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CPE-POWERENG 2023

TAL TECH Power Electronics Group

Materializing the Vision of "Flying Carpets"

Johann W. Kolar et al.

Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

June 14, 2023

BELLWETHER INDUSTRIES

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Ultra-Lightweight/Efficient Power Electronics Enabling Future Urban Air Mobility

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Bellwether Industries

June 14, 2023

Materializing the Vision of "Flying Carpets" — Ultra-Lightweight/Efficient Power Electronics Enabling Future Urban Air Mobility

Urban Air Mobility (UAM) based on electric vertical take-off and landing (eVTOL) aircraft – a 21st century materialization of the legendary "Magic/Flying Carpet" – are based on multi-rotor or tilt-rotor/duct/wing designs, can carry four to six occupants and operate from vertiports without runways. Compared to terrestrial alternatives this allows for a two- to six-fold faster means of point-to-point mobility. Aircraft electrification enables considerably higher overall efficiency as a larger number of small high-efficiency electric motors, i.e., distributed electric propulsion, can be used instead of conventional low-efficiency combustion-based propulsion architectures with few large units, resulting in reduced drag and greater flexibility to leverage the benefits of aero-propulsive coupling. Accordingly, urban and regional eVTOL aerial travel services are expected to massively expand over the next decades.

The talk first introduces key eVTOL aircraft designs currently in the R&D, prototyping, or production planning phases, discusses trade-offs of key performance indicators like range and payload using first-order principles, and highlights critical enabling technologies like high gravimetric energy density and/or high-power-density batteries and fuel cells, low-specific-weight electric motors, and advanced power electronics. Hybrid battery/fuel cell power supplies of eVTOL aircraft enable high peak power capability as well as long-range operation. However, the typically wide and overlapping voltage ranges of the batteries and the fuel cells require interconnecting bidirectional DC-DC converters with buck-boost capability.

Accordingly, the second part of the presentation comparatively evaluates performance limits of fully soft-switched, flying-capacitor-multilevel, and partial-power-processing buck-boost candidate converter topologies by means of comprehensive Pareto optimizations considering mission profile efficiency and gravimetric power density, and finally presents a 15kW 450V...730V / 480V...800V three-level flying capacitor converter module of a 150kW system featuring 98.5% efficiency and an unprecedented gravimetric power density of 62kW/kg.

Finally, a summary of first assessments of the primary energy and Greenhouse Gas Emissions impacts of eVTOLs vs. ground-based light-duty vehicles for passenger mobility is presented, which surprisingly indicates partly higher energy efficiencies than equivalent terrestrial alternatives at faster and more predictable travel times, and indicates a possible niche role of eVTOLs in future sustainable urban transportation.

Outline

- ► *Once Upon a Time …*

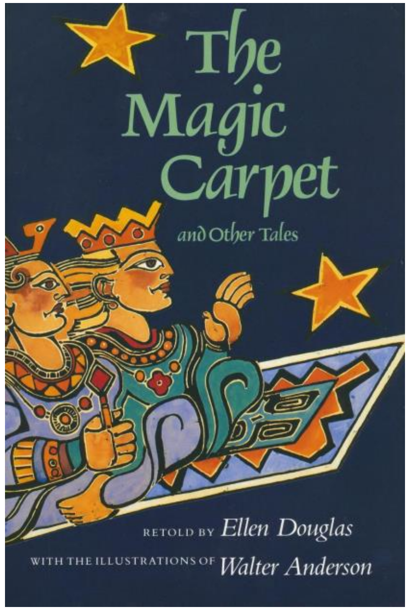
- ► *eVTOL Aircraft Concepts*
- ► *Energy / Power Sources*
- ► *El. Motor Technologies*
- ► *On-Board Power Electronics*
- ► *Ultra-Fast Battery Charging*

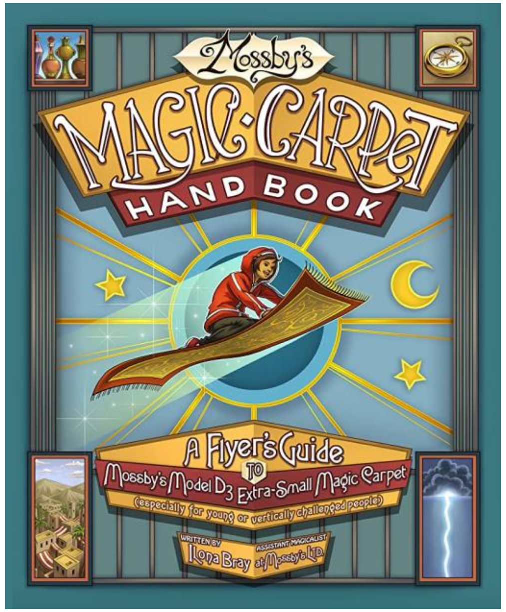
- ► *Sustainability*

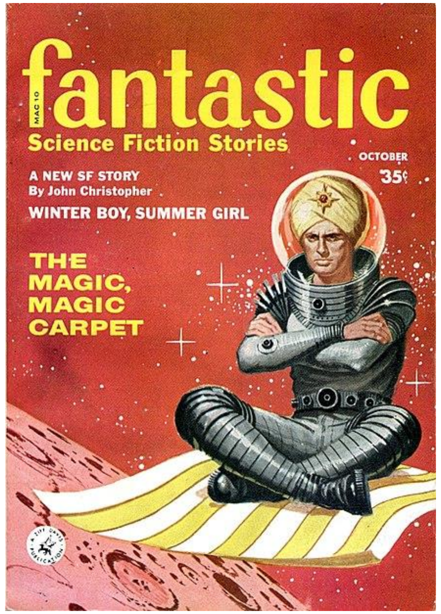
Acknowledgment Martin Ulmer

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
- 500´000 Hours of Productivity Lost / Single Day

Source: https://www.youtube.com/watch?v=44bSw-wPW4c

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

Power Electronic Systems Laboratory

Urban Air Mobility

Operation Characteristic
eVTOL Aircraft Types

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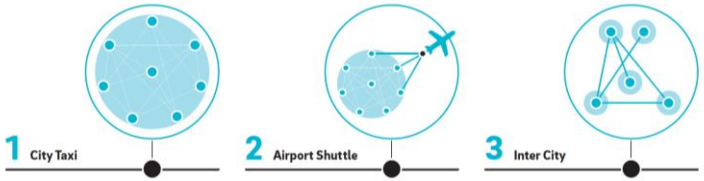
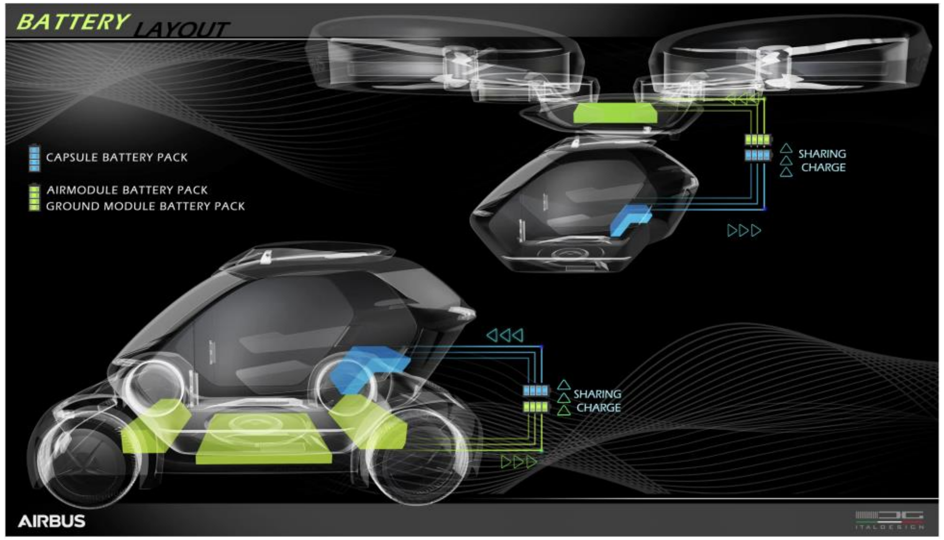
Urban Air Mobility (UAM)

- "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

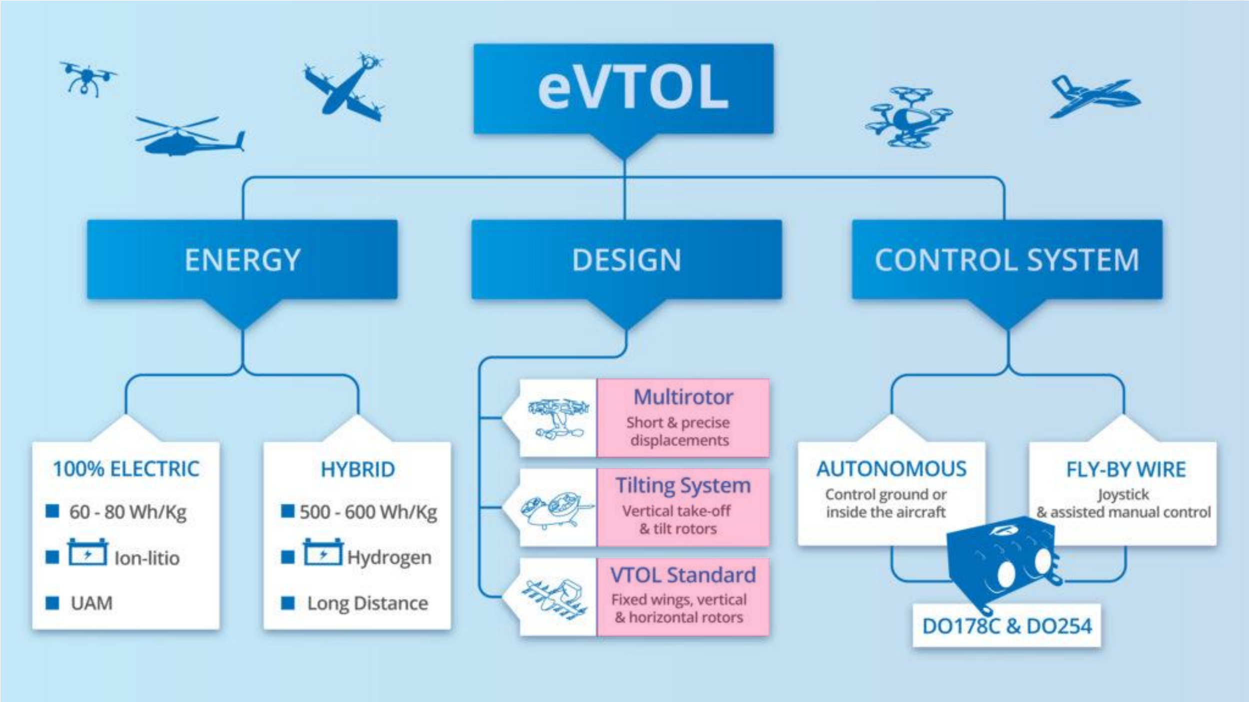




- "Pop.Up Next"— Modular All-Electric Drone — 4x2 Rotors | People-Pod | EV Chassis (Airbus & Audi until 2019)

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



Source: www.embention.com

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

eVTOL Aircraft Concepts (1)

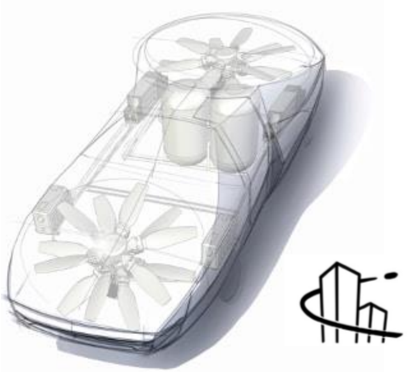
- Volocopter (Germany) — VoloCity
- 18 El. Rotors | Vert. Lift & Hover Flight | 900 kg Max. Take-Off Weight
- 2 Passengers | 110 km/h Cruise Speed | 36 km Range

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)

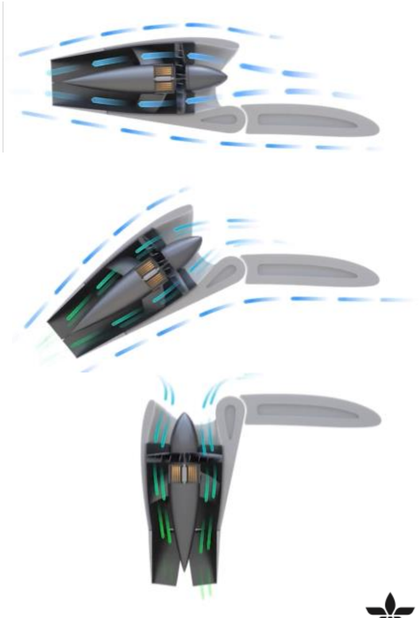
- Joby Aviation (USA) — Joby S4 2.0
- 6 Tilt-Propellers | Vert. Lift & Horiz. Flight | 2200 kg Max. Take-Off Weight
- 4 Passengers | 320 km/h Cruise Speed | 240 km Range

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

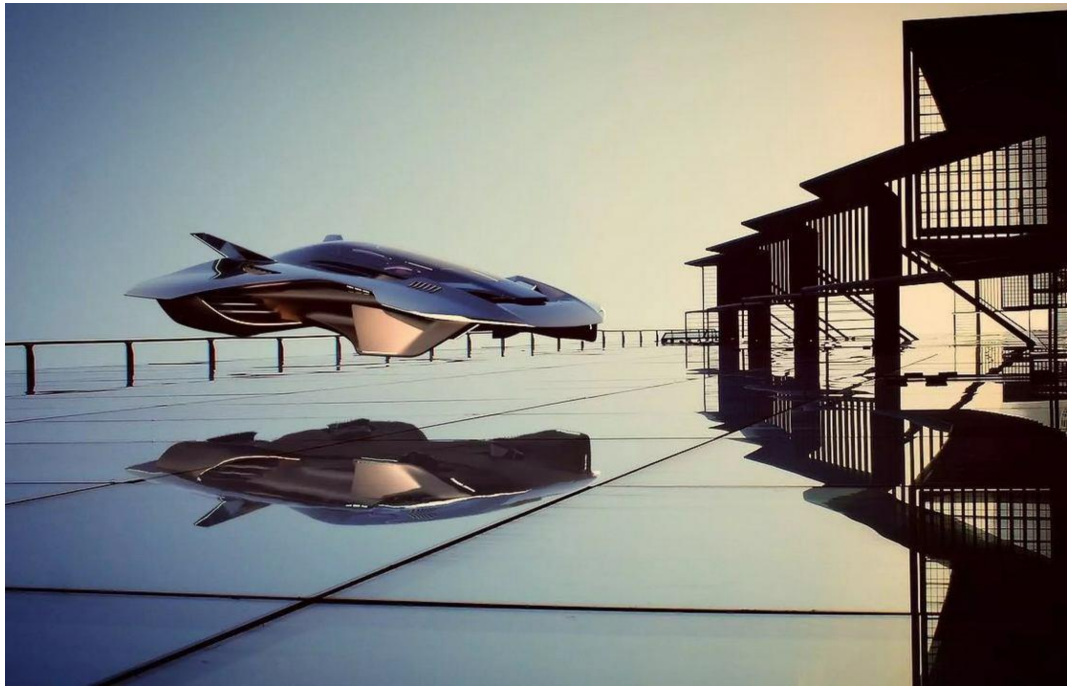


LILIUM

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

eVTOL Aircraft Concepts (5)

- Bellwether Industries (UK) — Volar Antelope
- 4 Ducted El. Fans | Hidden Propulsion System | 600 kg Max. Take-Off Weight
- 1-2 Passengers | 220 km/h Cruise Speed | 330 km Range



BELLWETHER INDUSTRIES

- Half-Scale Demonstrator Tested
- Full-Scale Production Aircraft Planned with 4-5 Passengers

eVTOL Aircraft Concepts (6)

- 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

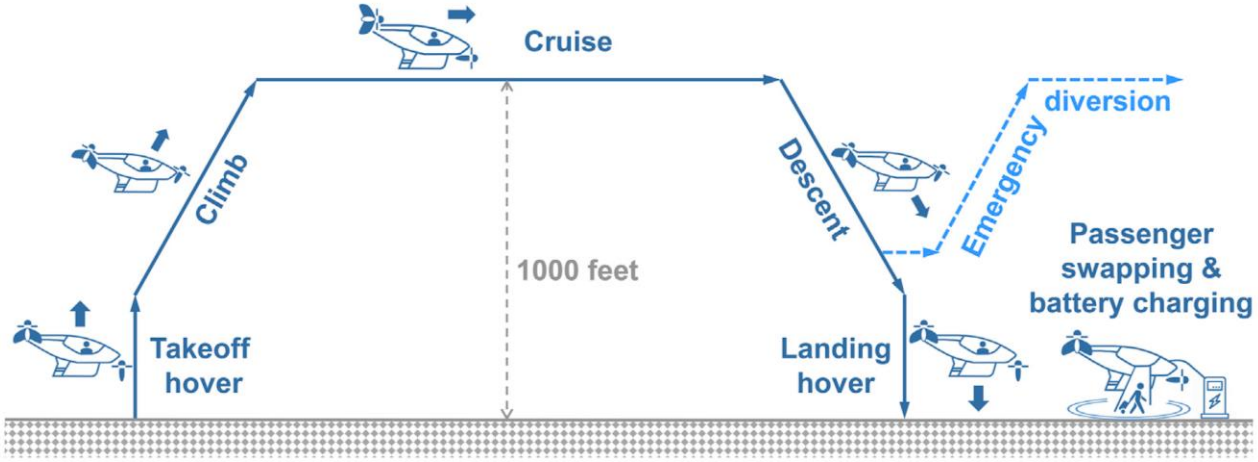
- Successful Manned Test Flight in 2020 / Type Certification Planned for 2025
- Mass Production of 30 kg Payload Cargo Drones Planned

eVTOL Mission Profile

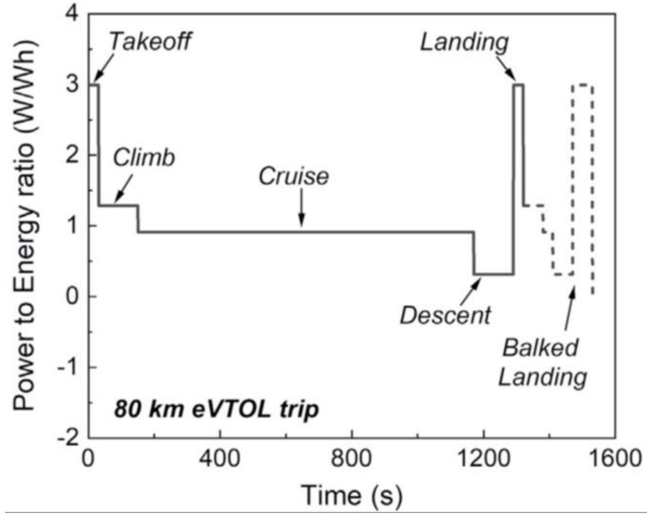
Operational Requirements
Power / Energy Sources

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



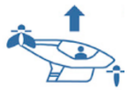
L|D ... Lift-to-Drag Ratio



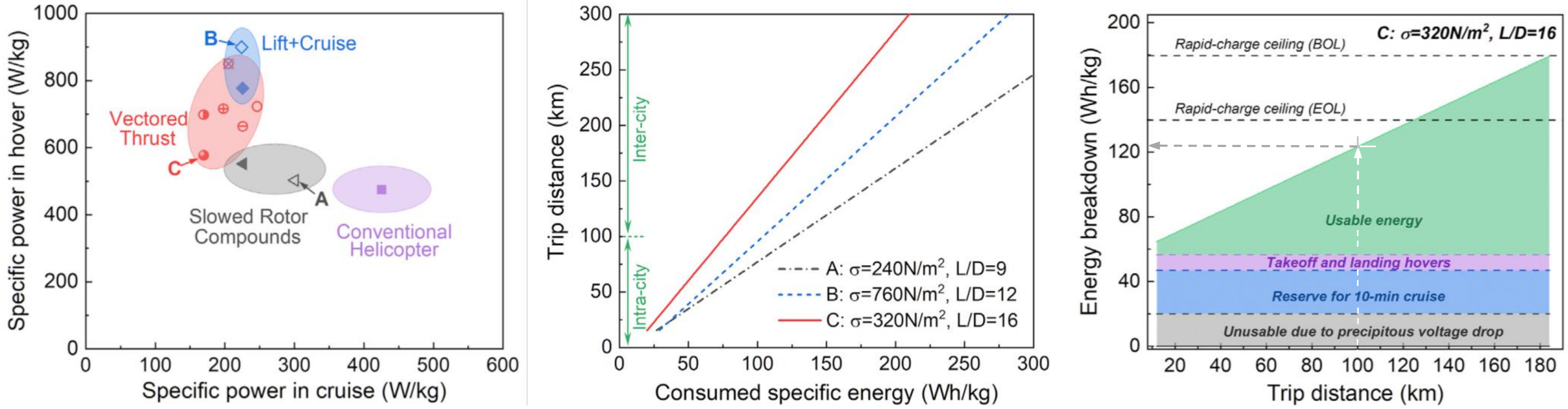
- Large Range — High Spec. Energy Battery
- High Payload — High Spec. Power / High C-Rate Battery
- High Vehicle Utiliz. | Low Batt. $$$ / Small Batt. — Fast High-Power Charging / High C-Rate / High # Cycles

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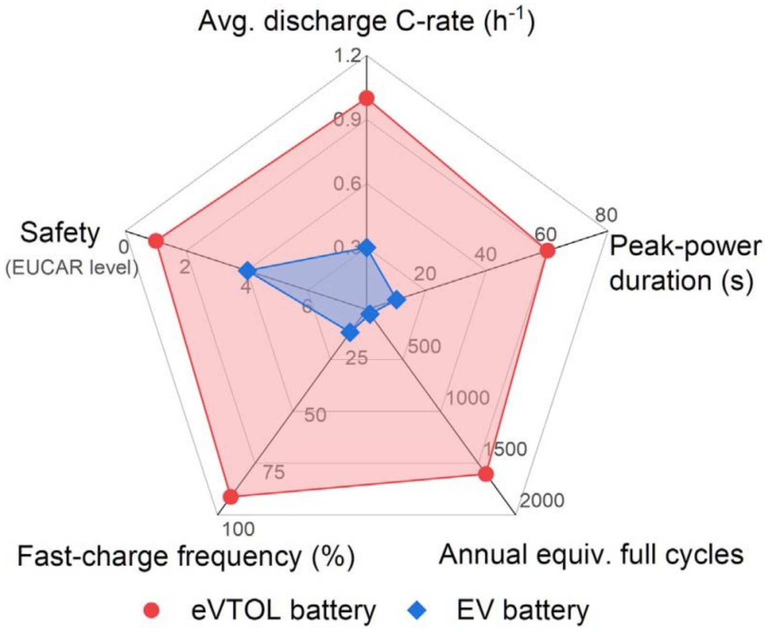
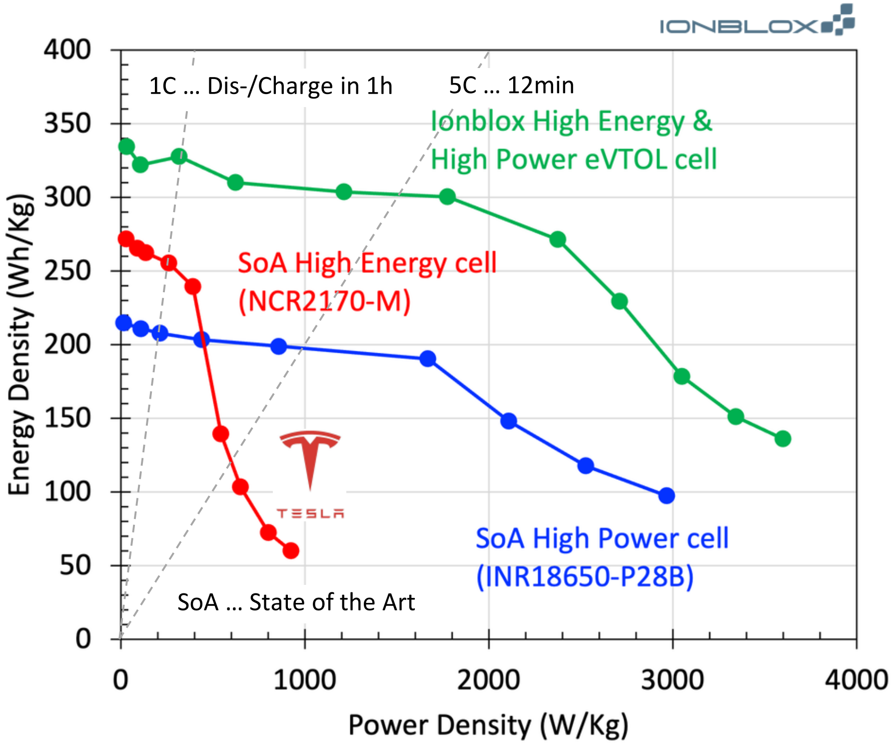
$$t_{char} = \frac{SE_{trip}}{SP_{char}} = \frac{R_{trip}}{SP_{char}}\frac{g}{\eta_c\omega_{bat}L/D}$$

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. >1000)
- 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

Power Electronic Systems
Laboratory

Ultra-Light Weight Power Electronics

Electric Power System Buck-Boost DC/DC Conversion

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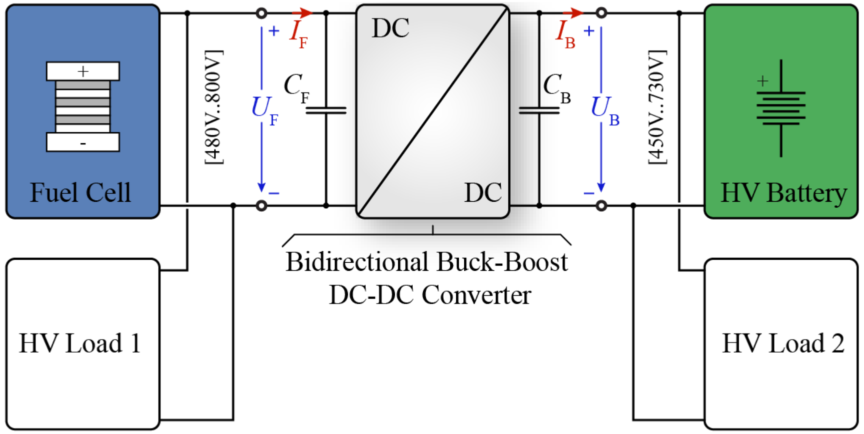
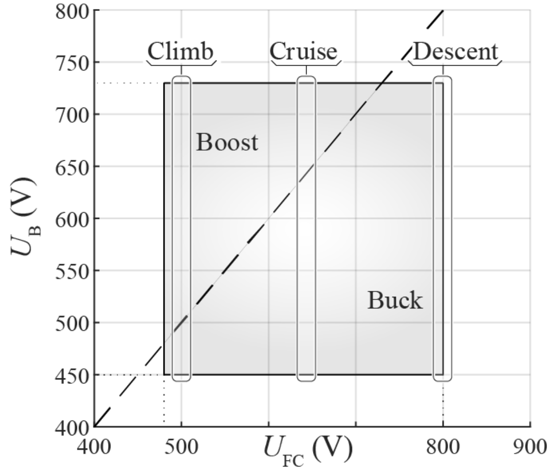
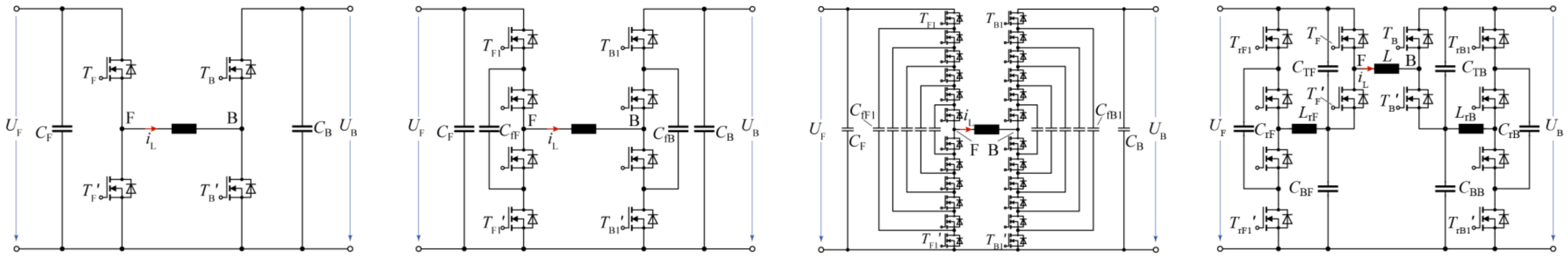
Fuel-Cell/Battery Power Electronics Interface

- 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...730V



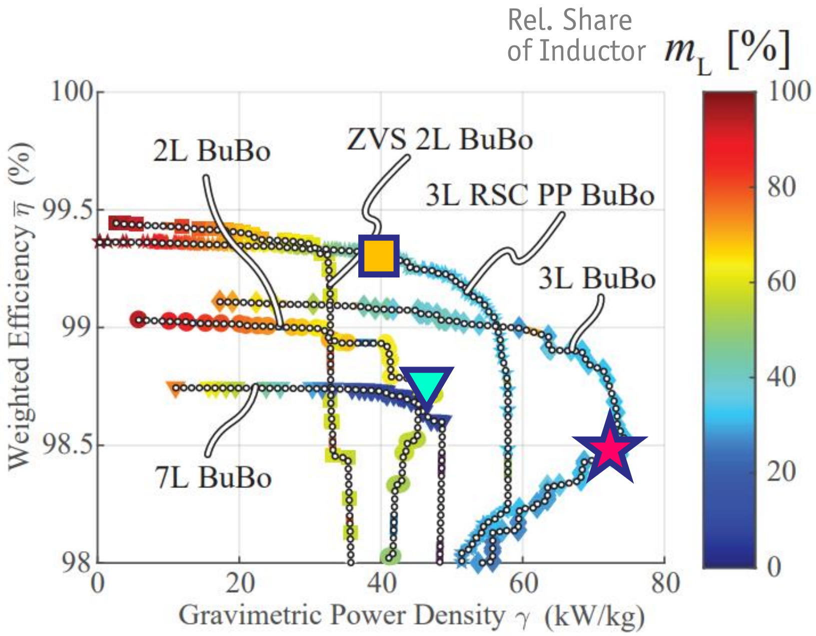


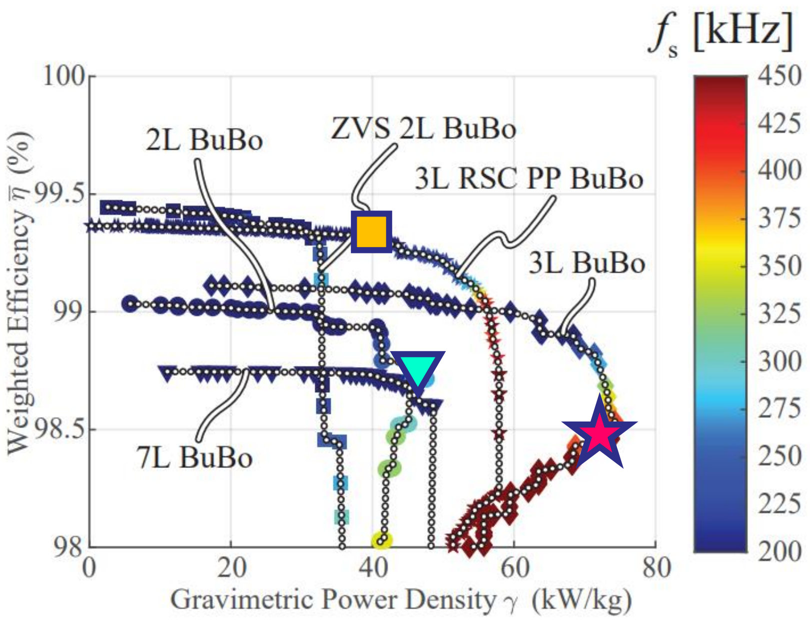


- Multi-Objective Comparative Analysis — 2-Level (ZVS) | Multi-Level | Partial Power Processing Topology

Fuel-Cell/Battery Power Electronics Interface

- Overlapping Input / Output Voltage Ranges — Buck-Boost DC/DC Converter
- Module — 15 kW | U_{FC} = 480...800V | U_{Batt} = 450...730V

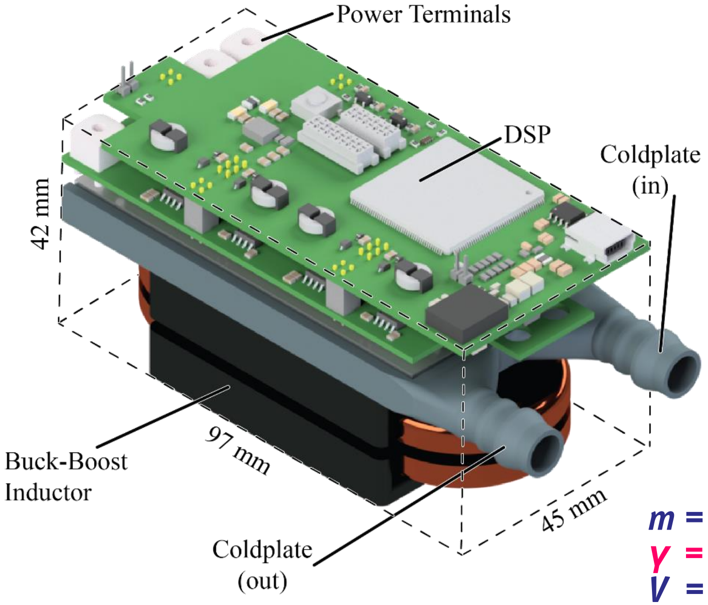




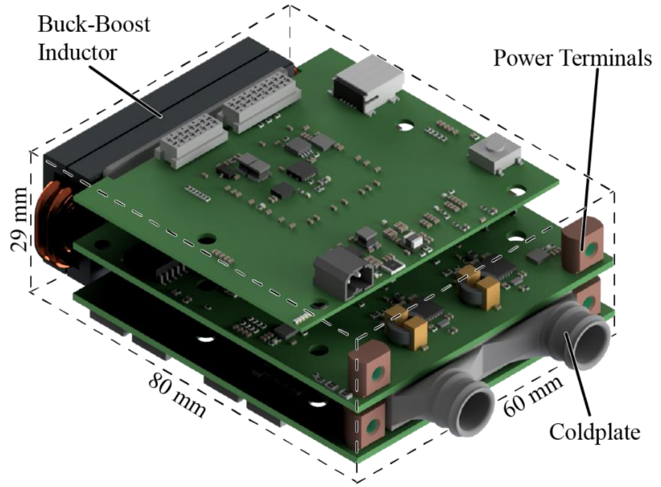
- Multi-Objective Comp. Analysis — 2-Level (SiC) f_{sw} = 275 kHz | 3-Level (GaN) f_{sw} = 400 kHz ($f_{sw,eff}$ = 800 kHz)
- Mission Efficiency — 50% Climbing / 50% Cruising / No Fuel-Cell Power During Descent – DC/DC Conv. Off
- System Considerations — Battery & Fuel-Cell Weight vs. Converter Weight – 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...730 V



2x →



2-Level Converter

m = 346 g
γ = 43 kW/kg
V = 183 cm^3
ρ = 82 kW/dm^3
η = 98.8 % (Mission)

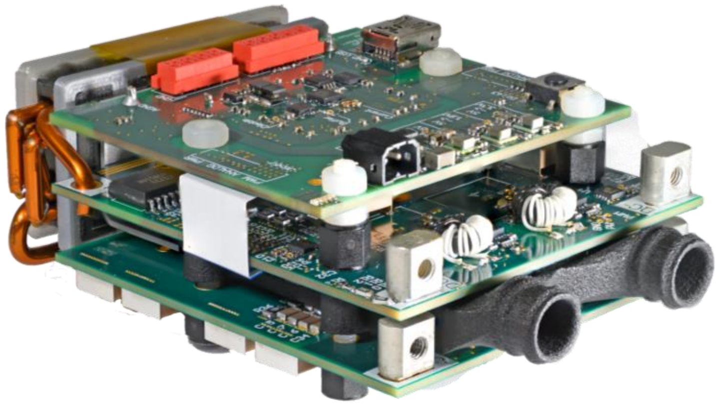
3-Level Converter

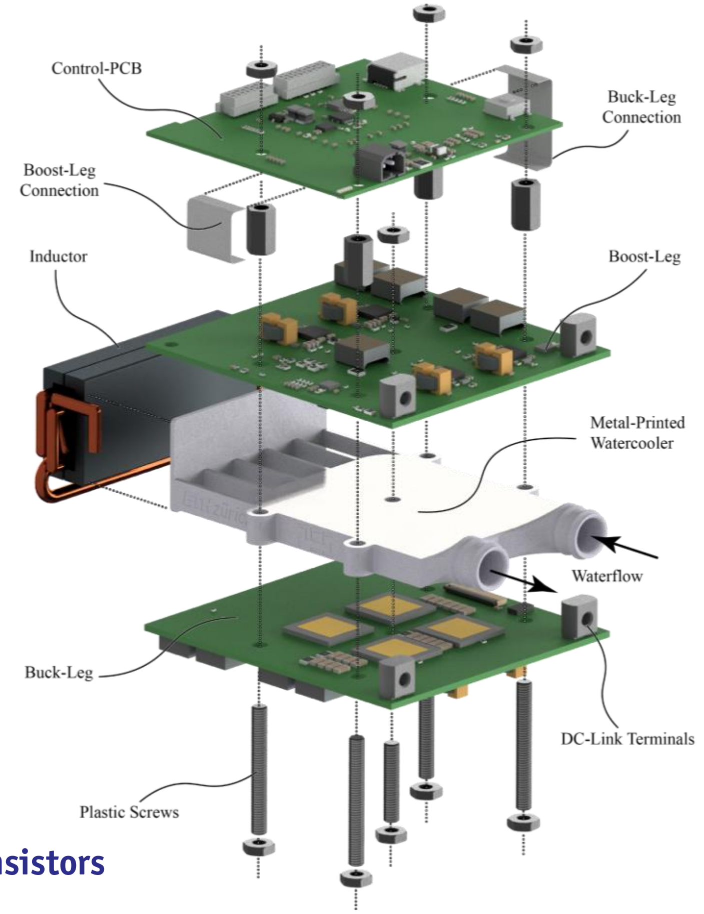
m = 175 g
γ = 86 kW/kg
V = 139 cm^3
ρ = 108 kW/dm^3
η = 98.5 % (Mission)

- 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...800 V | U_{Batt} = 450...730 V

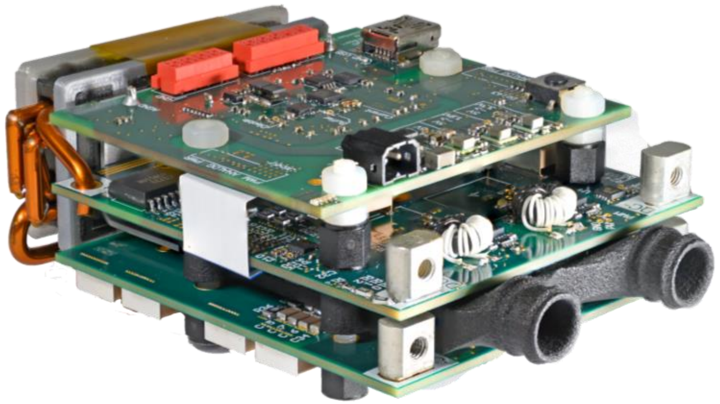


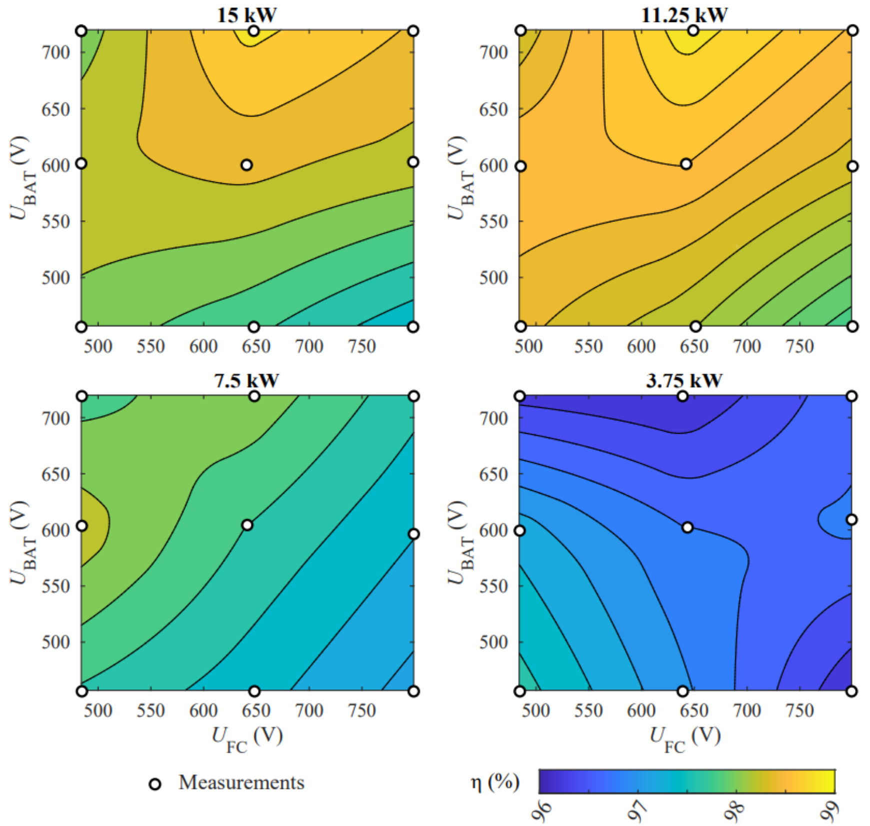


- 3D-Printed Alumina H_2O-Cooler / 600 V GaN Power Transistors

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...730V



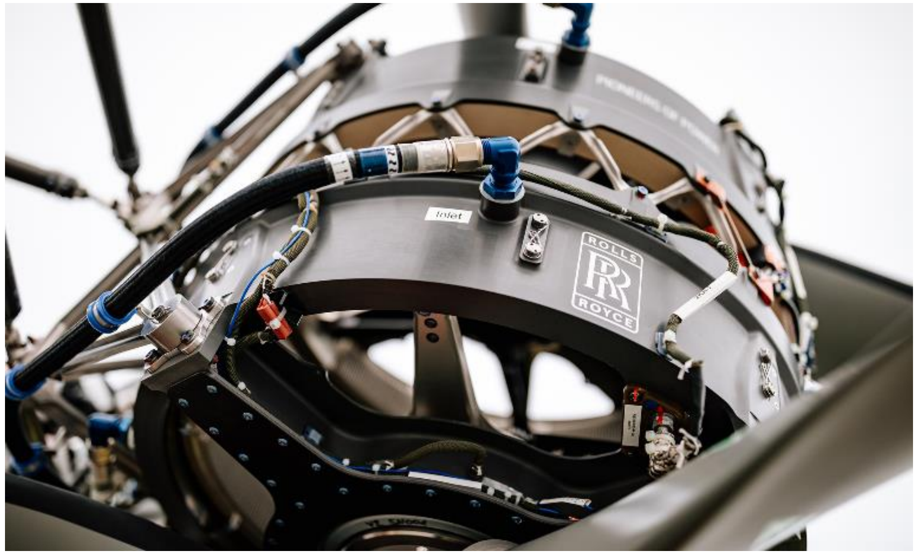


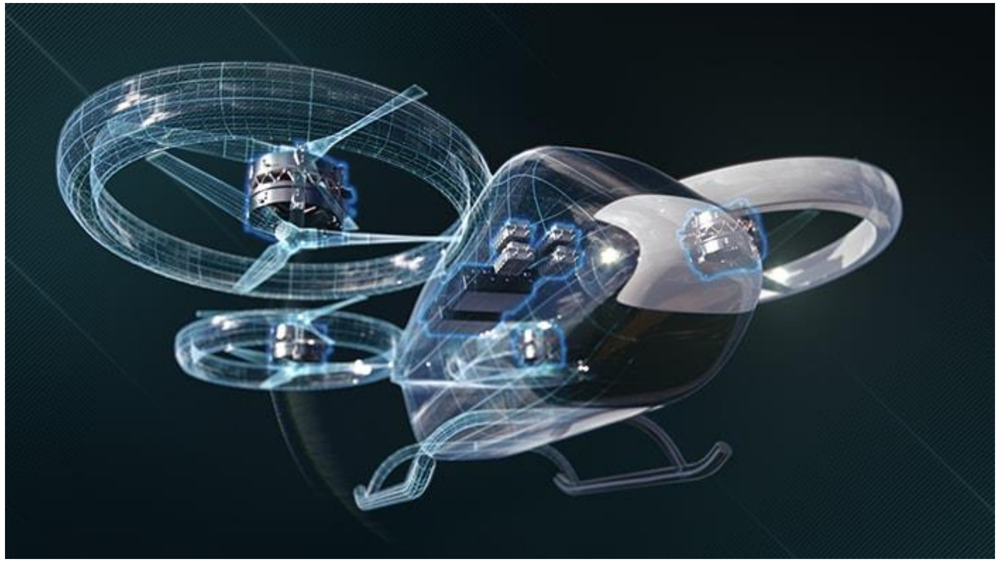
★ γ = 86 kW/kg @ η_{max} = 98.9 %

eVTOL 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

Power Electronic Systems Laboratory

High-Power Battery Charging

50Hz Transformer & Active Rectifier
Solid-State Transformers

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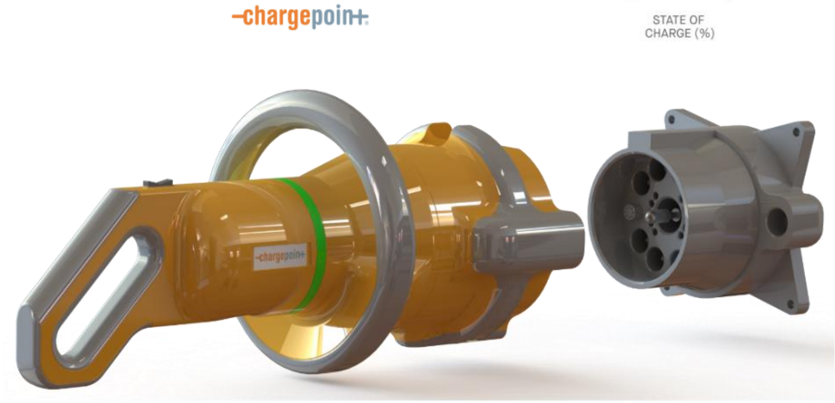
Up to 3.5 MW Ultra-Charging System

- 20% → 100% Charging of typ. 200...400 kWh Battery Pack in 15...20 min — High eVTOL Utilization
- MegaWatt Charging System (MCS) — New Charging Std. for Trucks | Buses | eVTOL Aircraft etc.

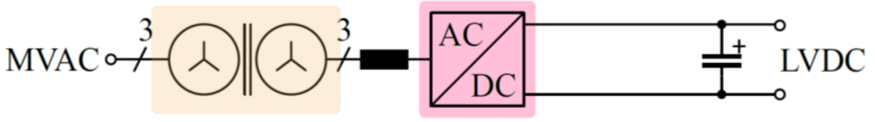


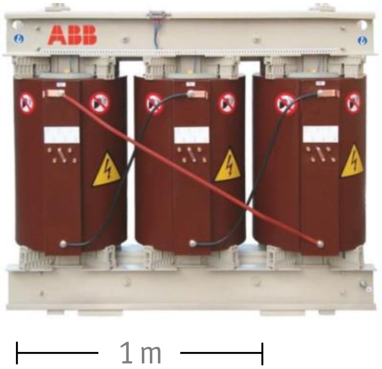
Source: NEW ATLAS

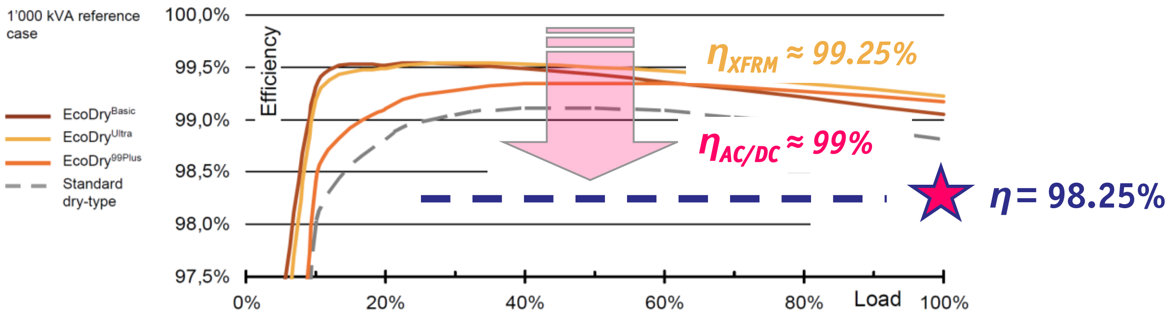
- ChargePoint High-Power Charge Connector (max. 1.5 kV/3000 A) incl. Liquid Cooling & Data Transfer

Dry-Type LFT Technology & SiC PFC Rectifier

- 400 kVA EcoDry™ High-Efficiency Transformer
- Vacuum Cast Coils — No Fire Hazard
- Amorphous Metal Core — Low No-Load Losses
- High Overvoltage / Overload Capability



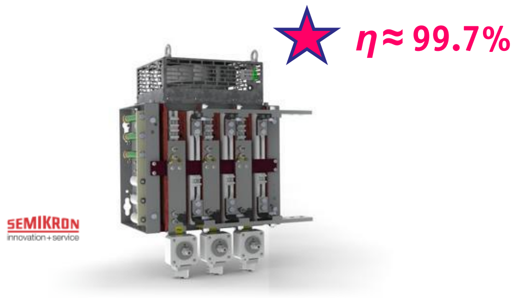


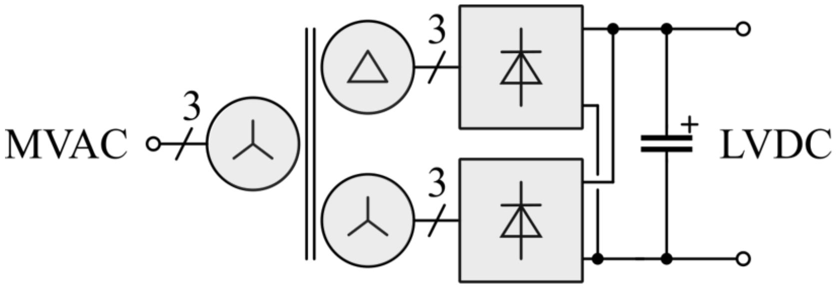


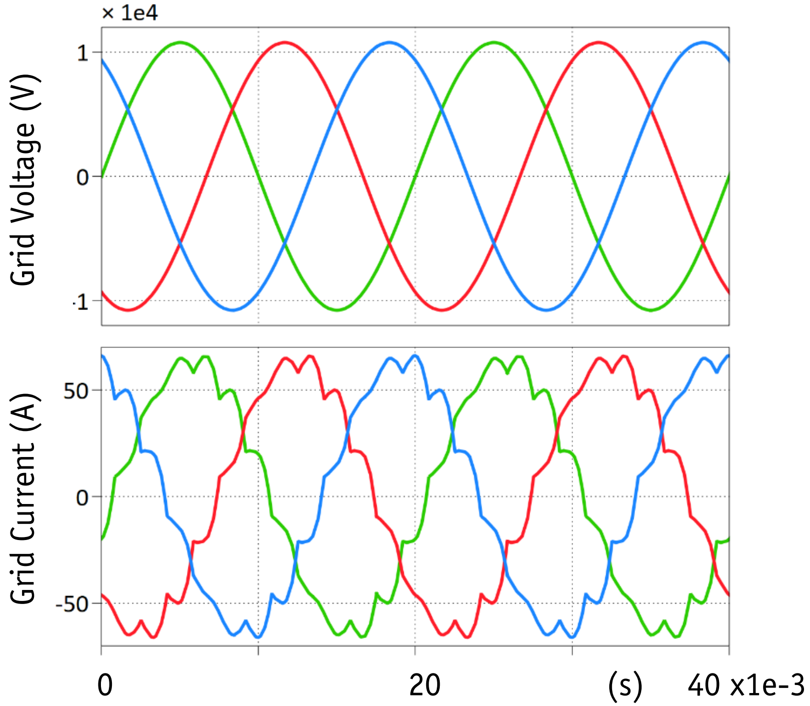
- Utilizing Proven LV SiC MOSFETs in AC/DC Stage → $\eta_{AC/DC}$ = 99+ % Efficiency
- Full Functionality — Bidir. Power Flow | Scalability to Higher MVAC-Levels
- No DC Fault Current Limit (!)

3-Φ 12-Pulse / Multi-Pulse Rectifier

- No Explicit PFC Stage (!) — Passive Realization of PFC with Phase-Shifting Transformer / No Inductors
- Low Complexity | High Robustness | Long Lifetime
- 18-Pulse, 24-Pulse for High Power Levels
- 4 kW/dm³ Rectifier Stage / Air Cooling





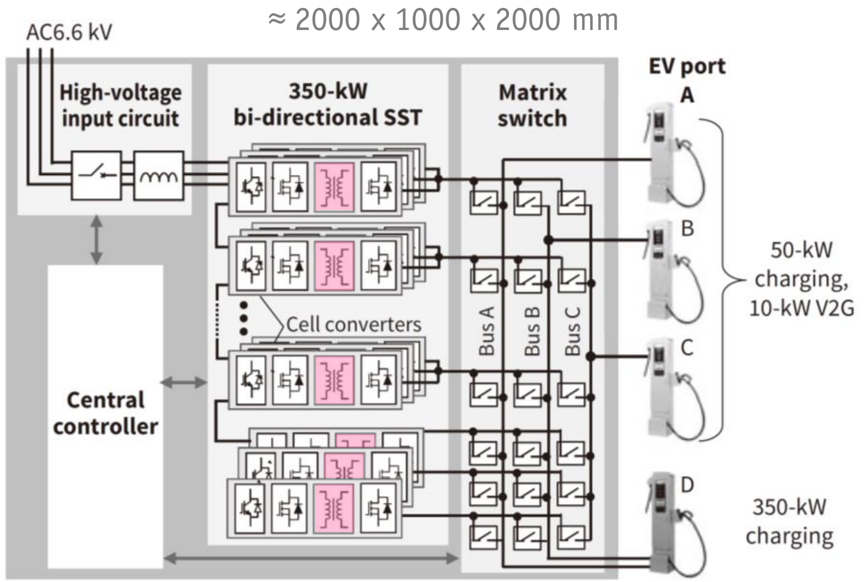


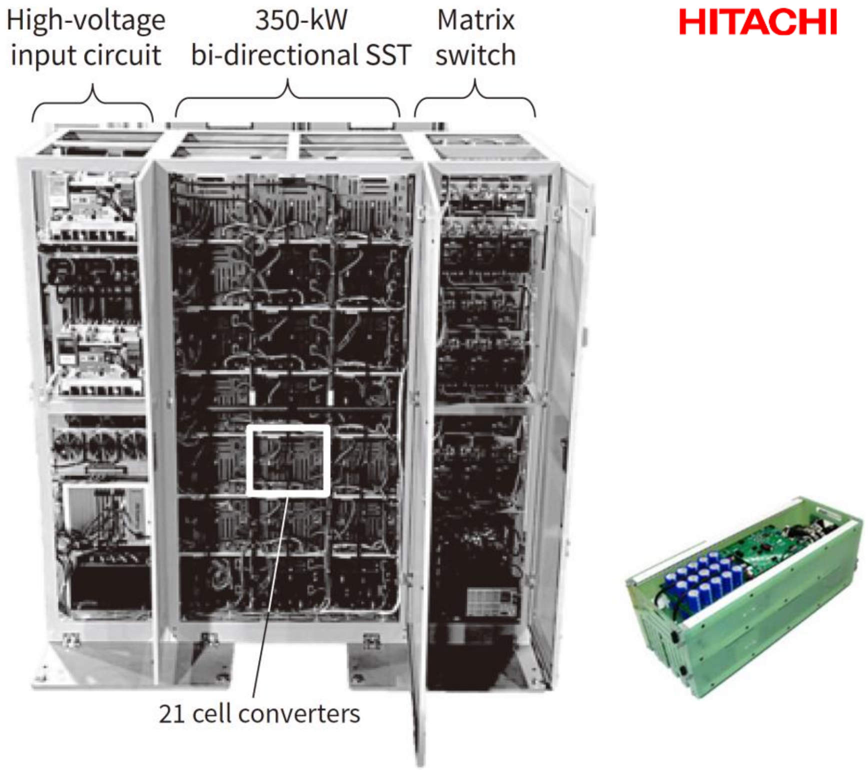
- Unidirectional
- No Active Output Voltage Control
- Remaining Current Distortion / Reactive Power Consumption

3-Φ 6.6kV / 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

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 / 350kW SST-Based EV Charger (2)

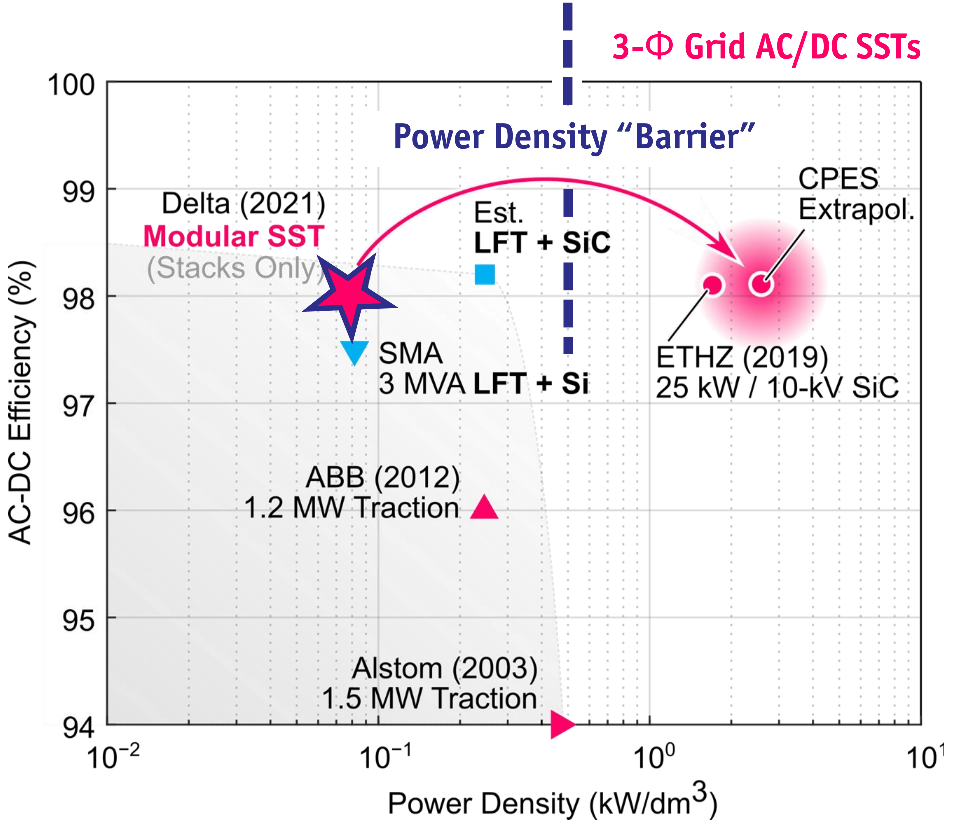
- 3x7 = 21 Cells | 5 kHz 1.7 kV Si-IGBT AC/DC Stage | 50 kHz 1.7 kV SiC 1050 V/400 V DC/DC Converter
- Matrix Switch Output for 21x 17 kW → 1x 350 kW Charging Port Config. & Cascaded Cell Balancing
- Forced Air Cooling

Source: HITACHI

- Power Density → 0.09 kW/dm^3 (System) | ≈ 0.18 kW/dm^3 (SST/Cells incl. Isol.)
- -40% Footprint / -70% Weight vs. LFT-Based Solution / 83% Lower Transf. Volume

Next.-Gen. SSTs — Research Targets

- 10+ kV SiC and/or New Topologies Might Facilitate to Overcome the Power Density Barrier
- AC/DC Efficiencies >98% Remain Difficult to Attain

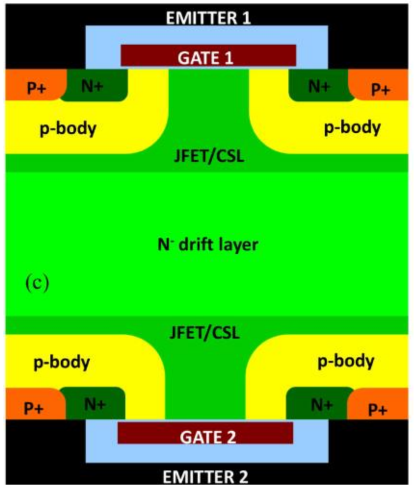


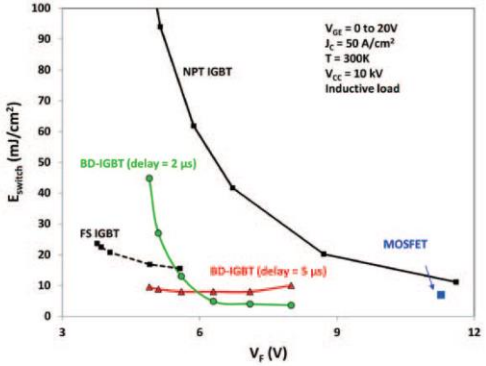
- Full-Scale Demonstrators incl. Mains-Side Overvoltage / DC-Side Overcurrent Protection (!)

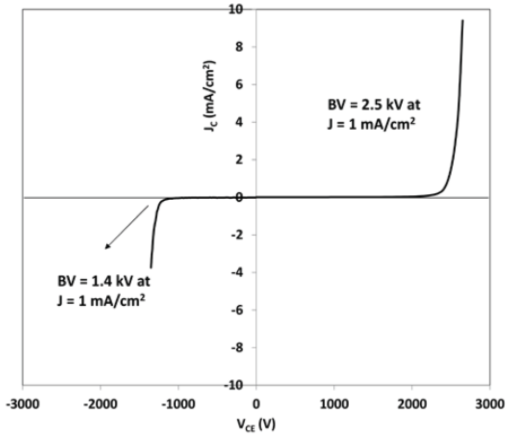
Next.-Gen. SSTs — *Monolithic Bi-Direct. 15 kV SiC IGBT*

- Planar-Gate Bi-Direct. IGBT Fabricated w/ Double-Sided Lithography Process
- Conduction & Sw. Loss Influence of Back-Side Gate Voltage Bias
- Challenging Packaging & Cooling

Chow et al., 2016



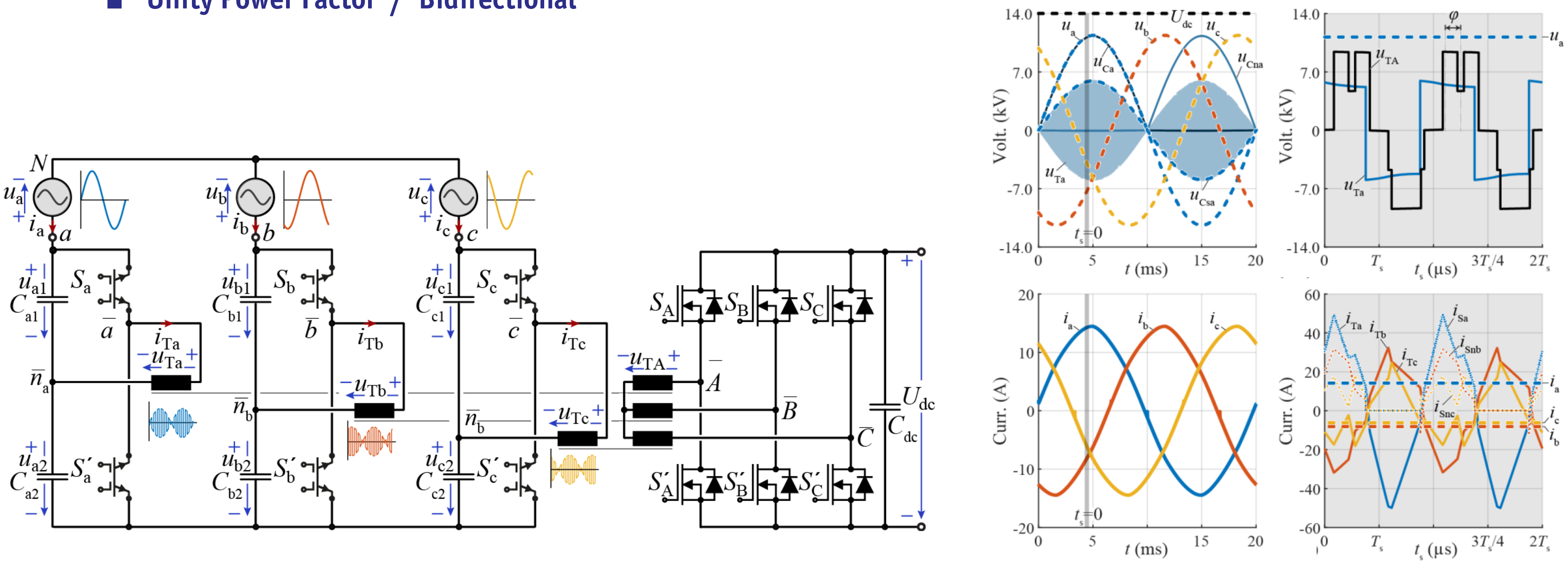




- Simul. Performance of a 15 kV BD-IGBT | Max. 7.2 kV Measured — Epi Layer Defects etc.

Next.-Gen. SSTs — *Novel Swiss-SST Concept*

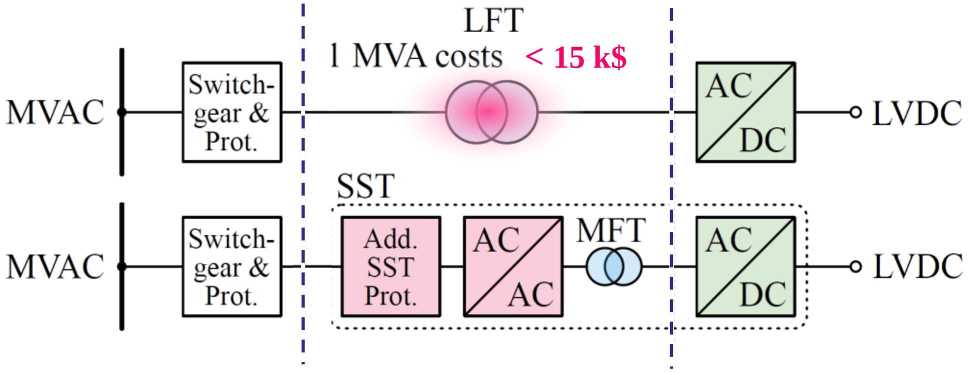
- "Isoltated Front-End"-Topology — Minimum Complexity of MV Power Electronics & Control Circuit
- 15 kV SiC MBD-IGBT — Direct Connection to 13.2 kV Distribution Grid
- Unity Power Factor / Bidirectional

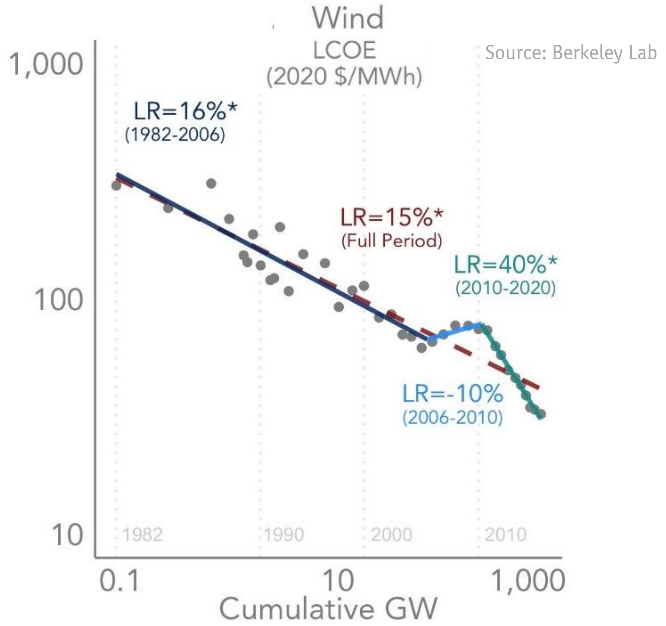


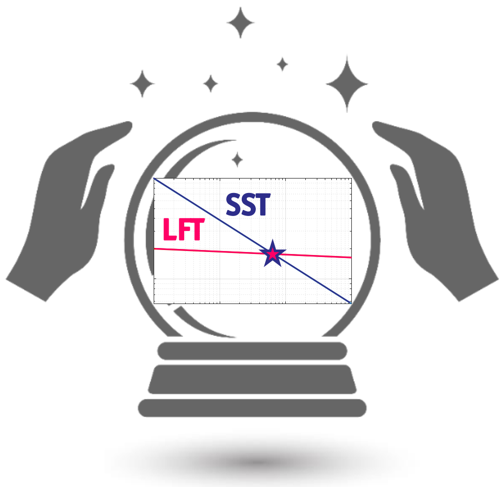
- Dual Active Bridge-Type Control
- AC-Side Phase Modularity — Full Rated Power Operation @ 1-Φ Input (!)

Outlook — *SST Technology Learning Curve*

- Learning Rate — Cost Reduction for Each Doubling of the Cumulative Production
- Prediction of Future Costs of a Technology (e.g. PV or Wind "Grid Parity")





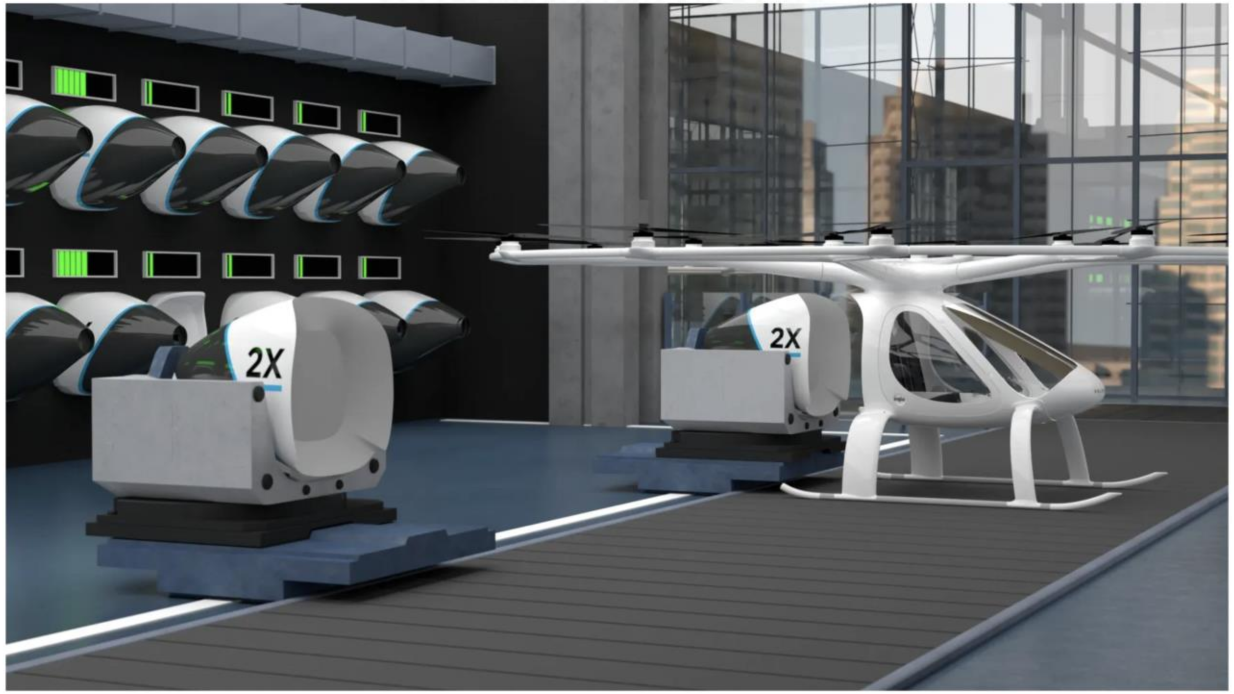


- Typ. Empirical Learning Rates of 15...25% → Dramatic Cost Reduction Over Longer Timespan
- 15 k$ Budget for 1 MVA SST MV Power Electronics & MFT ≈ 10 k$/1 MVA Power Converter → 10 $/kW (!)

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



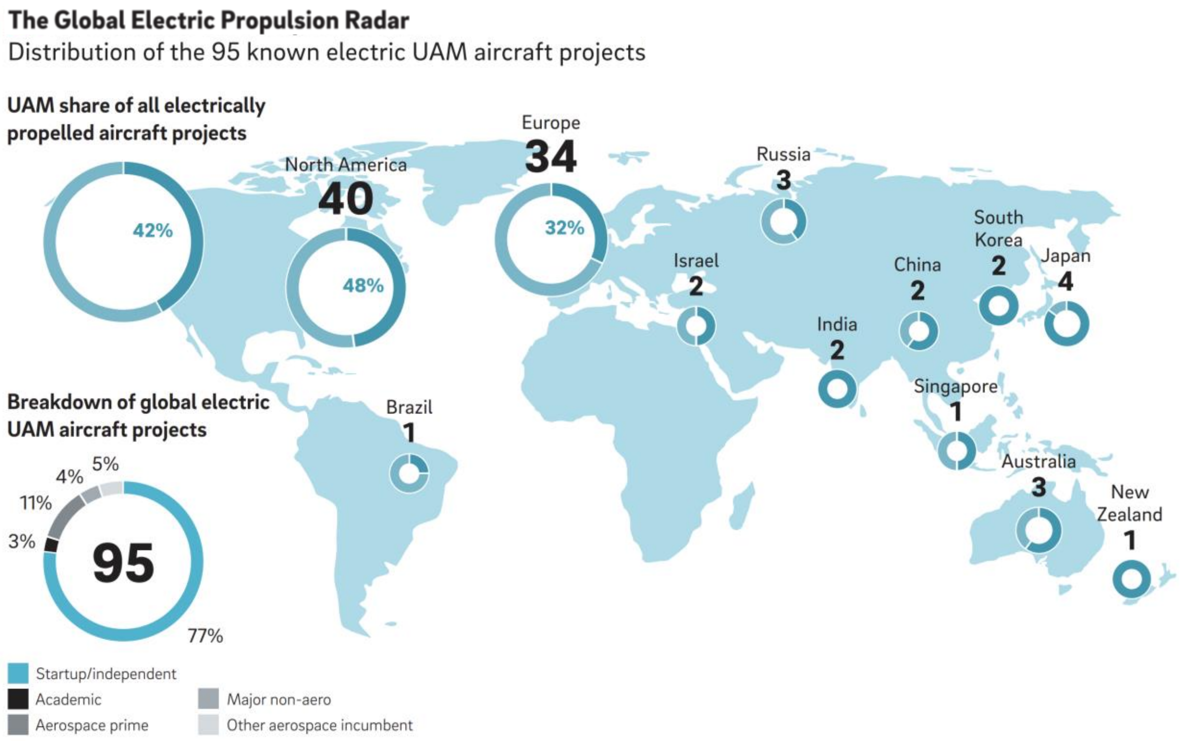
- Disadvantage of Standardized Single-Pack Battery Design & Battery Accessibility

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)



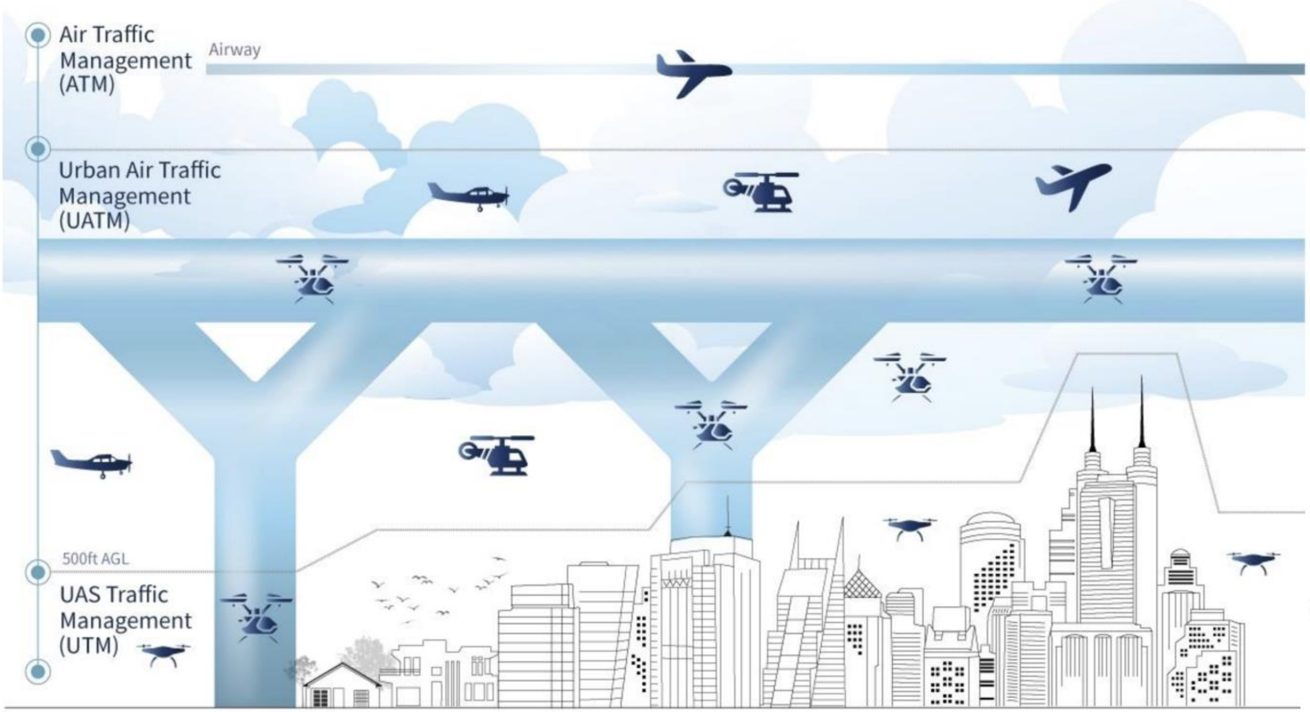
Source: Roland Berger 2020

- Industry Expected to be Ready for Take-Off in 2025
- 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

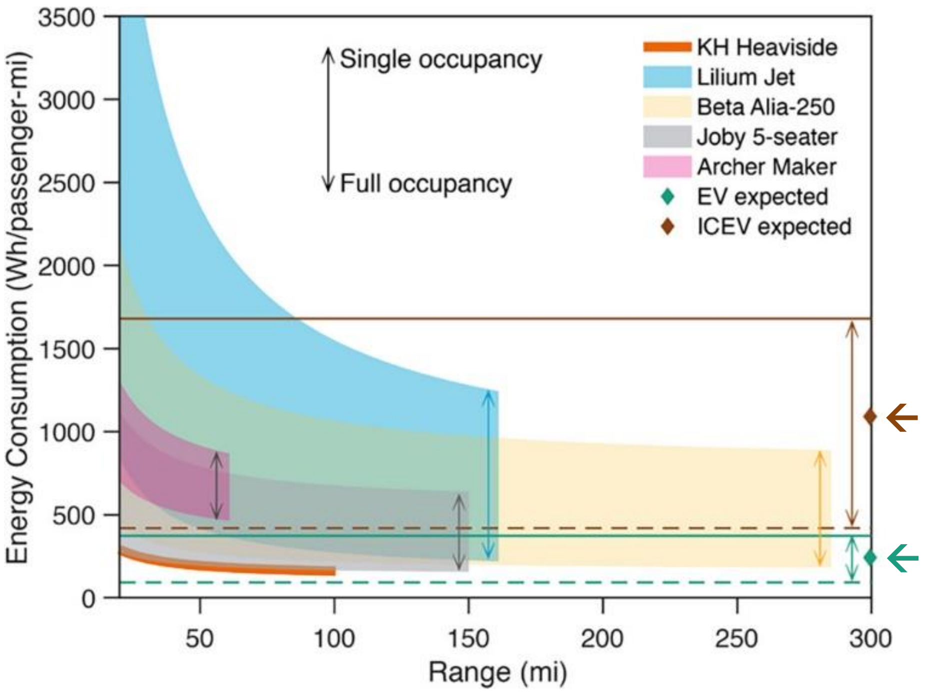
Car vs. eVTOL ◢

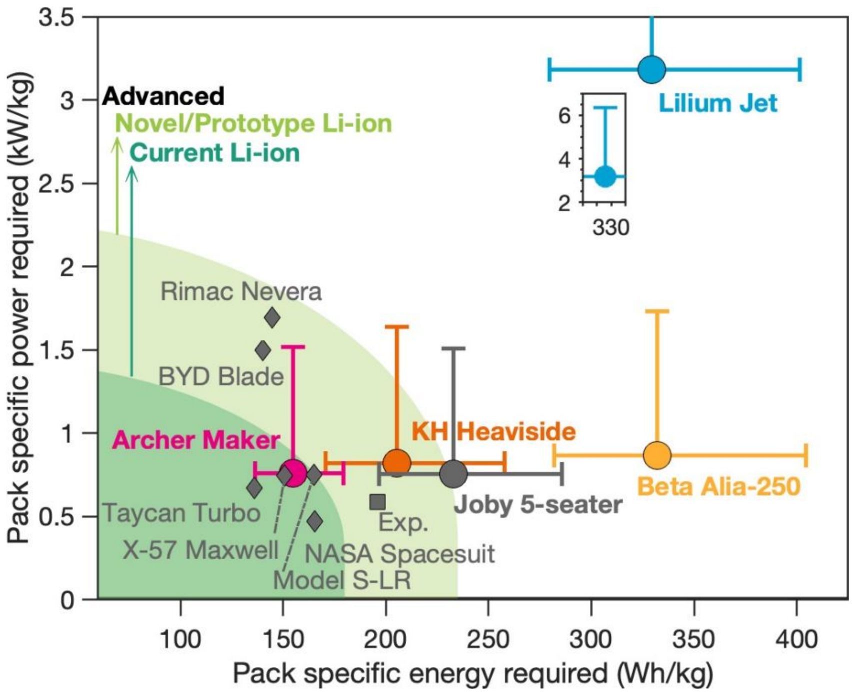
Uber study compared the cost and time of commuting between the cities of São Paulo and Campinas by car and eVTOL

- 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/