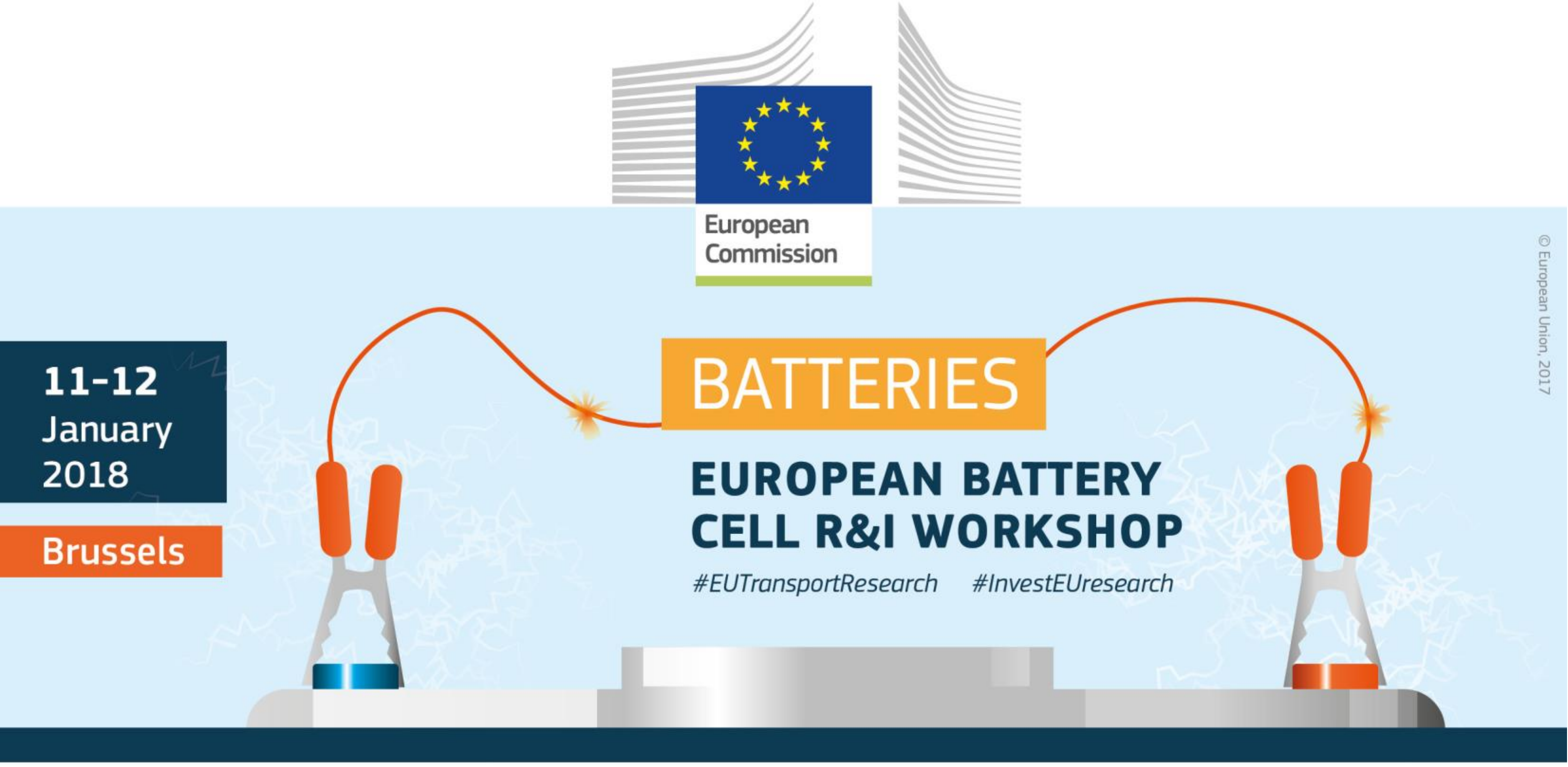

Final Report

12/02/2018

Research and
Innovation

TABLE OF CONTENTS

EXECUTIVE SUMMARY

1. General conclusions and recommendations on research and innovation needs

Traction batteries are considered as a Key Enabling Technology in electric vehicle (EV) drive trains. Current traction batteries are, to a large extent, based on lithium-ion (Li Ion) chemistry which is expected to remain **the technology of choice** for many years to come (decades). However, performance and safety improvements will lead to new generations in the next 5 to 10 years (generation 3b by ca 2023 and generation 4 by ca 2026).

Current Li Ion batteries for e-mobility are not yet close to their fundamental limits illustrated e.g. by their gravimetric & volumetric energy density, with current cell level state-of-the-art at 90-235 Wh/kg & 200-630 Wh/l and the expected fundamental limits at 350-400 Wh/kg and 750 Wh/l. Such a drastic improvement of performance must be achieved through the development of Advanced Materials covering cathode, anode, binders, separators, electrolyte, current collectors and packaging materials as to enable new Li Ion batteries, with a particular focus on **high voltage systems (4.5 – 5.0 V) and high capacity systems (generation 3b).**

Solid-state batteries (generation 4) are the next step on major OEM's roadmaps: they are an enabler for doubling the driving range based on targeted energy densities of 500 Wh/kg and 1000 Wh/l combined with better safety.

A European **research validation network of pilot plants** would be a valuable tool to strengthen European research and industry and therefore could be an important instrument of the Battery Alliance.

Stationary applications demand lower energy and power densities than mobile applications, as they are not constrained by volume or weight. Instead, stationary batteries must demonstrate a longer battery lifetime and lower costs. First research focus is to improve Li Ion for this purpose whilst non-Li Ion systems especially in energy applications may also offer opportunities.

There is a need for cross-cutting harmonisation and open data access tools. A **shared database** for test results and references would be necessary in Europe (example US-DoE). An **Innovation platform** is needed for multiscale and multiphysics modelling, multidisciplinary inputs, for and development of ageing models.

In order to boost the competitiveness of the EU funded projects, there is a need to integrate KPIs on **Intellectual Property** generation in the projects.

2. Recommendations for research and innovation topics

1. High capacity and high voltage Li Ion batteries (generation 3b)

Research must support the industrial development towards production of TRL 9 technologies with significant improvements in Advanced Materials on the level of cathodes (Ni rich or Li rich NMC with low Co-content, high voltage spinel...), anodes (graphite/Silicon…), 5V electrolytes, separators, interface layers etc. with following by stakeholders expressed particularities:

- Higher energy density at reduced safety is no compromise, understanding of surface degradation effects of electrode materials is essential;
- Work to increase Si content in Si/C anodes, even full Si anodes might be possible, develop strategies to improve cycle life of Si anodes e.g. by preconditioning/ prelithiation;
- Fast charging (of packs) is of particular importance and materials/design should allow for it;
- Incorporation of smart micro sensor systems for SoC and SoH;
- Design must be such that the batteries are directly reusable for second life applications. Design of smart cells and battery packs in a way that they can be dismantled and recycled in a cost efficient way (cost reduction, circular economy);
- Integrated modelling approach from atomistic level of materials to multiphysics modelling and transport on the electrode (mm) level to understand performance and ageing.

2. Solid state Li Ion batteries

Workshop participants proposed parallel tracks whereby polymeric, inorganic and composite/hybrid solid-state electrolytes should all be addressed. These development tracks can have a different timeline depending on the TRL and challenges specific to the technology.

A very interesting suggestion is to consider 2 sub- generations: 4 a: with conventional Li Ion materials (e.g. NMC/Si targeting 2020-2022) and 4b with Li metal as anode (e.g. NMC/Li targeting 2025-2030). The highest energy density is expected with Li-metal (4b), however the interface with the electrolyte needs to be improved to avoid dendrite formation (structural defects to be avoided, interfacial wetting with solid electrolyte to be improved, coatings to be applied, deposition or lamination techniques to be developed...).

Solid-state technology should have acceptable performances at room temperature (25-40°C) and it should meet the fast charging requirements of BEVs.

Six research topics were proposed in the workshop: details in Annex 2:

Topic I: Cell design (call 2019): >400Wh/kg, 1000 cycles, < 100€/kWh
Topic II: Multiscale modelling (call 2019)
Topic III: In depth interface optimization, characterization and integration (call 2019)
Topic IV: Battery system design (call 2020)
Topic V: Processing and manufacturing (call 2020)
Topic VI: IP protection and know-how creation (call 2019)

3. *Stationary energy storage:*

Li Ion & non Li ion: research topic to improve specifically cycle life, calendar life and cost (capex, cycle cost) while maintaining the highest safety (in line with roadmap in Discussion Paper).

For non Li Ion, critical review of the proposals needed based on state-of-the-art and prior EU project results. Participants express progress and opportunities in redox flow and Na-ion batteries as first choice (with Mg and Zn systems for the longer term).

4. *Research Pilot lines*

A questionnaire was sent out to all participants to list the pilot lines already existing in Europe with details on their capabilities: 33 answers received 13 lines in operation and several others planned.

With reference to their operability for Generation 3b materials and technologies: no big technical issues expected.

With reference to Generation 4 solid state, much more challenges are expected but workshop participants came to the conclusion that it is too early to discuss or suggest pilot lines for all solid-state systems today. At present, the availability of materials is too low to operate a pilot line for these systems. Therefore, it is suggested to concentrate work provisionally on process research on a lab-scale.

It became clear that several questions remain open for networking, e.g. forms of possible cooperation, handling of IP, patents and competition, structure of cooperation, integration of industrial pilot plants, etc... Therefore, it was suggested that a short-notice meeting should be organized to discuss these topics, in order to find ways to build a European network of pilot lines, and to make sensible suggestions for funding topics.

An optimized pilot line for solid state is expected by ca 2025 depending on technology development and a call needs to be prepared for this in due time.

3. Establishing manufacturing base in Europe

Worldwide market prospects for Li Ion batteries are overwhelming: from about 85 GWh in 2016 to a forecasted 550 GWh by 2025, an exciting market potential driven by vehicle electrification and to a lesser extent by a steady growth in portable electronics and energy stationary storage accounting for +/- 30 GWh.

Led by China, battery cell manufacturing capacity has more than doubled today to 125 GWh, and is projected to double again to over ca 275 GWh by 2020. Many giga-factories are in the pipeline for 2025.

Europe welcomes foreign investments (LG Chem in Poland, Samsung SDI in Hungary, SK Innovation in tbd…) but actively starts developing its own major manufacturing initiatives (Northvolt, TerraE, Daimler…) and clearly expresses its ambition to become a leader in Advanced Li Ion and Solid State (in development and manufacturing).

Indeed, as manufacturing capacity build-up for Li Ion is already ongoing in Asia particularly in China, it does not seem effective to spend significant efforts to establish a mass production chain in Europe on current Li Ion commercial technologies. Efforts for establishing manufacturing capacity in Europe should therefore primarily target Li Ion cells of min. generation 2b and preferentially beyond (with generations 3b and 4).[1]

In addition to the R&I challenge with regards to the electrochemistry, Europe lacks the skills to manufacture battery cells. A specific action is required in terms of building necessary skills in the battery cell manufacturing.

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[1] JRC-EU Competitiveness in Advanced Li-ion Batteries for E-Mobility and Stationary Storage Applications – Opportunities and Actions – Steen, M., Lebedeva, N., Di Persio, F., Boon-Brett, L. 2017).

1. CONTEXT AND BACKGROUND

Europe's current transformation to efficient low-emission transport and a sustainable energy economy requires specific means for energy storage. Batteries provide important solutions to achieve the overarching goal in electrification of the transport system and integrating battery energy storage systems.

Recent market trends demonstrate that investments to intensify battery development and production will rise significantly in the coming years due to the expected increase in the uptake of electric vehicles and use of energy-storage applications.

For this reason, the European Commission is supporting European battery cell competitiveness across the whole value chain through establishing the "EU Battery Alliance." As a result, a new industrial and manufacturing value chain of battery cells would be created in Europe, avoiding technological dependency with respect to a critical component and creating new jobs and revenues in Europe.

To date, together with private investments, EU-funded projects have mobilised resources of EUR 555 million for battery research since 2008 (for more details please see *Projects for Policy on Batteries* report[2]).

In the current Research and Innovation Work Programme for 2018-2020 four topics, with a total EC budget of 100 Million euros, have already been published to support the development of the next generation electrochemistry and production technologies for mobility and energy applications. Nevertheless, an **extra budget of € 100 million** has become available to finance new topics to be included in the Work Programme for 2019 and 2020.

In this regard, Directorate General for Research and Innovation (DG RTD) has organised the workshop "European battery cell R&I: setting short and medium-term priorities" to discuss the possible topics descriptions for determining how to wisely spend the extra budget.

The workshop gathered around 270 participants across the whole value chain and was held in Brussels on 11 and 12 January 2018.

[2] https://ec.europa.eu/info/sites/info/files/batteries_p4p-report_2017.pdf

2. OBJECTIVES

The additional budget will help to establish the future European base for mass production of next generation batteries by 2025-2030 and covered the following research themes:

1. Research on new materials and cell chemistry targeting the most promising advanced production technologies;
2. Paving the way for the creation of new cell production pilot lines (targeting next generation technologies) operational by 2020-2025;
3. Activities to ensure better accessibility to the existing cell production pilot lines to all research laboratories which are not equipped with such facilities for validation and testing purposes. Networking of existing pilot lines will be promoted, resulting in synergies and possibly technological harmonisation;
4. Cross cutting themes such as accessibility of raw materials in Europe, recycling potential, circular economy, integration of European equipment suppliers in the projects, integrate KPIs on IP (Intellectual Property generation) in the projects and dissemination strategy;

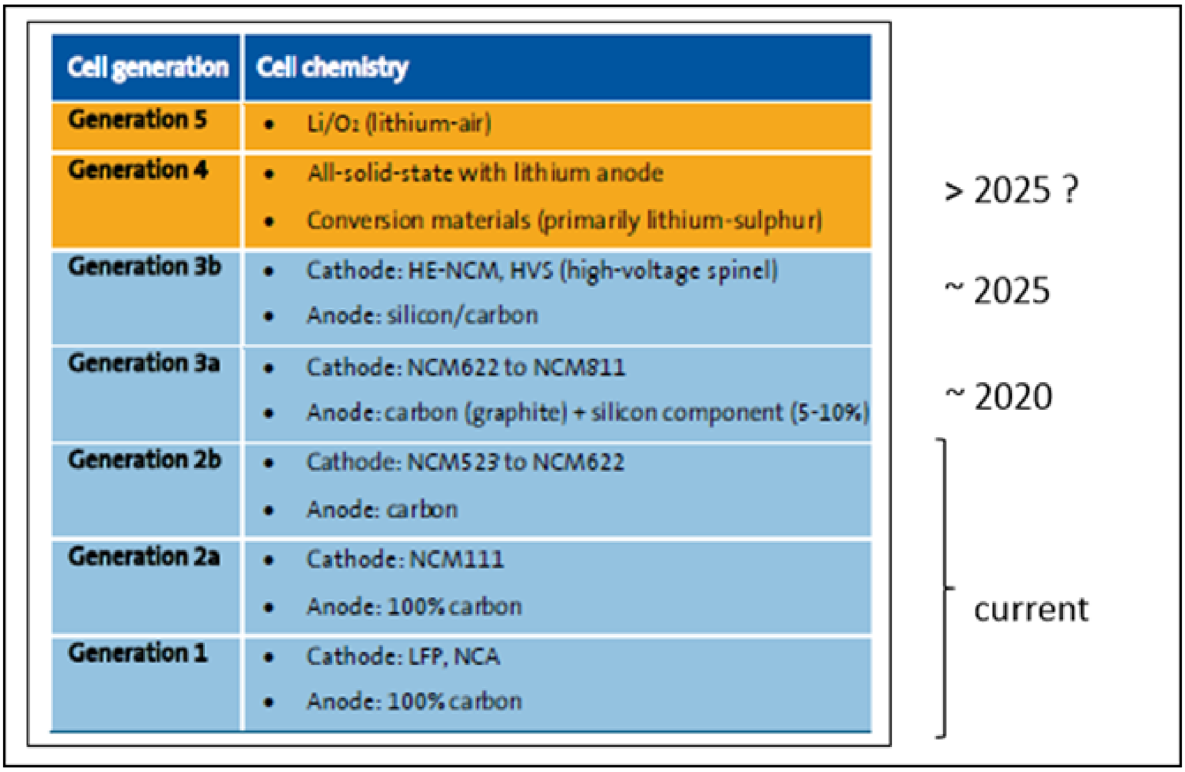
The workshop started with a **plenary session** on Day 1 with state of the art presentations on chemistries, pilot lines and manufacturing processes from European perspective.

On the Day 2, the discussions took place in **four technical break-out sessions** on:

- Advanced Li Ion technologies (generation 3b)
- Next generation solid-state Li Ion technologies (generation 4)
- Technologies for stationary storage applications
- Research Pilot Line network

As a general outline for the discussions reference is made to the "**Discussion Paper**" which was made to streamline the discussions of the various workshops: http://europa.eu/!wN88Qy

Denominations of the battery technologies are based on classifications published by Nationale Platform Elektromobilität and adopted by JRC[3]. (Fig.1)



Cell generation	Cell chemistry
Generation 5	• Li/O₂ (lithium-air)
Generation 4	• All-solid-state with lithium anode • Conversion materials (primarily lithium-sulphur)
Generation 3b	• Cathode: HE-NCM, HVS (high-voltage spinel) • Anode: silicon/carbon
Generation 3a	• Cathode: NCM622 to NCM811 • Anode: carbon (graphite) + silicon component (5-10%)
Generation 2b	• Cathode: NCM523 to NCM622 • Anode: carbon
Generation 2a	• Cathode: NCM111 • Anode: 100% carbon
Generation 1	• Cathode: LFP, NCA • Anode: 100% carbon

Fig.1

An overview of potential technological advancements (with indicative performance) differentiated by technology (Fig.2) was proposed in the Discussion Paper to be reached for Advanced Li Ion batteries (generation 3b) latest by 2025 and for Solid State Batteries (generation 4) latest by 2025-2030.

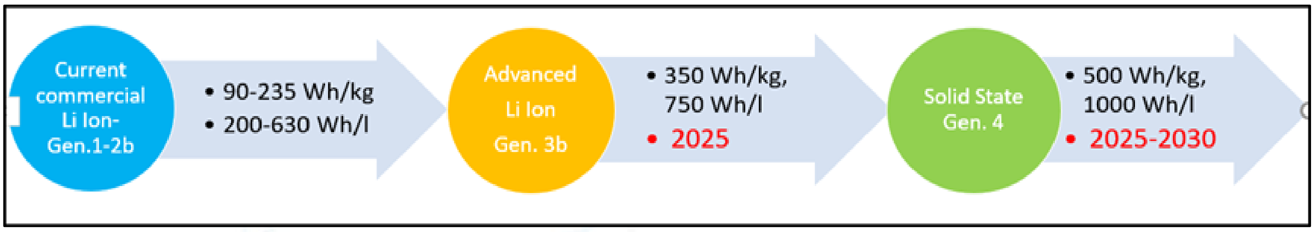


Fig.2

[3] *JRC-EU Competitiveness in Advanced Li Ion Batteries for E-Mobility and Stationary Storage Applications – Opportunities and Actions – Steen, M., Lebedeva, N., Di Persio, F., Boon-Brett, L. 2017).*

3. PLENARY SESSION

3.1. Policy presentations

Clara DE LA TORRE Director, European Commission, DG RTD Transport - welcomed all participants and underlining the importance of the Workshop.

Gwenole COZIGOU - Director, European Commission, DG GROW Industrial Transformation and Advanced Value Chains – explained that within the "European Battery Alliance", the European Commission is acting as facilitator for bringing together all segments of the European batteries industry value chain and gather key players to propose a strategy for battery cell manufacturing with EU intellectual property in Europe.

Said El KHADRAOUI - Adviser, European Political Strategy Center – emphasized that the battery research and innovation will provide the battery sector with new opportunities and a powerful momentum.

Peter DROELL - Director, European Commission, DG RTD Industrial Technologies – underlined the role of research and innovation on Advanced Technologies and Materials to reach the targeted battery characteristics. He also gave a short overview on how DG RTD supported research and innovation in FP7 and Horizon 2020, and what is planned for the next years, as e.g. the prize on innovative batteries.

José COTTA - Head of Unit, European Commission, DG RTD Advanced Energy Production - referred to the work done by SET Plan TWG Action 7 which resulted in a series of key activities developed in its Implementation Plan. Activities are summarized in Fig.3 and Implementation Plan is available online: https://setis.ec.europa.eu/batteries-implementation.

Implementation Plan

Focus Area 1: Material/Chemistry/Design+ Recycling	
1.1	Advanced Lithium-Ion batteries for e-mobility
1.2	Influence of Fast/Hyper charging of Li Ion batteries on materials and battery degradation
1.3	Advancement of batteries for stationary energy storage (ESS)
1.4	Beyond Li-Ion / Li-based batteries for e-mobility
1.5	Develop circular economy and de-bottleneck availability of critical raw materials
1.6	Lithium recovery from European geothermal brines and sustainable beneficiation processes for indigenous hard rock occurrences of lithium
Focus Area 2: Manufacturing	
2.1	Foster development of materials processing techniques and components for fast industrialization compatible with present mass production lines
2.2	Foster development of cell and battery manufacturing equipment
Focus Area 3: Application and Integration	
3.1	Hybridisation of battery systems for stationary energy storage (ESS)
3.2	Second use and smart integration into the grid

- Material Flagship
- Manufacturing Flagship
- Fast-charge Flagship
- Second-use Flagship
- Recycling Flagship

- Input to the R&I dimension of the EU Battery Alliance

Fig.3

3.2 Technical presentations

- Overview of battery cell technologies- Marcel MEEUS - EMIRI
- Progress and Challenges: Generation 3b - Tobias PLACKE - MEET
- Progress and Challenges: Generation 4 - Céline BARCHASZ - CEA Liten
- Research Validation Pilot Lines Network - Oscar Miguel CRESPO- CIDETEC
- Establishing Manufacturing Base in Europe - Paolo CERRUTI –NORTHVOLT

3.2.1 Overview of battery cell technologies- Marcel MEEUS -EMIRI

Market prospects for Li Ion batteries are overwhelming: according to Avicenne (The Rechargeable Battery Market 2016-2025) Li Ion represents about 85 GWh in 2016 in a total battery market of 450 GWh, still dominated by Pb-Acid. This picture is however drastically to change and reference is a.o made to Umicore forecasts with Li Ion at ca 550 GWh by 2025, an exciting market potential driven by vehicle electrification and to a lesser extent by a steady growth in portable electronics and energy stationary storage accounting for +/- 30 GWh[4] (Umicore presentation EU Innovation Summit Nov.28, 2017-EU Parliament).

Breakthrough technology improvements are expected from high capacity/high voltage configurations (Generation 3b) (Fig.4) and all-solid-state (Generation 4) and for the latter key is still to make drastic improvements to the solid electrolyte (Fig.5) and to integrate protected Li metal anodes in the design. In all designs ageing is to be controlled and prevented.

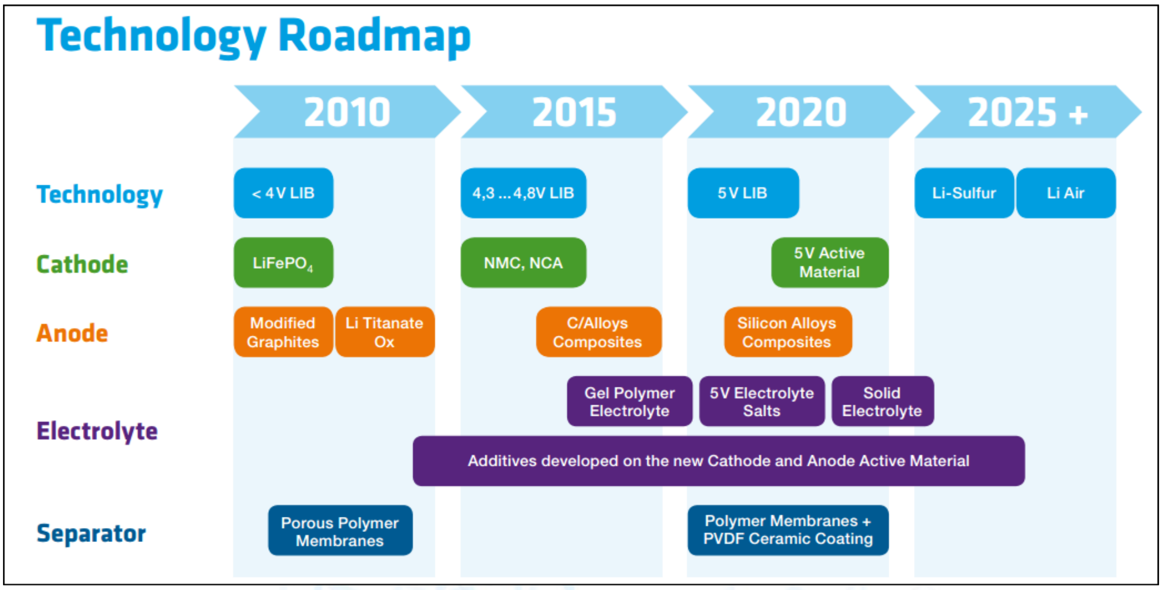


Fig.4 (Source Solvay)

[4] Umicore Dinner debate on Key Enabling Technologies & Industry in the future Framework Programme. EU Innovation Summit, 28 November 2017 . http://www.knowledge4innovation.eu/file/9theisketsdinnerdebatezip#overlay-context=file/agnieszkaeu-top-50-workshoppdf

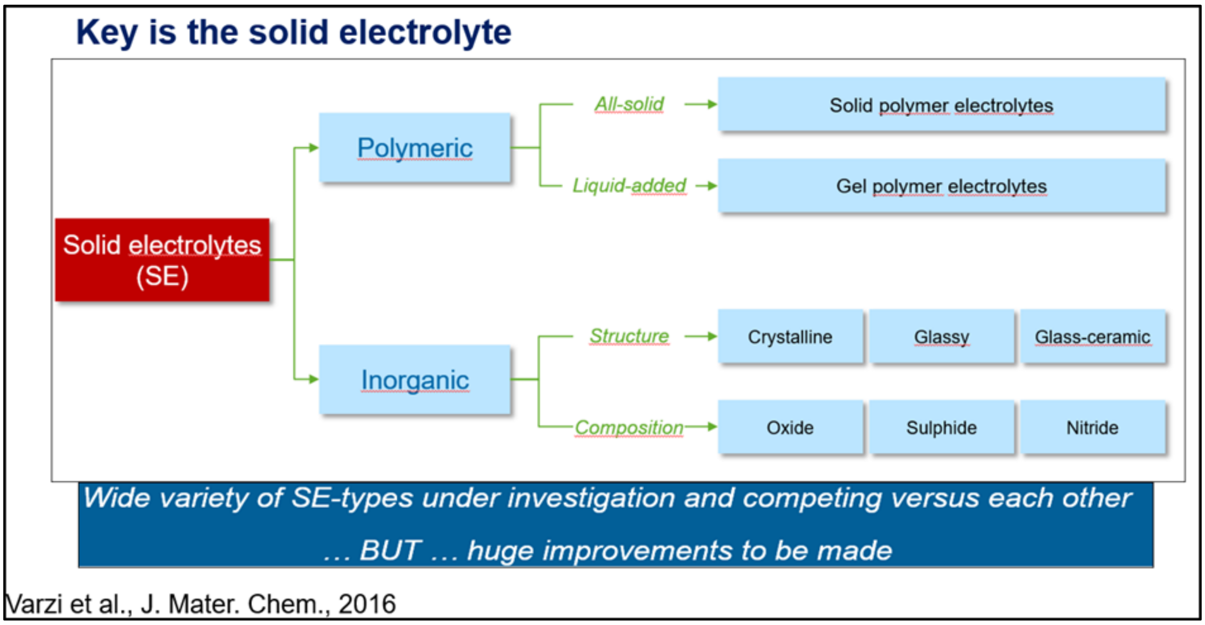


Fig.5

Specifically for stationary Energy Storage Systems (ESS) a roadmap was developed in the Discussion Paper setting targets and timings for power and energy applications as well for ESS designed Li Ion and non-Li Ion systems (Fig.6).

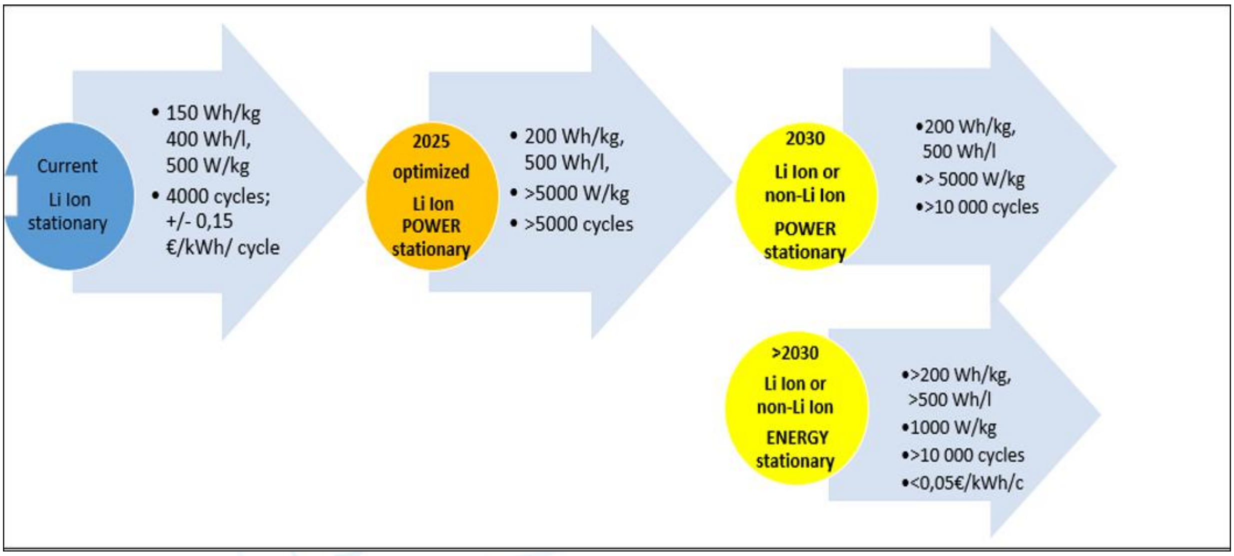


Fig.6

3.2.2 Progress and Challenges: Generation 3b Tobias Placke-MEET

Discussion points were the status of the various Li Ion generations and in particular the improvements to be made in advanced materials and system design for Generation 3b:

1. Promises of Generation 3b Cathode Materials: **LNMO**: High-voltage spinel (HVS; $LiNi_{0.5}Mn_{1.5}O_4$) and **LRNMC**: Li-rich NMC (HE-NMC; x $LiMO_2$. 1-x Li_2MnO_3).

2. Challenges and Strategies for Si-Based Anodes

The need for R&I Activity is defined by the author as follows:

- development of advanced Gen3b cathode materials (Ni-rich NCM and HENCM, HVS, protective coatings for safety improvements, gradient materials, etc.),

- development of Si/C anode materials (Si >>5 wt%) and strategies for stabilization, e.g. concepts for pre-lithiation,

- development of high voltage electrolytes and electrolyte additives for interphase stabilization (SEI, CEI) at the electrode/electrolyte interfaces and safety improvements,

- development of suitable inactive materials (binders, conductive carbons, current collectors, separators e.g. ceramic coated membranes) for high capacity and high voltage (> 4.5 V) systems,

- development of advanced processing technologies for the above,

- development of advanced electrode and cell/module designs and formats to maximize the energy content while ensuring a high power density and safety,

- development of advanced processing/production routes for novel materials (e.g. aqueous processing, solvent-free processing, conductive binders, etc.),

- strategies for recycling and/or 2nd life of batteries,

- focus on sustainability (materials, etc.), CO_2-footprint (energy-efficient processes, etc.) and “smart batteries” (sensing technologies, etc.),

3.2.3 Progress and Challenges: Generation 4 - Céline BARCHASZ - CEA Liten

There is little doubt that the solid state technology is considered by many OEM’s as the next step in their roadmaps (Fig.7), they are an enabler for doubling the driving range, they would have better safety and would be denser thus allow potential reductions in the amount of passive components.

3 types of solid electrolytes were discussed by the author: a) Inorganic crystalline materials (perovskites, garnets, Nasicon), b) Inorganic amorphous materials (LiPON, glass sulfides…) and c) Solid polymers (polyethylene oxide, PILs, single-ion) and this for their advantages and inconvenients. A special attention was given to GARNET material : LLZO ($LiLa_3Zr_2O_{12}$).

Main issues for inorganic systems: high interfacial resistance and poor interface contacts , reactivity between solid electrolyte and electrodes during cell assembly & cycling ,thick electrolyte layers / high density materials, NEW ARCHITECTURES, NEW PROCESSES NEEDED.

Main issues for polymeric systems: poor ionic conductivity, electrochemical stability, working temperature, Lithium dendrites.

Main issues for all-solid-state hybrid systems: polymer stability (high voltage), transport mechanisms to be solved, role and importance of interfaces in the composite to be understood.

A very interesting suggestion is to consider 2 sub- gnerations: 4a: with convential Li Ion materials (e.g.NMC/Si) and 4b with Li metal as anode (e.g. NMC/Li). See Fig. 8.

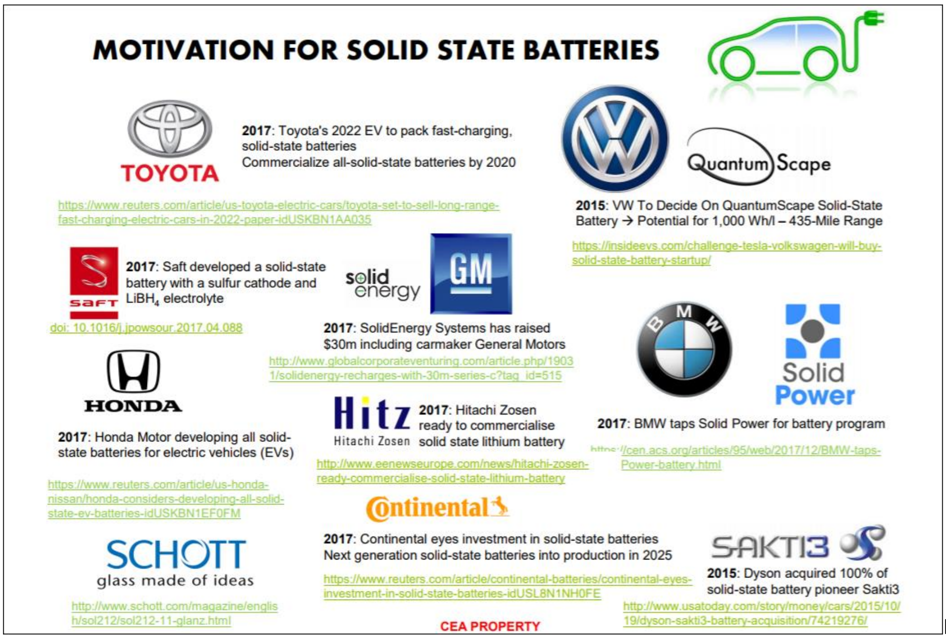


Fig.7

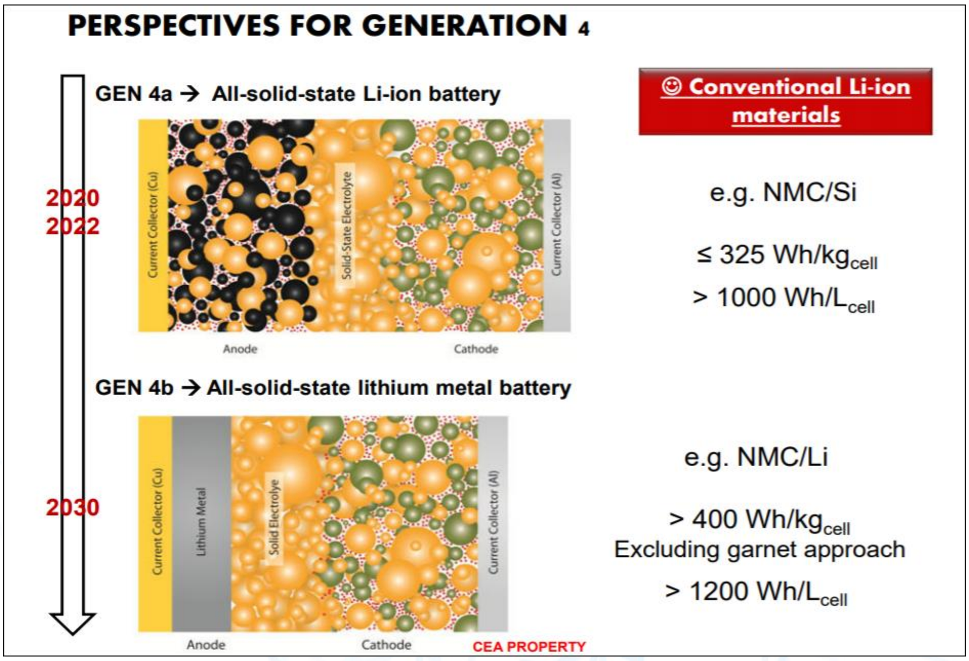


Fig.8

3.2.4 Research Validation Pilot Lines Network - Oscar Miguel CRESPO- CIDETEC

Speaker introduced a series of pilot lines (Fig.9) already operational in Europe (more to follow in the corresponding Workshop based on a questionnaire survey). .As an introduction whether they would be technically suitable for Generation 3b development, see Fig.10: with minor adaptations they are. Different is the situation for Generation 4 (solid state), as Fig.11 shows still a lot of challenges need to be resolved.

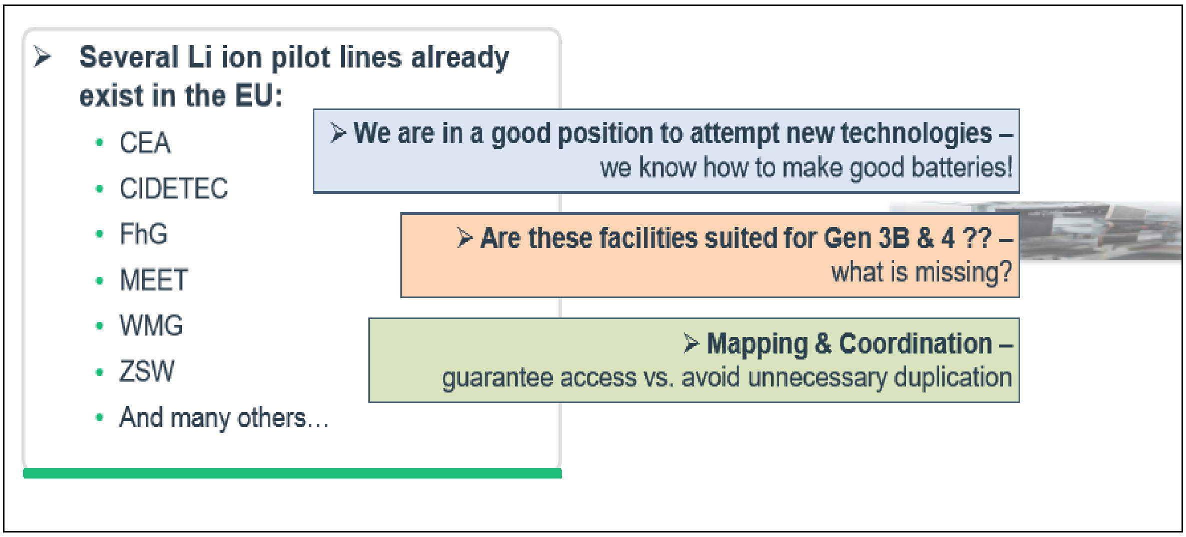
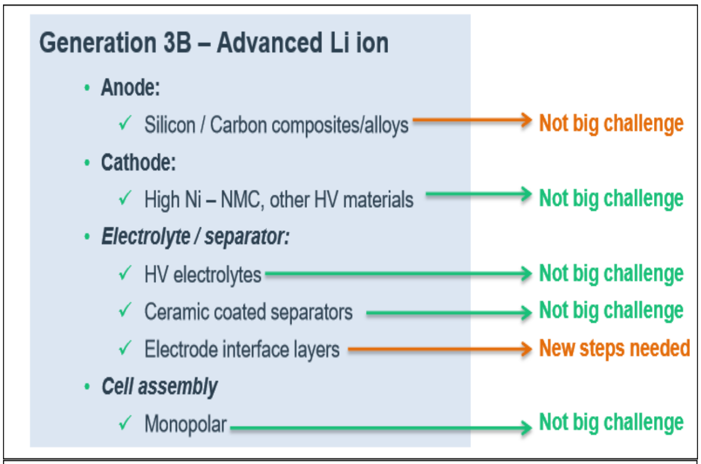


Fig.9



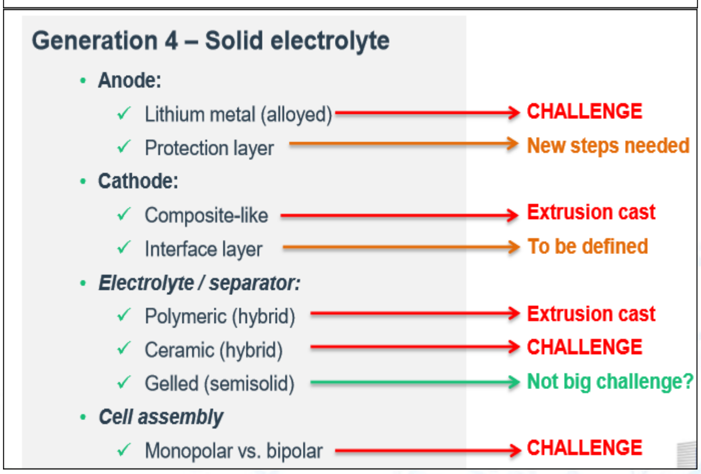


Fig.10 & Fig. 11

3.2.5 Establishing Manufacturing Base in Europe - Paolo CERRUTI - NORTHVOLT

Europe's largest battery plant is in the pipeline in Sweden: for the automotive, energy storage and industrial sectors, 32 GWh in four phases, 500,000 m2, creating around 2,500 jobs.

Based on a) cutting edge technology (product roadmap, process innovation, equipment and quality control), b) structural cost advantage (vertical integration, inexpensive energy) and c) world's greenest battery (minimum carbon footprint, circular and sustainable).

Timeline: Q2 2017 build up a team in Stockholm, Fall 2017 site selection, Second half of 2018 start of construction, 2019 demo line completed, 2020 start of production and 2023-24 fully built out capacity.

Where the EU can help:

- Access to capital: accompany the birth of an industry with dedicated funding, set up a structure to facilitate access to private debt;
- Promote education initiatives in process/industrialization;
- Have a strategy in securing key raw material access and recycling;
- Push the differentiation: a CO2 label;

A low focus of Academia on battery manufacturing was explicitly expressed by the speaker!

4. WORKSHOPS: SUMMARY AND RECOMMENDATIONS

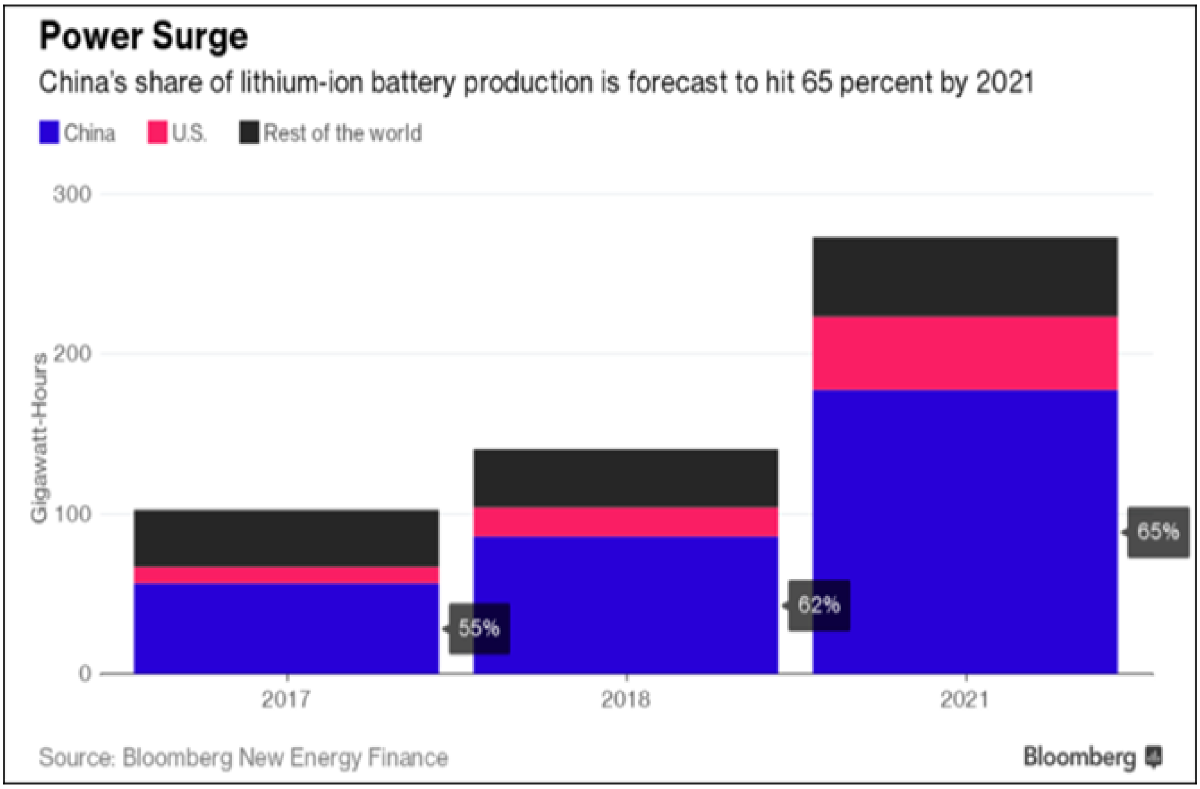
Lively discussions took place in the 4 workshops especially for the R&I topics on Generation 3b and 4 for which we refer to the reports in annexes from the rapporteurs and to the executive summary. For stationary energy storage (ESS) the situation is somewhat less clear, everybody agreeing on the targets and the work to be done on Li Ion improvements specific for ESS. However, for the wide range of possible non-Li Ion technologies, discussions did not yet lead to conclusive choices: most interest went to Redox Flow and Na Ion.

Reports from the workshops are available in the annex of this document.

5. DISCUSSION: SHAPING THE FUTURE OF BATTERY CELL MANUFACTURING IN EUROPE

An exciting world market potential (550 GWh by 2025), capacities building up worldwide to +/- 275 GWh by 2021, with still important opportunities left for reinforcing Europe's present rather weak position.

Source: Umicore



Manufacturing in Europe is catching up with several short term planned new capacities (foreign investments and internal EU initiatives).

Europe clearly expresses its ambition to become a leader in Advanced Li Ion and Solid State (in development and manufacturing). Indeed, as manufacturing capacity build-up for Li Ion is already ongoing in Asia particularly in China, it does not seem effective to spend significant efforts to establish a mass production chain in Europe on current Li Ion commercial technologies. Efforts for establishing manufacturing capacity in Europe should therefore primarily target Li Ion cells of min. generation-2b and preferentially beyond (with 3b and 4).

Dr. Marcel Meeus- EMIRI

ANNEXES

BREAK-OUT SESSION REPORTS FROM RAPPORTEURS

Annex 1. Report from Session 1: Generation 3b materials

Moderator. J. Affenzeller, AVL

Rapporteur: M. Fichtner, HIU and CELEST

The discussion was stimulated towards giving ideas for possible contributions to the upcoming call by the EC. The summarized items are either general comments or inputs that might lead to potential topics in such an announcement.

Most contributions were made to Theme 1 (Energy Density). Other Themes such as "Cost" and "Safety" were regarded as generic and relevant topics are expected to come up in the other Themes. However, some specific suggestions were made also here.

Introduction

- Key for success is the close collaboration of institutes with industry, otherwise the process of establishing battery production suffers from losses, may go in loops and, eventually, may lead to no sufficient progress.
- Research must support industrial development of production towards TRL 9. Research can contribute solutions at different TRL levels.
- We didn´t discuss the targets from SET plan etc. because those are clear and set, e.g. 350 Wh/kg and 750 Wh/l in 2025.

Theme 1: Increasing Energy Density

General comments

- Improve collaboration between stakeholders, to break R&I silos (see above).
- Higher E. density at reduced safety is no compromise, esp. in large battery systems.
- **Fast charging** (of packs) is of utmost importance and **volumetric energy density** should be improved.
- New materials must be compatible to existing production lines.

Materials in General

- Prototyping is necessary for materials evaluation. What is the minimum of Co and Ni in layered insertion materials?
- Design of efficient combination of materials to increase energy density and to lower cost.
- Further materials research is needed for understanding materials interaction and properties. **Numerical simulation** of materials is needed to solve the question how is the materials level reflected in properties that are found on the cell level? Further contributions to research on cell ageing. Find ways to accelerate testing!

Cathodes

- **Low Co** cathodes needed. Understanding of **surface degradation** effects of electrode materials is essential.
- Further development of HV spinels using surface engineering technologies.

- Observe and qualify other materials which are not in the current 3b-list but in the research pipeline of, e.g. the FET-OPEN project "LiRichFCC", if they show disruptive properties and can be scaled-up.

Electrolytes

- **IL electrolytes** production and upscale is needed.
- Electrolyte systems for higher voltage, for high V materials.
- Understanding electrolyte reactions, esp. for Si based anodes.
- Understanding SEI formation for Si based anodes

Anodes

- **Full Si anodes** may be possible and should be developed. Lack of fundamental understanding of charge transfer from electrolyte to anode.
- Increasing Si content in Si/C anodes; use of thinner separators.
- Develop strategies to improve cycle life of Si anodes, e.g. by preconditioning/ prelithiation.
- Study trade-offs of synthetic vs. natural graphite.
- Development of high capacity Si based anode with focus on EV.
- Make **graphene** viable to RLR processes.

Cells/Packs/Systems

- Lighter materials, optimized cell and packaging design. Cooling and mechanical properties must be further optimized, new technical solutions for optimizing cooling are needed.
- Consequent reduction of empty volumes on pack level.
- Compensation of volume changes during cycling.
- **Integrated approach** needed of modelling, materials development and electrode development to study the interaction of energy density, power and cycle life.
- How do we find the best cell design for a specific material?
- **Optimized BMS software** has a positive impact on energy density.
- Battery packs for buses must be developed and qualified to replace ICEs.

Theme 2: Which cost reduction is expected?

This is an Integrated part of other themes also; costs are determined not only by single aspects but from the interplay of different factors.

- The impact of research activities must be regarded in their effect on the costs.
- Cost targets must be kept in mind; they should not be taken as a decisive aspect too early because costs cannot be regarded separately for one part of the chain only if their side effects may play a role.
- Preferred integration of abundant materials in the process for making **„green "batteries** at lower cost.
- TCO in Cts/km should be evaluated

Theme 3: Impact on fast charging

There are different demands of passenger cars and heavy duty trucks (there, fast charging is necessary).

- Develop new controls for fast charging.
- Reduce the plentitude of charging systems. Bring stakeholders and developers together.
- Better understanding of Li plating, as a function of anode material, anode structure, and charging profiles.
- New graphites/coatings and applicable processes are necessary.

Comments:

- 200 fast charge cycles are allowed, among 800 in total for BEV (VW, passenger cars). Differs very much for buses and taxis where many more fast-charging cycles may be needed.
- Do we need fast charging for every application? Compromise is needed (6 min charging of a 60 kWh battery needs 650 kW electric power and a cooling station with several 10 kW).

Theme 4: Expected safety, which specific measures?

This is again a generic topic. To be considered in all other themes also.

- New safety approaches from other industries should be considered.
- Get heat propagation measured and controlled at „best cost “.
- The key component for securing safety is the separator: future R&D to identify the „best “separator.
- Are the current safety measures still sufficient in aged systems? (e.g. when the separator gets brittle).
- Handling of exhaust gases in the case of cell runaway currently not implemented.

Theme 5: Competences in computational analysis

- A **shared data base** for test results and references would be necessary in Europe (example US-DoE).
- An **Innovation platform** is needed for multiscale and Multiphysics modelling, multidisciplinary inputs, development of ageing models

Models for materials/cell properties and ageing

- Fundamental understanding and models are needed for prediction of lifetime. Current prediction based on statistical models is not enough.
- Integrated modelling approach **from atomistic level of materials to Multiphysics modelling and transport on the electrode (mm) level** to understand performance and ageing.
- Physically based simulation and modelling to identify ageing mechanisms: to exploit full battery potential, fast charge etc.

Theme 6: IP issues in manufacturing, value chain, …

- Development of the whole battery cycle opens possibilities for creating IP.
- Research on producibility should be made in an early phase because production capabilities of new and novel systems together with optimized cell design (incl. related IP) must be developed.
- Cell components which are patented by EU companies should have „**freedom to operate** “in an EU production.
- Materials selection and development to be linked with manufacturing studies.

Theme 7: Smart battery design

Recycling and second life

- Also smart systems must be sustainable.
- Design must be such that the batteries are directly reusable for second life applications.
- Design of smart cells and battery packs in a way that they can be dismantled and recycled in a cost efficient way. (cost reduction, circular economy)

Technical suggestions

- Algorithms are needed to control phase change cooling in different layouts.
- Create „smart modules “integrating safety and thermal management.
- Development of **smart micro sensors** to monitor cell status age , health.
- Smart BMS to increase accuracy and lower cost.
- Standardized smart controls are needed.
- Integration of batteries in PV modules requires dedicated BMS and inverters.

Comment

- Are we „only “considering EU cell/battery production or should the cell components come from EU also?

Annex 2. Report from session 2: Solid State Batteries-Generation 4

Moderator: Simon Perraud CEA
Rapporteur: Noshin Omar VUB

The discussion was divided in 6 main themes, which are summarized below:
Theme 1: Anode
Theme 2: Cathode
Theme 3: Solid state electrolyte
Theme 4: Interface optimization and aging
Theme 5: Advanced modelling
Theme 6: Upscaling and manufacturing
Theme 7: Battery system

Below you can find a summary about the key discussion points that were raised during the interaction with the participants. To the end, a general SWOT analysis and a number of research recommendation topics were identified.

Summary of discussion points

Solid-state battery is a key technology for EU that can meet the automotive requirements in terms of energy, cost, durability, safety etc. This technology is in the roadmap of most of the European OEMs.

Blue Solutions technology is based on solid-state (LMP®: Lithium Metal Polymer) technology, where the anode is Lithium metal and cathode being lithium iron phosphate and the electrolyte is solid polymer. For the cell description reference is made to the producer's website.

There is some knowledge available in the field of solid-state but it is limited to few players due to IP restriction, the IP landscape looks challenging for Europe.

UMICORE: the available cathode materials are developed and optimized for liquid electrolytes. Those materials should be further optimized in combination with solid-state electrolytes (either polymeric, inorganic or composite/hybrid) in terms of morphologies, 3D structuring, particle distribution, surface treatments, interface optimization …

SCHOTT: EU is competitive enough in terms of R&D in the field of solid-state electrolyte. However, this is only related to basic material competences. There is need for dedicated and unique expertise's and competences when this technology should be combined with cathode and anode. There is lack of competences when it comes to interface optimization, conductivity improvement, interface characterization, modelling, processing, integration, upscaling, …
Polymer challenges: high voltage stability, acceptable ionic conductivity at room temperature, pre-conditioning & processing, crystallization at room temperature

During the discussion there was no consensus, which solid-state electrolyte technology (polymeric or inorganic) will be closer to the market in the coming 5-10 years. However, there was a consensus on the fact that the short and medium term R&I actions should focus on developing Li Ion solid-state battery technologies based on already existing material chemistries. Indeed, the main R&I challenges are related to the combination of the different materials within the solid-state battery cell, the control of interfaces, and the development of new manufacturing processes. In order to properly address those challenges, it is more efficient to rely on known material chemistries and to adapt the materials to the case of solid-state design (e.g., adaptation of the particle size and morphology in the case of cathode active material).

Toyota: the focus in Japan is more on ceramic-glass technology.

There was an agreement that the solid-state technology should have acceptable performances at room temperature 25-40°C and it should meet the fast charging requirements of BEVs. Room temperature is required to simplify the thermal management and to improve the energy efficiency. High temperature solid-state is an interesting strategy for fleet applications only (Cfr Bluecar initiative in France).

The participants proposed to have parallel tracks whereby polymeric, inorganic and composite/hybrid solid-state electrolytes should be considered. These development tracks can have a different timeline depending on the TRL and challenges specific to the technology. The selection of the appropriate technology will be defined in function of the application requirements.

It is difficult to define KPIs on material levels, because the integration, combination and processing will have a high impact on the final performance concept. Thus, the only KPI can be defined at cell level, which will come from the application.

EUCAR: the selection of the final concept and combination of materials will be highly depending of the system requirements. Thus, a top-down approach should be followed where clear targets can be defined for the proof of concept at cell level (TRL 5) from the beginning. Then, the concept can be optimized from the bottom up approach.

The impact of each architecture on the battery system design and thermal management should be taken into account.

CHALMERS: polyethylene oxide (PEO) is well established. The polymeric technology has advanced, significantly. The conductivity and stability have improved as well.

The main bottleneck remains at the anode part such as lithium metal, lithium alloy. The available knowledge is restricted to few players such as Bolloré. In addition, there was a clear agreement that the missing skills are in terms of coating, processing, handling, upscaling and manufacturing.

FRAUNHOFER ISC: The cell design should be considered from the beginning. The ionic conductivity should not be only the key parameter. Electrical conductivity is also should be considered.

There are a few pilot lines that can deal with solid-state technology up to 1Ah such as the ones at Fraunhofer ISC, TUM, CEA, IPAT, IMEC and up to few Ah at VUB, CIC energiGUNE. New investments would be necessary in order to deal with solid-state technologies in pilot lines. A bottleneck to date is the availability of solid-state electrolyte (kg-scale) to supply pilot lines.

The mechanical stress, processing, failure and aging are different from the liquid based technologies. Therefore, modelling is very essential in the development process from atomistic to macroscopic level.

The TRL level of the dedicated cathode materials and solid-state electrolytes is between 2 -3. The main challenge is to optimize the materials, including surfaces, for integration and to develop the skills for manufacturing.

Processability and cost are two key elements that have to be considered in parallel with active material optimization and during the processing and up-scaling. Notably, the way on how to process and combine materials will to a large extent drive the material development. Therefore, strengthening 'process research' is the first priority. Subsequently, pilot and demonstration projects for improved large-scale production of new generation battery cells need support.

IP protection is a key in the field of solid-state.

Advanced modelling will play a key role in the development and design of process. Therefore, there is a need to strengthen the interaction with European Material Modelling Council (EMMC). Competences to characterize battery materials and their surfaces need to be developed in parallel. An interaction with EMCC could be helpful.

SWOT analysis

Strengths	Weaknesses
➢ Basic material competences ➢ Excellent researchers and basic research ➢ Modeling experts	➢ Process and integration engineers ➢ Upscaling and manufacturing skills ➢ High specific capacities anode knowledge in terms of coating, handling, processing and manufacturing ➢ Interface characterization, modeling and optimization ➢ Cell design skills ➢ Limited dedicated large scale pilot lines for solid state
Opportunities	**Threats**
➢ To produce solid state in EU based on **European** know-how ➢ To strengthen the battery electric value chain in EU ➢ To develop low CO_2 foot print batteries in EU	➢ IP know how at anode level (i.e. Lithium metal and lithium alloy)

Recommended research topics for 2019-2020

Topic I: Cell design (call 2019)

The targeted **energy density** should be >400Wh/kg for targeting the electric range of 500km with a cycle life around 1000 cycles and cost <100€/kWh. The targeted TRL level should be higher than 5 (large cells around 10Ah).

- Cell designs including polymer based as well as organic free cell concepts
- Membrane solutions to enable dendrite free Li metal anodes
- The aging and mechanical stress factor should be clearly addressed.
- The full performance analysis should be done at large cell level (energy, power, safety, fast charging).
- Processing and cost of processing should be considered.
- The focus is not on material development (i.e. known material chemistries are used as a starting point), but material optimization, integration and processing.
- In depth advanced multiscale modelling approach should be integrated if it can guide the materials development.
- Starting TRL: 2-3, final TRL: 5

Topic II: Multiscale modelling (call 2019)

- Estimation and prediction of aging phenomena
- Mechanical stress
- Transport phenomena
- Interface modelling
- 3D architecture, morphologies, optimal particle distribution
- Optimal cell design
- Improvement routes towards ionic and electrical conductivity
- Manufacturing processes
- Close interaction between European Material Modelling Council
- Starting TRL: 2, final TRL: 5

Topic III: In depth interface optimization, characterization and integration (call 2019)

- Required coating, surface and particle engineering
- To improve the cycle life
- To reduce the impedance
- Close interaction with European Material Characterization Council
- Starting TRL: 3, final TRL: 5

Innovation action

Topic IV: Battery system design (call 2020)

- Optimal battery cell design
- Optimal battery system architecture
- Thermal management
- Housing
- Safety
- Smart sensing techniques
- Battery management system
- Starting TRL: 3, final TRL: 7

Topic V: Processing and manufacturing (call 2020)

- The cells should be made based on low CO2 footprint
- Full understanding of the impacted processing and manufacturing parameters on battery cell performances.
- The impact of up-scaling should be fully addressed.
- Exchange of researchers should be encouraged to maximize the impact between partners.
- Starting TRL 3-4, final TRL 7

Coordination and Support Action

Topic VI: IP protection and know-how creation (call 2019)

- Analysis of different roadmaps worldwide
- Exploring the available competences outside EU
- Analyzing the full value chain
- Impact of raw materials
- Network of pilot lines in EU

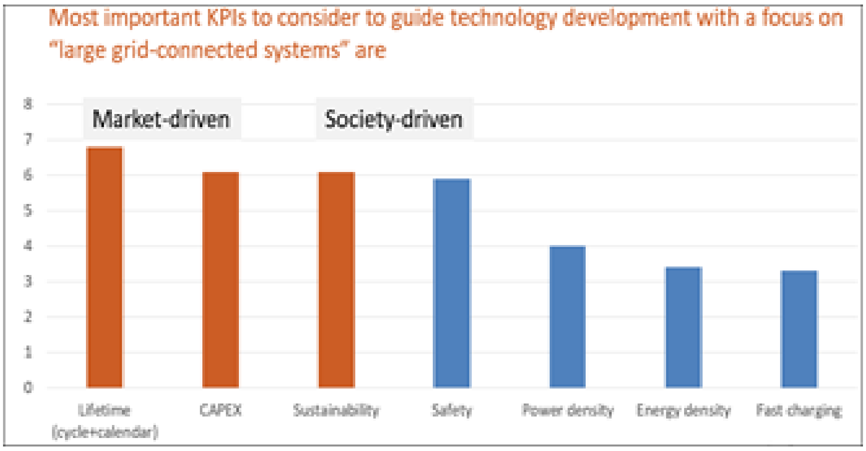
Annex 3. Report from session 3: Stationary energy storage

Moderator: Lucia Grüter- Leclanché
Rapporteur: Fabrice Stassin- EMIRI

A poll via Sli.do was organized along following themes:

1. What are the 3 most important KPIs for ESS and rank them?

Volumetric energy density, power density (discharge), cycle life, calendar life, investment cost, safety, fast charging, sustainability (circular economy, materials accessibility).



2. Claim: Li Ion will stay the most relevant technology for stationary storage applications → R&I need and topics?

- Improve the advanced materials / chemistries used in mobility (to benefit from scale-induced cost effects) and explore their use into ESS (focus is to be here on cycle life)
- Increase cycle life through improving the electrolyte stability & tackling interfacial instabilities.
- Calendar life in high/low temperature regions in relation to degradation is important.
- Research in modelling and simulation (e.g. physio-chemical models to better understand and predict cell aging processes).
- Development of cathode materials for durability, development of high durability electrolytes with high ionic conductivity at room temperature and below, low CRM.
- Consider operating temperature of batteries in their design.
- Reduce amount of inactive materials (towards thicker electrodes).
- Increase depth of discharge (to reduce material intensity).
- Ensure processability of advanced materials into cells & development of flexible advanced manufacturing technologies (to switch between serving EV & ESS segments)
- Improvements in production processes (especially further automation and further horizontal integration e.g. of battery and sensors/electronics)- considering the whole battery lifecycle and recycling (especially methods for reliable estimation of remaining useful life, e.g. based on historical usage data/profiles from battery management system).

- Innovate in the design of the battery to optimize 2^{nd} use & recycling (cost benefits & environmental benefits), low cost recycling

<u>For stationary projects the battery CAPEX is key. What actions are needed to reduce costs without jeopardizing other important KPIs?</u>

- Closer integration of cells and their control (integrating sensors and battery management electronics with the cells).
- Avoid using critical raw materials (e.g. cobalt and nickel).
- Making high energy density possible by reducing inactive materials amounts: make thick electrodes possible that can still be charged in reasonable time. In that way Cu and separators could be omitted, use full capacity of active materials and not just a DoD of between 20-30 and 90%.

<u>3. Claim</u>: Li Ion will not stay the most relevant technology for stationary storage applications □ R&I need and topics: Which are the most relevant non-Li Ion chemistries with the highest market potential in stationary applications?

- **Flow batteries**: chemistry of electrolyte to improve cycle life and cost, electrode materials for higher power densities, tackling corrosion, move away from Vanadium e.g. by Zinc Bromine batteries (quoted to stay at 95$/kWh for contracts delivering at 2022). For sustainability and toxicity: semi organic / organic batteries (e.g. quinones) for a full recyclable battery and low environmental impact.
- Vanadium Redox Flow Batteries (VRFB) make them competitive with foreign countries (USA, Japan, Korea, Australia and China).
- Li-S (interesting in terms of cost and capacity): improvements calendar life and recyclability.
- Li metal polymer (LMP): improvements in energy density, reduce Li content.
- High temperature liquid metal batteries.
- Battolyser (battery-electrolysers): increase energy density.
- **Na-ion**: although the technology has strong similarities with Li Ion, there are still many fundamental issues to tackle to unlock its potential, need to better understand the insertion and conversion storage mechanisms as well as the ionic transport through the interfaces with the electrolyte.

- **Mg batteries** (e.g. Mg S): including pure metal/ intermetallic/ composite materials for the negative electrode of high power systems, metal dissolution and precipitation need to be investigated and optimized, dedicated cell concepts/ designs to be developed. For the positive electrode Mg storage via insertion into suitable host systems or reactions into Mg-compounds looks promising.

- **Zn based systems**: application of Zn-Air batteries still suffers from fundamental problems such as lack of suitable bi-functional reduction/evolution (ORR/OER) catalysts and the dendrite formation during Zn- deposition on the Zn anode (which leads to short-circuits).

4. Other elements

- Selection of R&I topics should keep in mind (1) timing of impact (starting TRL >4) and (2) magnitude of impact (technical & socio-economic) to reach critical R&I mass.
- Align Horizon 2020 & FP9 recommendations for R&I as much as possible on recommendations already made in Implementation Plan of Action 7 of Integrated SET Plan.
- Manufacturing technologies are key next to the chemistries.
- Modelling is an important tool (at different scales, also for manufacturing processes, also to understand system behavior and be predictive).
- Next to performance, move to be initiated towards more sustainable batteries (2nd life and recycling, lower content of CRMs …).
- Integrate ICT into battery solutions (importance of data mgmt. and interoperability).
- Standardization as a competitiveness tool. We need an "observatory" of battery R&I supported with public funds (a portfolio approach is needed in Europe to ensure effective & efficient use of resources in Horizon 2020 and FP9 – EMIRI and NAMEC started a first exercise).
- We need the people! Skills agenda

Annex 4. Report from session 4: Research Pilot Lines Network

Moderator: Oscar Miguel Crespo -CIDETEC
Rapporteur: Michael Krausa -Klib

Due to the short time available for the break-out session 4, the discussion was focused on two topics:

- European pilot line network
- Pilot plant for all solid-state battery chemistries

European pilot line network

To stimulate the discussion, Arno Kwade (Technical University of Braunschweig) introduced the ProZell competence cluster for cell production and pilot lines in Germany. It is the aim of the cluster to build a holistic and profound knowledge basis of the battery cell production by an interdisciplinary integration of material science, chemical and mechanical engineering. 22 institutes combine their efforts in four tasks: electrode production, further processing, assembly and activation. The results of the different groups will be validated in a research pilot line for preindustrial series production at the ZSW in Ulm.

In the discussion that followed, it became clear that bringing together the European competencies in cell production, on an interdisciplinary level, would accelerate the understanding of cell production. Thus, the development of cell manufacturing and the associated ecosystem could be accelerated and strengthened. It was mentioned that a deeper understanding of material properties and their processability is of significant importance. Therefore, materials science should be integrated directly into a pilot plant network.

It was mentioned that battery systems, other than Li Ion based systems, should be taken into account, e.g. redox-flow batteries. Li Ion batteries are not the only solution for all energy storage applications.
It was also recognized that the cooperation of the pilot line network with industrial pilot plants and/or their direct integration into the network could push the knowledge transfer from the research pilot lines directly into industrial plants. Vice versa the experience of industrial pilot plants might stimulate the efforts of the research pilot lines. How industrial pilot plants could interact reasonably in a pre-competitive research network must be clarified.

The participants came to the conclusion that a European network of pilot plants would be a valuable tool to strengthen European research and industry and therefore could be an important instrument of the Battery Alliance.
It became clear that several questions remain open, e.g. forms of possible cooperation, handling of IP, patents and competition, structure of cooperation, integration of industrial pilot plants, etc... Therefore, it was suggested that **a short-notice meeting in February** should be organized, by DG RTD, to discuss these topics, in order to find ways to build a European network of pilot lines, and to make sensible suggestions for funding topics. Arno Kwade, Simon Perraud, Oscar Miguel Crespo and Michael Krausa will prepare the meeting and will match the agenda with EU RTD. It is also recommended that more active players in

Europe are found. Therefore, the participants are asked to inform about missing groups, universities, etc.

Pilot plant for all solid-state battery chemistries

At the moment, all solid-state Li systems are highly rated for electromobility applications. The question arises whether now is the appropriate time to build up pilot plants for all solid-state battery cells.

The participants mentioned that there is not yet a clear consensus on whether polymeric or ceramic systems will be the best choice. Therefore, pilot plants for both material directions would be needed at an early stage. However, the participants came to the conclusion that it is too early to discuss or suggest pilot lines for all solid-state systems today. At present, the availability of materials is too low to operate a pilot line for these systems. Therefore, it is suggested to concentrate work on process research on a lab-scale.

Moreover, it is mentioned that more chemical engineering research is important because of several open questions concerning polymeric and ceramic electrolytes, e.g.:

- Handling of pure Li and other materials
- cell design
- scale-up

Therefore, research in process development on lab-scale and fast prototyping should be strengthened in a preliminary phase for both material systems. These results would be the basis for a fast creation of research pilot lines as the next step, if larger amounts of material are available.

A questionnaire was sent out to all participants to find out which pilot lines already exist in Europe with details on their general capabilities.