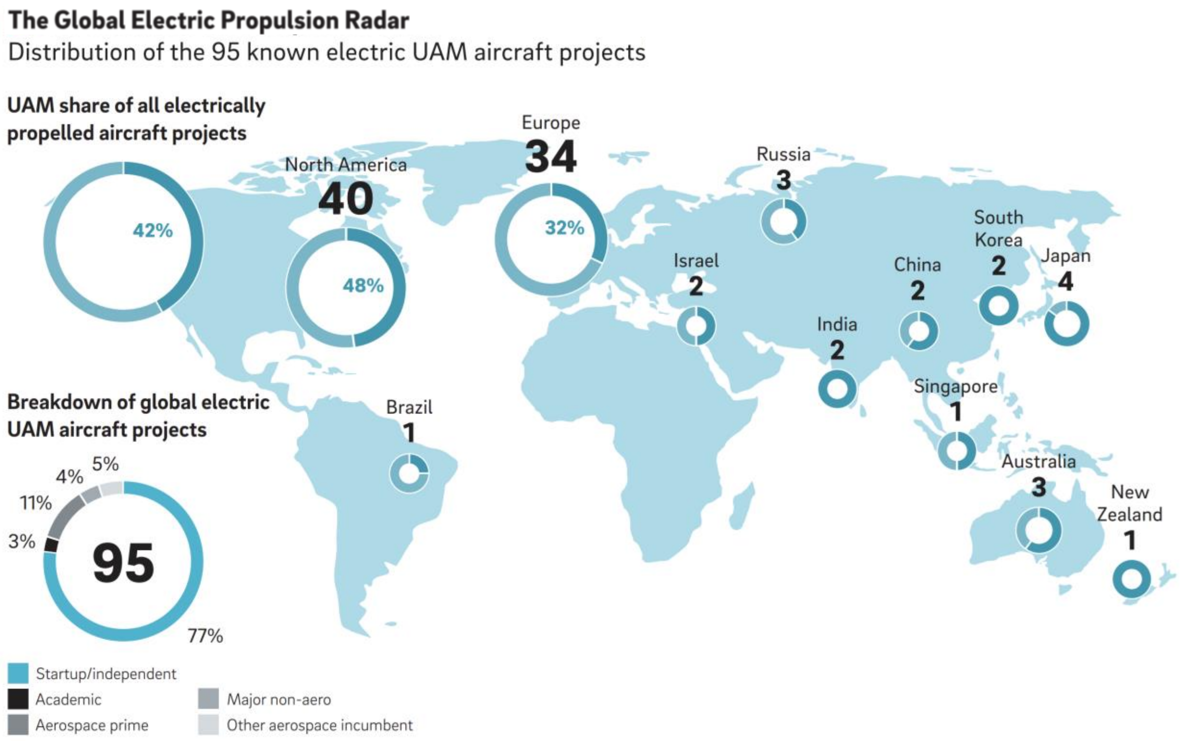
- Disadvantage of Standardized Single-Pack Battery Design & Battery Accessibility Required

Economic Perspectives & Sustainability

Market Growth Perspectives
Carbon Footprint vs. ICE & EV

Urban Air Mobility (UAM) Market Forecast

- 160´000 Passenger Drones Expected by 2050 — Add. Market for Services / Repairs etc.
- USD ≈900 Million Investments in 1st Half of 2020 — 20x Level of 2016 (Full Year)



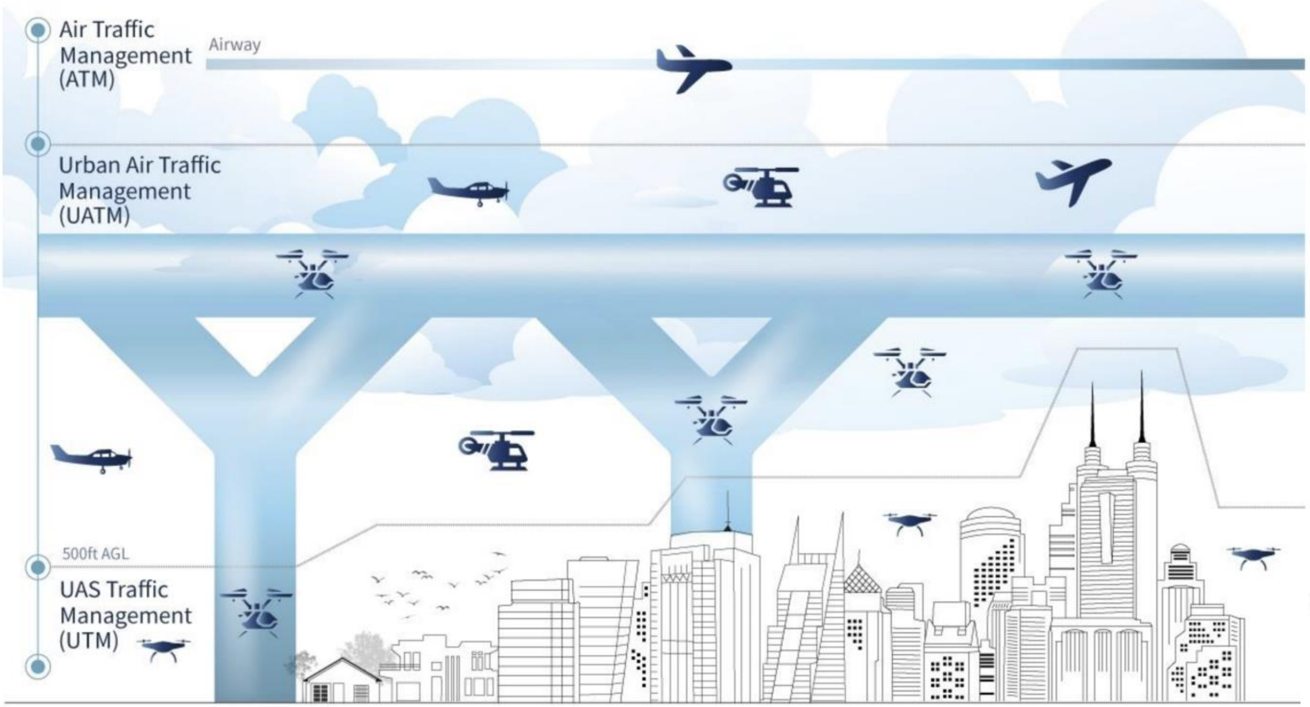
Source: Roland Berger 2020

- Industry Expected to be Ready for Take-Off in 2025 — 25% CAGR Predicted
- By 2050 Estimated Revenues of USD ≈90 Billion/Year (≈1 Billion in 2030)

Certification & Future Airspace Interaction Concept

- US Federal Aviation Admin. (FAA) / EU Aviation Safety Agency (EASA) — Regulations & Certifications
- Buildings / Towers & Noise-Sensitive Areas — Def. of Low-Altitude UAM Corridors & Holding Areas

Source: Y. Lee et al. | applied sciences



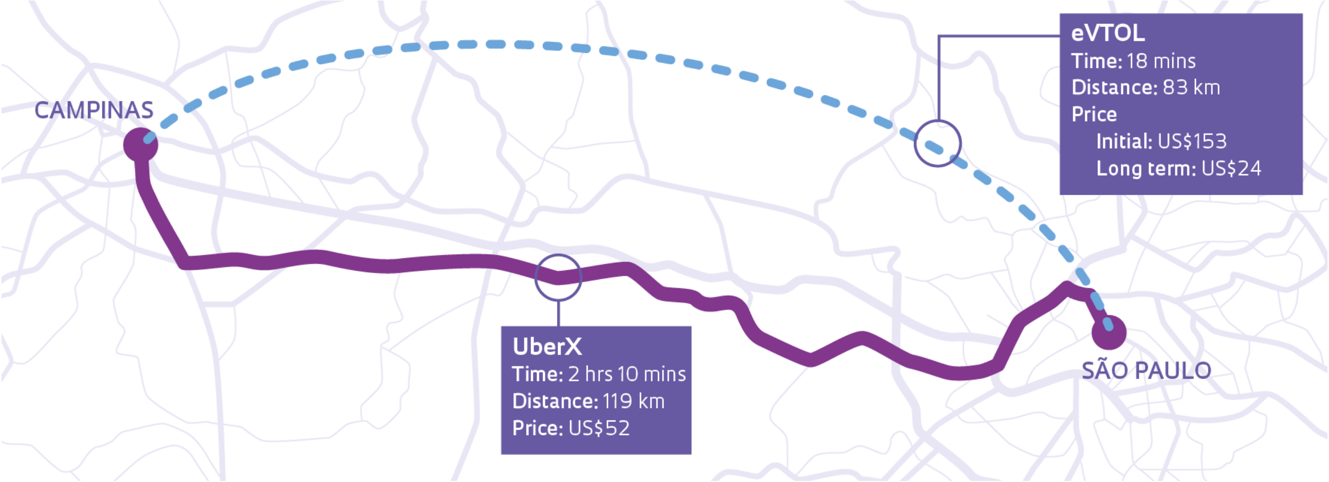
VOLOCOPTER — Targets EASA Certification for “VoloCity” in 2024

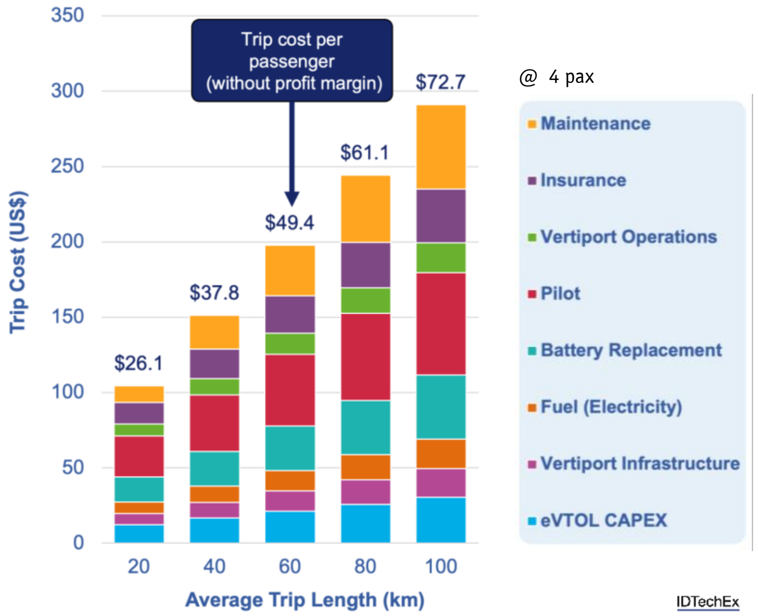
UAM Comparative Evaluation (1)

- Study of UBER Elevate (2015) on Cost / Time of Commuting btw Cities — eVTOL Aircraft vs. Cars
- «On-Demand» Urban Air Transportation — UberCopter as 1st Step

Car vs. eVTOL

Uber study compared the cost and time of commuting between the cities of São Paulo and Campinas by car and eVTOL

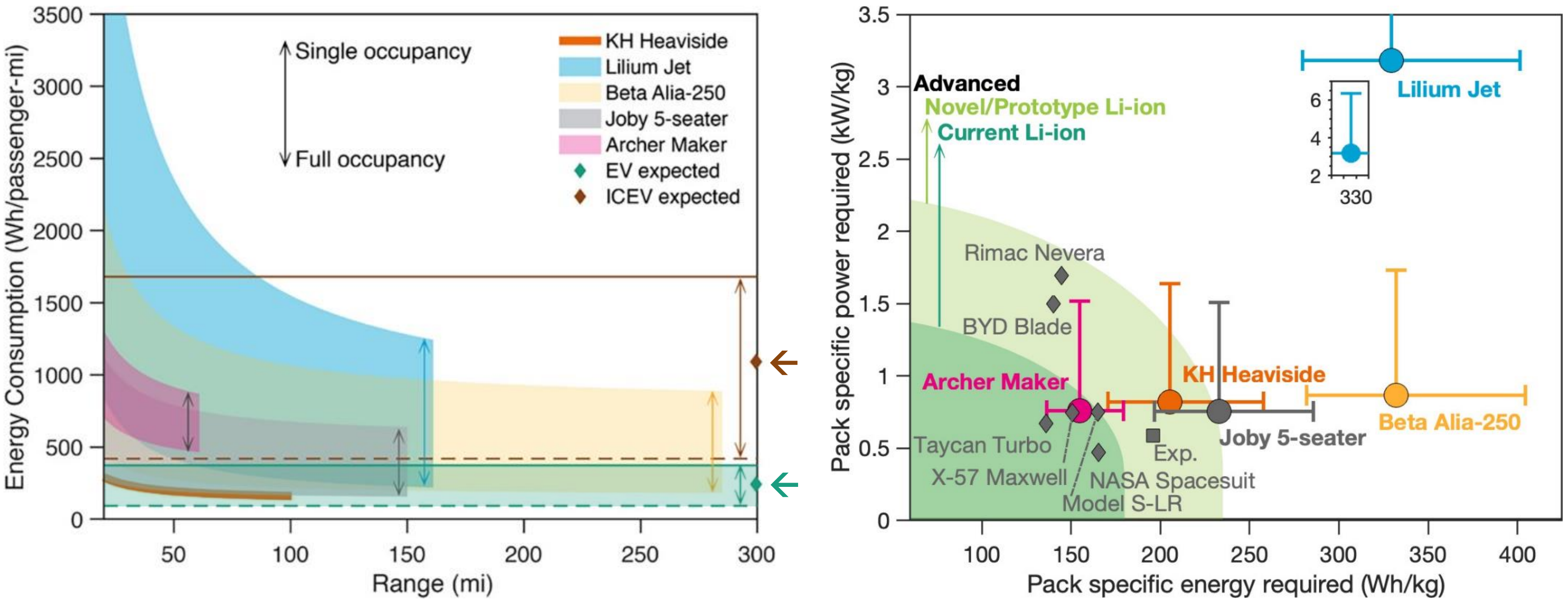




- Intercity Flights — Rel. Short Offset Transfer Time @ Vertiports | Time Saving & High eVTOL Utilization
- Lilium — 6 Passengers | 250km Range | 280km/h Cruise Speed | 20-25 Flights per Day

UAM Comparative Evaluation (2)

- eVTOL Aircraft Provide 2x ... 6x Faster Means of Point-to-Point Mobility
- Up to 300 mi of Range with up to 7 Passengers Using Latest Battery Technology



- EV and ICEV → 220 Wh/Passenger-mi and 1,000 Wh/Passenger-mi
- eVTOL Aircraft → 130 Wh/Passenger-mi ... ≈1,200 Wh/Passenger-mi Dep. on Design & Occupancy

Thank you!

Source: Paul Bunch
https://leslikely.artstation.com/