Electric & Hybrid Propulsion for UAV, eVTOL and General Aviation: State of the Art 2025

From battery-only to hydrogen fuel-cell hybrid architectures

Torino: December 9th, 2025
Speaker: Dr. Luca Bono

NEXT GENERATION 2025 MOBILITY

BE2HUB

ABOUT US …

Be2Hub s.r.l was founded in 2009 by a **team of professionals** who shared an ambitious challenge: supporting **small and medium enterprises** in advanced **energy management**.

Several collaborations with big companies in advanced studies for the **industrialization of high-performance Lithium cells** have strengthen our knowledge, so that high end **Battery prototypes** were designed and realized by Be2Hub.

Be2Hub has been working on **electrochemical cells analysis and measurement** and on **innovative BMS development,** in order to give 360° support to the customers.

HV BATTERY PACKS VALIDATION & PRE-PRODUCTION

- **Testing** and **measurement** activities on cells: a key support in choosing the best solution
- Supplier's management until production release of HV battery systems:
  - Support for **Validation activities** according to OEM-requirements
  - Support & S**election of suppliers**, creation of requirement specifications
  - Enabling of battery suppliers into customer specific development processes
- Advisory in **design**, **risk analysis** and verification of **safety functions** of the battery system
- Support for functional-, **hardware- and software development**
- Implementation of **software modules** into battery management environment
- Battery pack layout optimization to match mechanical and functional requirements of the end user.

HV BATTERY PACKS CONCEPTS AND PROTOTYPES

- Conception of **vehicular battery systems** and development of prototype especially focusing on:
  - **Risk Analysis** and preliminary design optimization
  - **Thermal management** {Cooling and Pre-conditioning)
  - **Battery management** {SOC, SOH, SOF)
  - Prototype: **modular and scalable system**
- Housing and assembly design of the battery system, including the integration inside the vehicle
- Cooling concept and simulations
- Development and dimensioning of HV wiring system
- Testing activities and performance checks
- Ensuring complete system integration with the vehicle electrical drive train
- Implementation of early diagnosis functions
- Support in concept validation on test bench and on the vehicle

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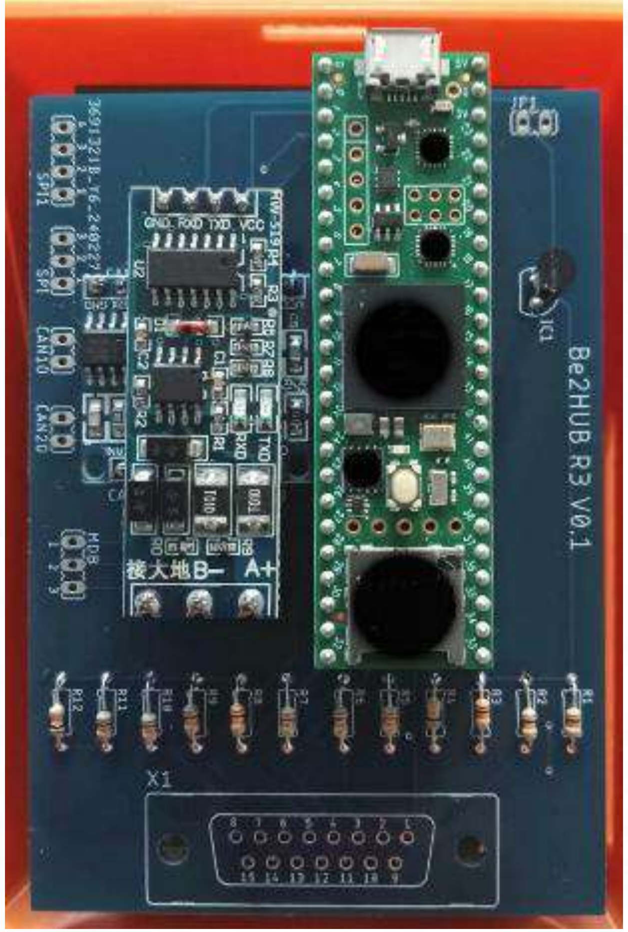
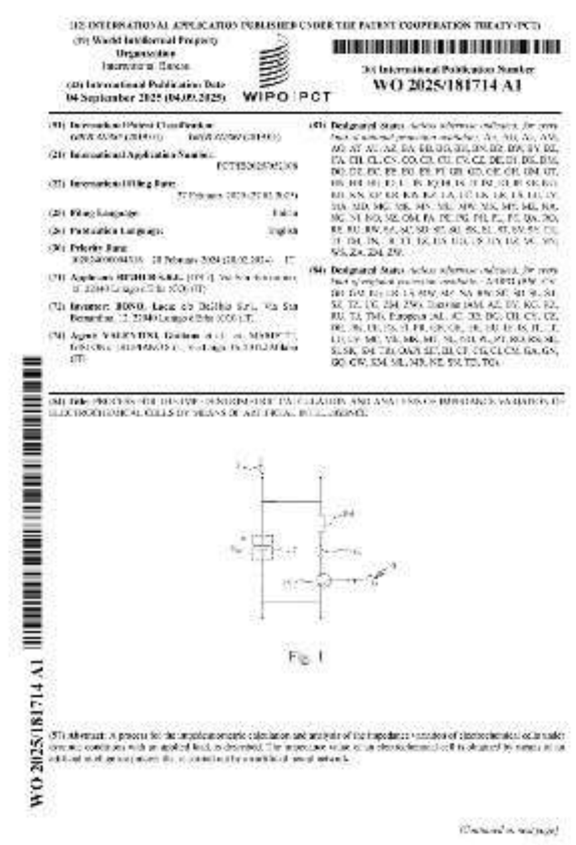


Be2Hub confirms the requirements already indicated in April: 200 Hz
The testing at 230 Hz has been already conducted, but not certified.

2024 APRIL Validated performances

- ADC 16 channels 24-bit resolution for Voltage
- ADC 12 channels 12-bit resolution for Temperature and Pressure
- N.2 FD Can Bus lines for Master BMS Communication
- N.1 Modbus Line for External Monitor/Debug
- 5ms Time Cycle (200Hz frequency sampling)
- <100mA Power Consumption
- Active Balancing System
- Extended dynamic EIS


WIPO | PCT
WO 2025/181714 A1
Fig. 1
WO 2025/181714 A1

The Future is Electric

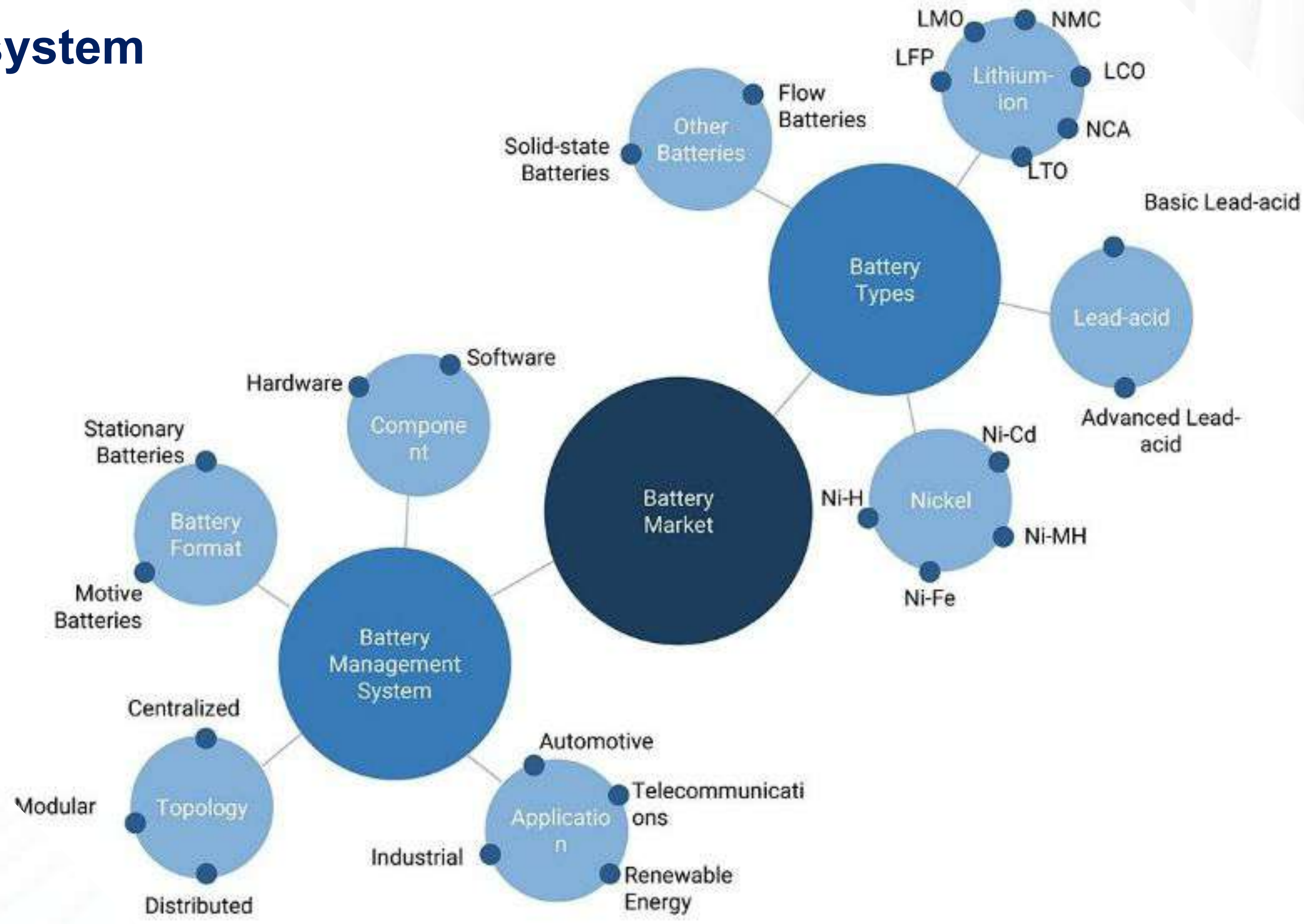
In addition to Electric Vehicles, other **modes of mobility** are rapidly transitioning

The future of grids relies heavily on performant and cost-effective batteries

Batteries power **future tech industry**

Cutting-edge batteries power **Europe's defence**

A complex Ecosystem



Agenda

Objective: Provide an integrated overview of components, aircraft platforms and industrial trends.

- ❑ Drivers of the transition to electric aviation
- ❑ Electrified propulsion architectures
- ❑ State of the art — UAV and eVTOL
- ❑ State of the art — General Aviation (GA)
- ❑ Fuel Cell & Hydrogen Electric systems
- ❑ Open challenges
- ❑ Roadmap 2025–2040
- ❑ Take-aways

Why Electrify UAV / eVTOL / GA

Technological and market drivers

- Aviation decarbonization and ICAO/EU regulations.
- Rapid growth of low-altitude missions: inspection, logistics, precision agriculture, civil safety.
- Urban Air Mobility (UAM): new operational models and EASA SC-VTOL standards.
- Noise reduction → enabling urban and suburban operations.
- Electric propulsion efficiency up to **80–90%** (vs **20–35%** for ICE).
- Distributed electric multi-motor systems → increased redundancy and controllability.

Challenges

- Battery energy density still insufficient.
- Critical thermal management during hover and high-power climb.
- Immature charging infrastructure and hydrogen refueling systems.

Electrified Propulsion Architectures

1. All-Electric (Battery Powered)

- Electric motors + inverters + batteries.
- Dominant for UAV < 30 kg and urban eVTOL.
- Zero local emissions.

2. Hybrid Electric (ICE + Generator + Battery)

- Series: ICE → generator → electric motors.
- Parallel: power split between ICE and electric motor.
- Turbo-electric: turbine/microturbine + electric power distribution.

Electrical Propulsion Architectures

There are three main architectures for Electrical Propulsion.

Hybrid-electric

Hybrid-electric is one of two architectures:

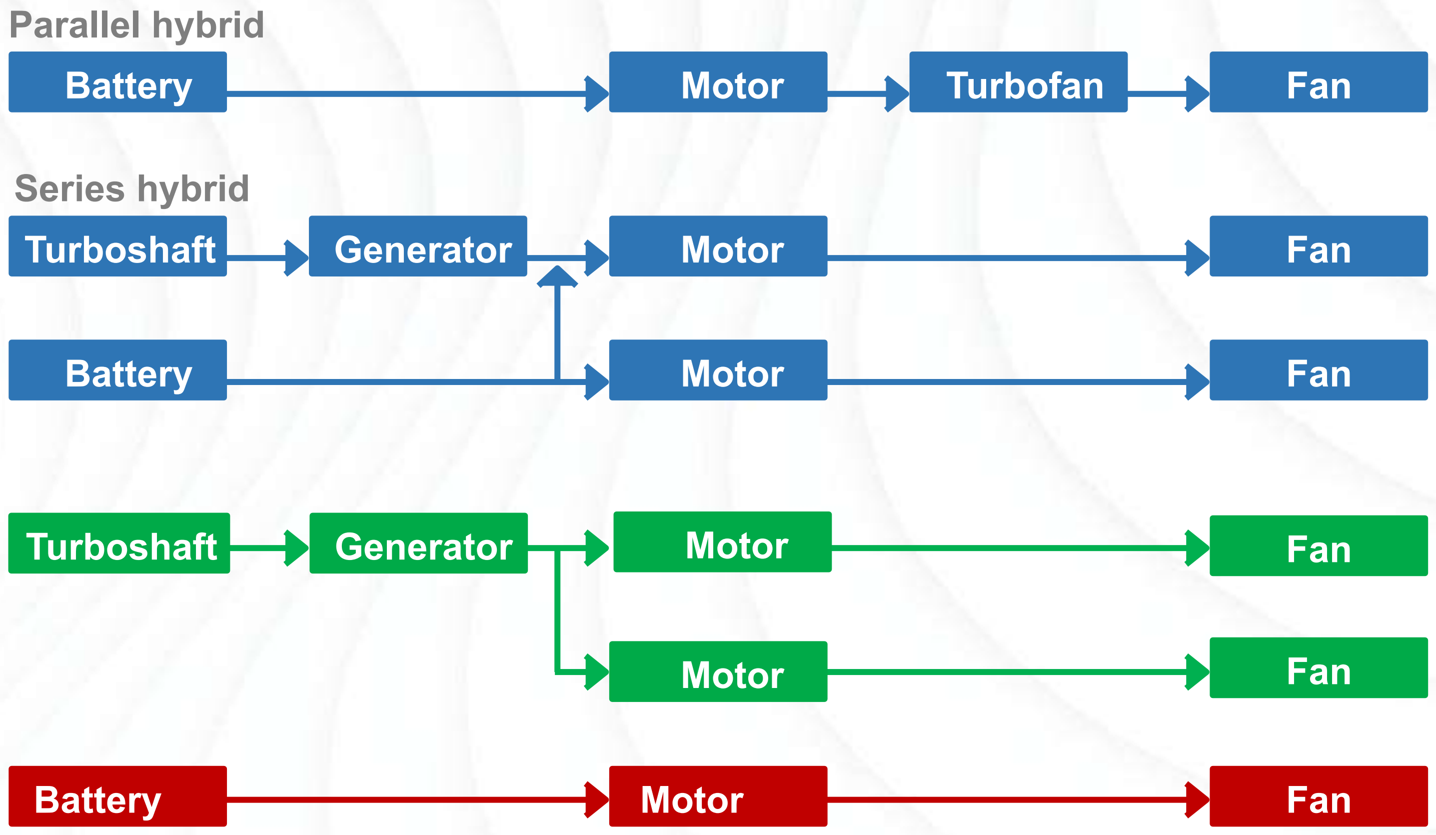
- Parallel or Series hybrid. Additional electric energy can be used for acceleration and in times of high power demand, and bi-directional flow of power is possible between the generator and battery.

Turbo-electric

The kinetic energy of a turbo shaft is transformed into electric energy via a generator to drive multiple, distributed fans, with the fans driven by electric motors.

All electric

One, or multiple, fans are driven by electric motors with energy stored in a battery.



Energy & Power Landscape

Batteries (today)

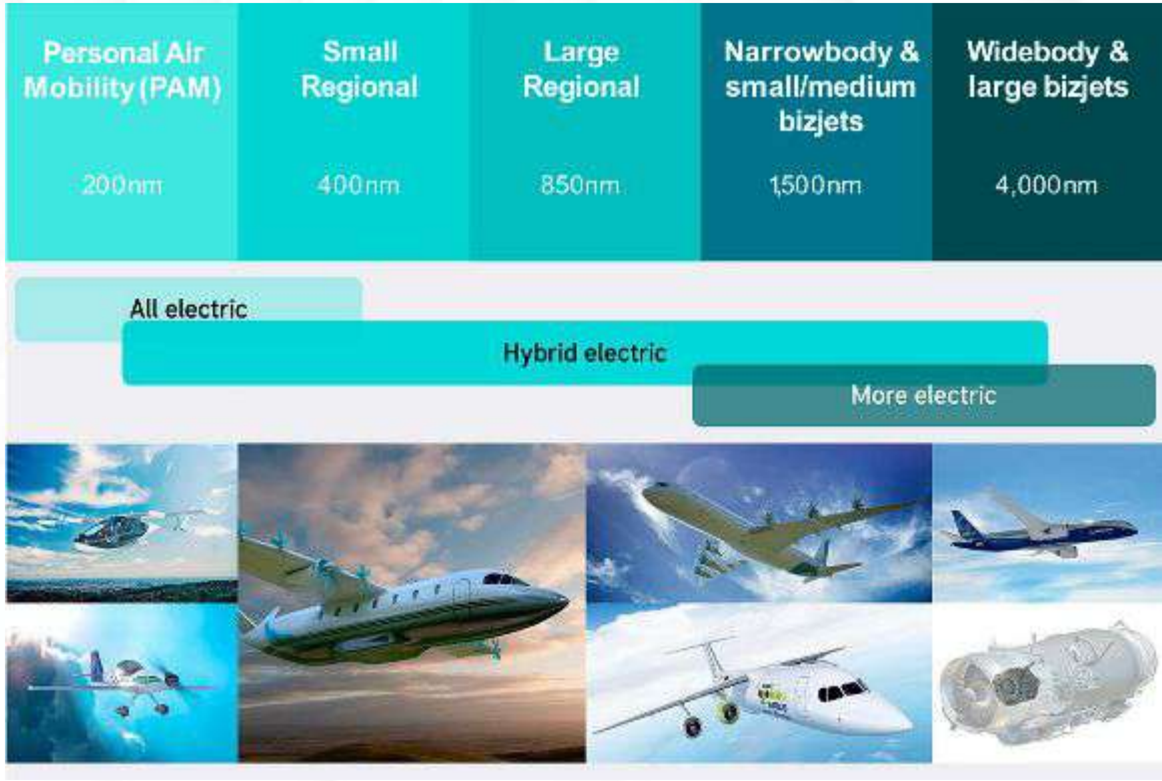
- 250–300 Wh/kg at cell level → **150–200 Wh/kg** at pack level for aviation.
- Annual improvement: **3–5%**.
- Main limiting factor for eVTOL.

Fuels/Energy carriers

- Jet fuel: ~12,000 Wh/kg (LHV).
- Compressed H_2 (700 bar): 2,000–3,000 Wh/kg (system level).
- Liquid H_2: higher density but requires cryogenics.

Implications

- All-electric: missions < 60–90 min.
- Hybrid-electric: extended range (2–5×).
- Fuel-cell: high-endurance missions and zero-emission potential.



UAV All-Electric: State of the Art 2025

Characteristics

- Dominance of Li-ion / Li-Po batteries.
- Simplicity, low weight, low cost.
- Excellent efficiency at low altitude.

Performance

- Typical multirotor endurance: **20–45 min**.
- Fixed-wing electric endurance: **1–3 h**.
- Solar-assisted: missions **10–24 h**, depending on profile and solar area.

Limitations

- High C-rate hover → thermal and capacity degradation.
- Significant endurance drop with payload.

Hybrid UAV (Generator + Battery)

Motivation

Overcome endurance limitations of fully electric multi-copters.

Architecture

- Small ICE + generator → “range extender”.
- Battery handles transients (take-off, maneuvers).

Advantages

- **3–10×** greater endurance.
- Suitable for long missions with meaningful payload.

Disadvantages

- Vibrations, maintenance, fuel safety.
- Higher complexity in multi-source energy management.

Source: HYBRiX - Quaternium

Source: YANGDA Sky Whale Hybrid Heavy Lift Long

Hydrogen & Fuel Cell UAV

Technology (PEM + Battery)

- FC provides continuous power.
- Battery handles peaks and transients.

Typical endurance

- Medium UAV with FC: 3–10 h, up to >12 h.
- Ideal for surveillance, scientific missions, telecommunications.

Challenges

- Pressurized H_2 tanks → weight & volume.
- Stack thermal management.
- Water management (humidity, freezing).
- System cost (stack + BoP).

Source: SDO 50 Swissdrone

Source: PRODRONE (J)

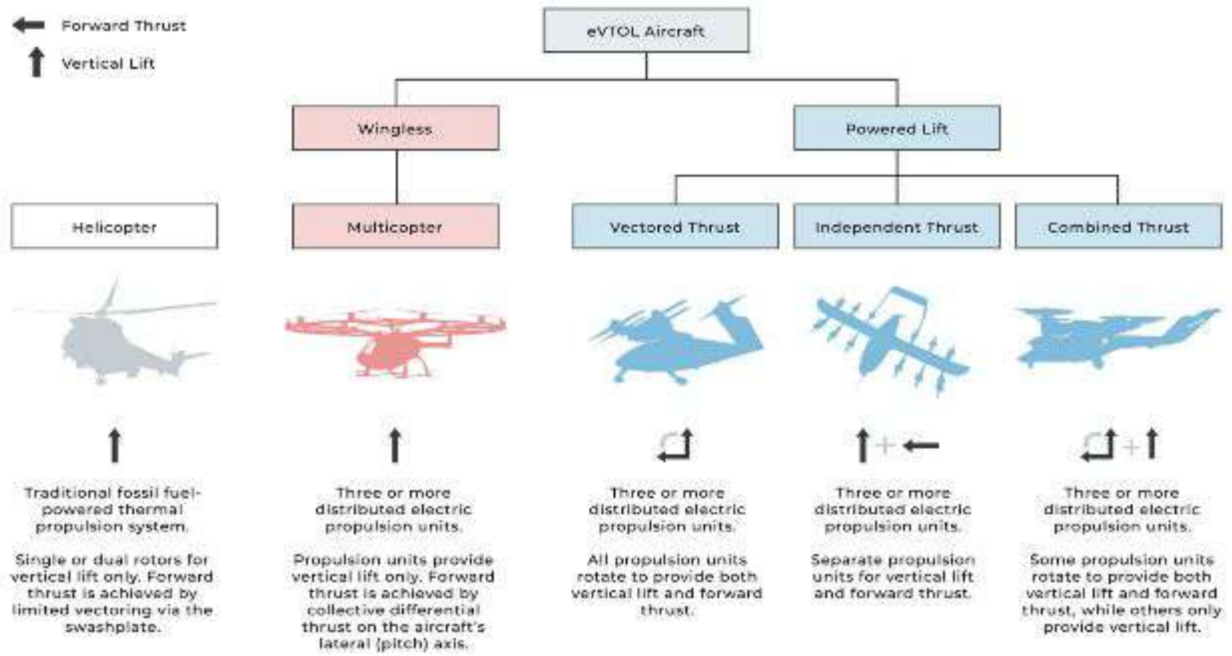
VTOL UAV & eVTOL: Technological Overview

Configurations
- Conventional multirotor.
- Tilt-rotor / tilt-wing.
- Lift + Cruise (dedicated lift and cruise motors).

Industry trend
- Nearly all UAM prototypes are all-electric.
- EASA SC-VTOL: very stringent safety requirements.

Limitations from 2023–2025 literature
- Battery mass fraction too high.
- Hover energy remains the main bottleneck.
- Need for fault-tolerant architectures (motor, inverter, battery redundancy).

Propulsion architectures of eVTOL aircraft



All-Electric eVTOL (Industry)

Examples

- Vertical VX4: 4 passengers, >100 nm, all-electric.
- Archer Midnight, Joby S4: similar architectures.

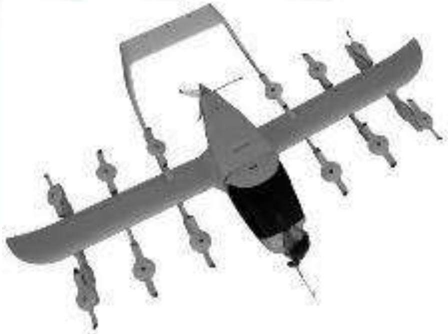
Advantages

- Low noise → urban operations.
- Zero local emissions.
- Simplified mechanical architecture.

Limitations

- Battery mass incompatible with >150 km range.
- Thermal stress over multiple flight cycles.
- Certification requires deep redundancy.

Joby Aviation eVTOL



Wisk Generation 5

Vertical Aerospace VX-4

Hybrid-Electric eVTOL

Why hybrid?

- Solve range/endurance constraints.
- Enable regional operations (200–500 km).

Examples

- Horizon Cavorite X7: hybrid-electric, 7 pax, 800 km.
- US/Canada turbine-generator hybrid experimental programs.

Benefits

- 50–70% reduction in battery mass.
- More flexible mission profiles.

Source: Horizon Aircraft Cavorite X7 (concept design)

Source: Archer Plans Hybrid VTOL

Electric General Aviation (GA ≤ 2 pax)

Current situation

- Velis Electro (EASA certified).
- Electric motorgliders for training.

Realistic applications

- Training (short cycles).
- Eco-tourism and short recreational flights.

Limitations

- 30–60 min endurance + reserve.
- Slow recharging infrastructure for heavy use.

Hybrid & Hydrogen-Electric General Aviation

Key projects 2024–2025

EcoPulse (Airbus/Daher/Safran):

- Demonstrator for distributed hybrid-electric on TBM 900.
- Energy savings and improved controllability.

ZeroAvia (Dornier 228):

- H_2-electric pod on 19-seat turboprop.
- Goal: 300–600 km flights.

Applications for GA 4–9 seats

- Serial/parallel hybrid as intermediate solution.
- Benefits: 20–30% fuel burn reduction, noise reduction.

Sorce: ZA600 - ZeroAvia

Sorce: TBM900 EcoPulse Hybrid-electric Aircraft

Fuel Cell Systems & Digital Twin

Key components

FC stack, compressor, humidifier, heat exchangers, DC/DC.

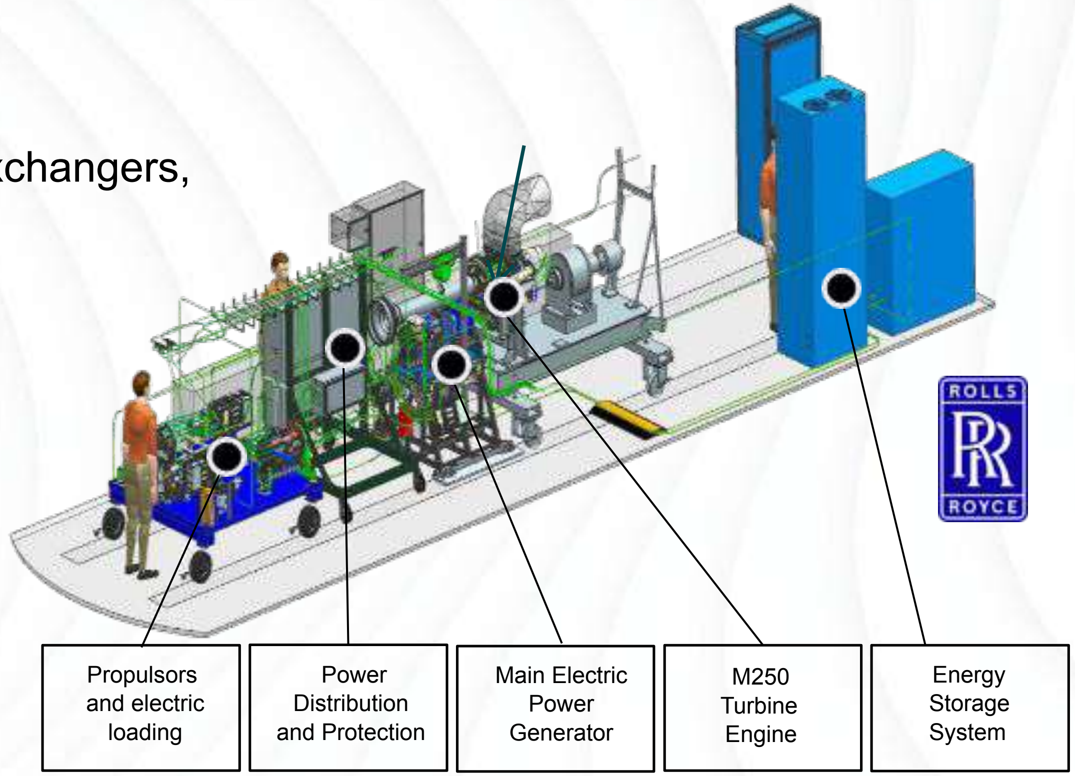
2024–2025 trends

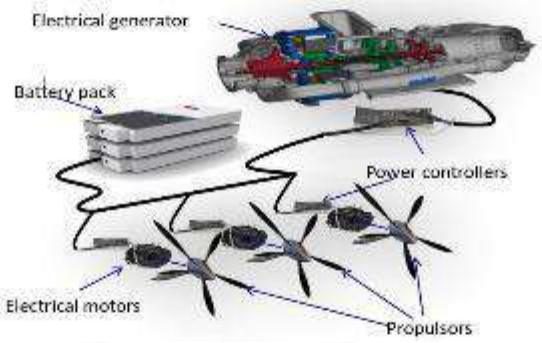
Digital twin adoption for:

- degradation modelling
- fault prediction
- power-split optimization
- virtual testing & certification

Benefit

Reduced physical testing → faster development and increased safety.





Demonstrating modes of operation:

- Series hybrid
- Parallel hybrid
- Turbo-electric

Initial ground tests successfully completed Q4 2018

Gaining understanding of how the architecture performs and the potential requirements for a future flight-ready system

Challenges (Challenge Matrix)

Technology

- Battery mass / H_2 tank mass
- Motor & inverter power densità
- Safety-related redundancy

Reliability & Certification

- Evolving SC-VTOL, CS-23, CS-25
- Safety requirements: DAL-A/B for commercial eVTOL
- Standards still evolving

Operations & Infrastructures

- Charging for urban eVTOL & Fast charging
- H_2 production & H_2 refueling
- Liquefaction and distribution for GA/regional aviation.

Thermal management & safety

- Cooling for motors
- inverters
- FC stacks
- fire protection & crashworthiness

Costs & business model

- Operating costs → high TCO
- LCOE for drone logistics, UAM, and regional turboprop operators.

Market

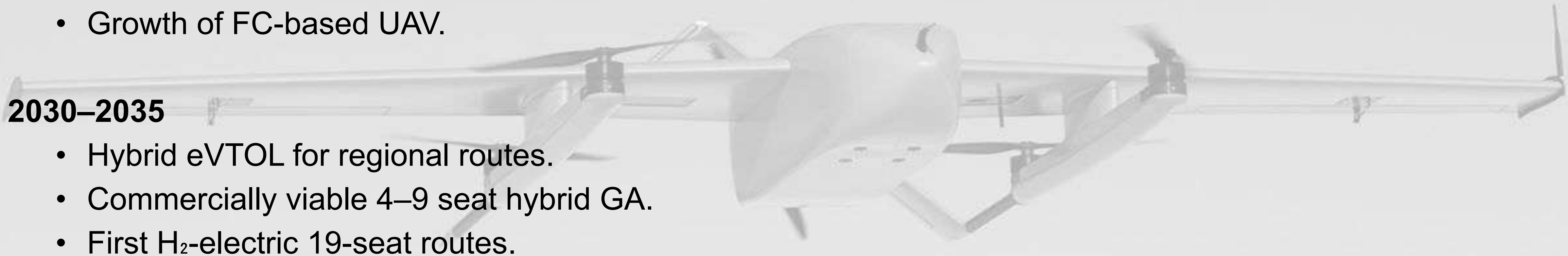
UAM business model still immature

Fleet ROI and urban integration challenges

Roadmap 2025–2040

2025–2030

- First certified all-electric eVTOL.
- Hybrid-electric demos in GA.
- Growth of FC-based UAV.



2030–2035

- Hybrid eVTOL for regional routes.
- Commercially viable 4–9 seat hybrid GA.
- First H_2-electric 19-seat routes.

2035–2040

- Hydrogen-electric regional turboprop (40–70 seats).

Implications for Operators & Industry

- **UAV**: growing demand for long-endurance (FC) and hybrid-electric versatility.
- **eVTOL**: convergence toward mixed architectures balancing safety, endurance, noise.
- **GA**: first practical sector for hybrid-electric adoption.
- **Regional aviation**: next frontier for hydrogen-electric.

Take-aways

Electric propulsion is not just about batteries, but a scalable combination of:

- Batteries, fuel cells, ICE/turbine, solar power.
- No single solution: batteries, FC and ICE/hybrid will coexist.
- Main bottleneck: **energy management** (density + thermal).
- Breakthroughs will come from **system–aircraft–mission integration**.
- Hybrid systems will remain key for at least 15 years.
- Hydrogen-electric is the long-term destination for regional aviation.

UAVs and VTOLs serve as a laboratory for:

- multi-rotor architectures, DEP, advanced power management.

General Aviation is the training ground for certifiable technologies (engines, BMS, fuel cells).

The real challenge is not only the cell, but:

- the integration of system–aircraft–mission–business model.

Collaboration is essential across:

- aerodynamics, structures, electrochemistry, control systems, and regulatory frameworks.

References

- Yu F. et al., *A Review of Hybrid-Electric Propulsion in Aviation*, **Aerospace**, 2025.MDPI
- Kuśmierek A. et al., *Review of the Hybrid Gas–Electric Aircraft Propulsion Systems*, **Energy Reports**, 2023.ScienceDirect
- Abdulrahman G.A.Q. et al., *A review of powering unmanned aerial vehicles by clean and renewable energy technologies*, **Sustainable Energy Technologies and Assessments**, 2025.ScienceDirect
- Y. Alqudsi et al., *A Comprehensive Review of VTOL UAVs: Design, Technologies and Applications*, **Preprints**, 2025.Preprints
- Shen Z. et al., *A Review on Key Technologies and Developments of Hydrogen Fuel Cell Powered UAVs*, **Energies**, 2024.MDPI
- SciOpen, *Review of key technologies for hydrogen powered UAVs*, **Chinese Journal of Aeronautics**, 2024.SciOpen
- Donateo T. et al., *Simulation Approaches and Validation Issues for Open Cathode Fuel Cell Systems and Digital Twins*, **Energies**, 2024.iris.unisalento.it
- GAMA, *White Paper on Electric Aviation*, April 2024.GAMA
- ZeroAvia, *Scaling Hydrogen–Electric Propulsion for Large Aircraft*, 2024.zeroavia.com
- Clean Aviation Joint Undertaking, *Work Programme and Budget 2024–2025*, 2023.clean-aviation.eu
- Airbus, *EcoPulse results suggest a bright future for hybrid-electric aviation*, 2025.

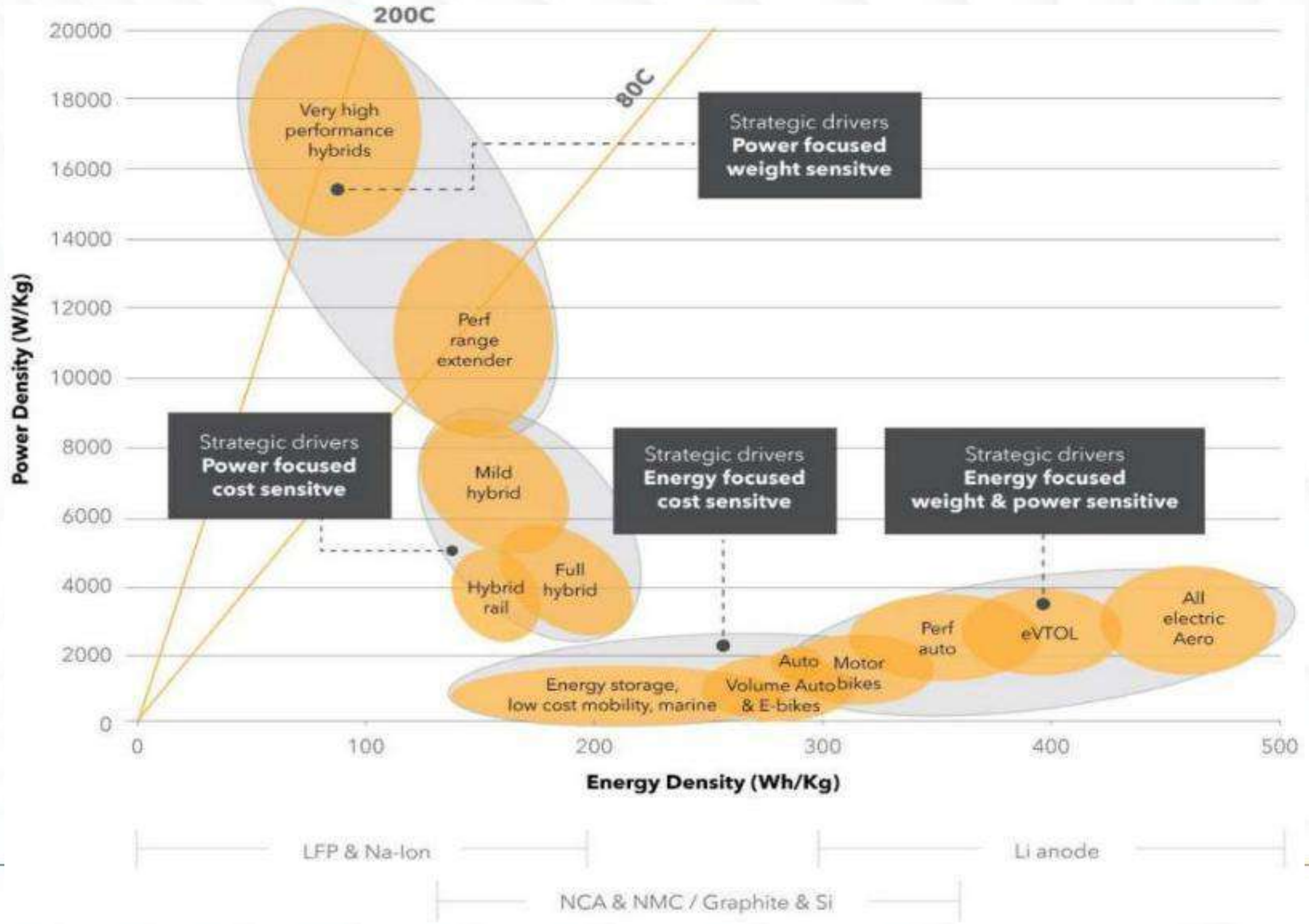
Using these Next-Gen Materials

- **When will these materials be readily available?**
- **How will these materials be embedded into production?**
- **How can the supply chain be ready to adopt Next-Gen materials?**



ELETTRIFICATION: DREAM or REALITY?

Cross Sector Performance Requirements



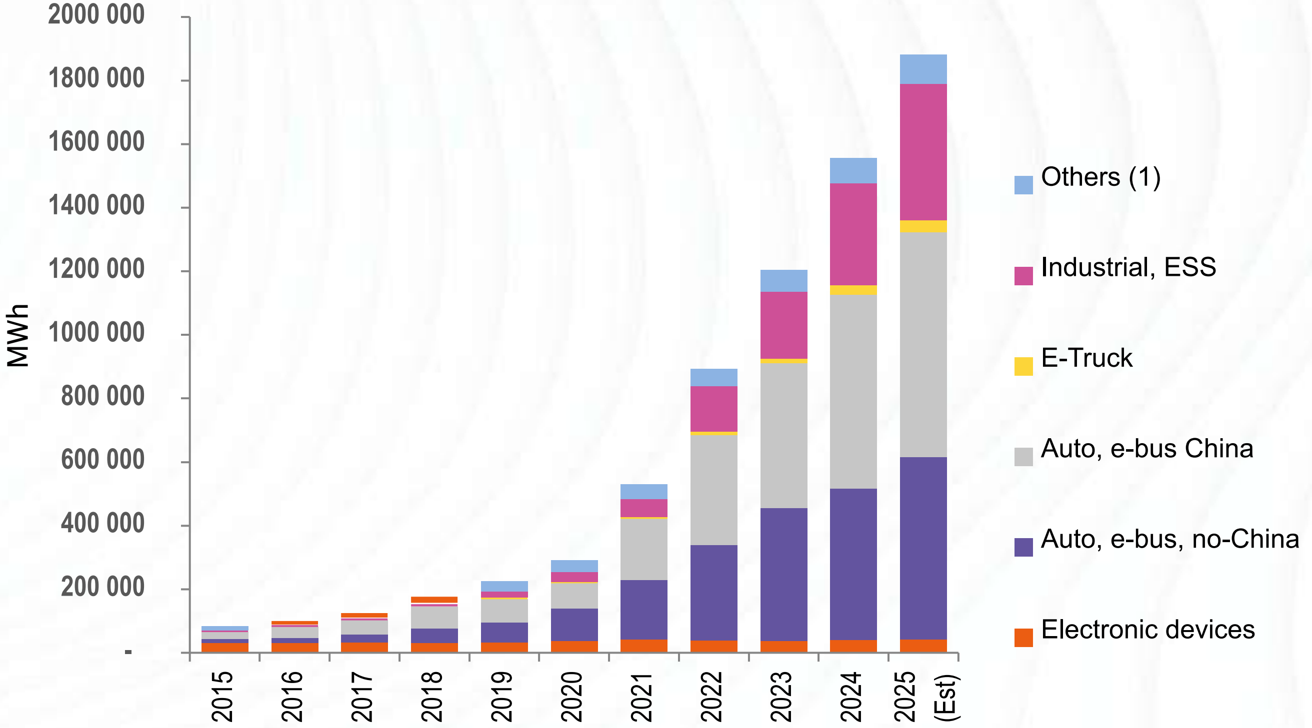
The Lithium-ion battery market 2000 - 2025

In 2024, EV, e-buses & e-trucks account for 72% of the li-ion battery market with a total LIB market of ~ 1.600.000 MWh

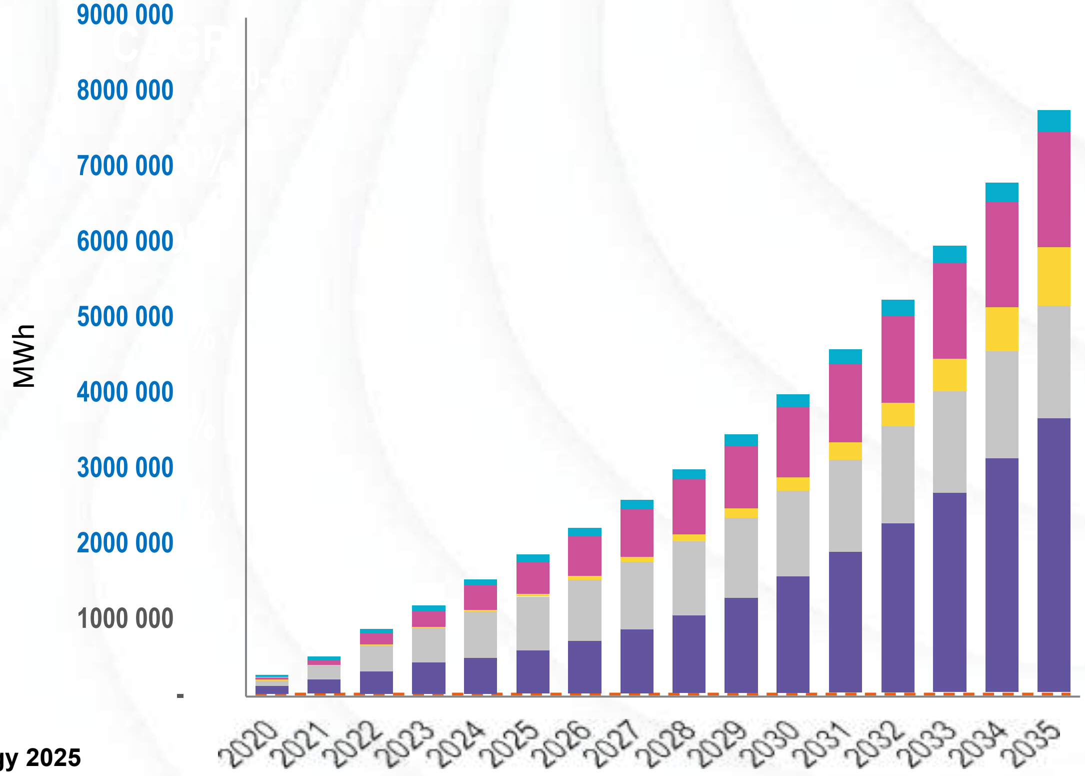
Li-ion battery market forecasts - 2035

The Lithium-ion battery market will grow to ≈7.800 GWh in 2035, with a CAGR 25-35

Li-ion Battery sales worldwide, 2015-2025, MWh



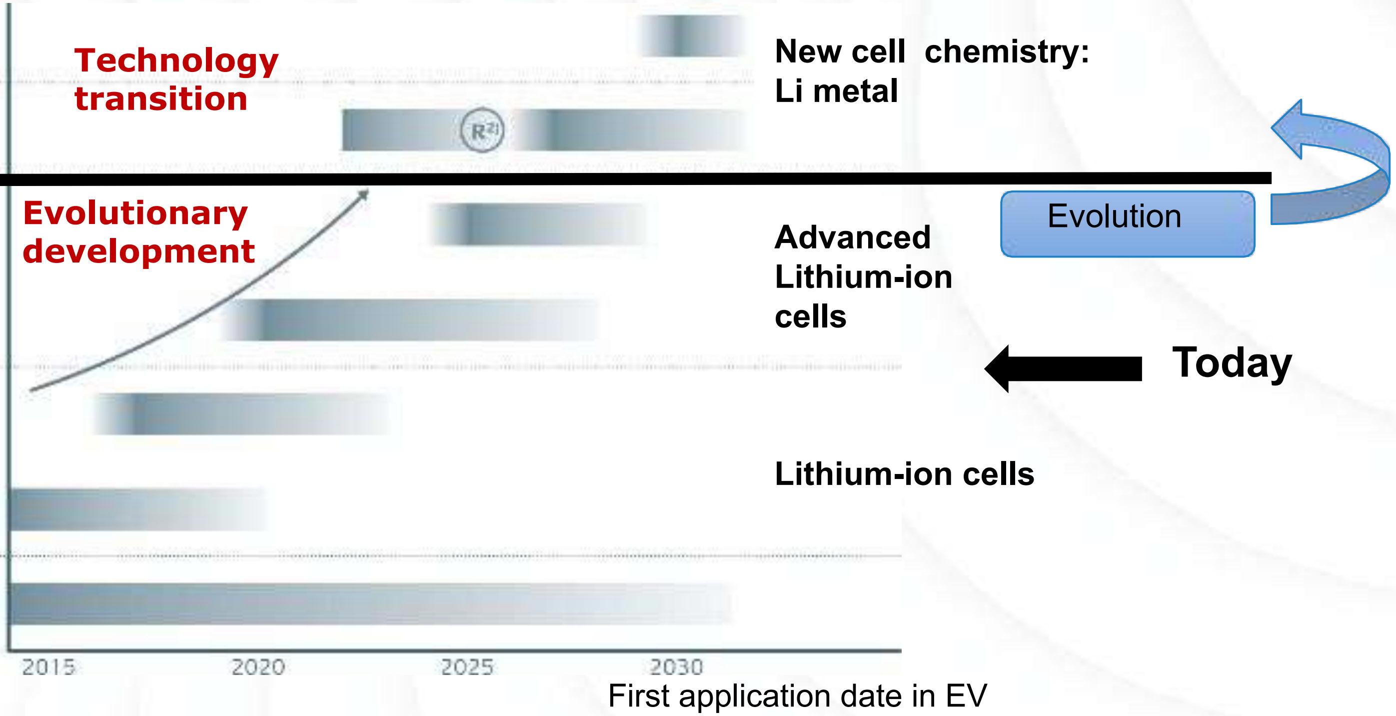
Li-ion Battery sales, Worldwide, 2020-2035, MWh



Source: Avicenne Energy 2025

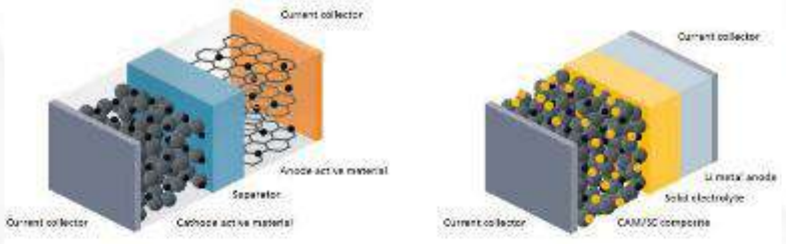
Technological Roadmap of Battery Cell Chemistries

Generation 5	Li/O_2 (lithium-air)	
Generation 4	All-solid-state with Li metal anode; Conversion materials (Li/S)	
Generation 3b	Cathode: HE-NCM, HVS Anode: Silicon/carbon	
Generation 3a	Cathode: NMC622 to NMC811 Anode: Carbon + Si (5-10%)	
Generation 2b	Cathode: NCM523 to NCM622 Anode: 100% Carbon	
Generation 2a	Cathode: NCM111 Anode: 100% Carbon	
Generation 1	Cathode: LFP, NCA Anode: 100% Carbon	



Adapted from: Nationale Plattform Elektromobilität (NPE), *Roadmap integrierte Zell- und Batterieproduktion Deutschland*, **2016**.

Solid State Batteries Advantages



Liquid electrolyte LIB   Solid-state battery

Higher Energy Density
Can store more energy per volume or weight.

Improved Safety
Solid electrolytes are non-flammable, reducing fire risk compared to liquid electrolytes.

Wider Operating Temperature Range
Solid electrolytes are more thermally stable, allowing safer high-temperature operation.

Longer Cycle Life
Potentially less degradation over time due to reduced dendrite formation and stable interfaces (with the right materials and engineering).

Faster Charging (Theoretically)
If interfacial resistance is managed, SSBs can support higher current densities and faster ion transport.

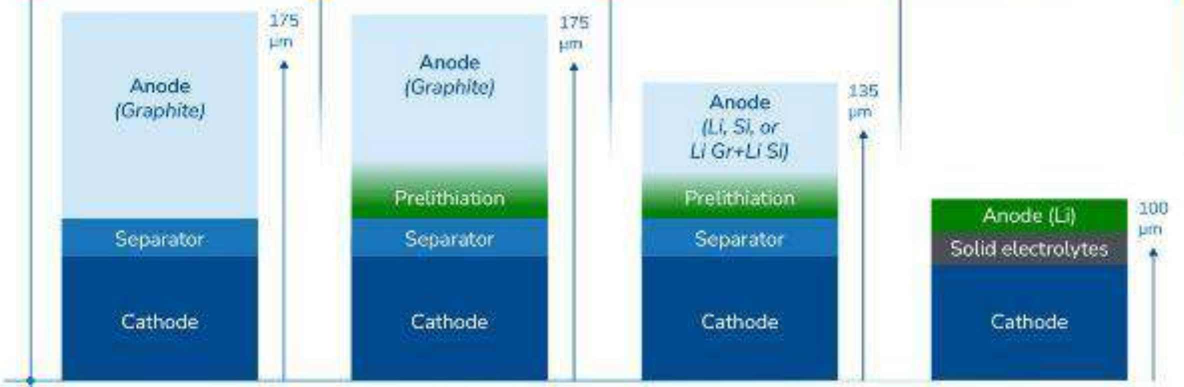
Compatibility with Lithium Metal Anodes
Enables use of lithium metal, which can boost energy density significantly over graphite anodes.

Lithium-ion Industry Energy Density Roadmap

Elevated’s ultra-thin lithium solutions improve battery performance across a wide set of applications

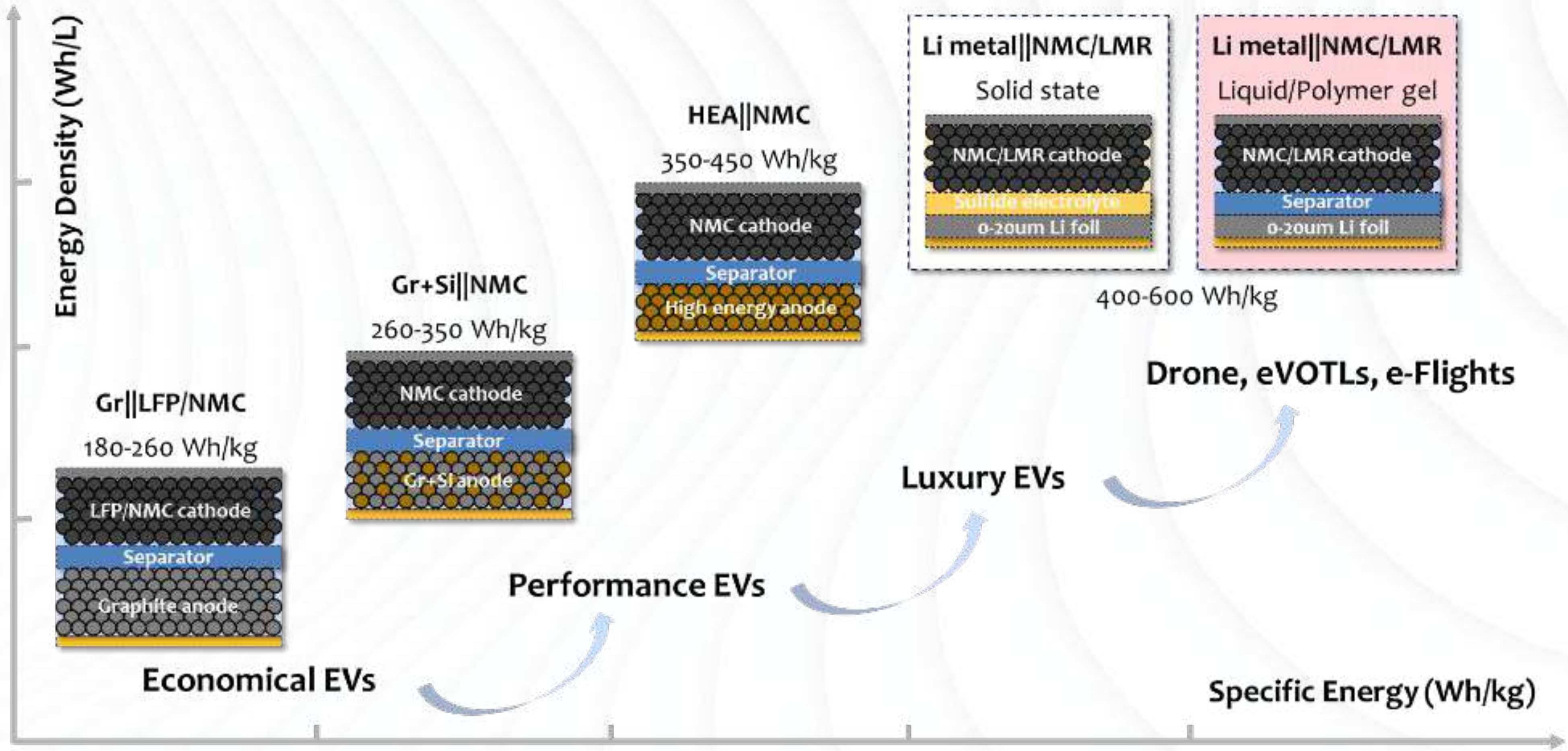
Technology Roadmap

Ultra-thin lithium is required for all high performing batteries



	Graphite (baseline)	Graphite (+LFP cathode)	Graphite + Silicon	Lithium Anode (Hybrid or all SSB)
Ultra-thin lithium		2 - 3 µm	4 - 10 µm	10 - 20 µm
Energy density	250 Wh/kg	+10%	+30 - 40%	+70%
Cycle life	1,000 - 5,000	3X (12,000)	>1,000	>1,000
Rapid charge	30 min, 100%		15 min, 100%	
Applications		EV (Grid storage)	EV, eAircraft, CE	EV, eAircraft

Motivation of liquid/gel electrolyte based LMB



Cell level energy density (ED) and performance metrics by battery technology

Technology development	Current Li-ion (NMC vs graphite)	Lithium-metal anodes	Silicon anodes	Lithium sulfur	Solid state sulfidic	Solid state oxidic
Current gravimetric ED Wh/kg	~280	-	~350	-	-	-
Future gravimetric ED Wh/kg	~300*	~450*	~450*	~500*	~500*	~400*
Current volumetric ED Wh/L	~700	-	~850	-	-	-
Future volumetric ED Wh/L	~800*	~1,000*	~950*	~700*	~1,200*	~1,200*
Power capability	Average	Good	Good	Poor	Good	Good
High temperature operation	Poor	Poor	Poor	Good	Good	Good
Low temperature operation	Average	Average		Average	Poor	Poor

Solid State Batteries Limitations

Manufacturing Complexity & Cost
Difficult and expensive to produce at scale; thin, defect-free solid electrolyte layers are challenging. Processing often requires dry rooms or high pressure.

Interfacial Challenges
Solid–solid interfaces are hard to maintain with good contact over time (especially under cycling or stress). High impedance and degradation at interfaces can cause performance loss.

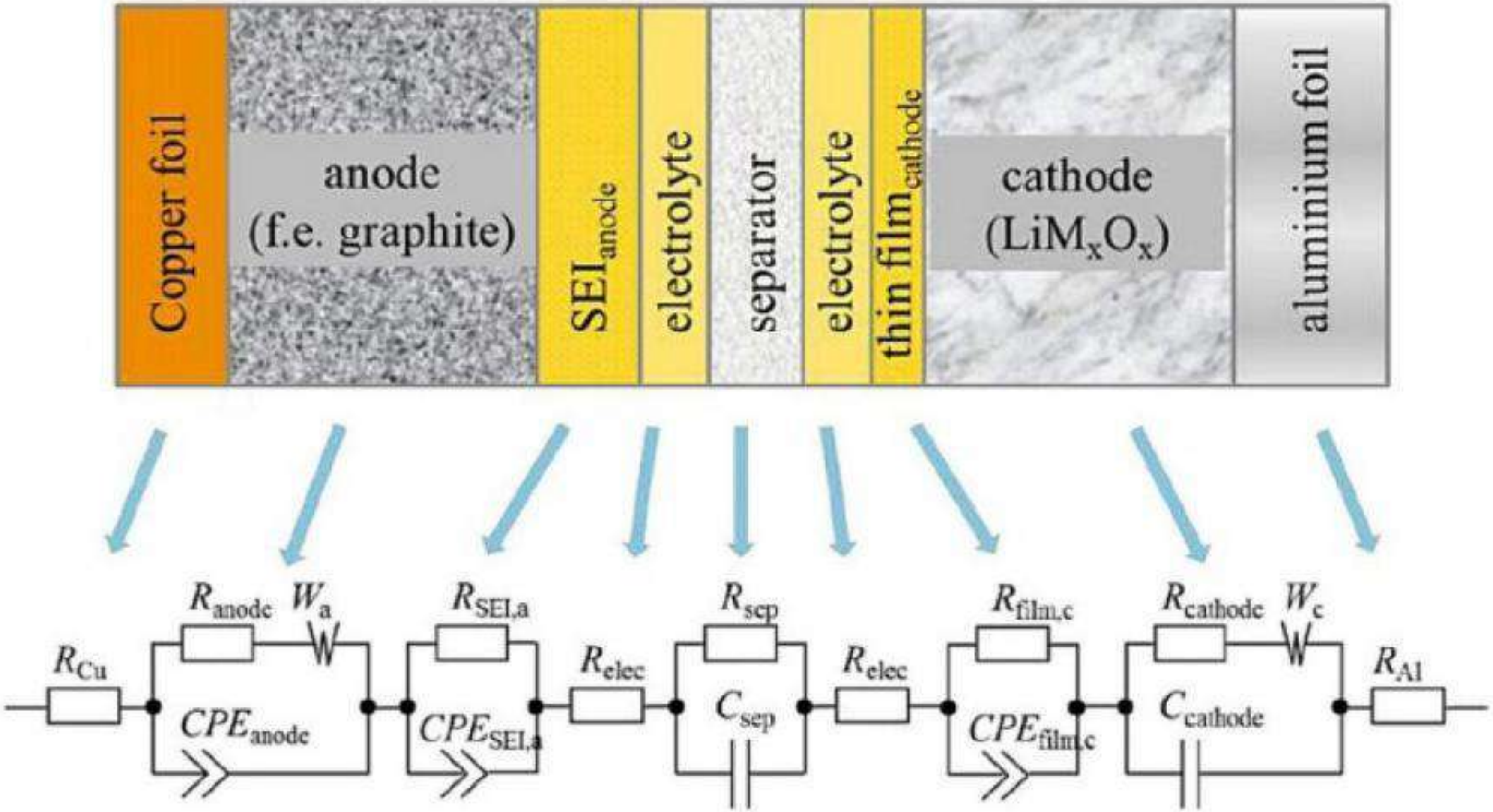
Dendrite Growth Risk
Despite improved suppression, dendrites can still form, especially under high current density if the interface isn't engineered properly.

Limited Proven Lifespan (as of now)
Real-world data on long-term cycling is still emerging; few systems have demonstrated commercial-scale longevity.

Low Ionic Conductivity (in some materials)
Solid electrolytes generally have lower conductivity than liquids, which can limit power output without thin designs.

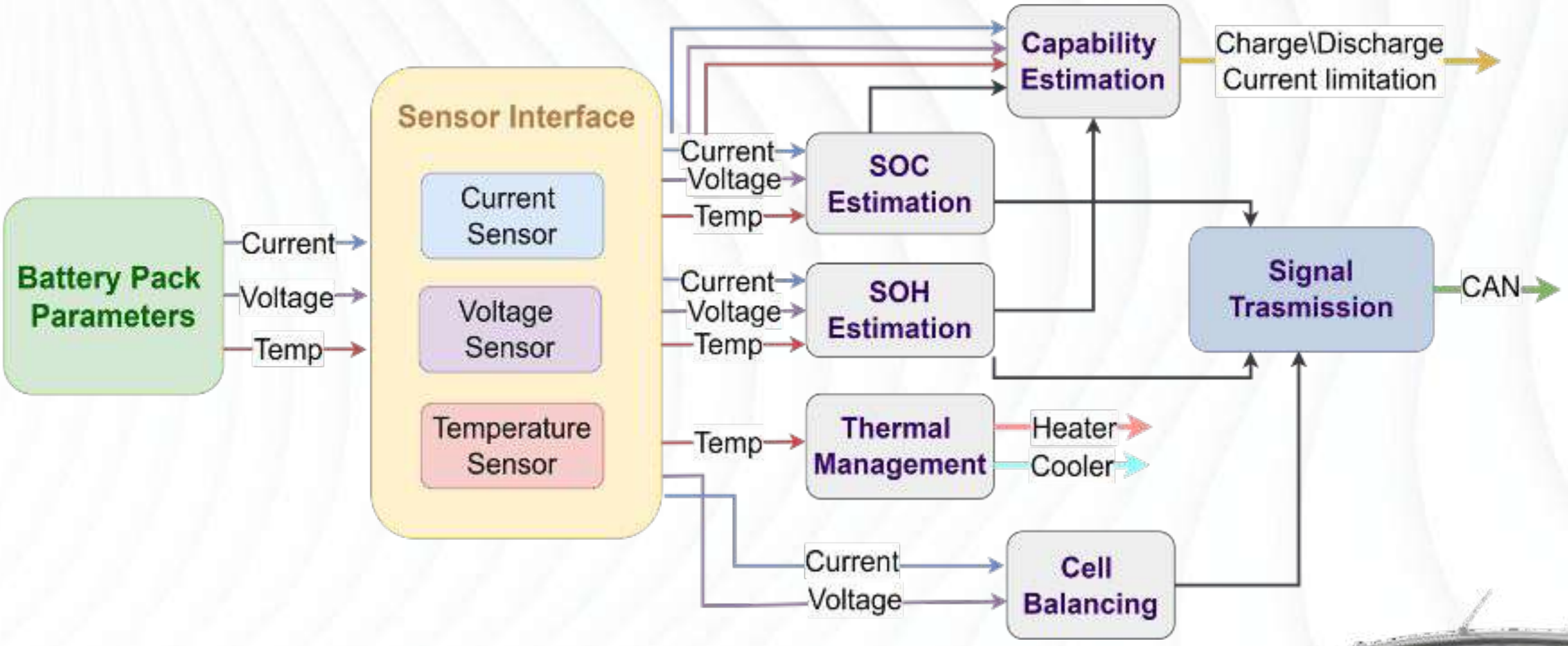
Mechanical Stress and Fracture
Solid materials can crack or delaminate during cycling due to volume changes, impacting reliability.

Complete Cell Electronic Conversion

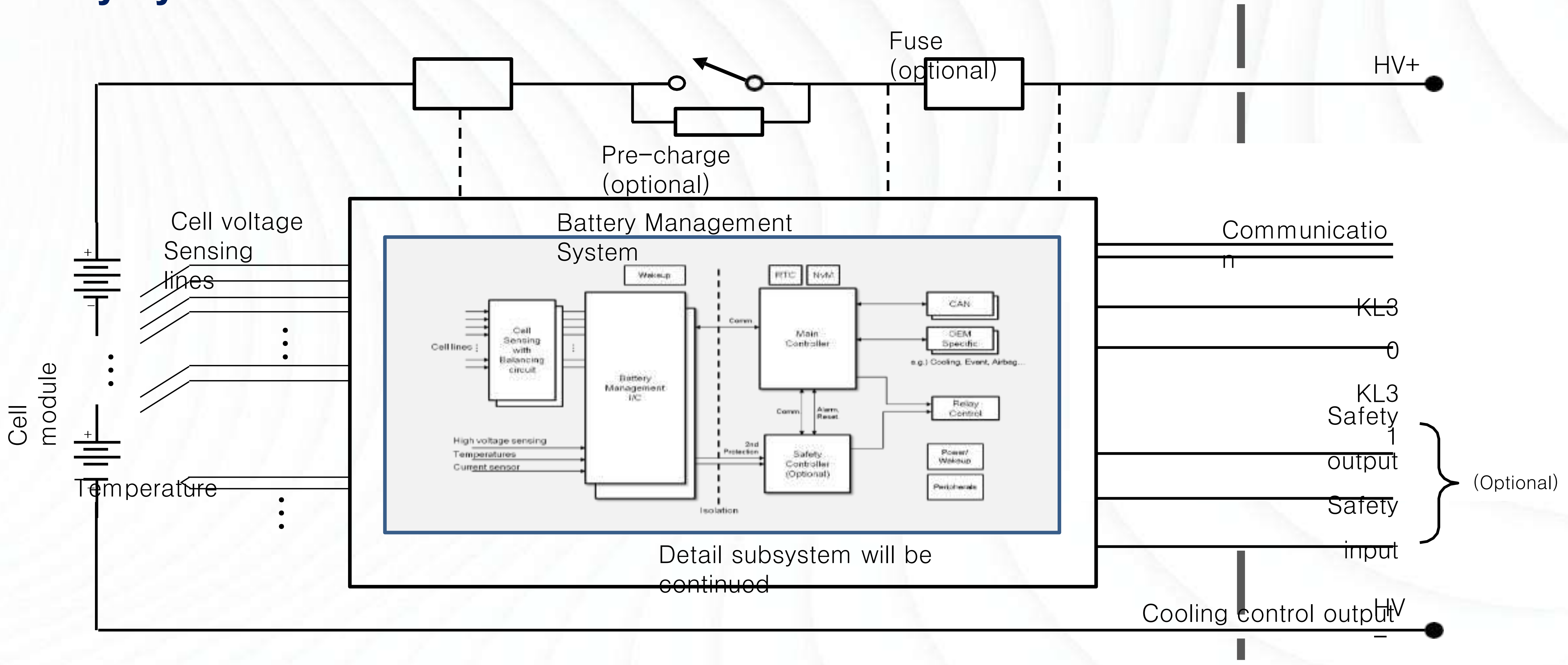


resistors(R)
inductors(I)
capacitors(C)
Constant phase element (CPE)-ddl
Warburg elements(W)

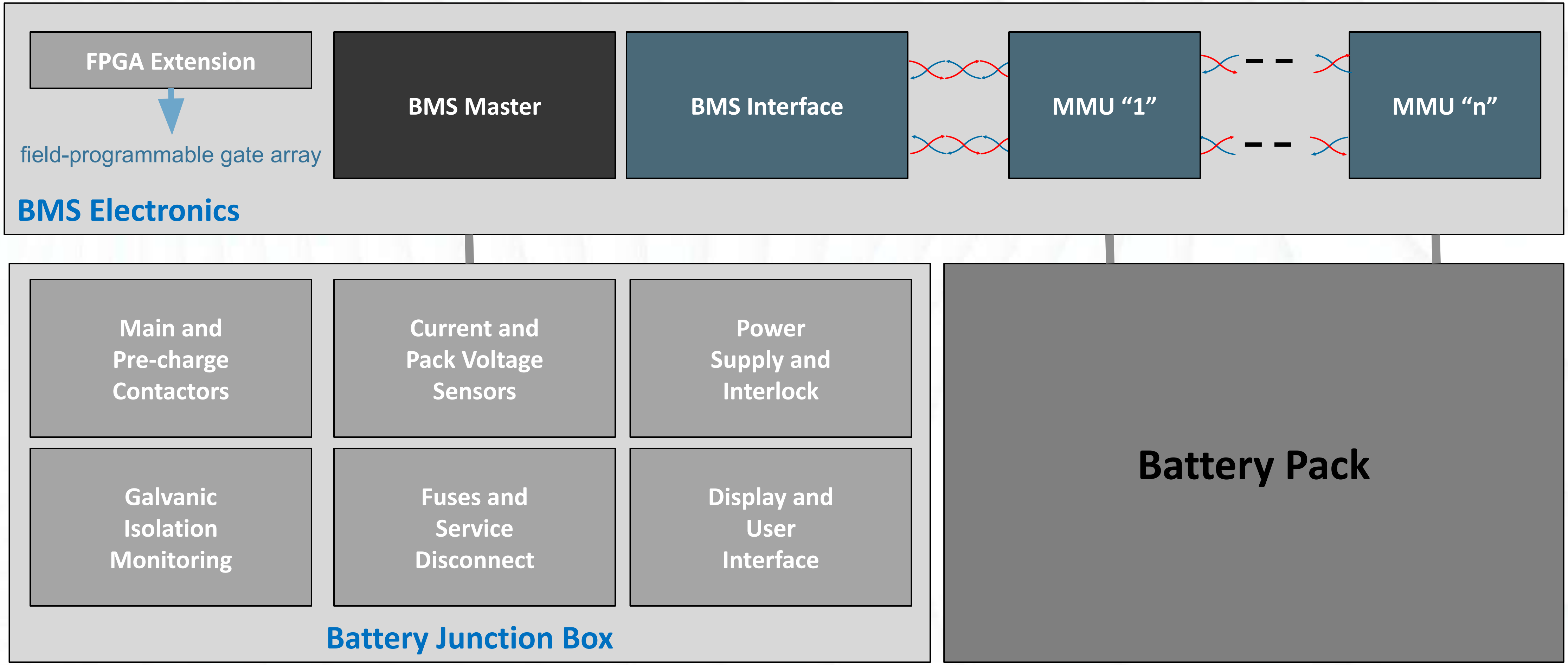
Battery Management System (BMS)

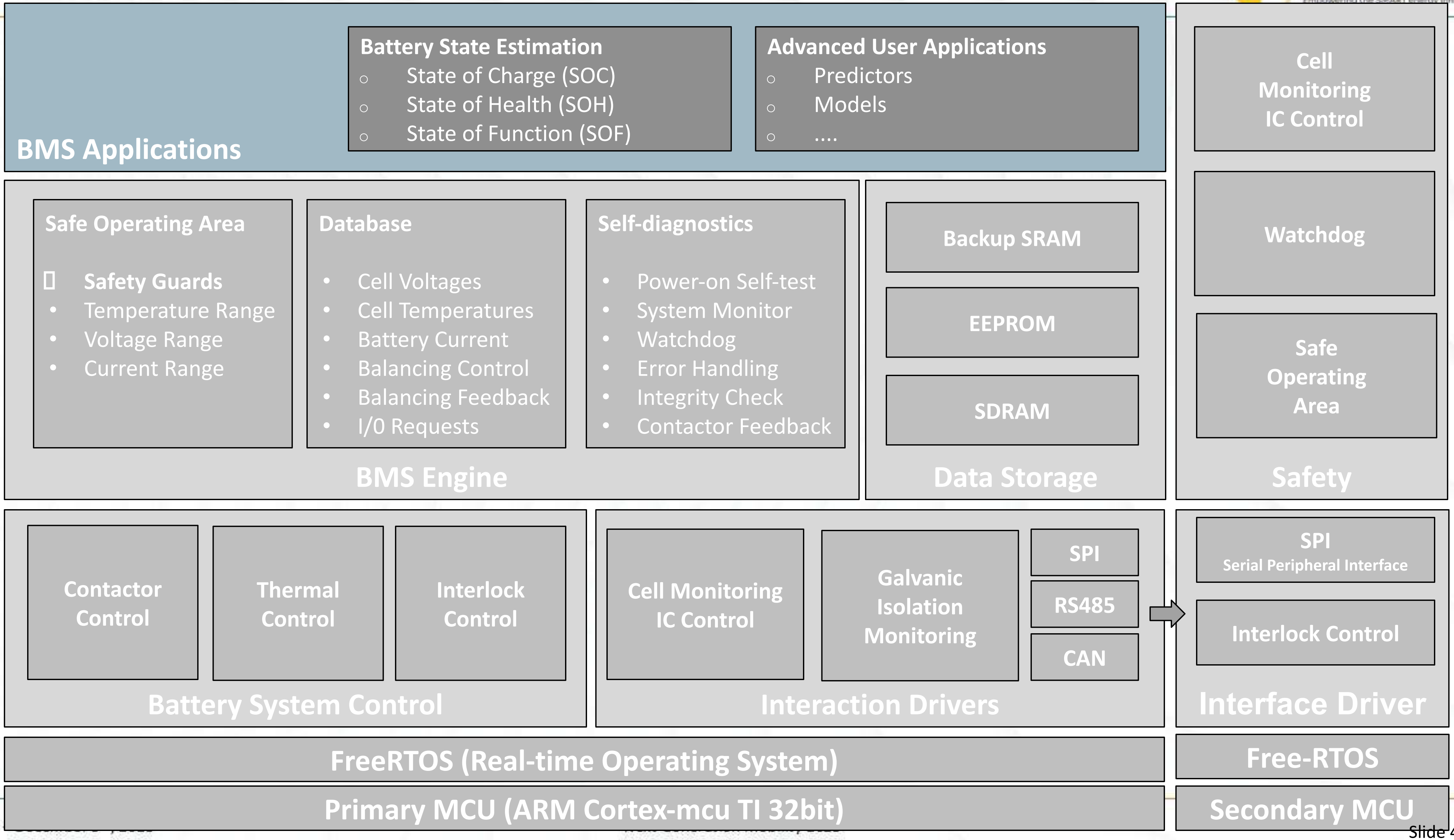


Battery System Overview



Development environment for the design of Battery Management Systems (BMS)

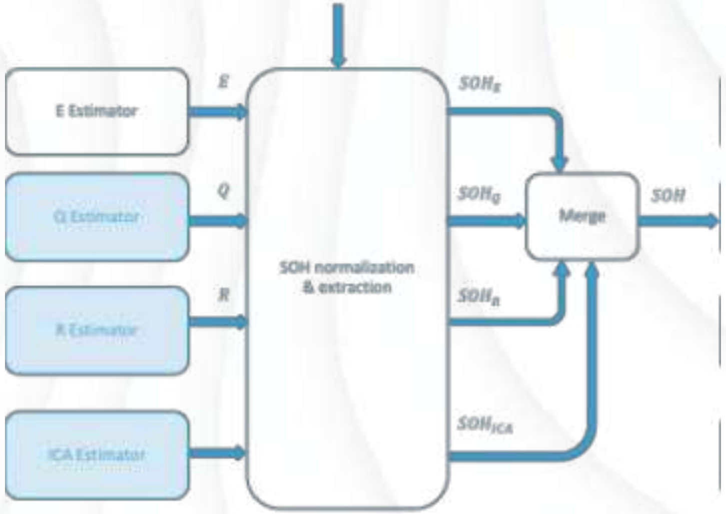



BMS Applications
Battery State Estimation
State of Charge (SOC)
State of Health (SOH)
State of Function (SOF)
Advanced User Applications
Predictors
Models
....
Cell Monitoring IC Control
Safe Operating Area
Safety Guards
Temperature Range
Voltage Range
Current Range
Database
Cell Voltages
Cell Temperatures
Battery Current
Balancing Control
Balancing Feedback
I/0 Requests
Self-diagnostics
Power-on Self-test
System Monitor
Watchdog
Error Handling
Integrity Check
Contactor Feedback
BMS Engine
Backup SRAM
EEPROM
SDRAM
Data Storage
Watchdog
Safe Operating Area
Safety
Contactor Control
Thermal Control
Interlock Control
Battery System Control
Cell Monitoring IC Control
Galvanic Isolation Monitoring
SPI
RS485
CAN
Interaction Drivers
SPI
Serial Peripheral Interface
Interlock Control
Interface Driver
FreeRTOS (Real-time Operating System)
Free-RTOS
Primary MCU (ARM Cortex-mcu TI 32bit)
Secondary MCU

Smart BMS System

SOH:

- Developed 3 new SOH calculation algorithms:
  - SOH_Q: Capacity estimation with Recursive Least Square (RLS)
  - SOH_R: Resistance estimation with R-pulse algorithm
  - SOH_ICA: Incremental Capacity Analysis (ICA)
- Improved SOH accuracy: global accuracy <3%, able to detect single cell degradation

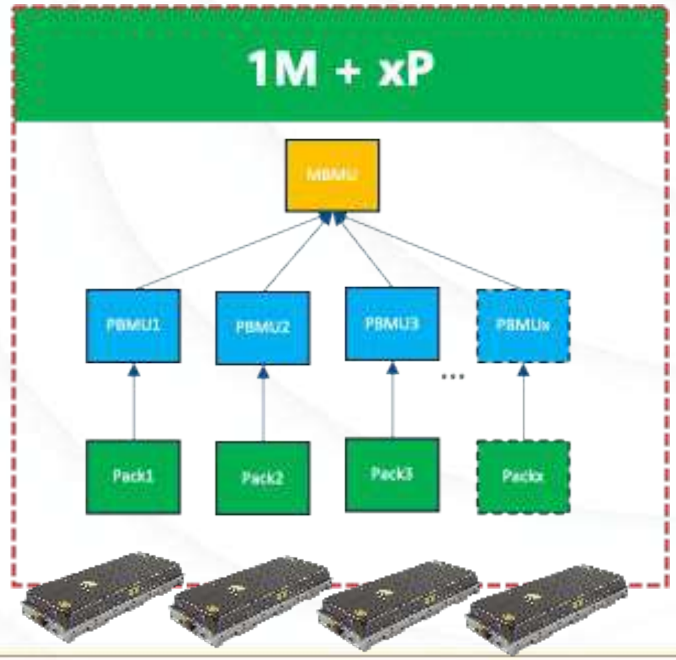


SOC:

- Optimized SOC estimation by integrating Extended Kalman Filter (EKF) SOC method
  - Global accuracy reaches 3%, in SOC range [20-80%] reaches 2%
- Developed new HPPC test process for efficient ECM parameter identification procedure

Multi-String Management:

- Multi-string system for high modularity and scalability
- Automatic string voltage balancing control:
  - In the event of significant string voltage differences, the battery system automatically enters limp mode
  - String voltage differences can be balanced automatically during chagrining or driving process, without any manual intervention
- Adaptive performance control:
  - In case of mixed usage of new and aged strings, the adaptive SOP control enables a stable operation of the battery system even under high dynamic situations
  - At the same time, it tries to keep the best possible performance of the system



Accelerating Battery Development - Virtual Material Design

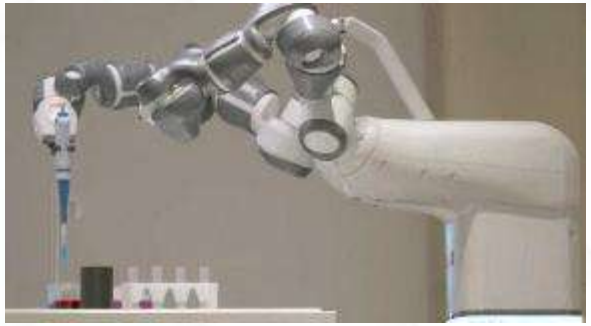
Digital-first
Using design simulation and virtual adhesives to accelerate innovation and reduce development time.

Early design collaboration
Co-creation with OEMs and battery manufacturers from concept to validation.

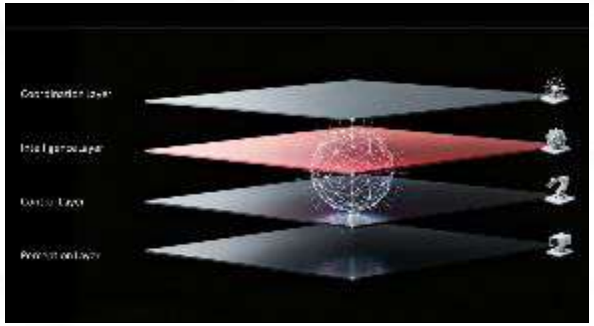
Rapid scale-up
From digital model to scalable, mass-production-ready solutions in weeks.

Level 1
(10 tests per week)

Level 2
(10 intelligent tests per week)



Level 3
(10 tests per **hour**)



Level 4
(cognitive)

Factory software integrations can take months and often fall Short!

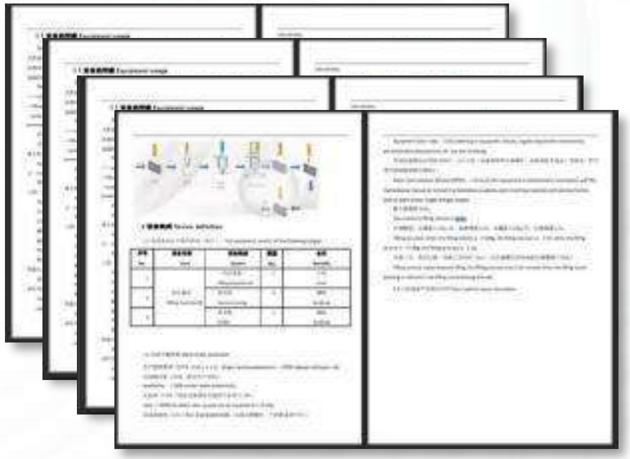
Fragmented Worlds

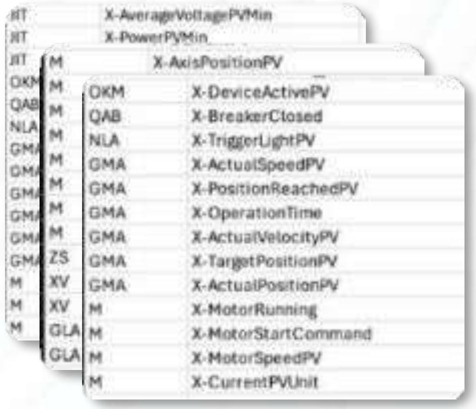
Factories are a patchwork of legacy systems

Data without Context

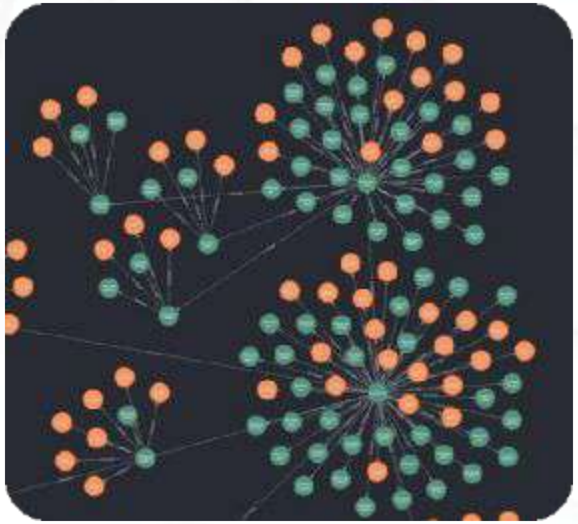
It shows what happened, not why

Ramp factory to work with AI <u>within hours</u>!





Knowledge graph built with Aris agents



UDT l ist , PLC code, Process data, machine manuals, SOPs, Control Plan, PFMEA, Maintenance manuals

Contextualized Data for Agents

Comprehensive End-to-End Traceability: The future digital tire passports

Solutions for material provenance and compliance for more responsible and sustainable sourcing

Create digital twin

Trace material through industrial process

Identity
Material + Batch ID

Origin
GPS / QR / NFC Tags

Extraction
Mass Balance

Shipping
Container Tracking

Manufacturing
Mass Balance

Logistics
GPS & RFID

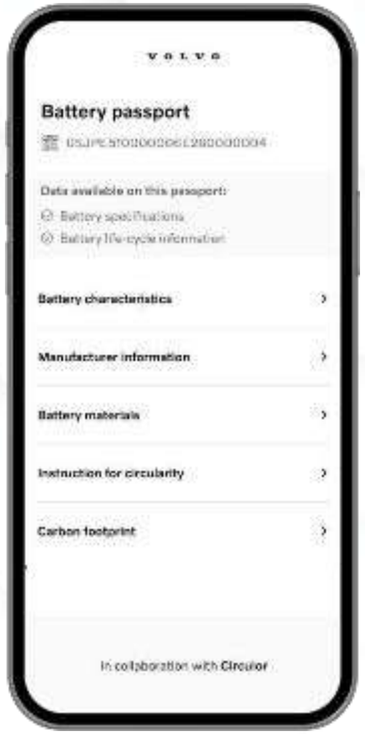
Assembly
Product ID

Material traceability

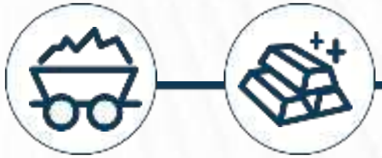
Activity, reporting & alerts

Attributed CO_2 e footprint

ESG Disclosures & Reporting



Benefits of building a responsible and increasing circular battery economy



Miner Refiner

- Providing customers with proof materials are responsibly sourced
- (Automated') auditing for ESG compliance

Recycler

- Increased recycling yield and quality
- More efficient testing and disassembly

Collector

- Increased recycling yield and quality
- More efficient testing and disassembly

2nd hand user (vehicle trader, refurbisher)

- Reduced handling cost
- Reliable value assessment through SoH report

Precursor and CAM producer

- Price premium for ESG certified materials
- Energy and carbon efficiency potential

Cell producer

- Price premium for ESG certified batteries
- Energy and carbon efficiency potential

Auto OEM

- Liability risk reduction (e.g., for 2nd use)
- Cost reduction of EoL safe handling

User

- Enabling conscious purchase decision
- Reduced effort for (de-) registration/disposal

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Thank You, for your attention!