Green Transport Delta

Electrification

Modular battery management system solutions aligned with future battery passport regulations and technologies

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BRAINPORT DEVELOPMENT
economische ontwikkelingsmaatschappij

AUTOMOTIVE INDUSTRY NL

Battery Competence Center

Agenda

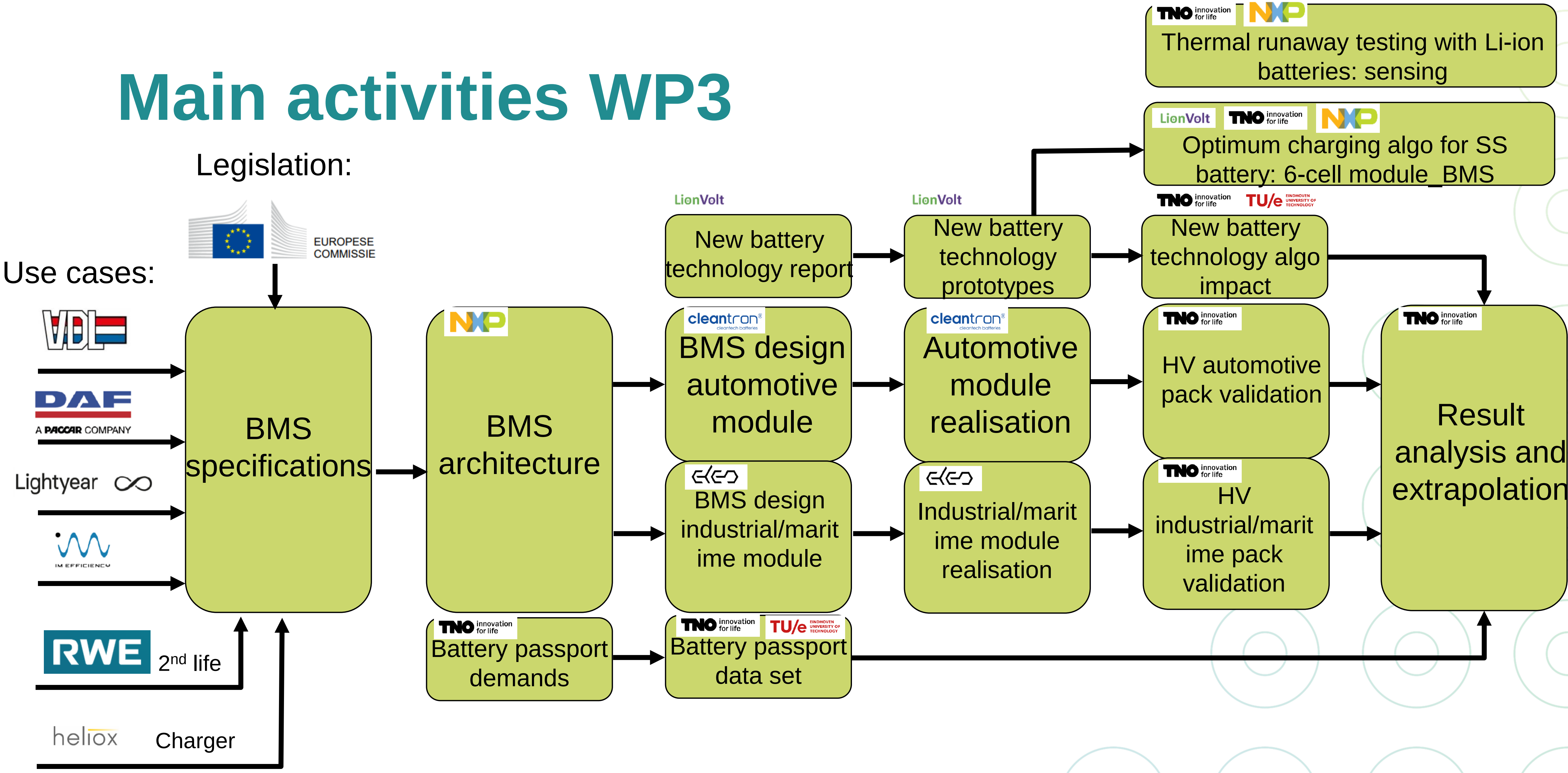
- Introduction WP3 (Battery Management Systems)
- Generic BMS requirements and architectural choices
- Battery passport requirements
- Novel algorithms and models to fill battery passport
- Battery module designs (automotive and industrial/maritime)
- Battery module validation including battery passport
- Future battery technology and its impact on BMS
- Thermal-runaway detection using novel sensors
- Main conclusions and next steps

GTD-E WP3 (BMS)

WP3: Battery management systems

- Goal: Develop a future-proof BMS architecture that:
  - Serves as generic base for a range of applications
  - Takes demands of full life cycle into account by design
  - Satisfies legislation, i.e. battery passport (including algorithms to fill it)
  - Is modular, where modules can be re-used in other applications
  - Is ready for future battery technologies
- Partners:

Main activities WP3



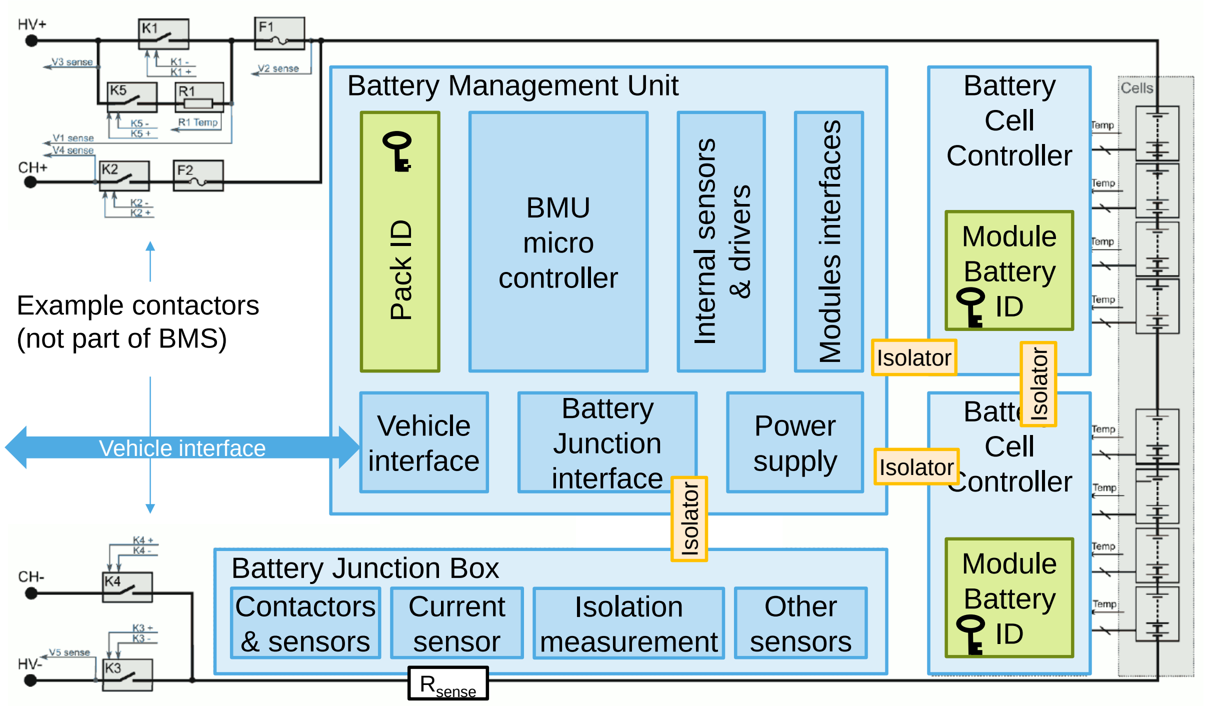
BMS requirements and architectural choices

BMS requirements

- Requirement categories:
  - Generic requirements for GTD-E partners:
    - Don’t mix&match, but allow faulty-module replacement
    - Allow parallel/series (up to HV) stacking of modules
    - Allow reuse of modules incl. BMS in another application
  - EU battery directive: module should have a passport
  - Interfaces:
    - Module-to-pack, pack-to-vehicle: protocol for passport interface (standard messages)
    - Power/mechanical/cooling interfaces not standardized
  - Software: allow programming and OTA updates
  - Functional safety: impact of 1^{st}-life and 2^{nd}-life ASIL/SIL levels

BMS architectural choices

Common BMS architecture:



Architectural choices:

- Dumb (ID, no MCU) or intelligent modules (ID, MCU)
- Data storage size (local algorithm outcome)
- Measurements:
  - V on cell level (always)
  - I on module or string level
  - Granularity of T measurements
  - Impedance (sync. V & I)
- Interface (e.g. CAN)
- Safety level: ISO26262 (automotive), IEC61508 (industrial/maritime)

Battery passport requirements

Battery passport introduction

The new EU Battery Regulation demands a Battery Passport per 18 February 2027, for:

- All Light Means of Transport (LMT) batteries (e.g. bikes, scooters, steps, etc.)
- All Industrial batteries bigger than 2kWh
  E.g. grid storage batteries
- All Electric-Vehicle batteries
- Regulation - 2023/1542 - EN - EUR-Lex (europa.eu)

High-level requirements:

- Data storage and data sharing infrastructure
- Online accessibility of the Battery Passport
- Access control to various parties
  - Split in 'Public', 'Legal' and 'Legitimate interest*'
- Potentially new BMS algorithms

- Data from various sources
  - Raw materials and design (incl. dismantling information)
  - Manufacturer
  - BMS (new and existing algorithms required)

* To de defined by EC by 18 August 2026

Battery passport required data

- Main BP data requirements from BMS point of view:
  - The current amount of battery **capacity fade** (in %) should be available
  - The current amount of battery **power fade** (in %) should be available
  - The current amount of internal **resistance increase** (in %) should be available
  - The current amount **energy round-trip efficiency fade** (in %) should be available
  - The average/maximum/minimum battery **temperature** should be available (that the battery has been used in)
  - The average/maximum/minimum battery **temperature during charging** should be available
  - The minimum/maximum **operating current** should be available (in which the battery has been used in, to detect abuse)
  - The minimum/maximum **operating cell voltage** should be available

Typically available

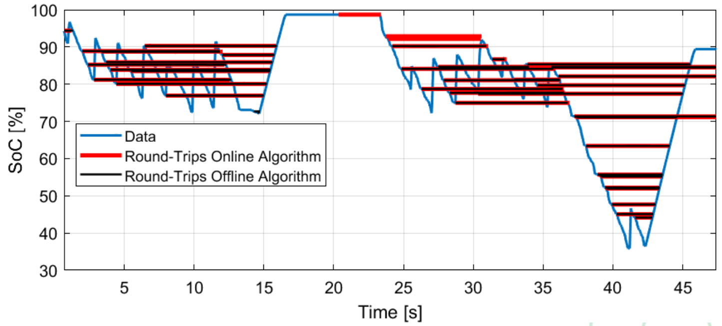
SoH-Eff developments

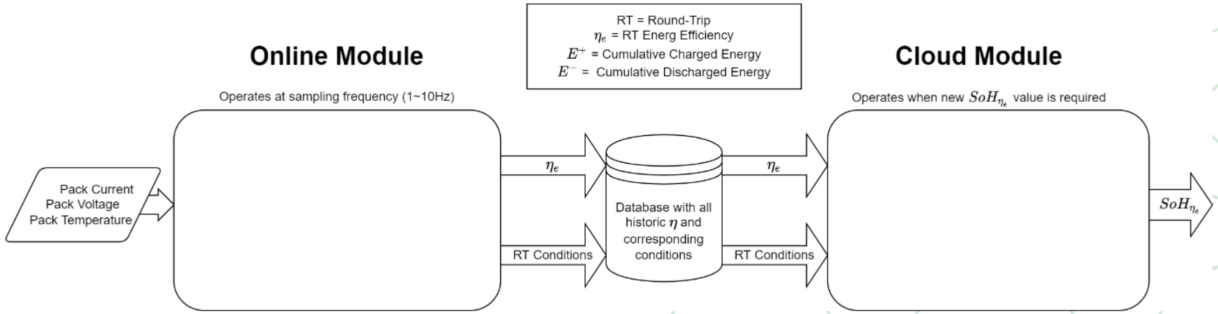
SoS developments

Novel algorithms and models to fill battery passport

Novel algorithms developed in WP3

- **SoH in terms of round-trip energy efficiency**
  - ‘Online’ calculation module embedded in BMS software
    - Identifying and characterizing individual round-trips
  - ‘Cloud’ calculation module integrated in Battery Passport Cloud environment
    - Combining individual round trips in a single SoH value



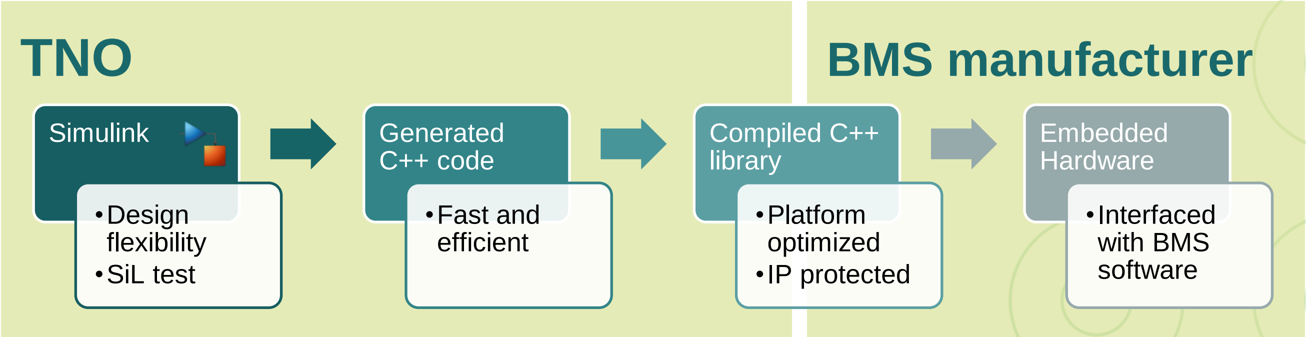


- **State-of-Safety**
  - Required data not suitable for prediction of safety issues
  - Suitable prediction found in battery ageing behaviour

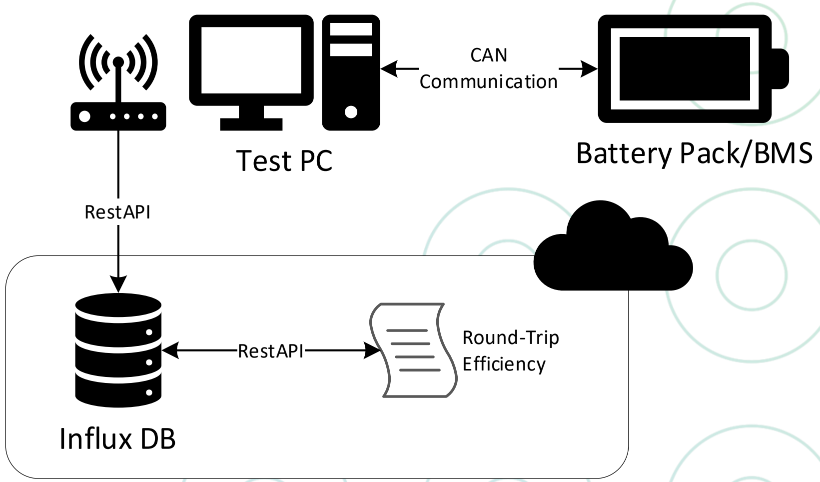
$$SoS = f_{C_0}\left(\frac{dC_0}{dc}\right) \cdot \mathrm{f_R}\left(\frac{dR}{dc}\right)$$

Novel algorithms developed in WP3

- **Algorithm implementation in BMS**
  - Simulink algorithm developments
  - Embedded in BMS HW of battery systems developed by project partners



- **Battery Passport Demonstrator realized**
  - Suitable architecture developed based on IDS standard
  - Whitepaper written on implementation
    - Link to Whitepaper



Novel algorithms and models

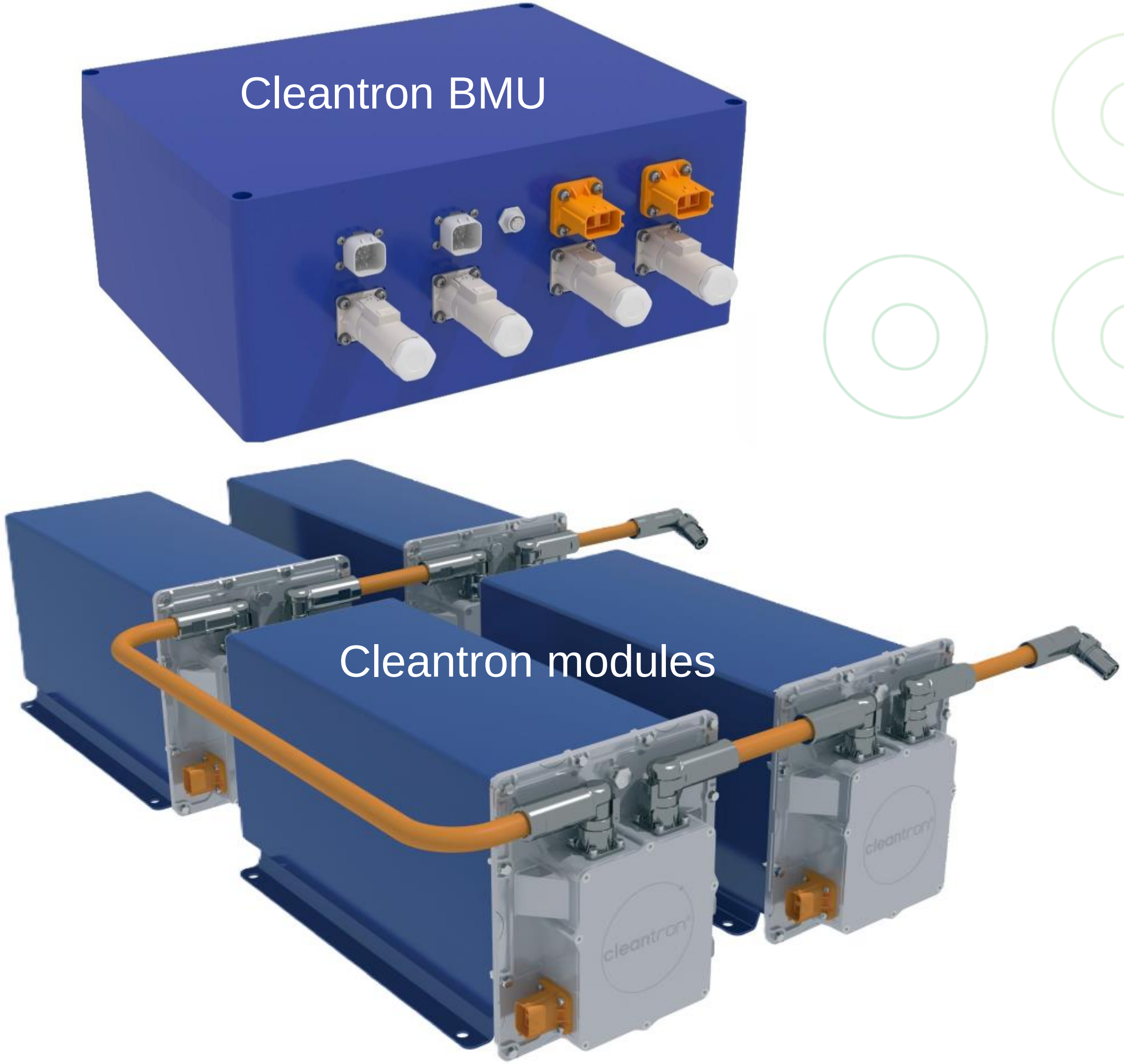
- All state-estimation algorithms need good models
- Improved Equivalent-Circuit Models:
  - Proper SoC, current magnitude/direction, T dependence
  - Proper parameter identification experimental data sets (I, T)
  - ‘Keep it simple’: sparse models, prevent overfitting
  - Code available in Python: PyBatteryID

SCAN ME

Battery module designs

Cleantron design (automotive)

- Cleantron GX module (24V) connected in 4S dual HV string configuration. Total battery system voltage of 96V and 11 kWh of capacity.
- The BMU measures, monitors and controls the power from the HV strings to the application system.
- Voltage and temperature measurement is performed in the GX module. String-level current measurement is performed in the BMU.
- Every GX module as enough storage for over 5 years of battery passport operational data.



ELEO design (industrial/maritime)

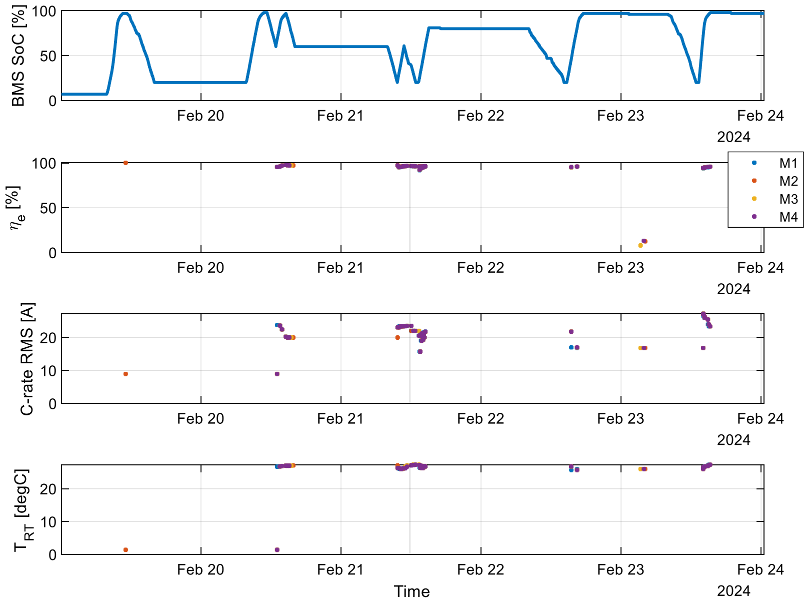
- The ELEO battery system consists of multiple modules in a series/parallel configuration and one BMU.
- Each module can monitor cell voltages, temperature and module current. The modules can directly store this usage data on internal memory for the battery passport.
- The BJB is integrated in the BMU. This BMU contains the contactors to connect the modules to the application. The BMU also contains essential pack features such as insulation monitoring and communication with the vehicle.

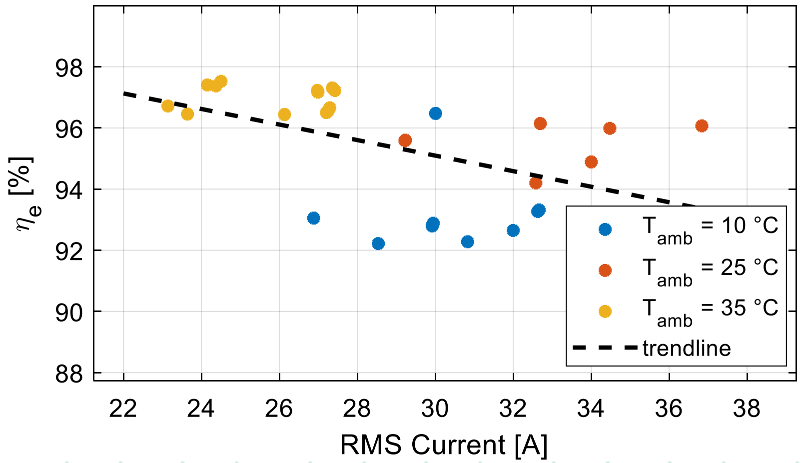
Battery module validation

Results task 3.4

- **Capacity tests**
  - Various conditions
  - Incl. 2nd life configuration

- **SoH-Eff tests**
  - Varying load cycles, temperatures, Depth-of-Discharges, SoC and charging rates
  - Results directly uploaded in the Battery Passport Cloud implementation

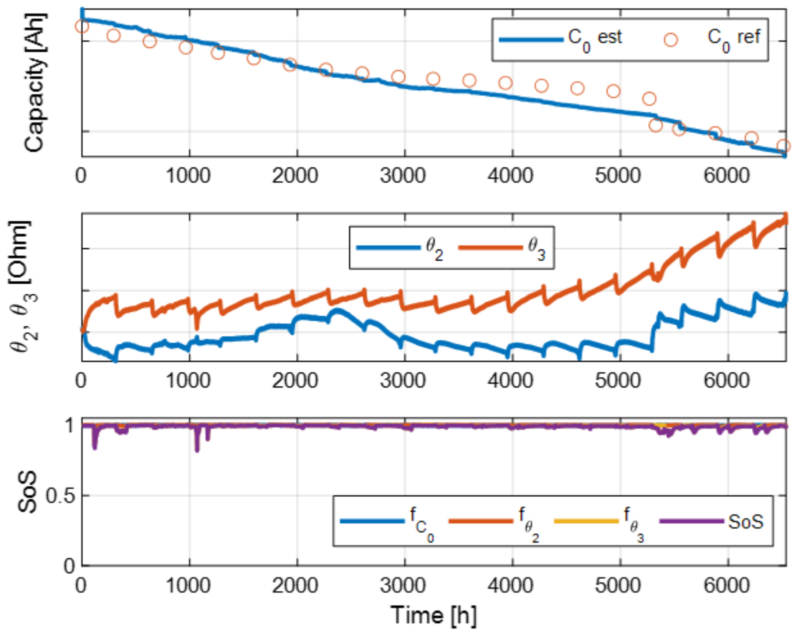


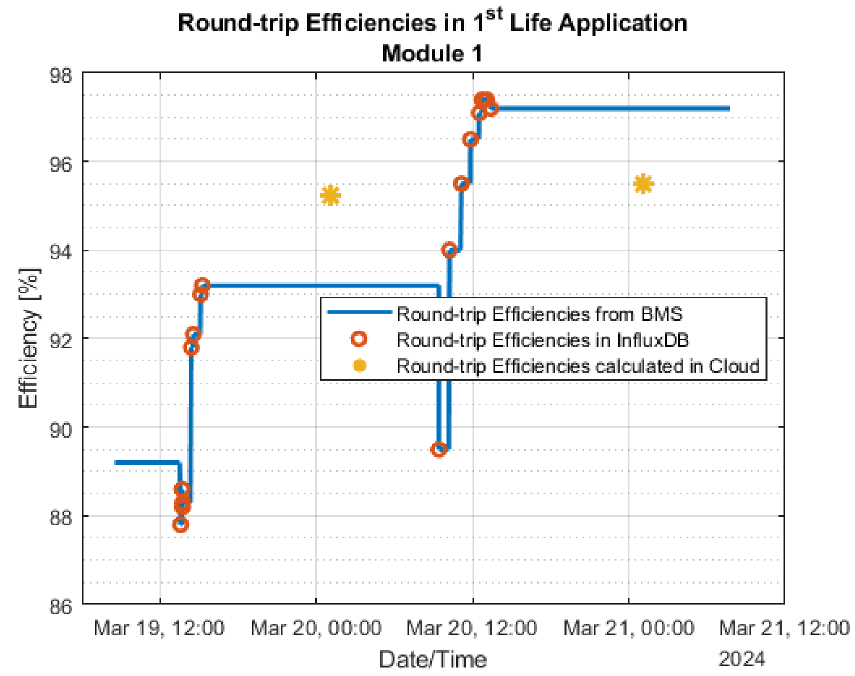


Results task 3.4

- **SoS tests**
  - Verified by cell-level aging testing
  - Verified by post-processing pack testing results
    - Pack-level tests too short to expect ageing and related safety issues

- **Battery Passport Demonstration**
  - Running alongside battery pack testing
  - Continuous uplink of data
  - Daily Cloud calculations of SoH-Eff





Future battery technology and BMS impact

Selected future battery technologies

- Ranking the technologies

Battery Technology	TRL	Nominal Voltage V	Voltage window (V)	Gravimetric Energy Density Wh/kg	Volumetric Energy Density Wh/L	Operational C rate	Maximum cycle life	Self-Discharge ranking
Li-ion battery	9-10	3.2 (LFP)	2.5-3.65 (LFP)	160-200	390	0.2C to 1C	2000	2
		3.6 (NCA)	3.0 - 4.2 (NCA)	250-280	550	0.2C to 1C	1000	
		3.7 (NMC)	2.5-4.2 (NMC)	265-290	735	0.5C to 2C	1500	
Sodium-ion battery	6-7	3.2 (NVP)	2-3.8 (NVP)	150 to 200	~190	0.2C to 10C	3000 (25)	2
Li -Sulphur	4-6	2.1 (S)	1.8-2.4	350 to 400	~600	0.2C to 1C	150	3
Li-M-SSB	2-4	3.2 (LFP)	2.5-3.65 (LFP)	300 to 450	~800	0.2C to 1C	250-500	1 (least)

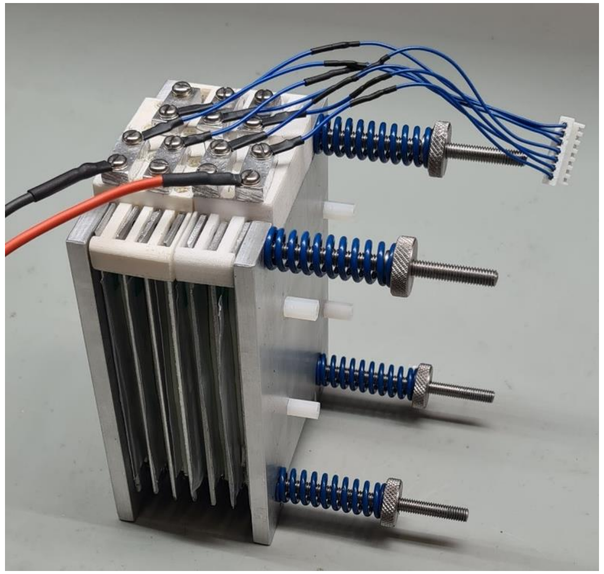
Ref.: Battery Report 2022. [Online] https://www.volta.foundation/annual-battery-report.

- BMS impact

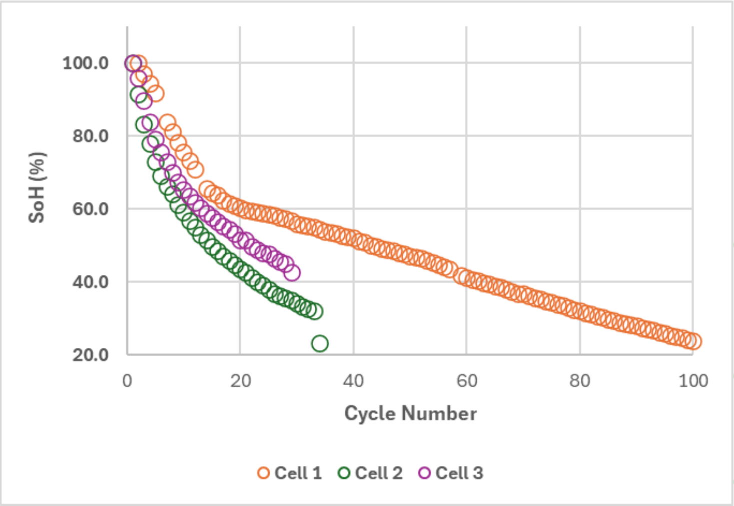
Battery Indicators	Description	Sodium-ion battery	Li-S battery	Li-metal battery (Semi-solid and all-solid state)	BMS area to be impacted
High C-rate working	Cycling of the cells at different high C rates	✓	Similar to Li-ion battery	*To be optimized & improved*	SOC & SOH estimation
Lifetime testing	Life of Li-ion battery for 5000 cycles is shown and key features such as %CE and Resistance behavior is depicted applicable to all types of batteries.	✓	✓	✓	SOC & SOH estimation
Voltage profile	Voltage-vs-capacity plots are discussed and their uniqueness w.r.t. Li-ion battery is shown	✓	✓	✓	SOC & SOH estimation
Pressure sensing	Change in the cell pressure during cycling of battery is discussed	Insufficient literature	Insufficient literature	✓	BMS hardware & packaging
Low temp cycling + asymmetric cycling	The cell performance at different temperature and operating at C rates different for charging and discharging	✓	Insufficient literature	✓	BMS hardware & packaging
Thermal safety	The thermal runaway temperatures are discussed	✓	✓	Insufficient literature	BMS hardware & packaging

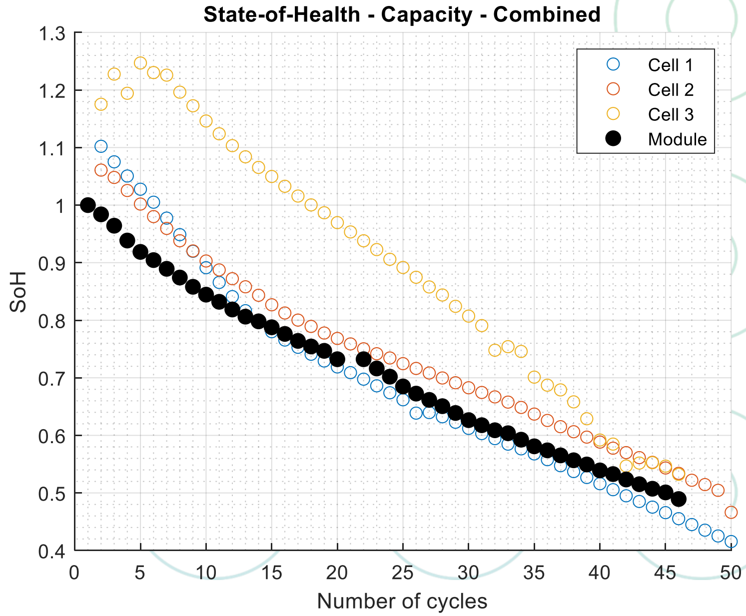
Improved charging algorithm for Li-metal battery

- Problem with charging Li-M batteries:
  - Dendrites formed on anode while charging
  - SEI formation
- Multi-step dynamic charging algorithm to promote conformal Li surface deposition while maintaining higher C-rates
- Programming of dynamic algorithm and practical validation by 6 cells in series on TNO battery module + NXP BMS board



Coin-cell, multi-step CCCV charging with dynamic feedback loop (cell 1), and traditional single-step CC charging (cell 2 & 3)

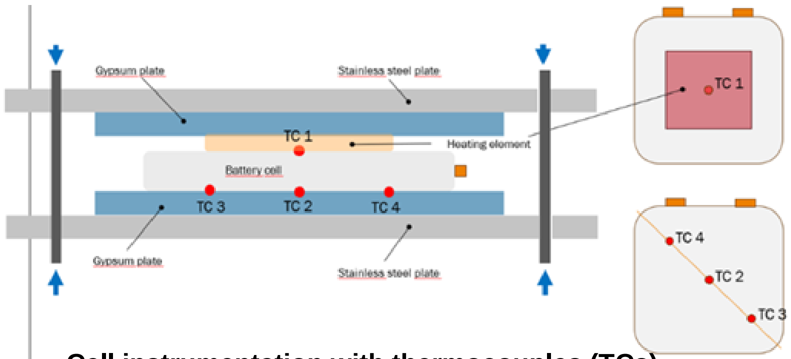




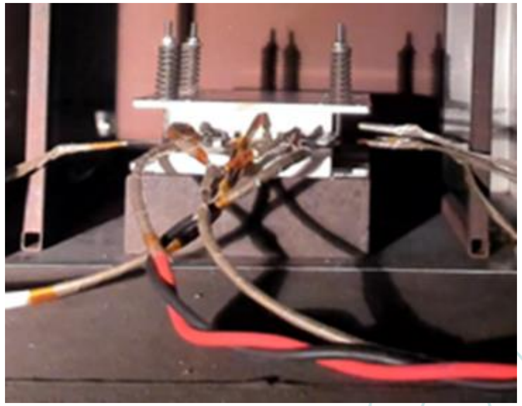
Thermal-runaway detection

Early-warning thermal-runaway detection

- Single-cell thermal-runaway (TR) experiments
  - Experimental TR characterisation (checking consistency over cells)
  - TR initiation of pouch form factor NMC | Graphite cells via:
    - A) External direct resistance heating (10^{o}C/min until event) (5 experiments)
    - B) Overcharging (C-rate: 1C until event) (4 experiments)
- Objective
  - Early detecting TR, prior to its onset, by exploring the potential of Electrochemical Impedance Spectroscopy (EIS) and gas sensors in addition to temperature sensing and cell swelling (visually)



Cell instrumentation with thermocouples (TCs)



Experimental setup with the Device Under Test (DUT) inside a semi-open enclosure

First early-warning results

- Repeatable results for both TR initiation methods
- Comparative advantage of EIS is evident in the early-warning time observed
  - EIS outperformed slightly only by temperature sensing in 3 out of 4 external heating TR experiments
- EIS and sensors to detect swelling (e.g. force sensors) can be used together with temperature sensing for TR early-warning

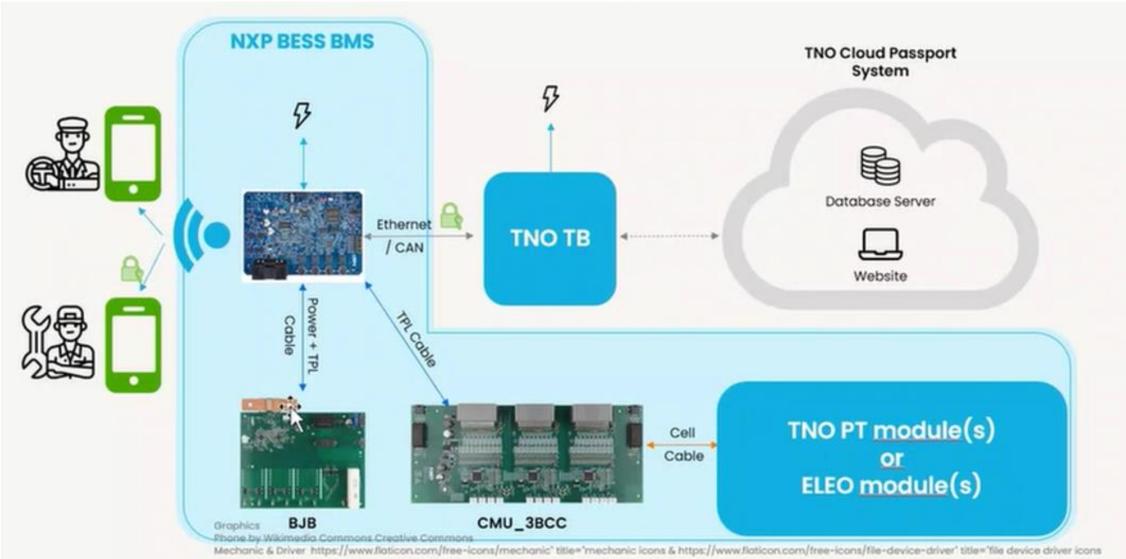
Main conclusions and next steps

Main conclusions

- Design of future-proof modular BMS:
  - Design choices to allow reuse and BP implementation mapped out
- Clear picture of battery passport data need and algorithms
- First battery passport implementation exploiting edge and cloud computing demonstrated, including reuse aspects
- Main future battery technologies: sodium-ion, Li-S, Li-M (SSB)
  - No major BMS impacts expected for these technologies
  - Example implementation of novel charging algorithm Li-M
- EIS and swelling sensors seem good addition for early-warning TR detection

Next steps

- TKI funded project TNO-NXP: SeBaPad
  - Secure battery passport implementation



- Nationaal Groeifonds 3: Circular Batteries call
  - CIMBATT consortium (building on GTD-E consortium)
  - Extension of applications to truck, off-highway, maritime, aerospace, including integration of pack into application and system design simulation tooling
  - Fast charging, active balancing, scaling to multiple packs, TR mitigation into BMS including additional sensing such as EIS, wireless BMS, algorithms based on physics-based models

Thank you!