Berner Fachhochschule
Haute école spécialisée bernoise
Bern University of Applied Sciences

Ende 2018 soll die Produktion des Citaro E-Cell starten.(Bild: Daimler)

Batterien – Auslegung, Technik, Recycling und Entsorgung

VöV-Bustagung 29. / 30. Mai 2018

Prof. Dr. A. Vezzini,
Head BFH Zentrum Energiespeicherung

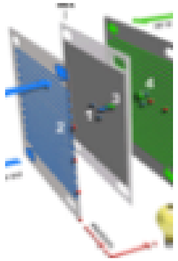
BFH Energy Storage Research Centre

BFH Energy Storage Research Center (ESReC)

- One of the largest independent energy storage research centers for academic R&D activities available to the Swiss industry

Testing and characterization of large capacity cells and modules and development of hard- and software for complete battery and energy systems

Manufacturing technologies for large lithium-Ion cells and modules for a cost effective production of the key components of electrical storage systems



Application, test and development of decentralized and mobile fuel cell systems as a basis for long term storage of electrical energy.

Use and test of energy storage systems for mobility applications to substitute non-renewable fuels and reduce CO2 emission for all mobility carriers (land, air, sea)

Use and test of PV integrated energy storage systems to enable the integration of new renewable energy sources and their impact on power quality and grid stability

Integrated analysis of Innovation-ecosystems enabling the diffusion of battery storage systems as a means to manage the energy turn-around

Embedded in three national Research Networks

- FUTURE SWISS ELECTRICAL INFRASTRUCTURE - SCCER-FURIES

SCCER - FURIES

Shaping the FUtuRe SwIss Electrical InfraStructure

- EFFICIENT TECHNOLOGIES AND SYSTEMS FOR MOBILITY – SCCER MOBILITY

sccer mobility

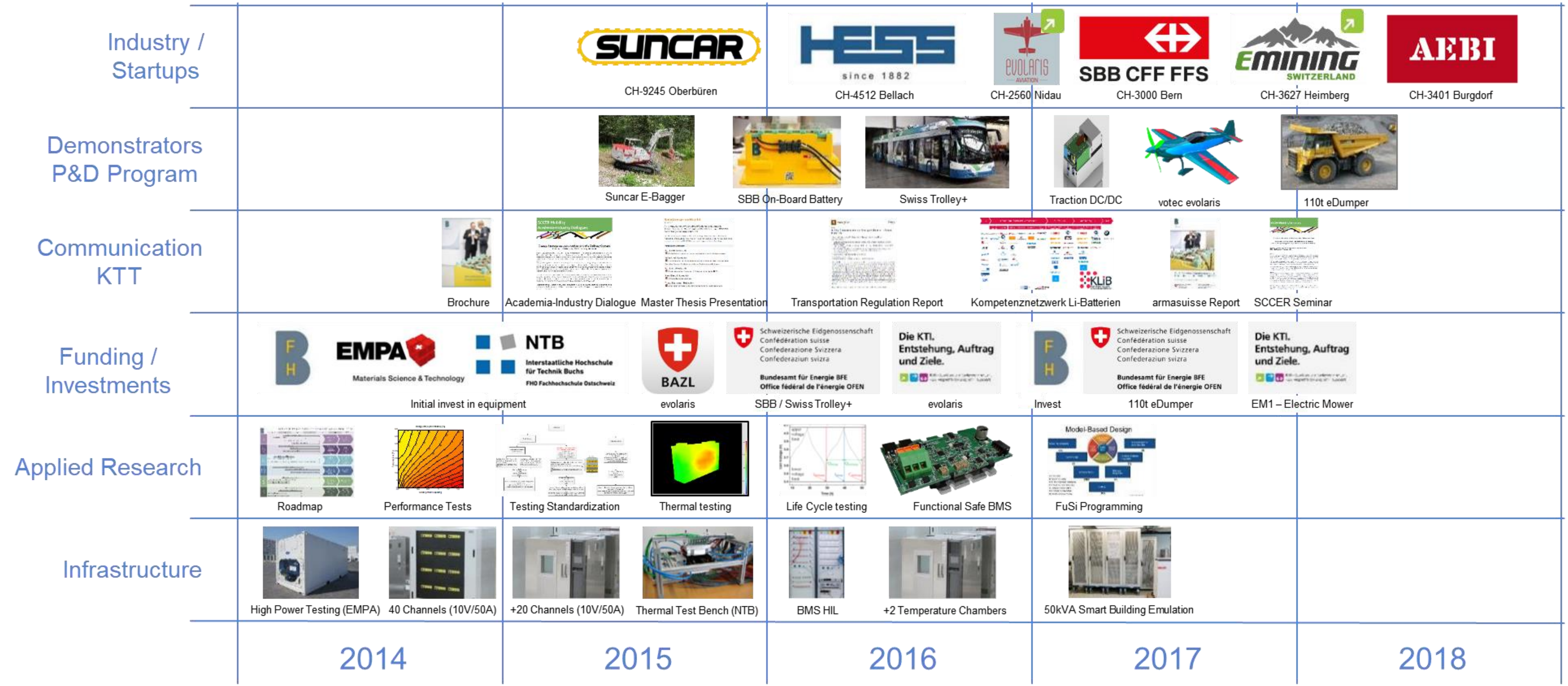
Swiss Competence Center for Energy Research
Efficient Technologies and Systems for Mobility

- HEAT AND ELECTRICAL STORAGE – SCCER STORAGE

Storage

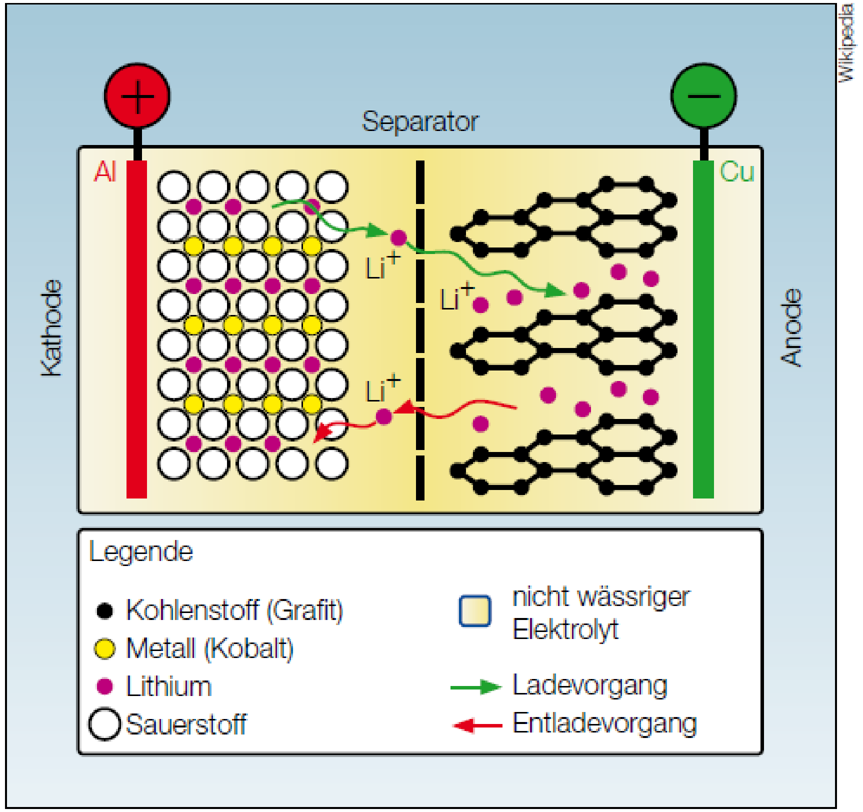
Swiss Competence Centers
for Energy Research

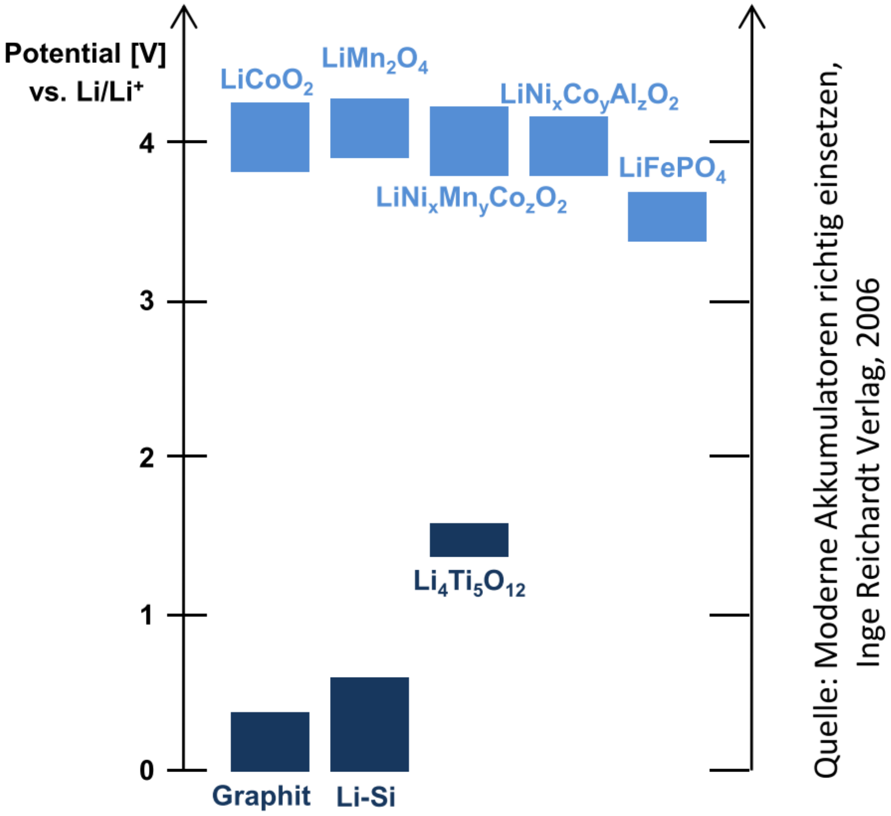
Von der Forschung zum Produkt: SCCER-Mobility (E-Mobility)



Lithium-Ion Battery Technology

Focus on Lithium Based Technologies



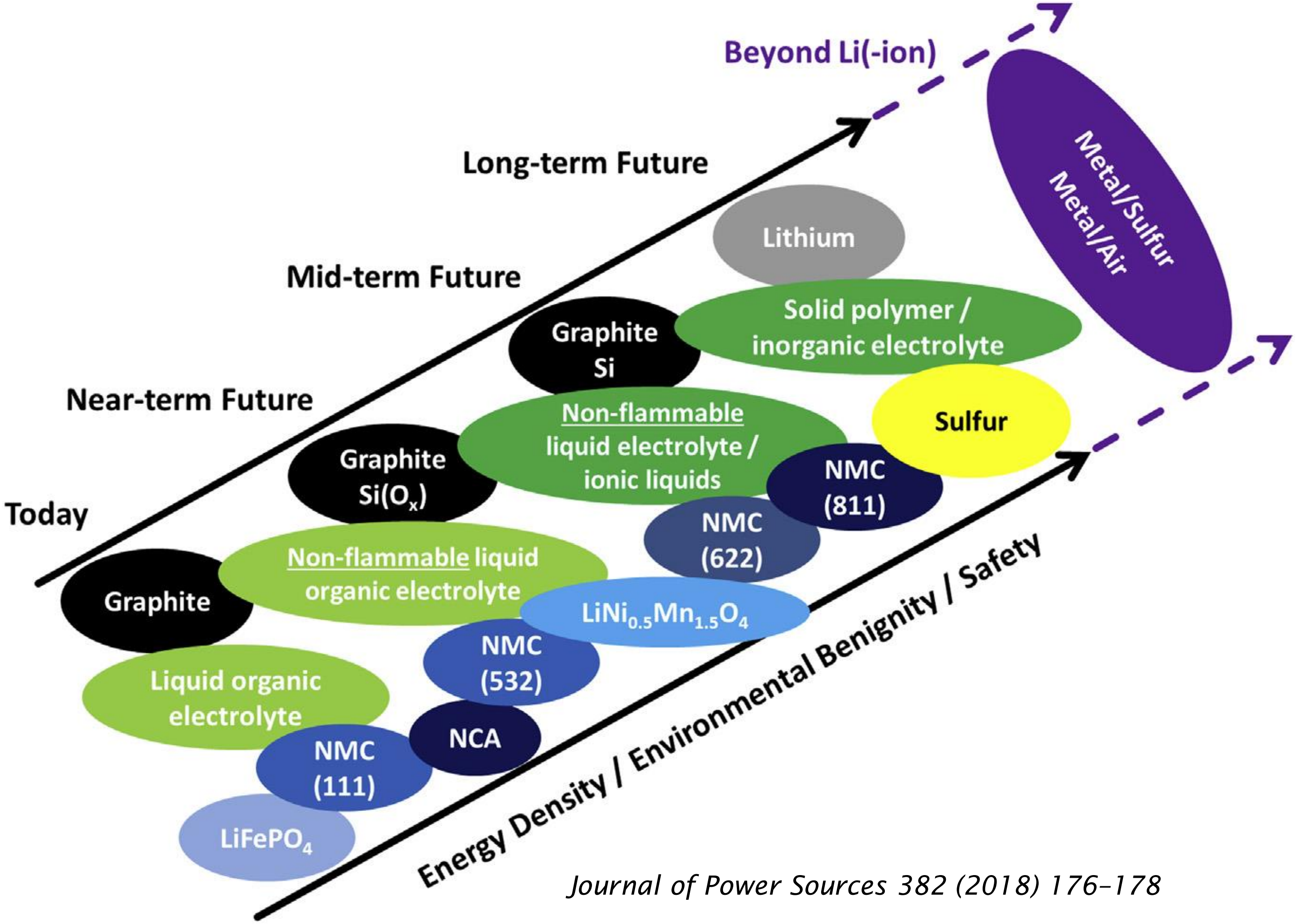


- The anode of a conventional Li-ion cell is made of carbon, the cathode is a metal oxide, and the electrolyte is a lithium salt in an organic solvent.

- The Voltage of the cell depends on the difference on the reduction scale.
- The capacity of the Anode Material dominates the cell capacity

Source: Leclanché SA

One of hundreds of battery development roadmaps

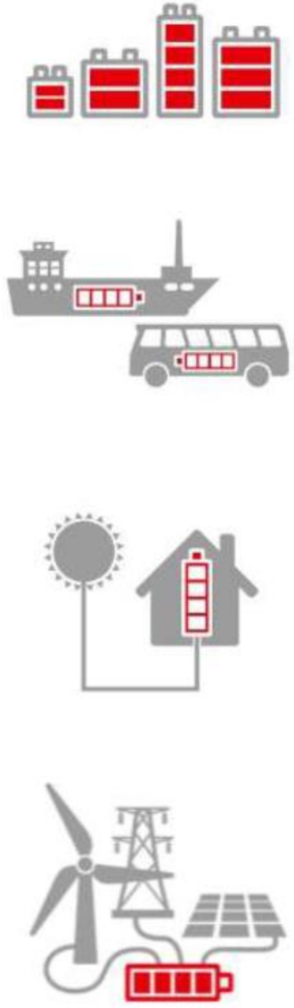


Journal of Power Sources 382 (2018) 176–178

- General trend for the present automobile battery R&D objectives with respect to the employed anode, electrolyte, and cathode materials; please note that this trend is to be taken rather indicative and not fully strict, as the precise targets of each country and company may vary
- Todays market for bus batteries is dominated by NMC and LTO batteries. Historically and due to their use in Chinese busses also LiFePO played a role for battery busses, although their lower energy density is a disadvantage

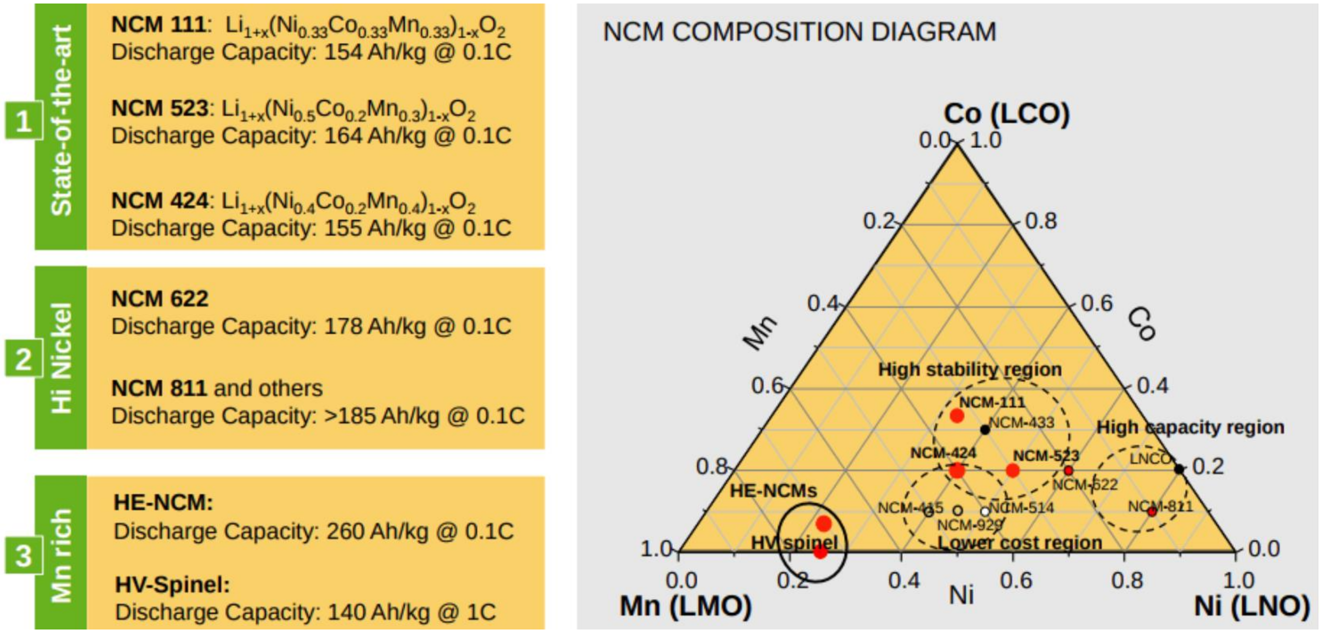
Leclanché comparison of **LTO** and **G-NMC cells**

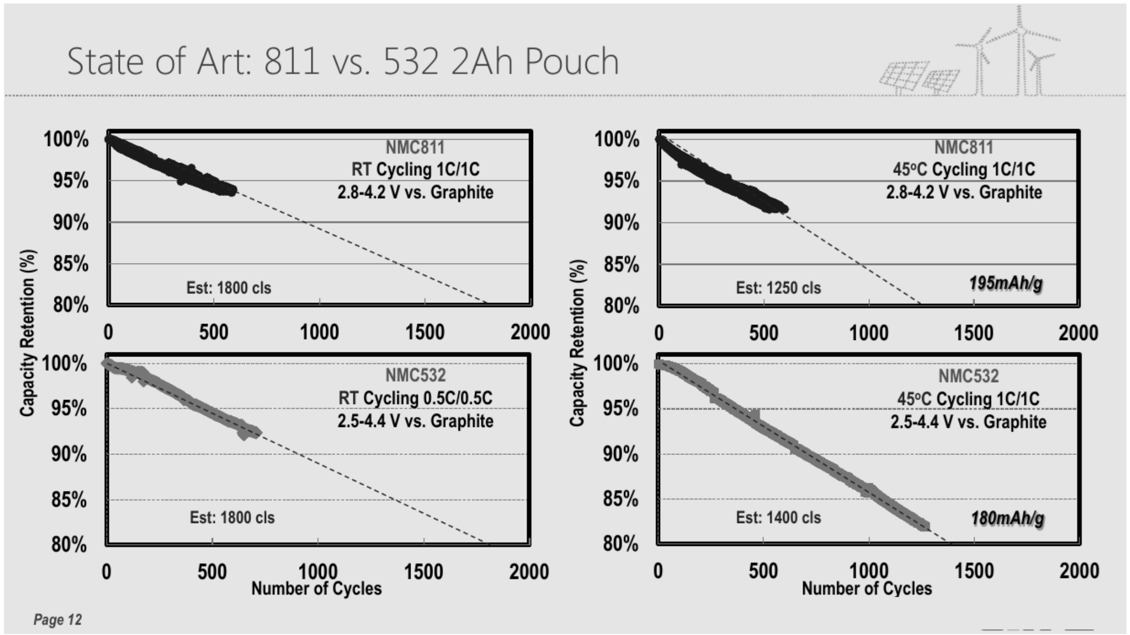
	Lithium Titanate Oxide (LTO)	Lithium Graphite/NMC (G-NMC)
Cycle life	15,000 @ 100% DoD >20,000 @ 80% DoD	4,500 @ 100% DoD 8,000 @ 80% DoD
Lifetime & warranty	Up to 20 years	Up to 10 years
Charge time to 90% SoC	Less than 15 minutes (5C)	1 hour (1C)
Energy Density	70 Wh / kg	160 Wh / kg
Temperature range	-20°C to +55°C	0°C to +45°C
Safety	Superior ceramic cell technology	Superior ceramic cell technology
Ideal use case	• Power intensive applications • Long lasting applications • Applications needing rapid response • Grid stability projects	• Energy intensive applications • Low- or micro- cycle applications • Bulk storage or weight critical applications • Renewable energy integration projects



NMC811 as the next step in battery technology

https://c1cleantechnicacom-wpengine.netdna-ssl.com/files/2018/02/NCM-Composition.png





- High Nickel Content Cells (NMC811) will reduce dependency of cobalt supplies while at the same time increasing energy density of the cells
- So far life cycle has been an issue for nickel rich batteries, especially at higher temperature, but development is progressing fast

Battery Design Approach

Electrified Bus-Concepts

Electric Hybrid Bus (Volvo 7900) with Opportunity Charge (ABB TOSA) and up to 70% purely electric Drive

Pure Hybrid Bus (Volvo). No external charging of smaller on-board battery. Improved fuel efficiency (40% savings) through kinetic energy recuperation.

Swiss Trolley-Plus von HESS with charging through overhead lines and up to 10km purely electric drive

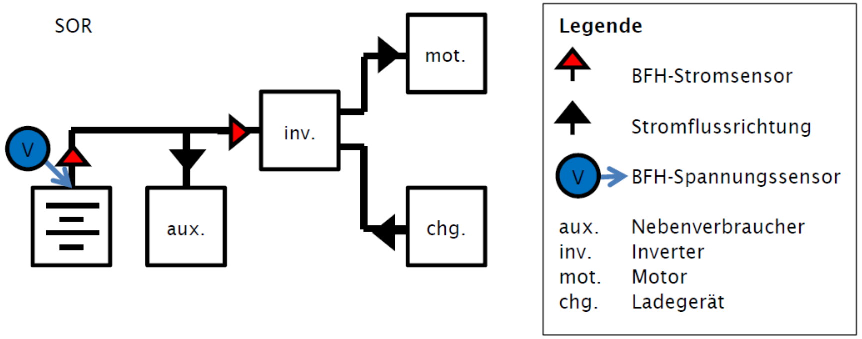
Fully Electric Bus with Batteries larger than 200kWh for extended electric operating range and centralized charging infrastructure

Specifications

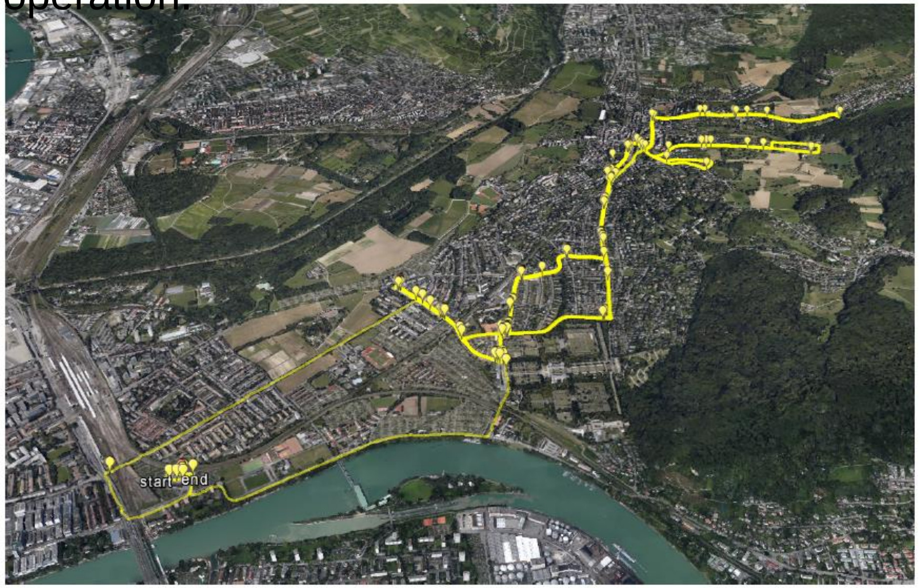
- Bus Operators have to learn to write relevant specifications
- While technical details are interesting, they should base the specifications on performance and regulations

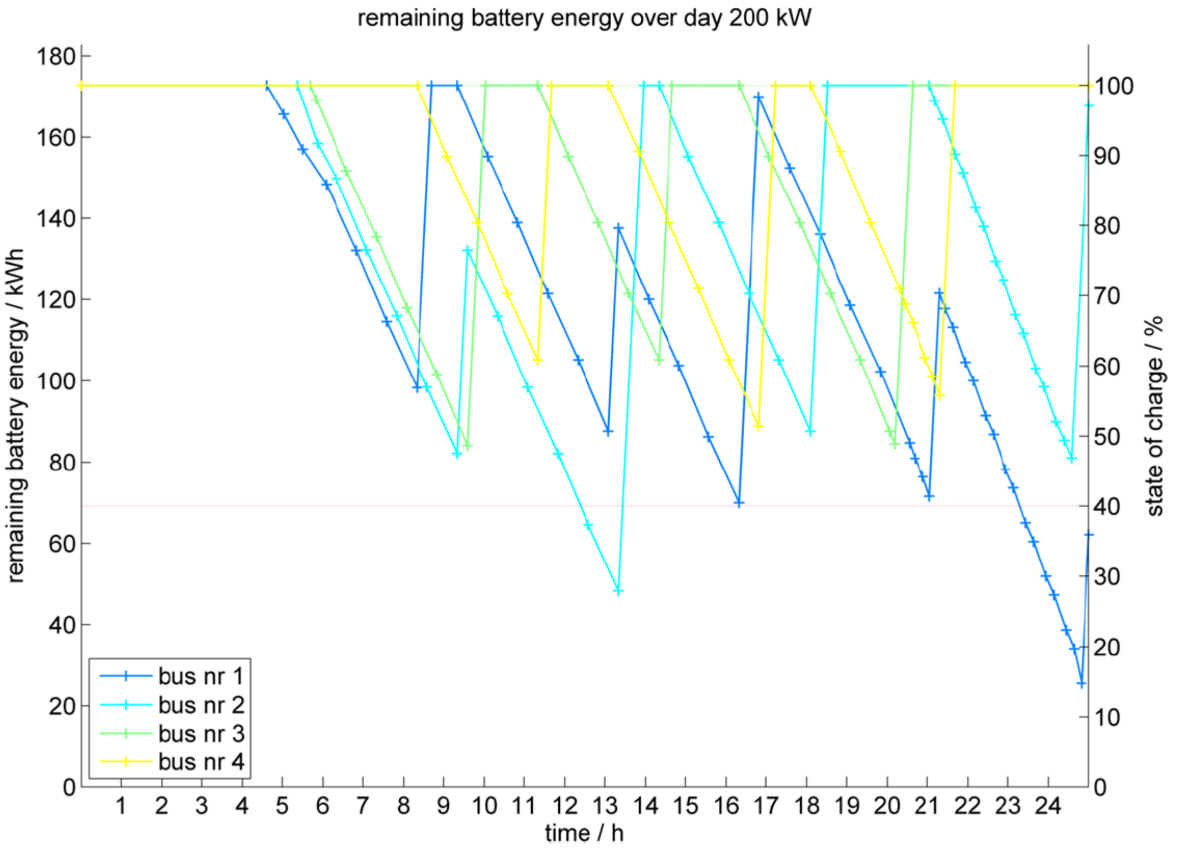
Betriebsbedingungen	Zu berücksichtigende Batterieparameter	Verknüpfung
Der Bus muss Fahrprofil A oder B ohne Fahrleitung absolvieren können. (Strecke, Geschwindigkeit, Steigung, Beladung) A: 3 x 500m, 50 km/h, eben, vollbeladen B: 1 x 200m, 40 km/h, 9% Steigung, 33% beladen	Die Speicherkapazität der Batterie muss unter Berücksichtigung ihrer Alterungsvorgänge mind. X kWh betragen und mind. Y kW während Z Sekunden während einer Bremsung vor einer Haltestelle auffangen können.	Kombinierter Energieverbrauch aus Traktion, HLK und Nebenantriebe während Belastungsprofil.
Während der Nacht und zwischen den definierten Fahrprofilen kann die Batterie während mindestens 20min geladen werden.	Maximale Ladeleistung (Laderate) der Batterie. Ladezustandshaltung unter Berücksichtigung der Länge der kommenden oberleitungsfreien Strecke.	Maximale Ladeleistung von Infrastruktur, Zeitabschnitte der Ladung / Fahrt mit Oberleitung.
28 Wiederholungen pro Tag, 300 Einsatztage im Jahr	Grundsätzliche Auslegung Ausgangskapazität, Ladeleistung und -dauer,	Belastungsbedingte Alterung
Es ist eine Mindestlebensdauer von X Jahren gefordert	Grundsätzliche Auslegung Ausgangskapazität, Entladetiefe, Kühlungskonzept	Belastungsbedingte- und Kalendarische Alterung
Das Produkt muss den Normen XY entsprechen und für den Strassenverkehr nach XXXX zugelassen sein. (Diese Anforderungen sollten bereits heute bestehen und sind bekannt)	Spezielle, aufwändige Prüfungen, falls kein Standard-Produkt	Homologationsverfahren, Sicherheit und Zuverlässigkeit

Validation through pilot test phase and/or simulation



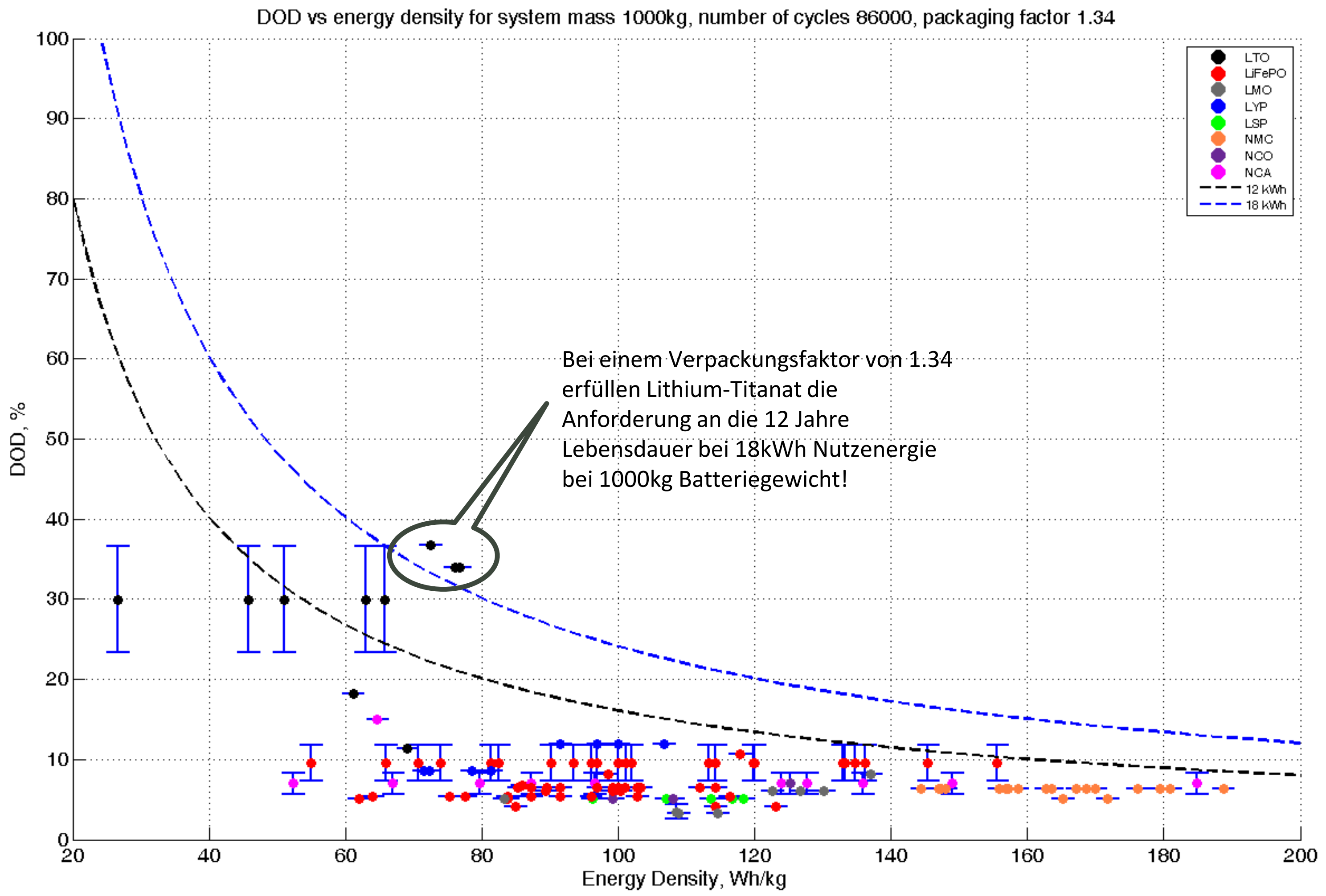
In the pilot test, the electric bus is equipped with a data logger to record all relevant data directly during operation.





In this charging scenario, a bus is to be permanently connected to the charging station at the end station. Each time a driver finishes his shift, he connects his bus to the charging station and the previously loaded bus starts its service. So for the three courses 28, 29 and 30 four buses are necessary.

Service life of a 1000kg battery and packing factor 1.34



- Screening of over 200 existing lithium ion cells
- Weght is given by the possible additional weight in the bus
- Energy content based on requirement simulations
- Resulting battery capacity and DoD if DoD as curve for 12/18kWhr pack
- Number of cycles given by application
- Maximum DoD of each cell plottet based on datasheet

Beispielhafter Vergleich zweier fiktiven Systeme

Faktoren	Variante A	Variante B
Fahrzeugbatterie Zellen-Typ	Li-Titanat	Li-Cobalt-Mangan-Oxid
Energieinhalt	25 kWh	25 kWh
Gewicht kompl. Batt-System	340 kg (73.5 Wh/kg)	160 kg (156 Wh/kg)
Volumen / Bauform (go/no go)	X m^3, Abmessungen X	Y m^3, Abmessungen Y
Lebensdauer	14 Jahre	7 Jahre
Konzept des Thermomanagements	Abluft FZ (ausreichend, z.B. weil die Batterie in einem grossen Temperaturbereich einsatzfähig ist)	Wasserkühlung / Heizung (da leistungsfähiges Thermomanagement nötig)
Energieverbrauch Hilfsaggregate bei 14 h Betrieb, täglich und 300 Tage im Jahr	20 W ➔ 84 kWh/J In 14J: 1.2 MWh ➔ CHF 177.-	250 W ➔ 1050 kWh/J In 14J: 14.7MWh ➔ CHF 2'200.-
Anschaffungskosten (CAPEX)	CHF43’750.- (2200.-/kWh)	1) CHF 20'000 (800.-/kWh) 2) nach 7 Jahren: CHF 15’000 (600.-/kWh)
Kosten Einbau / Umbau / Stillstand	CHF 3'000.-	CHF 6'500.- (da 2x + Teuerung)
Durchschnittliche Entladetiefe	15 %	15 %
Anzahl Vollzyklenäquivalente	8‘400 (2VZ/d, 300d/J, 14J)	4‘200 (2VZ/d, 300d/J, 7J)
Masse-Bezogene Kosten für Verschleiss und Traktion; CHF 0.50/Kilo * Jahr (Annahme)	170.-/J ➔ 2'380.-/14J	80.-/J ➔ 1’210.-/14J
Summe der berücksichtigten Kosten auf 14 Jahre	CHF49'307.-	CHF 44’910.-

Kosten bei Energiepreis von 15 Rp/kWh. Bei Energiebezug auf Fahrzeug müsste der Übertragungs- und Umwandlungswirkungsgrad zwischen Stromzähler bis zum Verbraucher (500 VDC auf Bus) ebenfalls mitberücksichtigt werden.

Battery Testing Procedures and Results

Battery Aging

Cycle-lifetime

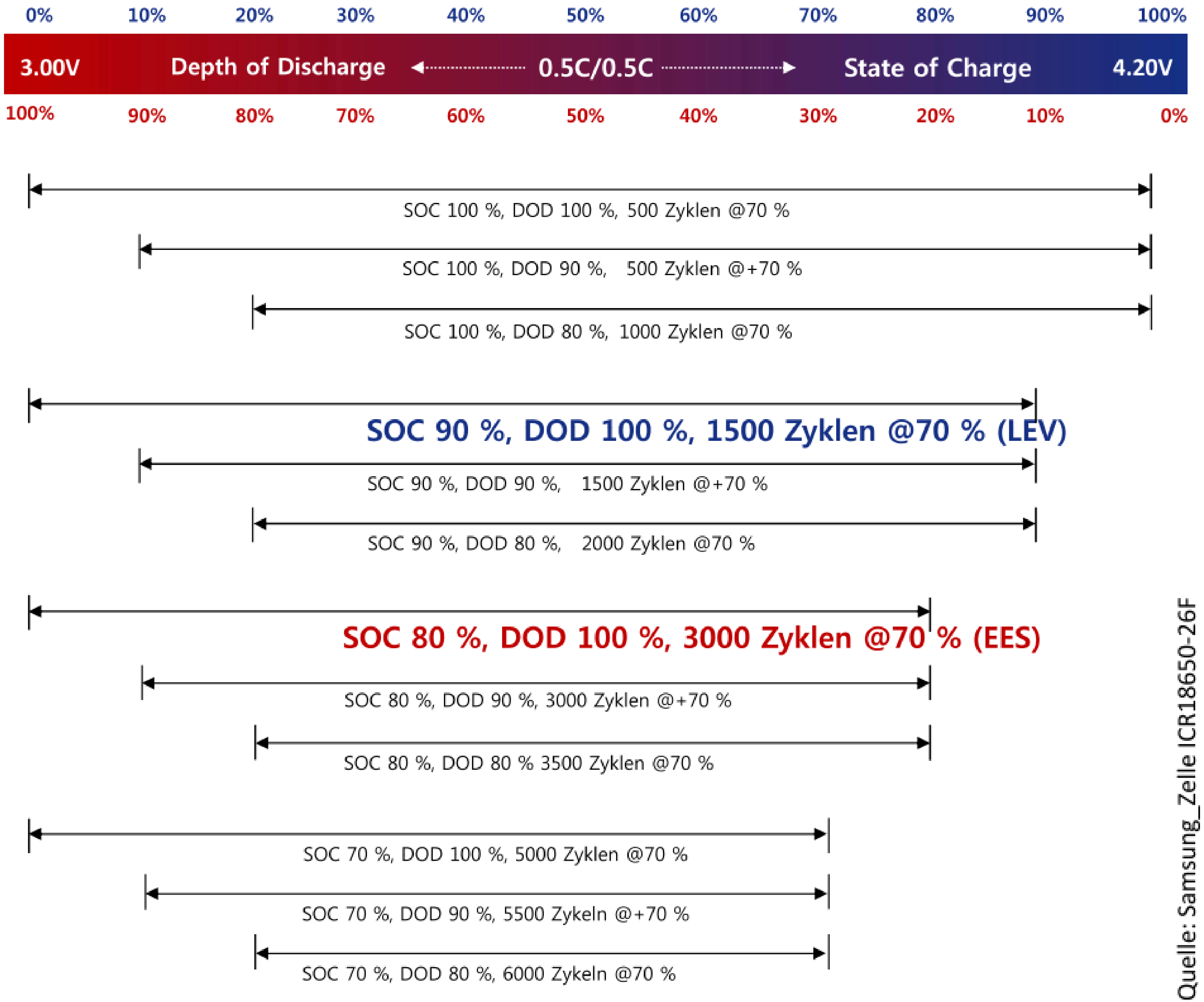
- Depending on:
  - Cell chemistry (e.g. active materials)
  - SOC ("State of charge")
  - "Depth of discharge" (DoD)
    - Partial cycles increase service life disproportionately
  - "Cell Imbalance" (cell-balancing)
  - charge/discharge current
  - operating temperature

Calendar life

- Dependent on:
  - cell chemistry
  - SOC - ambient temperatur
  - ambient temperature
    - RGT-rule: temperature increase by 10° C, doubles decomposition/resolution speeds
      - halved service life

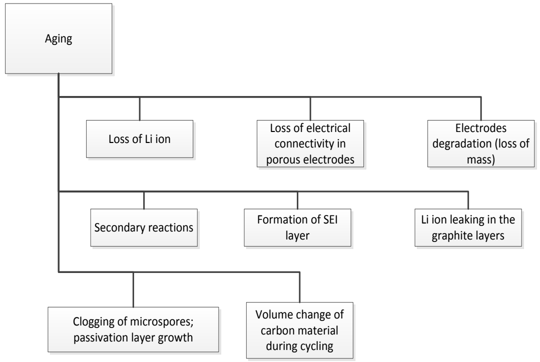
End of charge voltage

- Certain chemistries (i.e. Li(NiMnCo)O2 (NMC)) show a strong relationship between end of charge voltage and available life cycles.
- Operating strategies therefore mus take into account to keep the SOC window always between a certain range.
- This will add additional complexity to any battery and energy management system

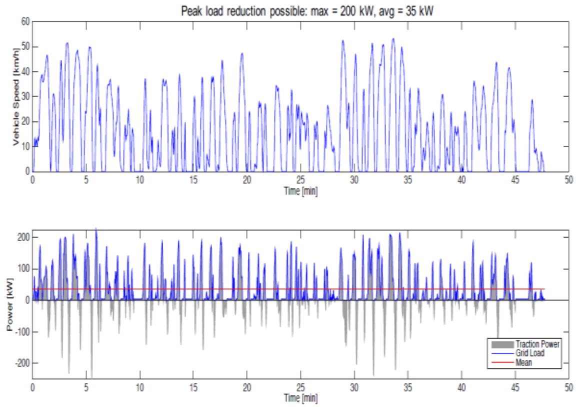


Quelle: Samsung_Zelle ICR18650-26F

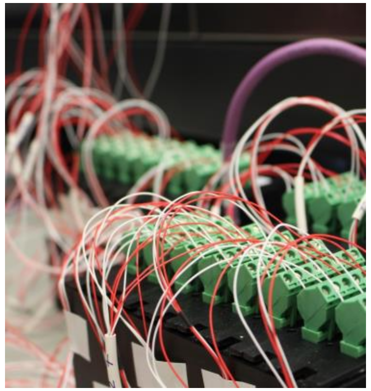
Lifecycle Research at BFH Energy Storage Research Centre



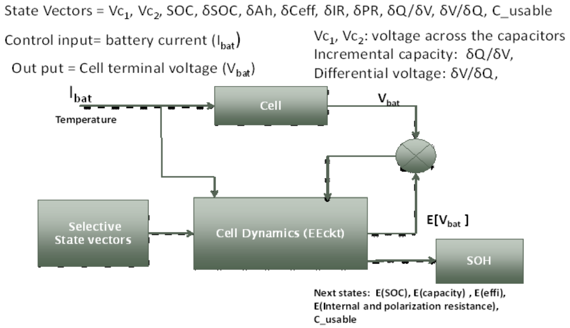
- Exploring Aging mechanisms



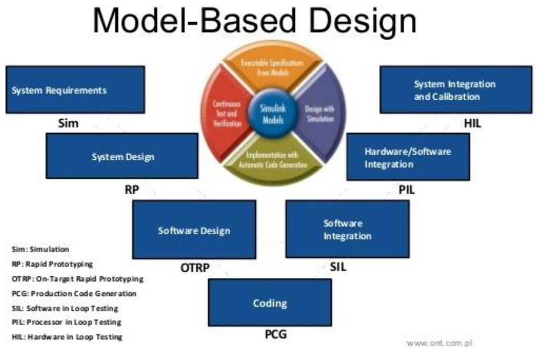
- Application specific load cycles



- Standardized lifetime tests



- Developing Life-cycle models



- Algorithms and software development

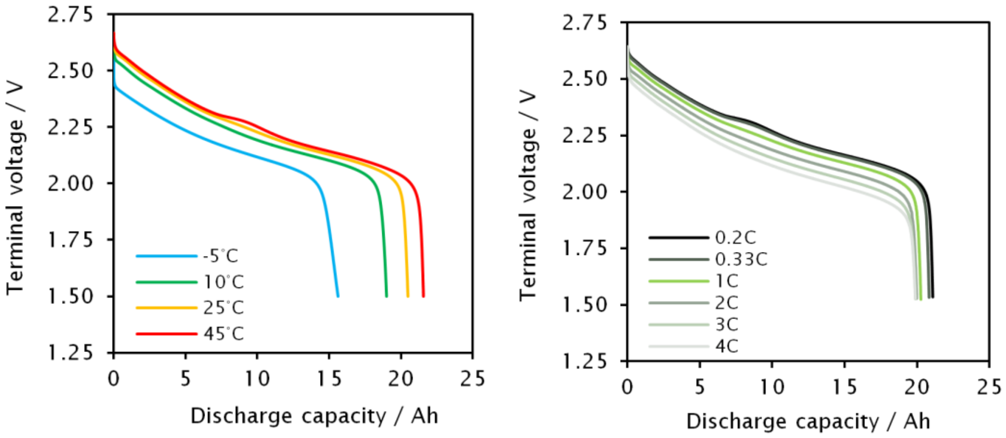
- Development of own battery Management systems

Life-Cycle testing and Life-Cycle Model development (LTO)

- Large testing phase since 2 years
- Several temperatures and C-Rates investigated
- Results will lead to model based life-cycle estimator for application specific load profiles

Chamber set temperature / °C	C-rate / h^{-1}	Order of execution
- 5	1	start
	2	x 2
	4	
	6	
10	1	
	2	x 2
	4	
	6	
45	1	
	2	x 2
	4	
	6	
25	1	
	2	
	4	x 2
	6	stop

Table 1: Standard life cycle test matrix developed in-house for the experimental Phase 1



Isolated effect of testing conditions on cell performance. In A, the charge and discharge rate was 1 C. In B, the test temperature was 25°C.

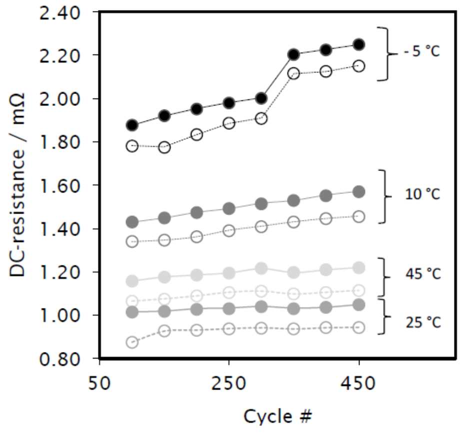


Figure 14: DC-resistance over cycle number. The hollow circles represent values measured for the tests performed at a discharging rate of 1 C. The full circles represent values measured for the tests performed at a charging rate of 1 C.

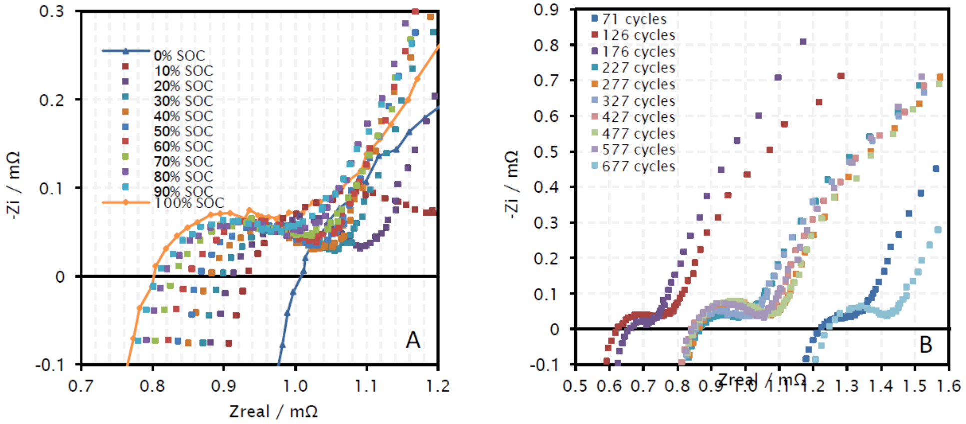


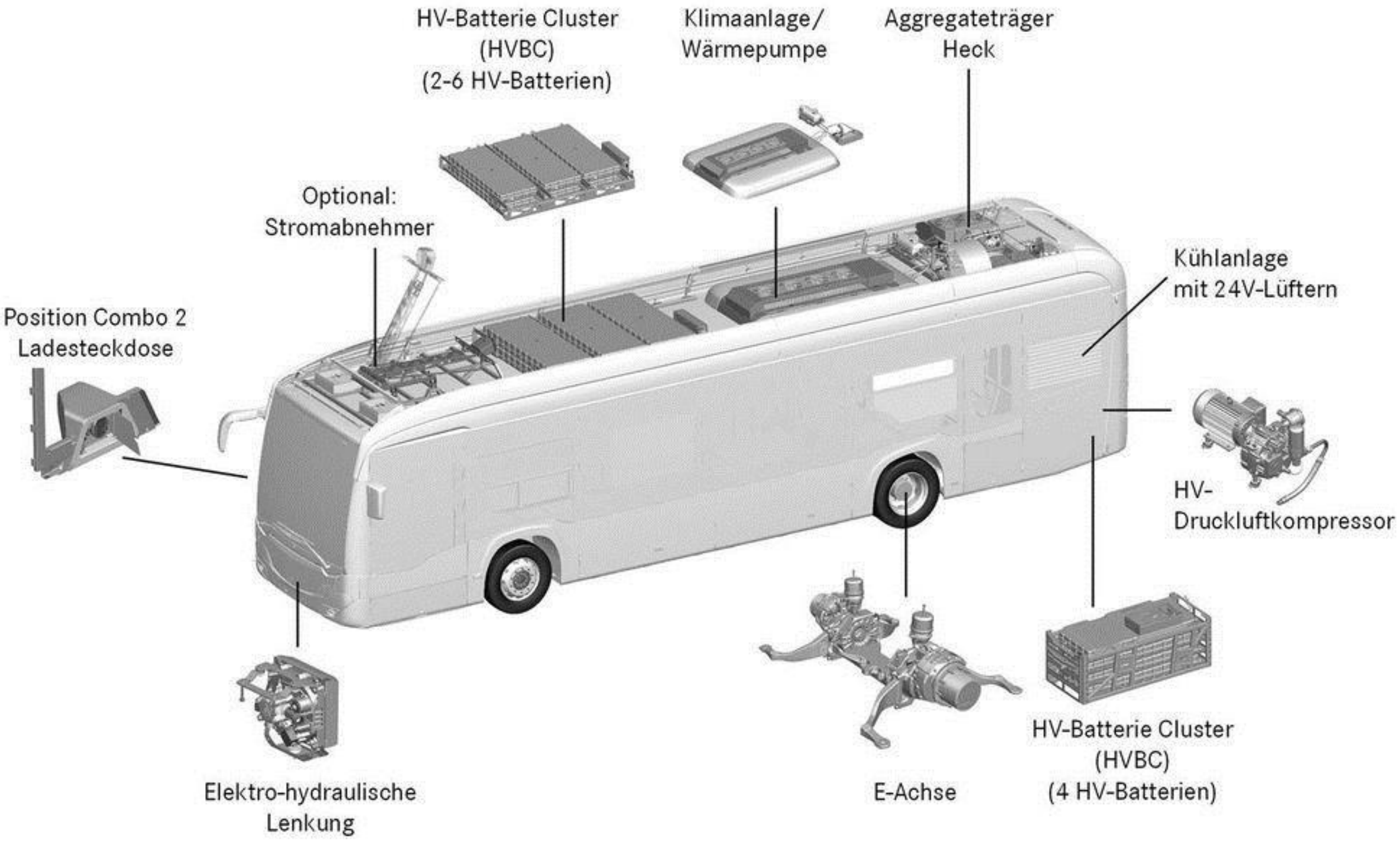
Figure 13: EIS results of one cell at different SOC after 327 cycles (A) and after different number of cycles at SOC = 50% (B).

Some Conclusions of Experiments

- It has been found that discharging is more detrimental for battery life than charging.
- Discharging with higher C-rates is more detrimental than discharging at lower C-rates.
- The discharge performance *is* more sensitive to changes in C-rate than on changes in temperature (for the parameters investigated in this study):
  - a change from 1 C to 6 C ends up in lower performance results than a 35° C change from 10° C to 45° C or a 30° C increase from -5° C to 25° C (62 % against 41 % lower performance, respectively)
- Charging at lower temperatures is more harmful for battery performance than at higher temperatures.
- Discharging at lower temperatures is less harmful for battery performance than at higher temperatures.

Battery Thermal Management

Structure of E-busses

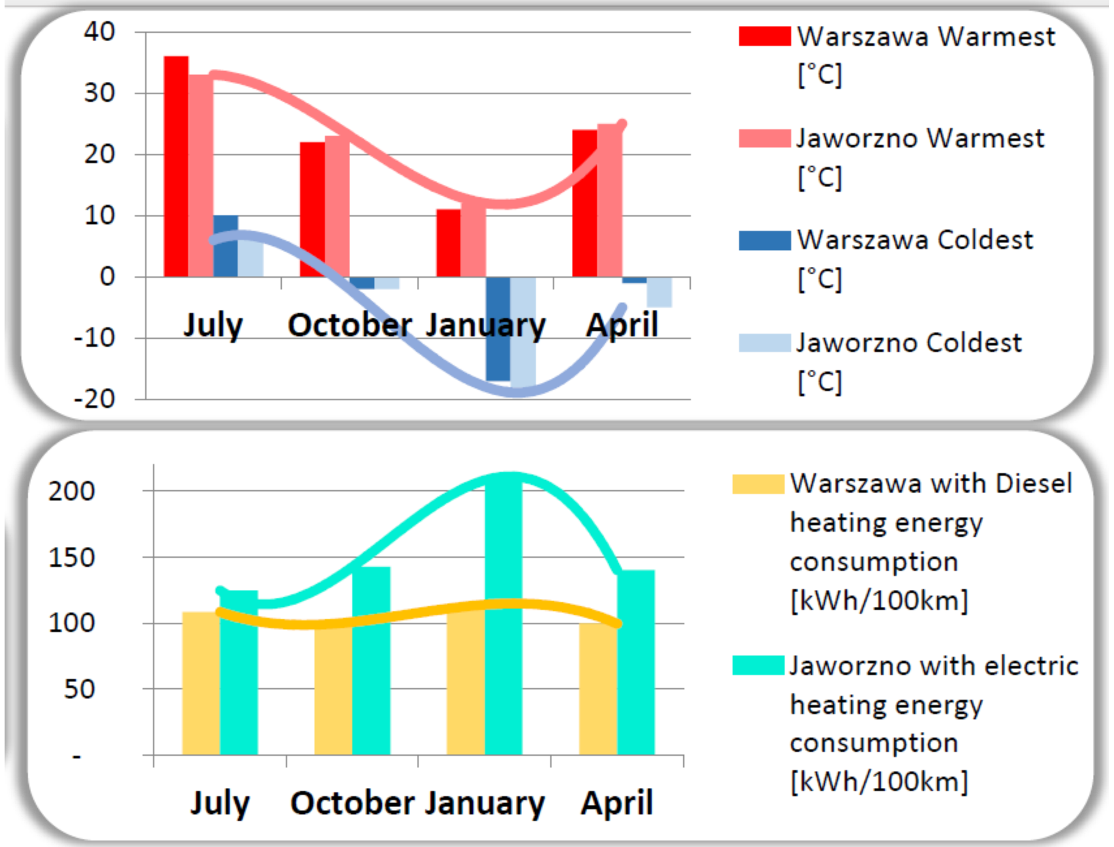


The bus concept of Daimler's electric Citaro is modular.
(Image: Daimler)

- Distributed Battery concepts due to space constraint and weighth distribution
- Batteries often on top. Directly exposed to heat and cold
- Battery Thermal Management combined with HVAC
- Additional electrified Auxiliaries (i.e. steering)

Battery and Bus thermal Management

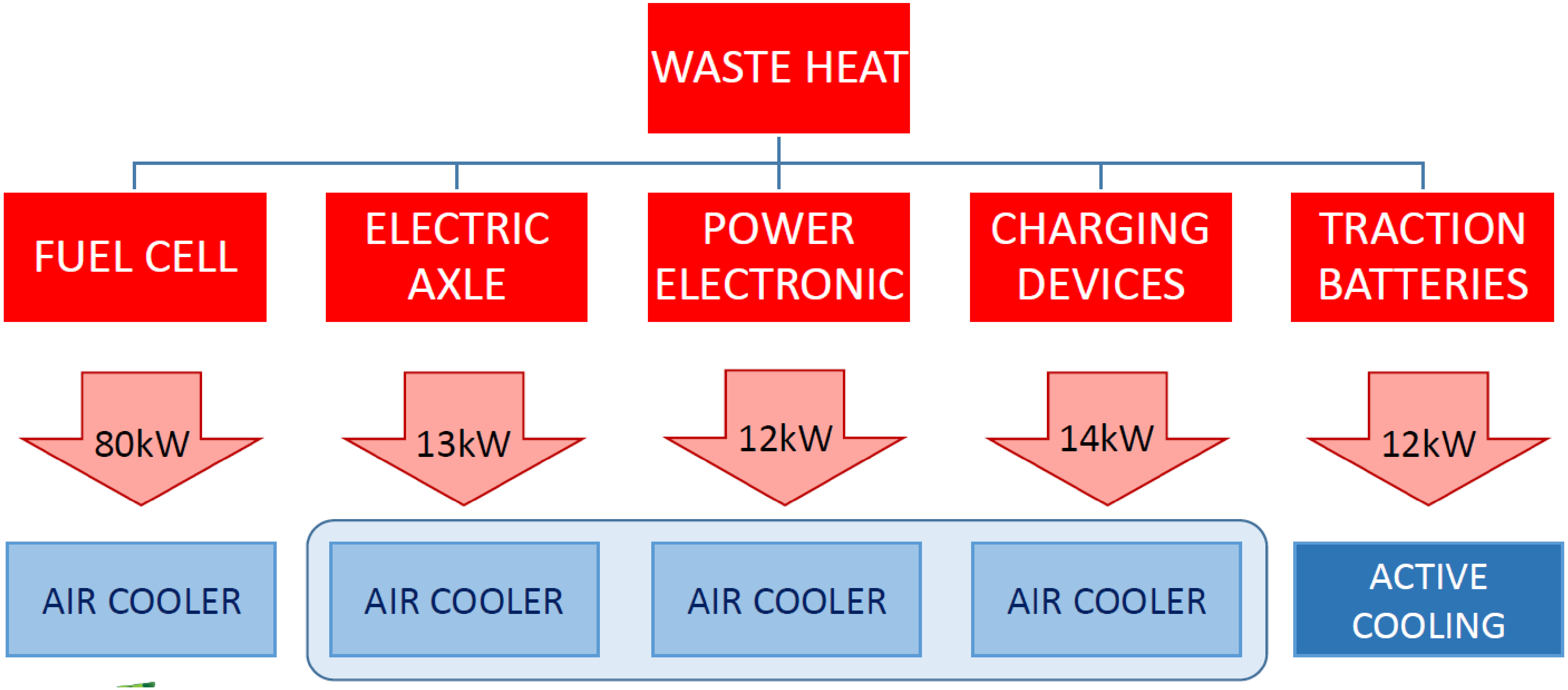
- Heating energy consumption is critical in regions with strong seasonal variation
  - HVAC energy consumption reduction through heat pumps development and waste heat recuperation
- Batteries' cells optimal temperature are at 25° C
  - Temperature variation will decrease performance (up to 20% lower usable energy with temperature below 0° Celsius) and reduce life cycle time of batteries (observed up to 30% reduction)
  - Batteries thermal management is therefore be based on active cooling/heating module often based on coolant water/glycol



Temperature Range and energy consumption measured in traffic operation by customers for the period 2015/2016 in Warsawa and Jaworzno

Challenges in thermal management for electric buses manufacturers, Maciej Mrozek
Solaris Bus & Coach S.A.

Typical Waste heat sources and their potential



Challenges in thermal management for electric buses manufacturers, Maciej Mrozek
Solaris Bus & Coach S.A.

Safety, Handling and Recycling

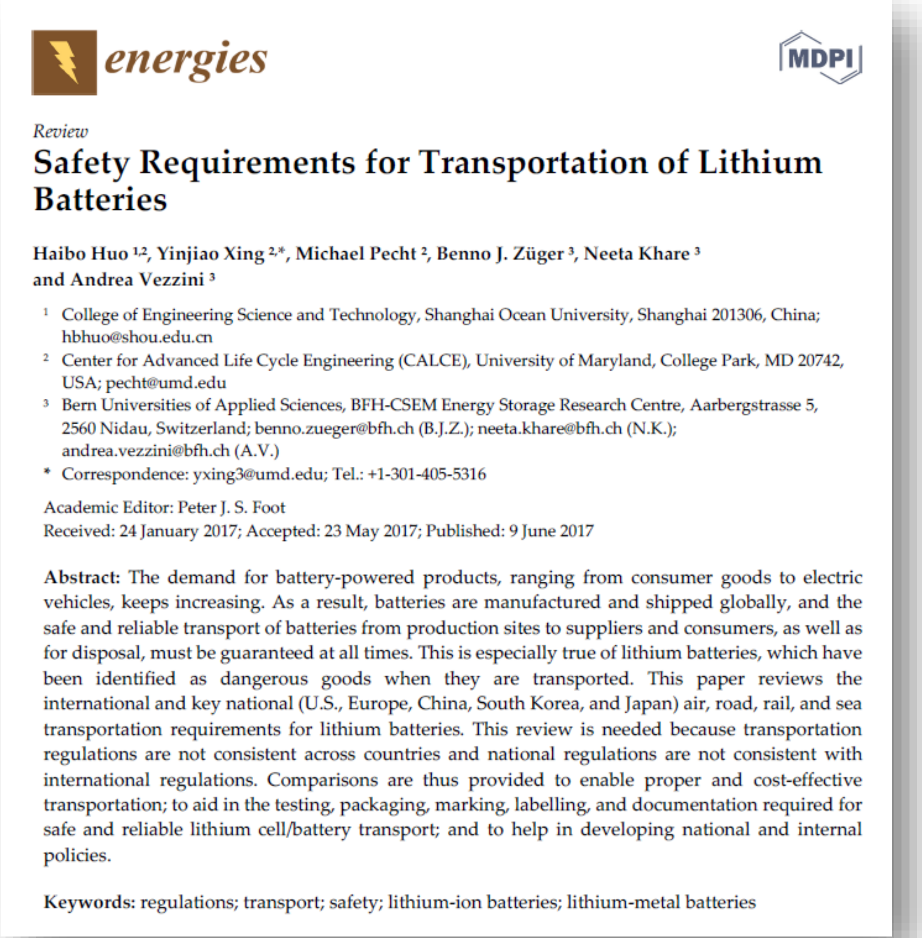
Lithium-ion batteries: Correct Handling

- Toxicity
  - In normal handling, no dangerous substances will escape from the lithium battery and one can therefore not come into contact with toxic substances.
  - no protective equipment required

- Environment
  - During normal handling, the lithium battery will not damage the environment. However, it must be disposed of separately after use as it contains hazardous chemicals.

- Disposal
  - The accumulator is hazardous waste!
  - The lithium battery may only be disposed of via a designated location. Under no circumstances should the lithium battery be disposed of with residual waste.

Review: Safety Requirements for Transportation of Lithium Batteries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Review

Safety Requirements for Transportation of Lithium Batteries

Haibo Huo [1,2], Yinjiao Xing [2,*], Michael Pecht [2], Benno J. Züger [3], Neeta Khare [3] and Andrea Vezzini [3]

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Abstract: The demand for battery-powered products, ranging from consumer goods to electric vehicles, keeps increasing. As a result, batteries are manufactured and shipped globally, and the safe and reliable transport of batteries from production sites to suppliers and consumers, as well as for disposal, must be guaranteed at all times. This is especially true of lithium batteries, which have been identified as dangerous goods when they are transported. This paper reviews the international and key national (U.S., Europe, China, South Korea, and Japan) air, road, rail, and sea transportation requirements for lithium batteries. This review is needed because transportation regulations are not consistent across countries and national regulations are not consistent with international regulations. Comparisons are thus provided to enable proper and cost-effective transportation; to aid in the testing, packaging, marking, labelling, and documentation required for safe and reliable lithium cell/battery transport; and to help in developing national and internal policies.

Keywords: regulations; transport; safety; lithium-ion batteries; lithium-metal batteries

- Review paper
- Reviews the international and key national (U.S., Europe, China, South Korea, and Japan) air, road, rail, and sea transportation requirements for lithium batteries.
- Since regulations are not consistent across countries comparisons are provided to enable proper and cost-effective transportation
- The paper aids in the testing, packaging, marking, labelling, and documentation required for safe and reliable lithium cell/battery transport; and to help in developing national and internal policies
- Labelling:

Figure 3. (a) Lithium battery handling label (* Place for UN numbers, ** Place for telephone number for additional information); (b) Cargo Aircraft Only label; (c) Class 9 hazard label.

- Collaboration with different universities (USA, China, Switzerland)
- Published in MDPI Energies, June 2017, 37 pages, 102 references
- Download: http://www.mdpi.com/1996-1073/10/6/793

Study: Technology assessment of lithium containing batteries (LIB)

- Study was carried out on behalf of the armasuisse (2016/17)
- Attended by a scientific accompanying group
- Content:
  - Introduction to the basic principles of Li-ion batteries
  - Overview about actual LIB technologies
  - Key chapters about "laws, norms and regulations", "safety aspects“ and "experience reports“ (e.g. transport regulation ADR 2017)
  - Recommendations about the five life phases of Li-ion batteries we considered: "procurement", "storage", "transport", "application" and "disposal
  - Out conclusion: With a good choice and a careful handling of the safe use of LIB is possible without any reservations - according to the listed recommendations

- Written in German, 124 pages
- More than 40 illustrations, 100 references, 55 norm references, …
- PDF version can be downloaded: bfh.ch/energy/publikationen

Berner Fachhochschule
Haute école spécialisée bernoise
Bern University of Applied Sciences

Herzlichen Dank für Ihre Aufmerksamkeit

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- BFH-CSEM-Zentrum Energiespeicherung: www.bfh.ch/energy