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Alliance for Batteries Technology, Training and Skills

2019-2023

Desk Research Report

R&D and Technological Perspectives for the Battery Sector

Co-funded by the Erasmus+ Programme of the European Union

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Table of Contents

Alliance for Batteries Technology, Training and Skills - ALBATTS - Project number 612675-EPP-1-2019-1-SE-EPPKA2-SSA-B.
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List of Abbreviations

AC	Activated Carbon
AI	Artificial Intelligence
AIMD	Ab Initio Molecular Dynamics
ASRS	Automated Storage and Retrieval Systems
BMS	Battery Management System
CV	Cyclic Voltammetry
DC	Direct Current
DEC	Diethyl Carbonate
DMC	Dimethyl Carbonate
DoD	Depth of Discharge
EBA	European Battery Alliance
EC	Ethylene Carbonate
EDLC	Electrical Double Layer Capacitor
EIS	Electrical Impedance Spectroscopy
EQF	European Qualifications Framework
EV	Electric Vehicle
FEC	Fluorinated Ethylene Carbonate
GDL	Gas Diffusing Layer
HOMO	Highest Occupied Molecular Orbital
ICE	Initial Coulombic Efficiency
IEA	International Energy Agency
LFP	Lithium Iron Phosphate
LIB	Lithium Ion Battery
LiBOB	Lithium bis(oxalate)borate
LiFSI	Lithium bis(fluorosulfonyl)imide
LMO	Lithium Manganese Oxide
LMP	Lithium Metal Polymer
LTO	Lithium Titanium Oxide
LUMO	Lower Unoccupied Molecular Orbital
NCA	Lithium Nickel Cobalt Aluminium oxide
NEDC	New European Drive Cycle
NIB	Na-Ion Batteries (sodium-ion batteries)
NMC	Lithium Nickel Manganese Cobalt oxide
NMR	Nuclear Magnetic Resonance
PEM	Proton Exchange Membrane
PEMFC MEA	Proton-Exchange Membrane Fuel Cells Membrane Electrode Assemblies
PGM	Platinum Group Metals
PVDF	Polyvinylidene Fluoride or Polyvinylidene Difluoride $-(C_2H_2F_2)n-$
SC	Supercapacitor
SEI	Solid Electrolyte Interface
SEM	Scanning Electron Microscopy
SoC	State of Charge
SoH	State of Health
SSE	Solid State Electrolyte
TEP	Triethyl Phosphate
TRL	Technical Readiness Level
TBMS	Thermal Battery Management System
WLTP	Worldwide harmonized Light-duty vehicles Test Procedure

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Glossary

For other concepts and more information on the different technologies, see Battery University[1]

Anode	Negative electrode at discharge (electrode from where the electrons "leave")
Battery	An association of battery-cells (usually some cells are associated in series to obtain a certain voltage)
Cathode	Positive electrode at discharge (electrode to where the electrons "arrive")
Capacity [Q]	Amount of stored charge usually expressed in $mAh.g^{-1}$
Cell	The cell is single, composed of electrodes, electrolyte, separator, and current collectors. It does not include any cell association.
Cycle life	Number of cycles yielded by the battery (usually measured until the capacity is 80% of the initial capacity of the cell)
Current collectors	Conductors, usually metals such as copper and aluminum that facilitate electric conduction in the battery (connect the external circuit through the tabs to the active material in the electrodes)
Cut off voltage	Voltage at which the capacity of the battery is measured (associated with the electrode with the lowest capacity)
Dendrites	Whiskers – fractals - of metal (e.g. Li, Na, or Mg,…) resulting from 3D nucleation. Dendrites may have sharp ends that cause short circuits
Dielectric	Insulating material; poor conductor of electrons. It can be polarized in presence of an electric field.
μ_i	The chemical potential of species i, $\mu_i = \left(\frac{dU}{dN_i}\right)_{S,T,N_{j\neq i}}$ or $\mu_i = \left(\frac{dG}{dN_i}\right)_{T,P,N_{j\neq i}}$
Electrodes	Negative electrode is the cathode on charge and anode on discharge (usually termed anode) Positive electrode is the anode on charge and cathode on discharge (usually termed cathode)
Electrolyte	Solution, polymer, gel, or solid containing mobile ions. The electrolyte should be an insulator (not conducting electrons) and a good ion conductor
Energy density	Energy per unit volume ($Wh.L^{-1}$)
S	Entropy
G	Gibbs energy
Faradaic reactions	Faradaic reactions may occur at the electrodes' surface; these electrodes are also known as charge-transfer electrodes
Fractal	Complex pattern that repeats at different scales
U	Internal energy
Lithiated	A material is lithiated when Li is inserted in the structure or reacts with the material
Li-S	Lithium-Sulfur batteries
LFP	Lithium Iron Phosphate ($LiFePO_4$)
LMO	Lithium Manganese Oxide ($LiMn_2O_4$ – spinel structure)
LTO	Lithium Titanium Oxide ($Li_4Ti_5O_{12}$)
NCA	Lithium Nickel Cobalt Aluminium oxide ($LiNi_xCo_yAl_zO_2$ with $x + y + z = 1$)
NMC	Lithium Nickel Manganese Cobalt oxide ($LiNi_xMn_yCo_zO_2$ with $x+ y + z = 1$)
N_i	Number of particles of species i
p-n junctions	Interface between negatively n- and positively p- doped semiconductors (extrinsic semiconductors)
Pouch cells	Battery cell or cell association wrapped in a rectangular polymer covered in an aluminum flat bag with external tabs to connect to the circuit

[1]Battery University. (2021, June 17). *Learn About Batteries*. https://batteryuniversity.com/articles (accessed on 25/06/2021)

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Primary battery cell	A battery cell fabricated under an architecture that involves irreversible reactions and therefore is non-rechargeable
Secondary battery cell	Rechargeable cell
Separators	In a battery, separators are insulating membranes that prevent short circuits between the two electrodes; in the SSE, the solid electrolyte may also play the role of the separator
Specific Energy	Energy per unit mass ($Wh.kg^{-1}$)
T	Temperature in Kelvin
Trona	Trisodium hydrogendicarbonate dehydrate and also sodium sesquicarbonate dihydrate, Na_2CO_3•$NaHCO_3$•$2H_2O$ is a non-marine evaporite mineral
Soda ash	An inorganic compound with the formula Na_2CO_3 and its various hydrates

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Executive Summary

The **Methodology** chapter introduces criteria for the selection of the most promising future battery technologies. These technologies are further analysed within the report. They represent especially those technologies implemented in start-ups and established companies and are complemented by technologies studied at universities and research institutions and presented in scientific papers and conferences. The **Drivers of change** chapter contains the main factors identified to be pushing the battery sector forward, with R&D-relevant specifics. Institutional and financial support from the EU is outlined in the **EU framework** chapter. The **Stakeholders** chapter addresses key relevant entities in battery R&D and their activities.

The **Technology** chapter provides an overview of the most promising future technologies in the battery sector, starting with **Lithium-ion batteries** and the potential improvements of its main components – cathode, anode, and electrolyte. When it comes to **cathodes** (NMC, NCA, LFP) the main driver of change for research is to reduce the Cobalt content and increase the batteries' safety while increasing the energy density leading to a greater range.

The main driver of change for the negative electrodes (**anodes**) is related to safety, e.g., the possibility of charging fast even at low temperatures without compromising safety. For cathodes with higher capacity, another type of anode is necessary - for example, one that adds to the traditional graphite silicon with much higher capacity. However, this brings new challenges into play. One of the key challenges concerning the **electrolyte** is increasing its performance and safety, since most of the current electrolytes used are flammable, which causes safety issues. Possible solutions include gel/polymer or solid-state electrolytes.

Promising alternatives to lithium-ion technology include **Lithium-sulfur** batteries with the possibility of 100% Depth of Discharge (DoD) and expected lower environmental impact, or **Sodium-ion batteries**, where no lithium, a scarce mineral, would be needed.

Structural batteries can carry a mechanical load while storing electrical energy. They can be incorporated in the structure of, e. g., a vehicle or a house, and have big potential to reduce

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the space needed to store the battery within an application, and especially not affecting the structural equilibrium, which is paramount for electrical vehicles.

Energy storage sources like internal combustion engines, fuel cells, and batteries work well as a continuous source of low power. However, they cannot efficiently handle peak power demands or recapture energy in today's applications because they discharge and recharge slowly. **Supercapacitors** and **ultracapacitors** can deliver quick bursts of energy during peak power demands, quickly store energy, and capture excess power that is otherwise lost. They efficiently complement other energy storage technologies in today's applications because they can charge while protecting them.

Fuel cells are especially important for heavy-duty vehicles such as buses as they have a higher energy density than batteries and are lighter. **Metal-air batteries** such as lithium-air are also designated fuel cells as they obey similar principles to those ruling fuel cells. **Lithium-air** batteries possess specific energy that is theoretically comparable to gasoline and is, therefore, very attractive, but there are many technological challenges yet to be overcome.

The **Job roles & skills** chapter builds on data gained from advertisements in the battery R&D sector published at the time of preparation of the report. Soft, academic, general transversal competencies, cross-sectoral specific competencies, and sector-specific competencies are analysed. The most frequently occurring **sector-specific skills** requested within the advertisements analysed are characterization techniques, cell evaluation, and validation, electrolyte development, or thermal management. **Knowledge** of cell design, battery components, lithium-ion battery chemistry, battery design, and battery material are among the most requested.

The **Education** chapter summarises competency needs as well as recommendations to both industry and academia on the education of experts on the master and Ph.D. levels, based on two recently published reports by Batteries Europe and Fraunhofer/EIT RawMaterials. It also refers to a list of EU initiatives in the education and skills area, in which the ALBATTS team is also involved.

1 Introduction

This report represents the second release of the desk research of the **project ALBATTS** (Alliance for Batteries Technology, Training and Skills). Building on and expanding research-related elements in the first iteration of the desk research from 2020[2], it provides an overview of the possible future technological development of batteries, stakeholders involved, relevant job roles and skills concerned as well as expert needs and recommendations for education and up- and reskilling of human resources.

The author of the core technology and stakeholder chapters is one of the ALBATTS project partners, **Professor Helena Braga,** Engineering Physics Department, University of Porto, Portugal.

The report was prepared by **Work package 5 – Intelligence in Mobile Battery Applications** - in close cooperation with partners of Work package 4 – Intelligence in Stationary and Industrial Battery Applications and other ALBATTS partners with the main purpose of researching areas that are relevant in the development of the overall sectoral roadmap.

[2]*Intelligence in Mobile Battery Applications (D5.1 Desk Research & Data Analysis IMBA – Release 1).* (2020). https://www.project-albatts.eu/Media/Publications/4/Publications_4_20200930_12811.pdf

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2 Methodology

ALBATTS conducted detailed desk research based on information available on companies' websites, press releases, scientific and technical publications. Other science background knowledge results from previous research work and contacts with the industry.

The main goal was to survey the energy storage technologies being implemented in start-ups as well as in established companies, both holding the possibility to change the landscape of energy storage technology, continuously and disruptively. The "hidden" evidence, relevant to compose the bigger picture of the future landscape, reflects what is being studied at the universities and research institutions and presented in scientific papers and conferences.

The United Kingdom has created the Faraday Institution, which regularly publishes "Faraday Insights"[3], evidence-based assessments of the market, economics, commercial potential, and capabilities for energy storage technologies and the transition to a fully electric UK. Concise briefings are aimed to help bridge knowledge gaps across the industry, academia, and government. The Faraday Institution initiated its research programme in 2018 with the following internal projects: **(1)** extension of battery life, **(2)** solid-state batteries, **(3)** multiscale modelling, **(4)** recycling, and reuse. In 2019, the following projects were initiated: **(5)** electrode manufacturing, **(6)** Lithium cathode materials, **(7)** Sodium-ion batteries, **(8)** Lithium-sulfur batteries, and **(9)** battery characterization. In 2020: **(10)** batteries for use in microgrids in emerging markets, and finally in April 2021: **(11)** battery safety. The "out of the box" approach with the foundations being laid from the most disruptive architecture approaches (e.g., Na-ion batteries) to the solution of remaining problems (e.g. battery safety) and niches of opportunities (e.g. batteries for use in microgrids in emerging markets), seems to indicate that the UK is anticipating technologies with the potential to change the paradigm. The UK seems to aim to be one of the leaders in future battery technology. Following the latter strategy under the lemma "From research discoveries to commercial spin-outs"[4], the institution is shaped by 21 leading universities, 50+ industry partners, and 450+ researchers[3].

[3] *2019/20 Annual Report – The Faraday Institution.* (2020). The Faraday Institution. https://www.faraday.ac.uk/2019-20-annual-report/ (accessed on 26/07/2021)

[4] *Research Projects – The Faraday Institution*. The Faraday Institution. https://www.faraday.ac.uk/research/(accessed on 26/07/2021)

The "Batteries Europe"[5], on the other hand, strongly recommended both European and national authorities to immediately prioritize and support next generation as well as long-term battery research and innovation to ensure the industry **remains in Europe**. A battery generations' categorization was established[6] (see **Table 1**) and the EU has opened calls for Li-ion and solid-state batteries[7] (Gen 4a and 4b):

Table 1: Prediction of the evolution of battery technology

Battery generation	Technology (Electrodes active materials)	Cell Chemistry/Type	Forecast market deployment
Gen 3b	• Cathode: HE-NMC, HVS (high-voltage spinel) • Anode: silicon/carbon	Optimized Li-ion	2025
Gen 4a	• Cathode NMC • Anode Si/C • Solid electrolyte	Solid state Li-ion	2025
Gen 4b	• Cathode NMC • Anode: lithium metal • Solid electrolyte	Solid-state Li metal	>2025
Gen 4c	• Cathode: HE-NMC, HVS (high-voltage spinel) • Anode: lithium metal • Solid electrolyte	Advanced solid-state	2030
Gen 5	• $Li\text{-}O_2$ – lithium-air / metal-air • Conversion materials (primarily Li-S) • new ion-based systems (Na, Mg, or Al)	New cell gen: metal-air/ conversion chemistries / new ion-based insertion chemistries	>2030

The industry, however, has its own pace and it is global. In this study, ALBATTS has chosen to focus on **technologies that are already being developed** by the battery, or battery-related, industry.

[5] *Batteries Europe.* (2020, July 9). Energy - European Commission. https://ec.europa.eu/energy/topics/technology-and-innovation/batteries-europe_en (accessed on 26/07/2021)
[6] European Technology and Innovation Platform on Batteries – Batteries Europe. (2020, December). *Strategic Research Agenda for batteries 2020*. European Commission. https://ec.europa.eu/energy/sites/ener/files/documents/batteries_europe_strategic_research_agenda_december_2020__1.pdf (accessed on 26/07/2021)
[7] *Funding & tenders.* (2021). European Commission. https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl5-2021-d2-01-03 (accessed on 26/07/2021)

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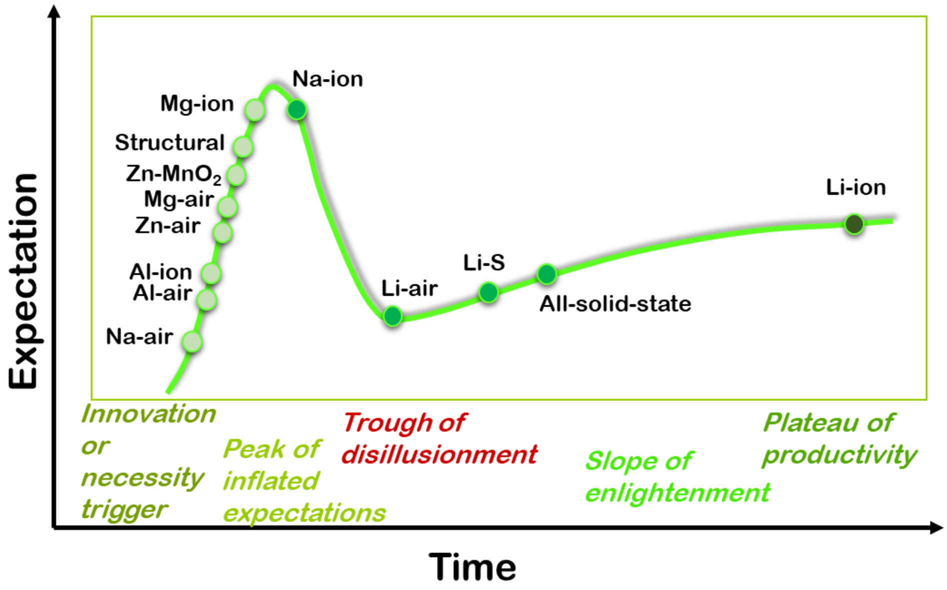

Figure 1: "Hype" graph reflecting the expectations for most of the more significant battery technologies from the research and development stage to mature technologies broadly adopted. This graph reflects ALBATTS's perspective.[8]

The "hype" graph in **Figure 1** is a consequence of ALBATTS desk research, reflects ALBATTS´s perspective, and does not intend to be quantitative; it configures a plausible approach and an interpretation of the battery landscape.

The hype graph should be read **from right to left,** e.g., the only technology that is known to be adopted is the one in "plateau of productivity". The technology in this condition is Li-ion, which is a mature technology in full production and widespread use. Li-air is a "trough of disillusionment" as even if a lot of research was invested in this technology, several difficulties persist associated with the reduced cycle life due to high internal resistance. All-solid-state and Li-S are on the "slope of enlightenment" in the pathway to becoming mature technologies. Na-ion suddenly reached the other side of the "peak of inflated expectations". A reason for this may be related to the fact that Lithium is much less available and, therefore, much more expensive than Sodium, and will eventually not be enough to cover all the future demands. Na-ion batteries (NIB) may become a mature technology without passing the other stages as part of the technology developed for LIBs applies to NIBs.

All the other technologies are at the beginning of their development; some might not reach maturity.

[8] *Understanding Gartner's Hype Cycles.* (2018). Gartner. https://www.gartner.com/en/documents/3887767 (accessed on 26/07/2021)

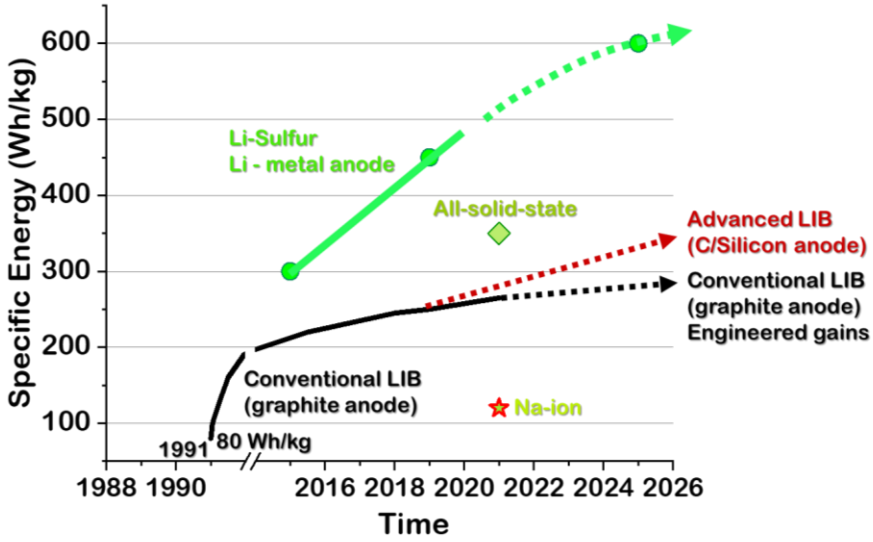

Figure 2: Evolution of battery cells of premature and mature technologies. Partially adapted from[9].

Figure 2 gives a historical perspective of the specific energy evolution within the thirty years of development of the LIB technology. It also gives a comparison between the specific energy of future technologies that are closer to being mature.

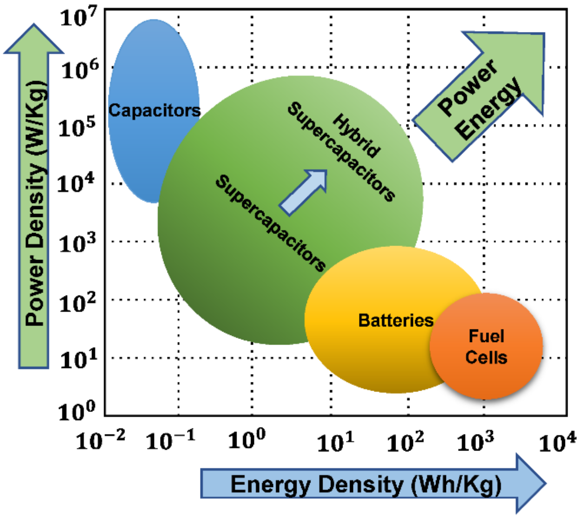

Figure 3: Evolution of battery cells of premature and mature technologies. Adapted from[10]

Finally, besides focussing on the battery technology, ALBATTS gives a small overview of capacitors, supercapacitors, and fuel cells as these technologies, together with the batteries,

[9]*Lithium sulphur (Li-S) is the alternative technology to Li-ion*. (2020, March 5). Oxis Energy. https://oxisenergy.com/technology/ technology (accessed on 06/07/2021).
[10]Wayu, M. Manganese Oxide Carbon-Based Nanocomposite in Energy Storage Applications. *Solids* 2021, 2, 232–248. https://doi.org/10.3390/solids2020015

cover almost the full range of available power and energy storage densities. Moreover, it is also shown that all these technologies have similar working principles which are discussed in this document.

Other fields of interest were the stakeholders, education and up/reskilling needs, drivers of change, and EU framework which were researched to provide more background and reasoning for the battery research and development within the EU battery sector.

3 Drivers of Change

The methodological approach adopted by ALBATTS project partners to have an updated overview of the Drivers of Change (DoC) influencing the battery sector (i.e., those factors which are key to transforming an industry) was the same as in the first desk research[11], however focusing more on recently published reports of a more technical nature. The reports are, for the most part, those representing the whole battery value chain and compiled by respected consultancy organisations or projects. Complementing the literature review, recent project results[12] were integrated as well as a one-to-one interview to eventually validate such results.

This approach was aimed at confirming, complementing, or amending the three macro areas of DoC and the nine sub-categories already identified in 2020, which were:

- **Climate goals, regulation, and environmental challenges**

  Batteries are one of the most important drivers to decarbonise land and maritime transportation and the transition to a renewable power system. The process of managing the complete lifecycle from concept to design, manufacture, service, and disposal contributes to the reduction in waste and pollution, whilst providing opportunities for significant cost reductions and calling for new skills in different areas. For this macro area, the following sub-categories had been identified:

  a. Reducing CO_2 emissions from battery manufacturing: increase in the share of renewable energies and energy efficiency in the production and battery value chain would be a major step;

  b. Electrification and green energy: batteries are a systemic enabler and play an important role in contributing to greenhouse gas neutrality in the transport and power sectors;

  c. Widespread charging/refuelling infrastructure: a robust and suitable charging infrastructure network is key to boost the development of storage-based technologies, easing access to more affordable battery systems.

[11] *Intelligence in Mobile Battery Applications (D5.1 Desk Research & Data Analysis IMBA – Release 1).* (2020). https://www.project-albatts.eu/Media/Publications/4/Publications_4_20200930_12811.pdf
[12] *Survey Results for Battery Sector*. (2021). https://www.project-albatts.eu/Media/Publications/19/Publications_19_20210601_185540.pdf

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- **Globalisation**

EV battery production is expected to heavily grow in the global markets and the EU must be prepared to get a competitive advantage, particularly within the following sub-categories:

d. Access to raw materials: is critical for the production of key components, so smart solutions are urgent to overcome shortages of some resources (limited in terms of quantity or geographical presence);

e. Global regulatory dialogue: The Commission, Governments, and public administrations in Europe will need to work in tandem for the elaboration of policies and strategies, from which the battery sector could benefit;

f. Restructuring: to facilitate the intermittent renewable energy sources, structural changes are expected in the battery sector to adapt to zero-emission mobility.

- **New technologies**

To swiftly act and mitigate climate change and making renewable energy a reliable alternative source, it is essential to invest in storage systems, like batteries, for mobile and stationary usage. Technological features are intrinsically connected, and the identified sub-categories require further developments:

g. Cybersecurity: exponential growth of IoT into BMS connected to a network, cloud infrastructures and the navigation and location information necessary to optimise the smart grid infrastructure can compromise private and collective security. This risky landscape requires the industry to modify the security approach and the resilience of the infrastructures to cyber-attacks;

h. Global technical harmonisation and standardisations: the introduction of new technology and changing market conditions will require the sector supply chain structure to adjust and meet the challenges;

i. Smart Grid: storage is one of the most important smart grid components due to its key role in complementing renewable energy generation. With the proper amount and type of storage broadly deployed and optimally controlled, renewable

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generation can be transformed from an energy source into a dispatchable generation source.

Thanks to further inputs from an ALBATTS project partner expert[13] meeting, the three above mentioned categories can be further integrated with a more specific set of Drivers of Change for new technologies that, given their importance, can be considered as trends on their own, as listed below:

- **Battery capacity/energy density:** climate goals and environmental challenges are key drivers to push the sector to invest into improving battery capacities, i.e., electric vehicles with longer range are likely to push climate goals forward;
- **Improved charger performance:** the shift from oil to electricity is one step for the decarbonisation process depending on battery capacity and also on better and faster charging tools to boost the use of Battery Electric Vehicles (BEV);
- **Country independence:** resulting from COVID-19, countries, and companies recognised the need to be more independent both in terms of battery construction and materials (e.g., fabrication of own cells);
- **Battery as a structure:** this refers to being able to use any structure (foundation of a house, chassis of a car, structure of an airplane) as a battery to reduce space, and maintain the right weight, the centre of gravity, and improve the charging infrastructure itself;
- **Heat conversion into electrical energy:** investing in processes to reconvert heat waste (kinetic energy) into electrical energy is important in the circularity of the process;
- **Safety:** the global adoption of regulations and standards in safety issues, especially regarding charging/recharging/ and discharging of batteries is necessary;
- **Energy accessible everywhere:** energy storage systems are key for the transition to sustainable energy sources, such as solar and wind energy, helping to maintain (and grow) current energy infrastructure stable and continuous everywhere.

[13] One-to-one meeting with Professor Helena Braga, Engineering Physics Department, University of Porto (PT), 25/05/2021

Highlights of Drivers of Change - Update

Also, for this desk-research process, the identified DoC were analysed based on:

- **Occurrence:** whether a DoC is cited in analysed reports; if a specific Driver of Change is cited multiple times in the same report or different DoC are cited, their occurrence is counted in any case as 1;
- **Importance**: a ranking from 0 to 5 (0 = not possible to evaluate, 1= not important, 5 very important) reflects the future status and direct implications on changes in the sector;
- **Urgency**: recognises a DoC overwhelming significance in a specific time frame (year).

One potential limitation of this methodological approach is that it is not specifically focused on the main topics of the second desk research – *battery manufacturing* and *future battery technologies*. This is due to the fact that narrowing down the approach would have prevented a harmonised aggregation of data and trend analysis between the first and the second desk research exercises, being the first one broader in terms of topics analysed.

Based on the above-mentioned methodological approach, the trend evolution regarding the occurrence, importance, and urgency of each DoC and per sub-category, is compared with the Desk research report from 2020.

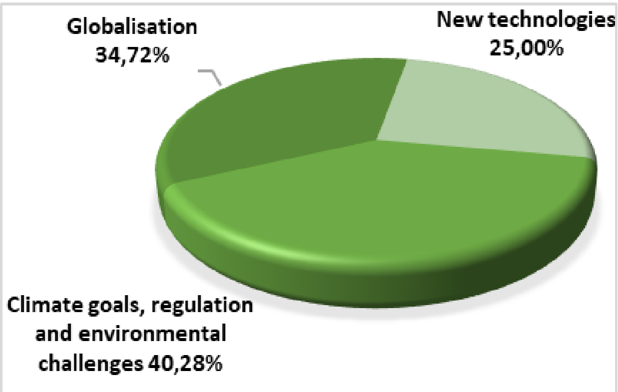
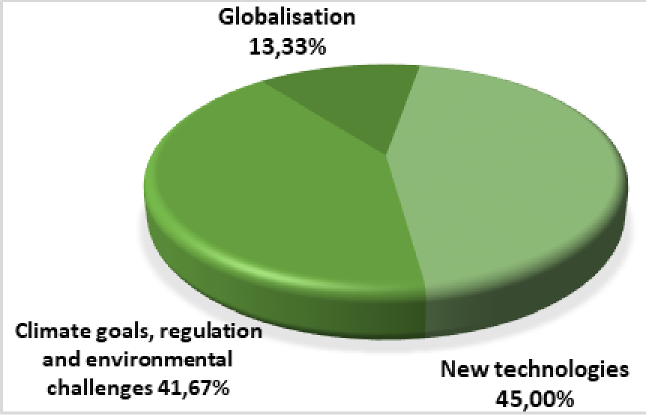


Figure 4: DoC occurrence - 2020 desk research

Figure 5: DoC occurrence - 2021 desk research



Overall, comparing the occurrence of the DoC in both desk researches (**Figure 4** and **Figure 5**), the consistency is confirmed. "Climate goals, regulation, and environmental challenges" have almost the same weight, but "new technologies" have a higher expression (from 25% to 45%), and "Globalisation" decreased its weight (34,72% to 13,33%).

Comparing research analysis for each sub-category, **Figure 6** and **Figure 7** show "Electrification and green energy" remaining equally relevant while "Reducing CO2 emissions from battery manufacturing" jumped to second and "global regulatory dialogue" lowered to rank 7. "Access to raw materials" is the 3rd, replacing "smart grid", now ranked 4th. This second desk-research process qualified the least importance to "cybersecurity".

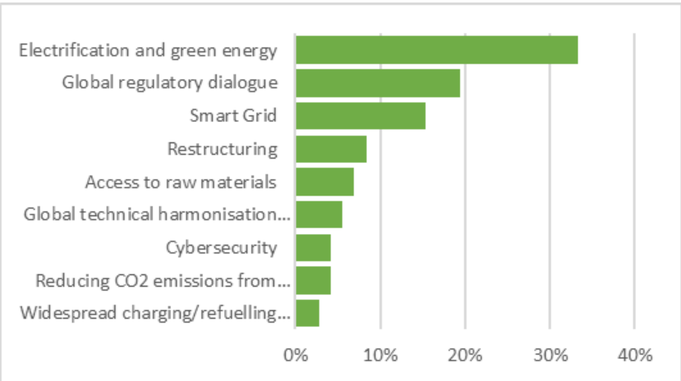


Figure 6: Occurrence of DoC sub-categories - 2020 desk research

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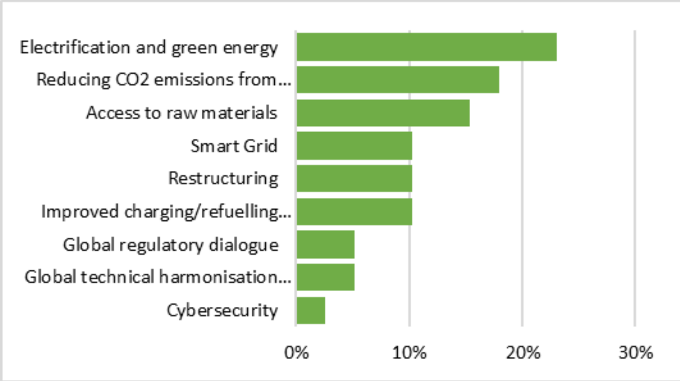
Figure 7: Occurrence of DoC sub-categories - 2021 desk research



When analysing the importance of each sub-category in both researches (**Figure 8** and **Figure 9**), it is similarly evidenced that "reducing CO2 emissions from battery manufacturing" is the most important, while "access to raw materials" became less significant (from 2nd to 7th in the ranking) and "global regulatory dialogue" has instead been upgraded (from 5th to 3rd). However, it is important to highlight that such changes are quite minor considering the numbers (indeed "access to raw materials" decreased only by 0.58 points - 4.38 and now 3.80).

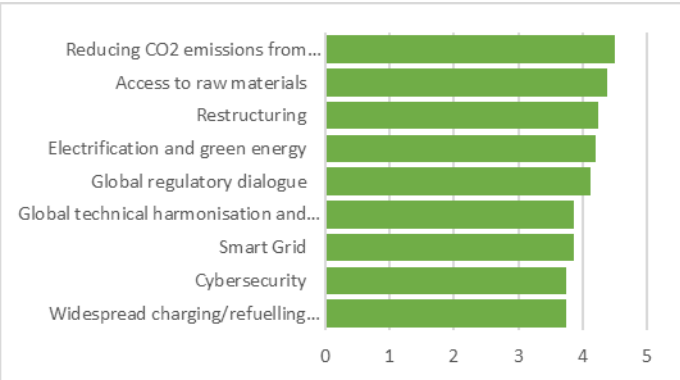
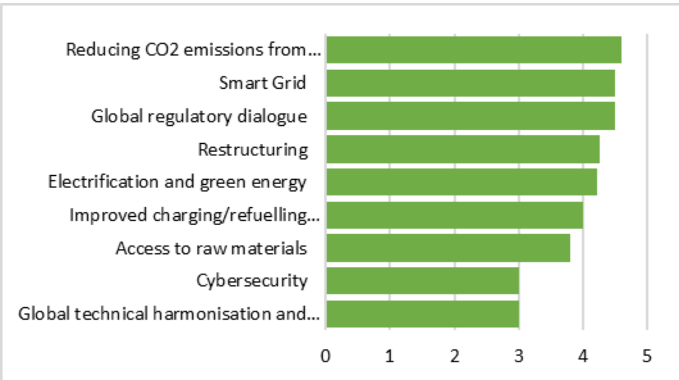


Figure 8: Importance of DoC sub-categories - 2020 desk research

Figure 9: Importance of DoC sub-categories - 2021 desk research



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Lastly, **Figure 10** and **Figure 11** analyse and compare the urgency of each DoC sub-categories. “Global regulatory dialogue” turned out to be the most urgent to tackle, together with “restructuring”. “Reducing CO2 emissions from battery manufacturing”, despite being the most important and frequently quoted in the literature, is a challenge to be faced in the long term (after 2030).

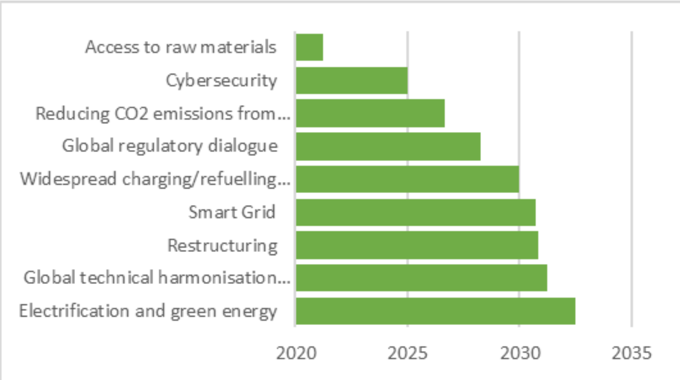

Figure 10: Urgency of DoC sub-categories - 2020 desk research

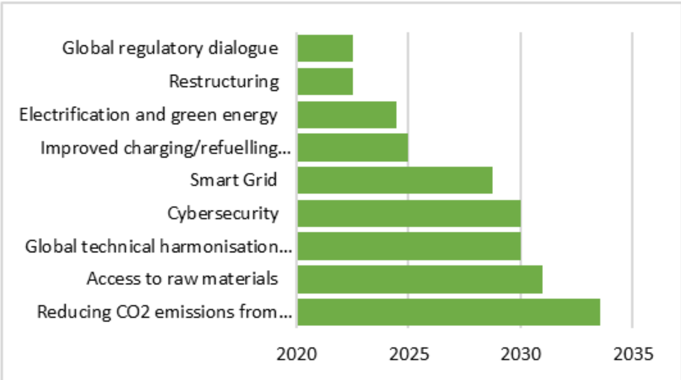

Figure 11: Urgency of DoC sub-categories - 2021 desk research

4 EU Framework

Achieving the goals of the Paris Agreement requires global efforts of reducing greenhouse gas emissions, comprising transformation of energy systems, industrial sectors, and transport. With its Green Deal and the aim to become climate neutral by 2050, the EU stands at the forefront of these activities. As mentioned in the previous chapter on Drivers of Change, batteries are one of the most important enablers for decarbonisation of road and maritime transport and transition to a renewable power system. Therefore, Europe needs to ramp up its battery production, which must be based on continuous research, development, and innovation to improve the current and come up with next generation technologies, attract talents and achieve a competitive position at the global level.

Batteries today's capabilities do not yet allow them to achieve the required performance and sustainability goals. The commercial success of batteries, in addition to performance, capacity, durability, sustainability, and safety, also depends on cost-effective large-scale production. The focus of EU policies on key priority areas: digital, green will need to be complemented by support for skills development.

In this process, EU instruments play a crucial role, encouraging and accelerating private R&D investments and activities. European companies recognize the greater need for structural investment in climate change, but at the same time usually favour shorter-term goals. The introduction of support instruments will ensure that companies do not face severe financial constraints and reduce the risks of longer-term investments. Therefore, there are important research and innovation initiatives also under the umbrella of the European Battery Alliance.

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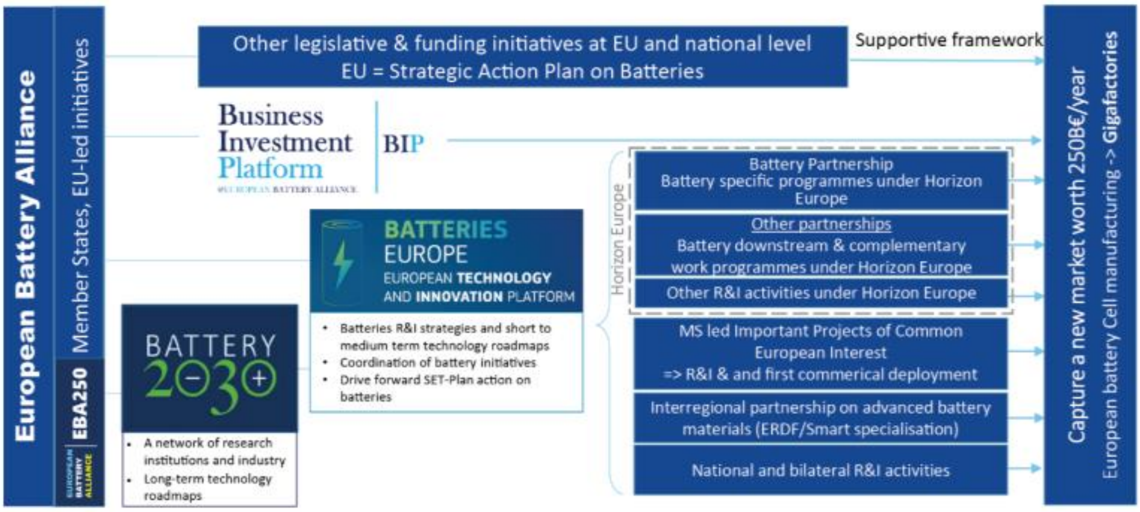

Figure 12: Overview of the European battery ecosystem under the umbrella of the European Battery Alliance[14]

A non-exhaustive list of different EU initiatives is mentioned below, illustrating the dynamic battery ecosystem in recent years in Europe[14].

The European Commission launched in 2019 the European Technology and Innovation Platform (ETIP) on Batteries dedicated to the entire battery value chain, **Batteries Europe**. European Technology and Innovation Platforms are generally recognised as key industry-led communities to develop and implement the Strategic Energy Technology (SET) Plan R&I priorities, to foster innovation in low-carbon energy technologies, and bring such new technologies to the market. Batteries Europe brings together key stakeholders from the public and private sectors (established companies, start-ups, research providers, and academia) from all over Europe, and national and regional representatives in addition to relevant representatives from the European Commission. They provide strategic advice covering technical and non-technological aspects (e.g., innovation barriers, need for specific research activities, the potential for international and interregional cooperation and education) and addressing linkages with other sectors. Through its national and Regional Stakeholder Group, Batteries Europe also serves as an information platform between member states and national projects. Another example of ETIP, relevant for batteries applications, is **ETIP Smart Networks for Energy Transition** (SNET).

[14] *Strategic Research Agenda for batteries 2020*. (2020). Batteries Europe. https://ec.europa.eu/energy/sites/ener/files/documents/batteries_europe_strategic_research_agenda_december_2020__1.pdf (accessed on 21/07/2021)

BATT4EU[15] is a co-programmed partnership established under Horizon Europe that aims to achieve a competitive and sustainable European industrial value chain for e-mobility and stationary applications. It is a contractual public-private partnership of the European Commission and BEPA (Batteries European Partnership Association), which puts together different industrial and research stakeholders. While Batteries Europe focuses on identifying all R&I needs across the battery value chain at every TRL level in a holistic manner, BATT4EU should aim at the most critical R&I priorities to be addressed within the Horizon Europe Work Programme.[16]

"Towards Zero-Emission Road Transport (**2Zero**)"[17] is a partnership within Horizon Europe to achieve carbon-neutrality in road transport by 2050. The 2Zero partnership will contribute to the development of the next generation of affordable multi-technology options towards zero tailpipe emission road transport for all types of vehicles from 2-wheelers to Heavy-Duty Vehicles and recharging infrastructure. It will also investigate zero-emission innovative mobility concepts and services for both people and logistics applications. Similarly, a partnership called Zero-Emission **Waterborne** Transport[18] is focused on ships and ports.

To address the need for investments into disruptive new knowledge and technologies, the European Commission launched **Battery 2030+**[19]. This large-scale research initiative is a European programme for long-term research on ultra-high performance, sustainable batteries with smart functionalities. Gathering high standing researchers within academia, institutes, and industry across Europe, the initiative aims to continuously provide the European battery industry with new tools and breakthrough technologies. Over 3 years, the implementation of the BATTERY 2030+ research plan is being executed in six research projects with a total EU support of €40.5 million.

[15] BATT4EU. https://bepassociation.eu/ (accessed on 18/08/2021)
[16] *The ETIP Batteries Europe – BATT4EU*. (2021). >BATT4EU. https://bepassociation.eu/synergies-and-collaborations/the-etip-batteries-europe/ (accessed on 18/08/2021)
[17] *2Zero Emission.* (2021, June 25). 2Zero Emission. https://www.2zeroemission.eu/ (accessed on 21/07/2021)
[18] *Welcome to Waterborne - Setting the agenda for Maritime Research in Europe - waterborne.eu*. Waterborne.Eu. https://www.waterborne.eu (accessed on 21/07/2021)
[19] Battery 2030. (2020). https://battery2030.eu/ (accessed on 21/07/2021)

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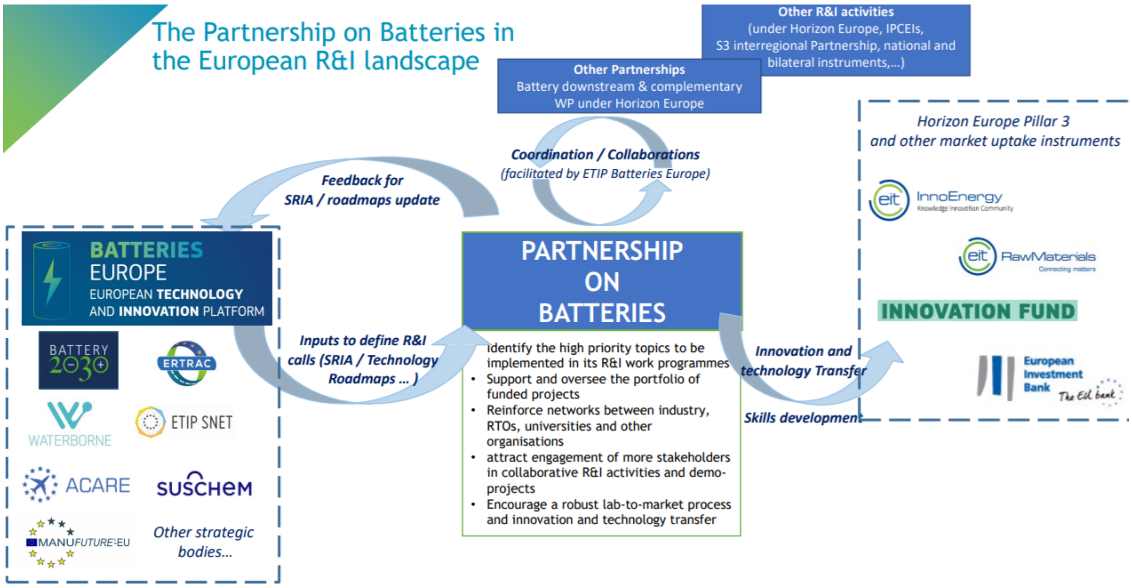

Figure 13: European research and innovation landscape in the battery technologies area[20]

To further accelerate the upscaling of pre-commercial projects, the Commission launches calls for **IPCEI**s in areas of strategic importance to the EU economy. An Important Project of Common European interest is a tool to support research and innovation under specific EU State aid rules. The rules have a specific provision for the Member States to fund disruptive and ambitious research and development, as well as the first industrial deployment of the technology in case of market failure. So far, the Commission approved two Batteries IPCEIs in 2019 and 2020.[21,22]

EBA250[23] is the European Battery Alliance's industrial workstream. The European Commission, interested EU governments, investment institutions, and important industry, innovation, and academia stakeholders are all connected through this cooperative ecosystem, which has over 500 members. The European Commission has entrusted **EIT InnoEnergy** with driving forward and promoting EBA250 operations, acting as a network manager.

[20] BATTERIES| *Towards a competitive European industrial battery value chain for stationary applications and emobility*. (2020, October 18). [Slides]. BATTERY 2030PLUS KICK-OFF. https://battery2030.eu/digitalAssets/900/c_900744-l_1-k_battery-european-partnership-ppp.pdf (accessed on 21/07/2021)
[21] *Press corner*. (2019). European Commission - European Commission. https://ec.europa.eu/commission/presscorner/detail/en/ip_19_6705 (accessed on 10/06/2021)
[22] di Caro, M. (2021, January 27). *EU approves €2.9 billion state aid for a second Pan-European research and innovation project along the entire battery value chain. European Battery Alliance*. https://www.eba250.com/eu-approves-e2-9-billion-state-aid-for-a-second-pan-european-research-and-innovation-project-along-the-entire-battery-value-chain/ (accessed on 10/06/2021)
[23] Energy Battery Alliance - EBA250. (2021, April 1). *ABOUT EBA250*. European Battery Alliance. https://www.eba250.com/about-eba250 (accessed on 21/07/2021)

LiPLANET[24] is a project supported by Horizon 2020, and its mission is to create a network of research pilot lines for the production of lithium battery cells. Dividing work into several expert groups will also focus on education and training, developing educational materials, training experts and pilot line operators, or creating trans-disciplinary training programmes.

As for financial resources in the area of R&D&I, the main EU instrument has been the framework programme for research and innovation, in the period 2021 – 2027 called **Horizon Europe**.[25] With a total allocation of 95,5 billion €, Climate, Energy and Mobility cluster under Pillar II or its Missions (e.g. Adaptation to climate change including societal transformation and Climate-neutral and smart cities), it will significantly contribute also to the battery related research in the coming years.

Other important sources of financing include European Structural and investment funds, Just Transition Fund, National recovery, and resilience plans, funded from Recovery and Resilience Facility, or national R&D&I. Significant amount of finances could be triggered by the **InvestEU** programme, which shall support investments that contribute to EU's climate objectives.[26]

Globally, there should be more than 3 TWh Li-Ion battery cell production capacities by 2030. Circa 30% of those could be located in Europe, according to the manufacturers' announcements[27]. As the **analysis of strategic dependencies and capacities**[28] (with Li-Ion batteries on the list) has shown, one of the key lessons of the COVID-19 crisis is the need to identify strategic products in the most sensitive industrial ecosystems. Work has already begun on several dependencies identified in the EU Industrial strategy to address or analyse these dependencies in more detail. Such measures include, in particular, the Action Plan on Critical Raw Materials and the European Raw Materials Alliance. The impact of the measures is enhanced by the analysis in the context of the EU Chemicals Strategy and concerning the essential inputs (such as batteries) necessary for the green transition.

[24]LiPLANET | Network of Research Pilot Lines for Lithium Battery Cells. https://www.liplanet.eu/about-us, (accessed on 21/07/2021)
[25]*Horizon Europe*. (2018, January 3). European Commission - European Commission. https://ec.europa.eu/info/research-and-innovation/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en, (accessed on 21-07-2021)
[26]*Contribution to the Green Deal and the Just Transition Scheme*. InvestEU. https://europa.eu/investeu/contribution-green-deal-and-just-transition-scheme_en (accessed on 21/07/2021)
[27]Presentation by Dr. A. Thielmann and Dr. Ch. Neef from Fraunhofer Institute for Systems and Innovation Research ISI made at Battery Virtual Exhibition on 29/04/2021
[28]*Strategic dependencies and capacities*. (2021). https://ec.europa.eu/info/sites/default/files/swd-strategic-dependencies-capacities_en.pdf (accessed on 21/07/2021)

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5 Stakeholders

Numerous research skills and research funds are being invested all over the world into pushing forward energy harvesting and storage. The most important driving force pushing the electrification of society is the urgency of reducing global warming.

Nonetheless, technology will only get “real” when it gets out of the laboratory bench at TRL 4-5 and is developed within a start-up, by early investors, or by an established company. This latter consideration was what guided ALBATTS to choose what the most promising technologies are. It was established that the technologies that are supported by companies had ultimately a higher possibility to be commercialized in the future. In **Tables 2 to 6** and the maps below them examples of those companies, as well as the technologies they are investing in, are shown.

While in the previous desk research report of ALBATTS we have shown that despite all the research and development in LIBs, most of the EVs battery makers were using graphite as anode and NMC as cathode, new developments came to light, such as the development of all-solid-state batteries[29] and, very recently the development of NIB by one of the most important battery manufacturers, which is CATL[30], China.

Finally, we are looking forward to following the next developments in batteries and other energy storage technologies. Here we refer to several technologies that may be predominant in the future based on all the investment that is being made in advancing these technologies.

Table 2: Companies developing new materials for LIB (selection)[31]

Company	Technology	Website
Advano, USA	SiF_x upcycling scrap silicon waste from semiconductor and solar-panel manufacturing	https://www.advano.io/science/
Amperex Technology (CATL), China	First company to begin mass-producing NMC 811 batteries in 2019	https://www.catl.com/en/
BASF, Germany	NMC & NCA	https://catalysts.basf.com/industries/automotive-transportation/battery-materials
Black Diamond, USA	SiO_x & SiAl@C anodes	https://www.blackdiamond-structures.com/technology/

[29]Electric, F. E. (2021, June 3). *TOYOTA’s Only Hope to Beat TESLA: Solid State Battery* [Video]. YouTube. https://www.youtube.com/watch?v=ZAXyTNKQTKA&feature=youtu.be (accessed on 10/7/2021)

[30]Batteries International. (2021, June 3). *Sodium-ion batteries to pose threat to lithium and lead industries*. https://www.batteriesinternational.com/2021/06/03/sodium-ion-batteries-to-pose-threat-to-lithium-and-lead-industries/ / (accessed on 20/7/2021)

[31]The criterion for marking on the maps in this chapter is a country in which it is **produced**

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CPI, UK	Slurries for the manufacture of electrodes	https://www.uk-cpi.com/next-generation-battery-technology
Enwires, France	Intrinsic, n- and p-doped Silicon nanowires, Si composites	http://enwires.com/
Hollingsworth and Vose, USA	Separators for LIB	https://www.hollingsworth-vose.com/innovation/
Imerys Graphite & Carbon, Switzerland	C-NERGYTM high purity graphite and conductive carbon black powders for positive and negative electrodes of LIB	https://www.imerys-graphite-and-carbon.com/applications/
Innolith, Switzerland	NMC new version stable to over 5V NMC and graphite electrodes using the Innolith proprietary electrolyte	https://innolith.com/technology/
Korepower, USA	NMC & LFP pouch cells	https://korepower.com/
Leyden-jar, the Netherlands	Porous pure silicon anode, allowing it to absorb the swelling of the silicon during lithiation	https://leyden-jar.com/technology/
Materion, USA	Composite current collectors	https://materion.com/technologies/composite-metals/
Johnson Matthey Poland	eLNO® nickel-rich advanced cathode materials NMC811 and NCA cathode materials LFP cathode	https://matthey.com/en
Nano One, Canada	NMC811 cathodes	https://nanoone.ca/
Nanopow, Norway	Nano crystalline Si powder for LIB anodes	http://www.nanopow.eu/
Nanospan, India	Graphene & nano Si composites	https://nanospan.com/
Nexeon, Japan	Si@C anodes, conductive additives, electrolytes & binders	https://www.nexeon.co.uk/company/
Northvolt, Sweden	NMC811 cathodes	https://northvolt.com/
PPK, USA	Boron nitride nanotubes	https://www.ppkgroup.com.au/
Sila, USA	Nanotechnologies, Si anode	https://silanano.com/
Silatronix, USA	Liquid electrolytes	https://silatronix.com/contact/
StoreDot, Israel	Self-healing 3D organic polymers Organic Electrode Additives Organic Binders Organic Electrolyte Additives	https://www.store-dot.com/technology
Trion, USA	Si@C anodes (15% Si)	https://trionbattery.com/
UMICORE, Belgium	NMC	https://rbm.umicore.com/en/portable-electronics/
Volkswagen, Germany	Partnerships LIB	https://www.volkswagenag.com/en/
Volvo Car Corporation, Sweden	Partnerships LIB & Structural batteries	https://group.volvocars.com/company

Figure 14: Companies developing new materials for LIB (selection)[31]

Table 3: Companies developing Li-S (selection)[31]

Company	Technology	Website
IoLiTec, Germany	Ionic liquids, Li-S	https://iolitec.de/en/products/
LG Chem, S. Korea	Li-S	https://www.chemengonline.com/lg-chem-completes-landmark-drone-flight-using-lithium-sulfur-battery/
LiSTAR, UK	Li-S	https://www.listar.ac.uk/
NexTech Batteries, USA	Li-S	http://www.nextechbatteries.com/
OXIS Energy, UK	Li-S	https://oxisenergy.com/
PolyPlus, USA	Li-S	https://polyplus.com/lead-product-glass-protected-lithium-battery/
PPK, USA	Li-S with boron nitride nanotubes	https://www.ppkgroup.com.au/site/what-we-do
Sion Power, USA	Li-S	https://sionpower.com/
Zeta Energy, USA	Graphene-Li anodes and Sulfur cathodes	https://zetaenergy.com/

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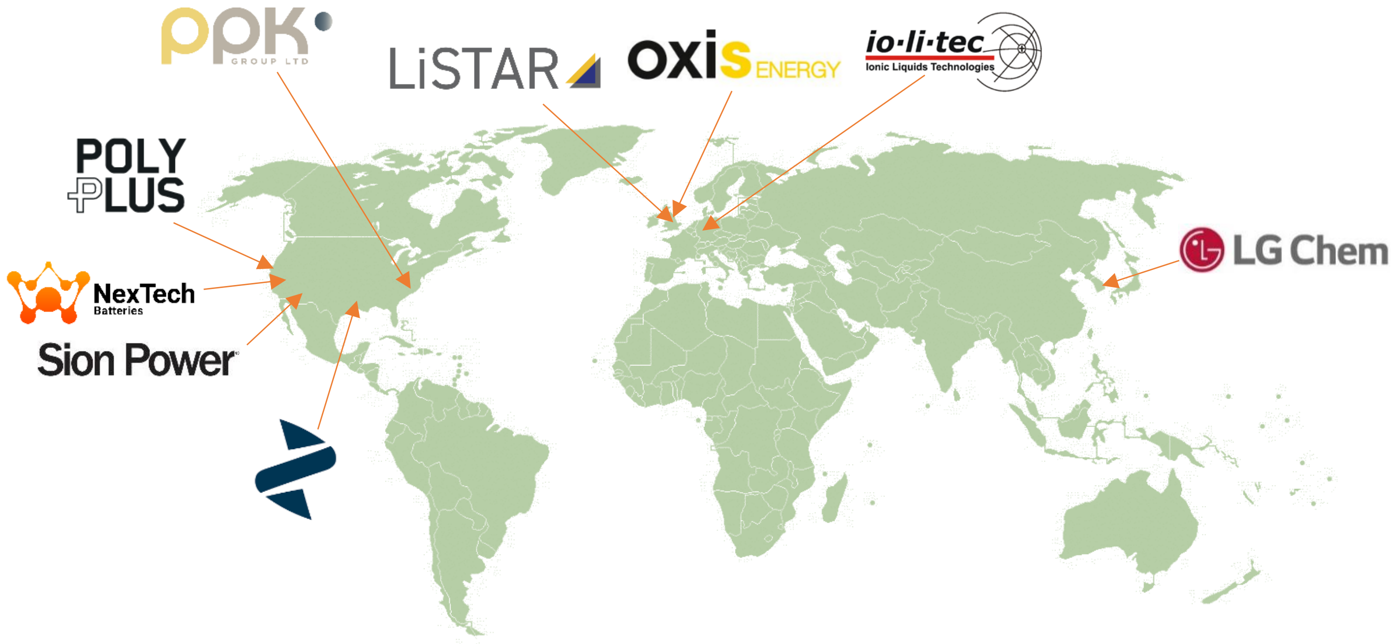

Figure 15: Companies developing Li-S (selection)[31]

Table 4: Companies developing NIB (selection)[31]

Company	Technology	Website
Altris AB, Sweden	Fennac® (often called "Prussian White") a framework material consisting of sodium, iron carbon, and nitrogen is a positive electrode material for Na-ion batteries (NIB)	https://www.altris.se/
Broadbit batteries, Finland	Sodium-based chemistries	http://www.broadbit.com/
CATL, China	Na-ion batteries	https://www.catl.com/en/ess/
Faradion, UK	Na-ion batteries	https://www.faradion.co.uk/technology-benefits/strong-performance/
HiNa Battery Technology, China	Na-ion batteries	https://www.hinabattery.com/en/
Natron Energy, USA	Natron Prussian Blue Sodium–Ion Battery (capacitor characteristics and architecture)	https://natron.energy
TIAMAT, France	Na-ion batteries for mobility	http://www.tiamat-energy.com/

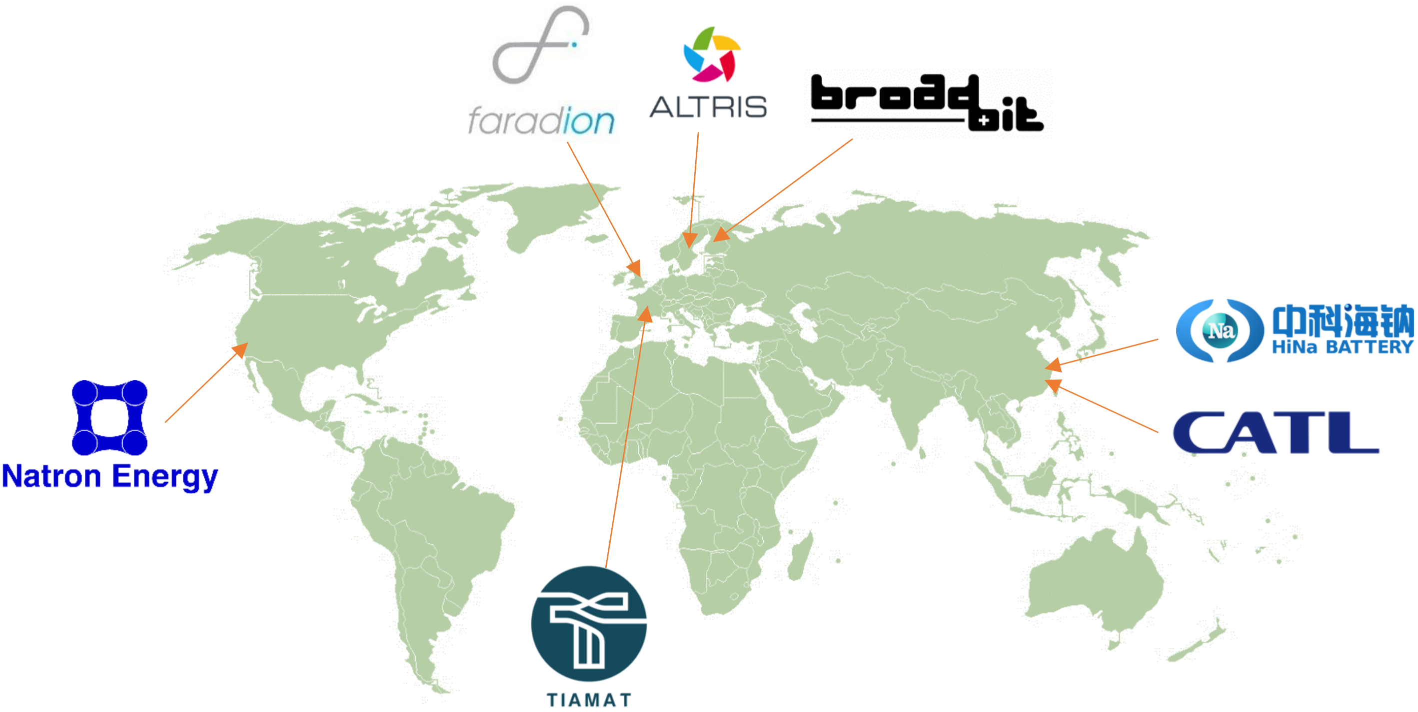

Figure 16: Companies developing NIB (selection)[31]

Table 5: Companies developing Solid-state batteries (selection)[31]

Company	Technology	Website
ABEE Avesta, Belgium	SSE	https://abeegroup.com/
Albufera, Spain	Al-air and Al SSE Advanced ion gels	https://albufera-energystorage.com/tecnologia/
Amperex Technology (ATL), CATL, China	lithium-iron phosphate (LFP) cathode with SSE	https://www.atlbattery.com/en/about.html
Battsys, China	Li-ion polymer electrolyte	https://www.fe123battery.com/en/
Bolloré's subsidiary **Blue Solutions**, France	Lithium Metal Polymer (LMP)	https://www.bollore.com/en/activites-et-participations-2/stockage-delectricite-et-systemes/blue-solutions-films-plastiques/
CALB, China	SSE	https://en.calb-tech.com/product.html
Factorial Energy, USA	SSE	https://factorialenergy.com/
Guoxuan High-tech power energy Co. Ltd, China	SSE	https://gosavetime.com/guoxuan-hi-tech-announces-solid-state-battery-roadmap/
Hitachi Zosen, Japan	All-solid-state Lithium-Ion Battery (working @ -40°C to 100°C)	https://www.hitachizosen.co.jp/english/technology/hitz-report/2018h30_11/index.html
Honcell, China	Li-ion polymer electrolyte including $LiFePO_4$ power cells	http://www.honcell.com/
Hydro Quebec, Canada	Polymer and ceramic SSE	https://www.hydroquebec.com/transportation-electrification/battery-materials.html
Ilika, UK	SSE	https://www.ilika.com/
Ionic Materials, USA	Polymers	https://ionicmaterials.com/

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LG Chem, S. Korea	SSE	https://www.lgchem.com/main/index
Murata Manufacturing, Japan	Oxide ceramic SSE	https://www.murata.com/en-us/news/batteries/solid_state/2019/0626
Panasonic, Japan	Li-ion SSE	https://news.panasonic.com/global/topics/2020/79803.html
PolyPlus, USA	Glass Protected Li Metal Batteries feature a solid-state lithium	https://polyplus.com/
Prieto Battery, USA	3D SSE Li-ion battery	https://www.prietobattery.com/
Prologium, Taiwan	90% ceramic SSE / liquid	http://www.prologium.com/index.aspx?02F0EA87FB60FF526BD81D51338B43D5
QuantumScape, USA	Anode less (Li) with ceramic SSE	https://www.quantumscape.com/
SAMSUNG, S. Korea	silver-carbon (Ag-C) composite layer as the anode with Sulfide (working @ 60°C, 20 atm)	https://news.samsung.com/global/samsung-presents-groundbreaking-all-solid-state-battery-technology-to-nature-energy
Solid Energy (SES), USA	Polymer + Liquid	https://launch.ses.ai/
Solid Power, USA	Sulfide SSE	https://solidpowerbattery.com/
Solvay, Belgium	SSE	https://www.solvay.com/en/innovation/science-solutions/fast-charging-safe-batteries
TNO, The Netherlands	Solid-State 3D Technology	https://www.tno.nl/en/focus-areas/information-communication-technology/
Toyota, Japan	Sulfide SSE	https://www.toyota.ie/world-of-toyota/articles-news-events/2021/solid-state-batteries.json

Figure 17: Companies developing Solid-state batteries (selection)[31]

Table 6: Companies developing Supercapacitors and Ultracapacitors - including Lithium capacitors (selection)[31]

Company	Technology	Website
Beyonder, Norway	Supercapacitors including Lithium-ion capacitors	https://www.beyonder.no/technology
Cerman.power+ Battery (Envites Energy), Germany	High Power Battery With ceramic separator	www.cermanpower.de
Ioxus, USA	Lithium capacitors	https://ioxus.com/product/cells/
Eaton, USA	Capacitor and capacitor banks	https://www.eaton.com/us/en-us/products/medium-voltage-power-distribution-control-systems/power-capacitors.html
Fastcap Ultracapacitors, USA	Supercapacitors powered by Neocarbonix™ polymer binder-free electrodes	https://www.fastcapultracapacitors.com/
Fujikura, Japan	Large-capacity Lithium-Ion Capacitor Cells and Modules	https://www.fujikura.co.jp/eng/newsrelease/products/2051508_11777.html
General Capacitor, USA	Lithium capacitors	https://www.ga.com/capacitors/
Geyser batteries, Finland	Water-based electrolytes	https://www.geyserbatteries.com/
JM Energy Corporation, USA	Lithium capacitors	https://www.jsr.co.jp/jsr_e/news/2020/20200127.html
Kamcap, China	Supercapacitors	https://www.kamcappower.com/
LiCAP, USA	Ultracapacitors and Lithium-Ion Capacitors	https://www.licaptech.com/?gclid=Cj0KCQjw9O6HBhCrARIsADx5qCR6rcFdVR4D6Lqopo3D3eae1QBnGPhTWkIdnH_H18FLs6qzGASau4QaAmK0EALw_wcB
Maxwell Technologies, USA	Including Lithium capacitors	https://www.maxwell.com/
Murata Manufacturing, Japan	Multilayer ceramic capacitors, Polymer aluminum electrolytic capacitors, Silicon capacitors, High-temperature film capacitors for automotive	https://corporate.murata.com/en-us/company/business/capacitor
Panoramic Laboratories, USA	Neocarbonix™ electrodes, Fastcap® Ultracapacitors, and Thermexit™ thermal interface gap filler pads.	https://www.nanoramic.com/
Nawa, France	Nanotube structure for electrodes (conductive polymers, Lithium, Sodium, Silicon, Sulfur, Titanate, and others) Ultra-Fast Carbon Battery	http://www.nawatechnologies.com/en/home-english/
Nippon Chemi-Con, Japan	EDLC supercapacitors	https://www.chemi-con.co.jp/en/
Olife, Czech Republic	Combination of Li-ion battery cells and supercapacitors	http://olifebattery.com/batteries/en/battery/technology
Panasonic, Japan	Polymer and EDLC supercapacitors	https://na.industrial.panasonic.com/products/capacitors
Skeleton Technologies, Estonia	Ultracapacitors	https://www.skeletontech.com/

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SPEL, India	Lithium-Ion Capacitor (LIC) and its hybrid variant as Hybrid Lithium-Ion Battery Capacitor (H-LIBC) EDLC Supercapacitor with Activated Carbon	https://www.capacitorsite.com/
Taiyo Yuden, Japan	Electric Double-Layer Capacitors and Lithium Capacitors	https://www.yuden.co.jp/eu/
Yunasko, UK	Electrochemical Double Layer Capacitor (EDLC) and Lithium-Ion Capacitors	https://yunasko.com/en/technology
ZapGo, UK	Carbon-Ion	https://zapgo.com/
ZoxCell, Hong Kong	Graphene Super Capacitor	https://www.zoxcell.com/

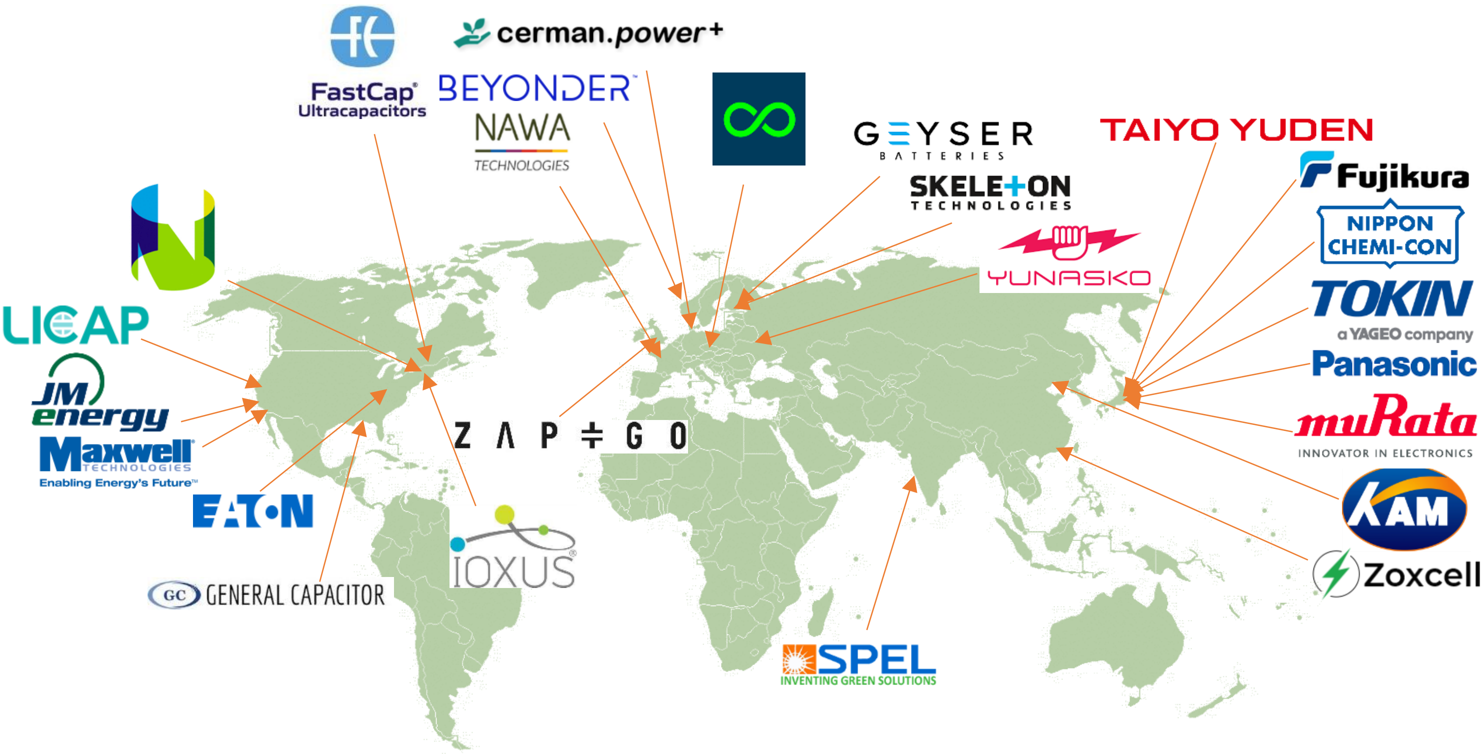

Figure 18: Companies developing Supercapacitors and Ultracapacitors - including Lithium capacitors (selection)[31]

6 Technology

Electric vehicles (EVs) are becoming serious substitutes to internal combustion engine vehicles[32]. According to the International Energy Agency (IEA), electric vehicles accounted for 2.6% of global car sales in 2019. This value increased to 4% in 2020, surpassing the initial estimate of 3% provided by the IEA[33]. According to the agency, the coronavirus pandemic caused an unbalanced drop in global car sales, more aggravated for non-electric vehicles. EV sales increased by 40%[34] in 2020. LIBs represent a significant market share of the batteries for EV vehicles.

Self-sustainable microgrids are viable options to ensure no overflow of the grid which were not anticipated to withstand the household's small and discrete supplies of energy. Microgrids should harvest and store free energy when available to serve when harvesting is not possible.

Essential concepts to understand energy storage devices:

In an energy storage device, such as a battery cell, the current of electrons that circulates in the external circuit supplying the energy is driven by the difference in chemical potentials between the electrodes (i.e., related to the internal energy which in turn is related to temperature, composition, pressure, magnetic and electric properties, etc). Here are, some important concepts that are common to most energy storage and even to energy harvest devices:

- As the battery-cell discharges, the electrons circulate spontaneously from the negative electrode (anode) to the positive electrode (cathode). **Figure 19** shows the electrons in yellow conducted through the external circuit and lighting the LED.
- The electrons move from the electrode with the higher to the lower energy, or better, from the electrode with the higher to the lower chemical potential, to equilibrate them (see **Figure 19** electrons in yellow conducted through the external circuit).
- The ions diffuse in the electrolyte to compensate for the difference in chemical potentials between the electrolyte and the electrodes (see **Figure 19** Li^+ ions in red).

[32] Salgado, R.M.; Danzi, F.; Oliveira, J.E.; El-Azab, A.; Camanho, P.P.; Braga, M.H. The Latest Trends in Electric Vehicles Batteries. Molecules 2021, 26, 3188. https://doi.org/10.3390/molecules261131

[33] Wheeler, E. *Electric Vehicles to Set New Market Share Record in 2020*. 2020. Available online: https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/electric-vehicles-to-set-new-market-share-record-in-2020-59050766 (accessed on 4/7/2021).

[34] Gorner, M.; Paoli, L. *How Global Electric Car Sales Defied Covid-19 in 2020*. 2021. Available online: https://www.iea.org/commentaries/how-global-electric-car-sales-defied-covid-19-in-2020 (accessed on 4/7/2021).

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- As the electrons cannot be conducted through an insulator such as an electrolyte (per definition of insulator), the ions move in the electrolyte instead, locally changing the concentration of the electrolyte and, therefore its chemical potential, to allow the dynamic energy equilibration between the electrolyte and the electrodes.
- As the battery-cell discharges, the energies of the electrodes tend to equalize (see **Figure 20** – discharge).
- The charging process is not spontaneous; hence electrical work is to be supplied by an external source, such as a charger, to charge the batteries by recovering the chemical potentials bias and overcome the internal resistance to ions and electrons movement, which results in wasted heat (see **Figure 20** – charge).

The element with the highest practical chemical potential is Lithium and therefore the highest battery-cell voltages (energies per charge) are obtained with Lithium as the anode. The graphite, which is used as anode in the Li-ion batteries, when lithiated after being charged resulting in the insertion of Li through the graphite's planes, shows a chemical potential that only differs 0.1-0.2 V from the chemical potential of the lithium. This is one of the reasons why graphite is used in Li-ion battery cells as anode; the other reasons are related to safety and with the graphite maintaining its chemical potential almost constant while most of the high voltage traditional cathodes discharge, allowing the maximum capacity (charge, Q) at the highest voltage to be obtained.

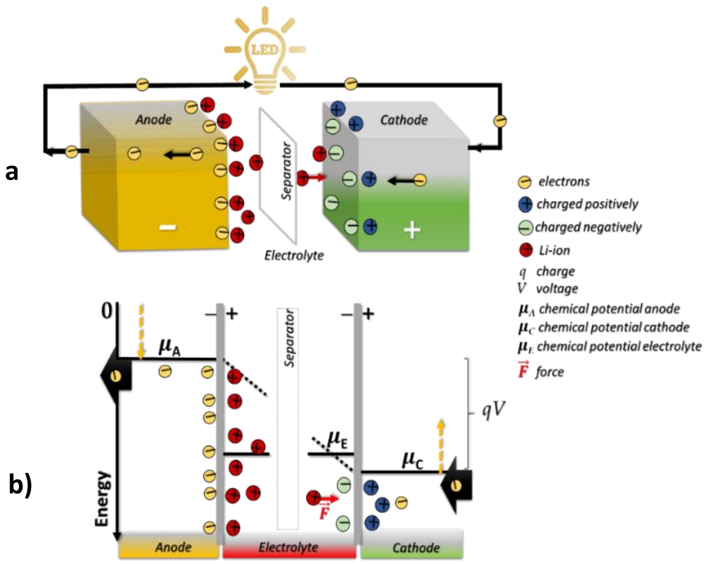

Figure 19: Schematics illustrating the discharge of a battery (spontaneous dynamics); a) representation of the circuit; b) representation of the variation of the internal energies (chemical potentials), the movement of ions inside the cell and electrons in the external circuit while the battery-cell discharges. For charging, external energy has to be supplied to the circuit to overcome the difference in chemical potentials between the anode and the cathode as well as the internal resistance to the movement of the ions and electrons.

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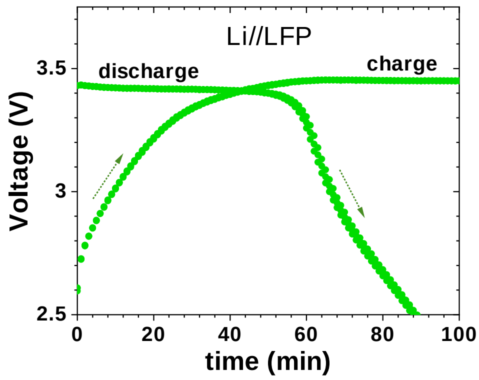

Figure 20: Charge and discharge of a Li-LFP half battery-cell with a liquid electrolyte to illustrate a battery cycle[35]

Other devices such as capacitors, photovoltaics, transistors, p-n junctions, fuel cells, among others, work under very similar principles. The differences in the mechanisms governing the latter working devices are responsible, for example, for the different specific energy and power.

A Li-ion battery, besides being constituted by electrodes (anode and cathode) and electrolyte, also contains metals that are current collectors and that facilitate the exchange of electrons between the external circuit and the electrodes. As in a Li-ion battery, the electrolyte is usually a liquid, a separator must be placed between the electrodes to avoid short circuits. **Figure 21** shows the most important constituents of a Li-ion and their corresponding percentages, and **Figure 22** shows how the gravimetric (specific) and volumetric energy decrease from their maximum in the simplest architecture (in which only active materials exist) to their minimum in the application.

[35]Braga, M. H. *Revista de Ciência Elementar* ISSN 2183-9697, and ISSN 2183-1270 and https://wikiciencias.casadasciencias.org (EDULOG • Fundação Belmiro de Azevedo) 8(3) (2020) "O lítio e a bateria de ião-Li" (Portuguese)

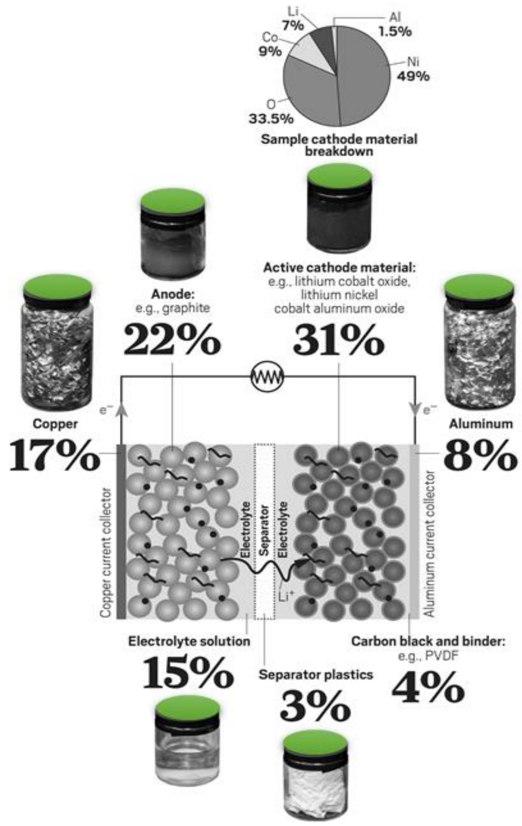

Figure 21: Materials used in LIB-cells. Adapted from[36]

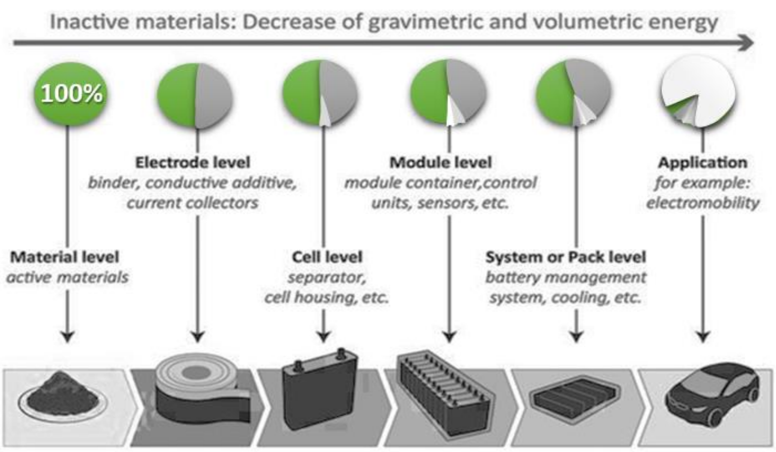

Figure 22: Inactive materials: decrease of specific energy and energy density. Adapted from European Commission[37]

[36] *It's time to get serious about recycling lithium-ion batteries*. (2019). Chemical & Engineering News. https://cen.acs.org/materials/energy-storage/time-serious-recycling-lithium/97/i28 (accessed on 21/07/2021)
[37] *Cloudflare*. (2020). All about Circuit. https://www.allaboutcircuits.com/news/china-will-account-for-two-thirds-of-the-global-ev-battery-value-chain-by-2030/ (accessed on 21/07/2021)

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6.1 LI-ION BATTERIES: THE PATH FORWARD

The first Lithium-ion battery (LIB) cells were commercialized in the 1990s and today they are widespread throughout the planet. What are the main challenges that remain and that drive the R&D around the world in universities, RTOs, small and big companies?

Main goals to achieve:

(1) Increasing safety by reducing dendrite formation and eventually by changing technology;

(2) Increasing power and energy density by using higher capacity anodes (e.g., Si@C and Lithium metal) with higher capacity cathodes such as sulfur (S_8) and tailored engineered implementations (e.g., by not soldering the tabs);

(3) Decreasing the use of less widely available materials such as Cobalt (e.g., using NMC811 formulation);

(4) Increasing recyclability, implementing second life strategies, and use of environmentally friendly materials;

(5) Reducing the volume (pack) by increasing cells' energy density and using less complex safety package with safer electrolytes (e.g., solid-state);

(6) Using all the available structural volume (e.g. using structural batteries);

(7) Reducing the thermal battery management system, TBMS, using cells architectures that do not require flammable electrolytes;

(8) Reducing fabrication and energy cost;

(9) Associating harvest with storage to reduce energy cost and improve efficiency.

Drawbacks of transforming the established Li-ion technology and production:

(1) Economic investment in research and development and qualified jobs;

(2) Necessity to convert existing infrastructures and equipment (e.g., increasing the CO_2 footprint momentously);

(3) Increase in raw materials demands (e.g., Li, Co);

(4) Using the available structural volume to store energy implies addressing simultaneously mechanical and electrochemical properties and using safe electrolytes (e.g., ionic liquids, polymers, epoxies, and all-solid-state electrolytes that usually have a low ionic conductivity < 10^{-3} S.cm^{-1});

(5) Associating harvest and storage capabilities adds to the complexity;

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(6) With new solutions come new problems to be addressed.

Hereafter, the above challenges and drawbacks are going to be analysed within different batteries architectures.

6.1.1 Negative Electrodes (anodes) for LIB

As exposed previously[38], the main reason for the Lithium's attractiveness for EV batteries is its high electroactivity (chemical potential) since this type of high-power vehicle has substantially high voltage requirements in the range of 400 – 800 V. LIBs allow for fewer batteries and battery packs (see **Figure 22**) to be associated in series to match the latter voltages, consequently reducing their internal resistance leading to lower heat losses, smaller size components, and thus reducing weight and cost.

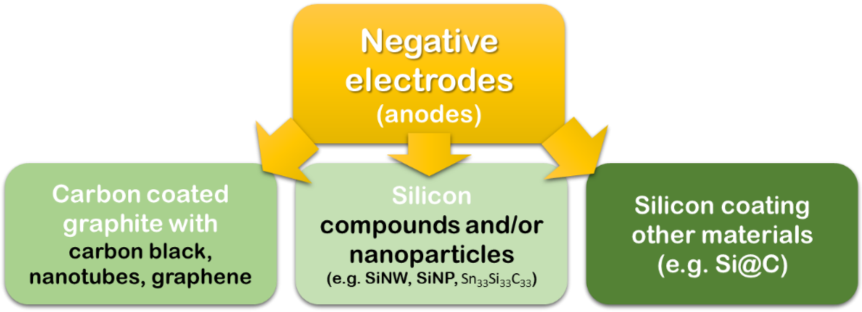

Figure 23: Negative electrodes' latest trends towards the future

Although graphite was introduced to substitute the Li anode in the 1980s due to safety, there are still safety issues associated with this active anode. A fast charge (e.g., when the battery is charged at low temperatures) may result in dendrites' growth, eventually leading to short circuits. Dendrites are metallic whiskers (fractals) of lithium that can show sharp ends, which can perforate the separator and lead to short circuits.

6.1.1.1 Graphite anodes

Graphite anodes not only possess relatively low specific capacity (theoretically, 372 $mA.g^{-1}$) but also have a typical cycle life of the same order as standard NMC cathodes, which means that graphite can limit the cycle life of the cell[39].

[38]In: Essential concepts to understand energy storage devices

[39]Toshiba. *What is SciB? 2020*. https://www.scib.jp/en/about/index.htm (accessed on 04/07/2021).

The reduction of the cycle life of a battery cell is largely attributed to the chemical instability that occurs at the electrode/electrolyte interface[40]. This fact, besides motivating research to find new materials, led to the development of Carbon coated graphitic anodes (see **Figure 23**). The advantages thus obtained consist of:

(1) a thinner solid electrolyte interphase (SEI), potentially leading to higher capacity[41], as the SEI consumes Li^+ – it is a mixture of solid-state insulating compounds mainly containing lithium;

(2) a reduction of chemical instability between electrode and electrolyte leading to a great improvement in cycling performance[42].

It is noteworthy that the SEI is formed spontaneously when the negative electrode and electrolyte become in contact during charge.

If the Lower Unoccupied Molecular Orbital (LUMO) of the liquid electrolyte has lower energy than the chemical potential of LiC_6, $\mu(LiC_6)$, an electron current leaks from the negative electrode to the electrolyte to align (equalise) their chemical potentials. Those leaked electrons reduce Li^+-ions and subsequently LiF, Li_2O, and Li_2CO_3 are formed (for the most common electrolyte solution, a carbonate solvent, and $LiPF_6$). The formation of these and other insulators inhibits the leakage of electrons to the electrolyte, enabling the conduction of electrons throughout the external circuit. Therefore, the SEI layer is very important in LIB and is responsible, *per se*, for a great deal of research. In the industry, the formation of the SEI layer in LIB is part of the optimizing routine before the cells leave the factory.

Other types of Carbon-based anodes with higher capacities have been the subject of research efforts, namely Carbon nanotubes and graphene. However, their use is limited due to the cost of the manufacturing process and discharge capacity degradation, respectively, although the

[40]Toyohara. *Toshiba IR Day 2019 Battery Division*. 2019. Available online: https://www.toshiba.co.jp/about/ir/en/pr/pdf/tpr20191114_7e.pdf (accessed on 04/07/2021).

[41]Zhang, H.L.; Liu, S.H.; Li, F.; Bai, S.; Liu, C.; Tan, J.; Cheng, H.M. *Electrochemical performance of pyrolytic carbon-coated natural graphite spheres*. Carbon 2006, 44, 2212–2218.

[42]Li, P.; Zhao, G.; Zheng, X.; Xu, X.; Yao, C.; Sun, W.; Dou, S.X. *Recent progress on silicon-based anode materials for practical lithium-ion battery applications*. Energy Storage Mater. 2018, 15, 422–446.

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latter have shown promising recent results, suggesting that this barrier will be overcome in the future[43].

6.1.1.2 Silicon anodes

Silicon anodes have long been the subject of intensive research due to their relative inexpensiveness (Si is the 2nd most abundant element on the surface of Earth), very high specific capacity (theoretical capacity approximately 4200 mAh.g^{-1} for $Li_{22}Si_5$ and 3579 mAh.g^{-1} for $Li_{15}Si_4$ phases)[44,45], and working potential, approximately 0.4 V lower than Lithium which is higher than the commercial graphite but lower than $Li_4Ti_5O_{12}$ (LTO)[46]. However, due to its low density, high volumetric expansion associated with cycling (lithiation), electrical conductivity, and unstable SEI film formation[47], materializations of this anode have suffered from performance degradation at an early stage[48]. The most promising solution for overcoming this problem passes by nanocrystallization[49] and the development of Si-composite materials (frequently combined). The main challenge that prevents its industrial development is high manufacturing cost and/or severe degradation mechanism. The former is related to the complexity of design solutions proposed for mitigating the latter, which is mainly caused by the disadvantages mentioned above. The huge volume variations from 200 to 400% during discharge/charge lead to a direct capacity loss (severe cracking), and broken/renovated SEI films, which consumes Li ions and the electrolyte, hampering ionic conductivity and reversibility (the initial formation of an SEI layer is responsible for very low Initial Coulombic efficiency ICE[50]). Similar to Ni-rich cathodes, mechanical stresses induced by volumetric expansion/contraction lead to severe crack initiation/propagation, and particle pulverization[51]. The advantages of using nanoparticles in composite materials are closely

[43] Son, Y.; Kim, N.; Lee, T.; Lee, Y.; Ma, J.; Chae, S.; Sung, J.; Cha, H.; Yoo, Y.; Cho, J. *Calendering-Compatible Macroporous Architecture for Silicon–Graphite Composite toward High-Energy Lithium-Ion Batteries*. Adv. Mater. 2020, 32, 2003286.
[44] Zhang, W.J. *Structure and performance of $LiFePO_4$ cathode materials: A review*. J. Power Sources 2011, 196, 2962–2970.
[45] Mohamed, N.; Allam, N.K. *Recent advances in the design of cathode materials for Li-ion batteries*. RSC Adv. 2020, 10, 21662–21685.
[46] Liu, X.H.; Zhong, L.; Huang, S.; Mao, S.X.; Zhu, T.; Huang, J.Y. *Size-Dependent Fracture of Silicon Nanoparticles During Lithiation*. ACS Nano 2012, 6, 1522–1531
[47] Bhandakkar, T.K.; Gao, H. *Cohesive modeling of crack nucleation in a cylindrical electrode under axisymmetric diffusion induced stresses*. Int. J. Solids Struct. 2011, 48, 2304–2309. doi:10.1016/j.ijsolstr. 2011.04.005
[48] McDowell, M.T.; Ryu, I.; Lee, S.W.; Wang, C.; Nix, W.D.; Cui, Y. *Studying the Kinetics of Crystalline Silicon Nanoparticle Lithiation with In Situ Transmission Electron Microscopy*. Adv. Mater. 2012, 24, 6034–6041.
[49] Domi, Y.; Usui, H.; Sugimoto, K.; Sakaguchi, H. *Effect of Silicon Crystallite Size on Its Electrochemical Performance for Lithium-Ion Batteries*. Energy Technol. 2019, 7, 1800946.
[50] Hwang, S.W.; Yoon, W.Y. *Effect of Li Powder-Coated Separator on Irreversible Behavior of SiOx-C Anode in Lithium-Ion Batteries*. J. Electrochem. Soc. 2014, 161, A1753–A1758
[51] Liu, X.H.; Zhong, L.; Huang, S.; Mao, S.X.; Zhu, T.; Huang, J.Y. *Size-Dependent Fracture of Silicon Nanoparticles During Lithiation*. ACS Nano 2012, 6, 1522–1531

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related to increasing ionic conductivity and designing porous structures capable of accommodating large volume changes.

In recent years, research on composite Si anodes has mainly followed the core/shell and yolk/shell approach (see **Figure 24**) towards designing electrodes with superior capacity retention and/or rate performance[52,53,54,55,56,57,58,59,60]. Besides Si@carbon, multiple multi-material solutions for the matrix have been proposed, often combining carbon with a metallic material (see **Figure 23**).

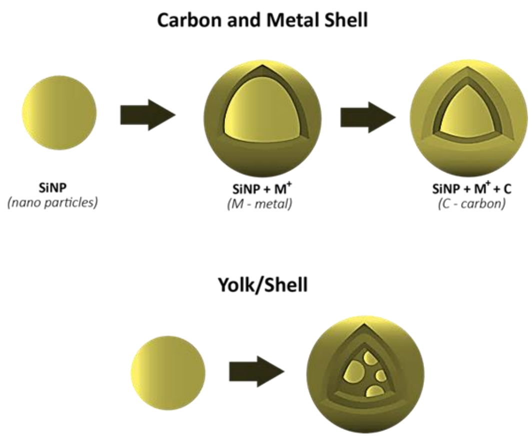

Figure 24: Examples of Si-based engineered structures

In summary, the main driver of change for the negative electrodes is related to safety (e.g., the possibility of charging fast even at low temperatures without compromising safety).

[52]Kelly, A. *Pollution Causing Birth Defects in Children of DRC Cobalt Miners–Study*. 2020. Available online: https://www.theguardian.com/global-development/2020/may/06/pollution-causing-birth-defects-in-children-of-drc-cobalt-miners-study (accessed on 4/7/2021)

[53]Hu, J.; Wu, B.; Cao, X.; Bi, Y.; Chae, S.; Niu, C.; Xiao, B.; Tao, J.; Zhang, J.; Xiao, J. *Evolution of the rate-limiting step: From thin film to thick Ni-rich cathodes*. J. Power Sources 2020, 454, 227966.

[54]Jürgens, J. *This is Why NMC is the Preferable Cathode Material for Li-Ion Batteries. 2019*. Available online: https://lghomebatteryblog.eu/en/this-is-why-ncm-is-the-preferable-cathode-material-for-li-ion-batteries/ (accessed on 4/7/2021).

[55]Bhandakkar, T.K.; Gao, H. *Cohesive modeling of crack nucleation in a cylindrical electrode under axisymmetric diffusion induced stresses*. Int. J. Solids Struct. 2011, 48, 2304–2309. doi:10.1016/j.ijsolstr. 2011.04.005.

[56]Zhang, H.; Zong, P.; Chen, M.; Jin, H.; Bai, Y.; Li, S.; Ma, F.; Xu, H.; Lian, K. *In Situ Synthesis of Multilayer Carbon Matrix Decorated with Copper Particles: Enhancing the Performance of Si as Anode for Li-Ion Batteries*. ACS Nano 2019, 13, 3054–3062.

[57]Majeed, M.K.; Ma, G.; Cao, Y.; Mao, H.; Ma, X.; Ma, W. *Metal–Organic Frameworks-Derived Mesoporous Si/SiOx@NC Nanospheres as a Long-Lifespan Anode Material for Lithium-Ion Batteries*. Chem. A Eur. J. 2019, 25, 11991–11997.

[58]Shi, M.; Nie, P.; Fu, R.; Fang, S.; Li, Z.; Dou, H.; Zhang, X. *Catalytic Growth of Graphitic Carbon-Coated Silicon as High-Performance Anodes for Lithium Storage*. Energy Technol. 2019, 7, 1900502, doi:10.1002/ente.2019005 02.

[59]Liu, J.; Li, C.; Dong, B.; Yan, Y.; Zerrin, T.; Ozkan, M.; Ozkan, C.S. *Scalable coral-like silicon powders with three-dimensional interconnected structures for lithium ion battery anodes*. Energy Storage 2020, 2, e187.

[60]Yang, J.; Wang, Y.X.; Chou, S.L.; Zhang, R.; Xu, Y.; Fan, J.; Zhang, W.X.; Kun Liu, H.; Zhao, D.; Xue Dou, S. *Yolk-shell silicon-mesoporous carbon anode with compact solid electrolyte interphase film for superior lithium-ion batteries*. Nano Energy 2015, 18, 133–142.

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6.1.2 Positive electrodes (cathodes) for LIB

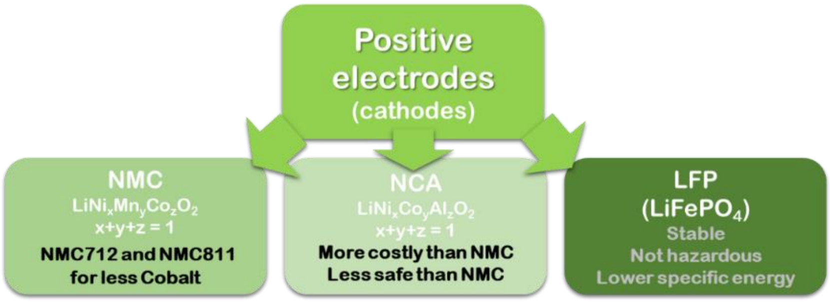

Figure 25: Positive electrodes' latest trends towards the future

Generally, commercial LIBs possess one or several types of combined oxide as active materials. These cathodes can be divided into layered, spinel, and polyanion oxides with layered, spinel, and olivine structures, respectively. Even though substantial improvements on all types of cathodes' energy storage features have been achieved, the structural, thermal, and chemical stability of cathode materials are largely a consequence of its oxide structure.

The main driver of change of cathode research is to reduce the Cobalt content and increase the batteries' safety while increasing the energy density leading to a greater range (see **Figure 25**).

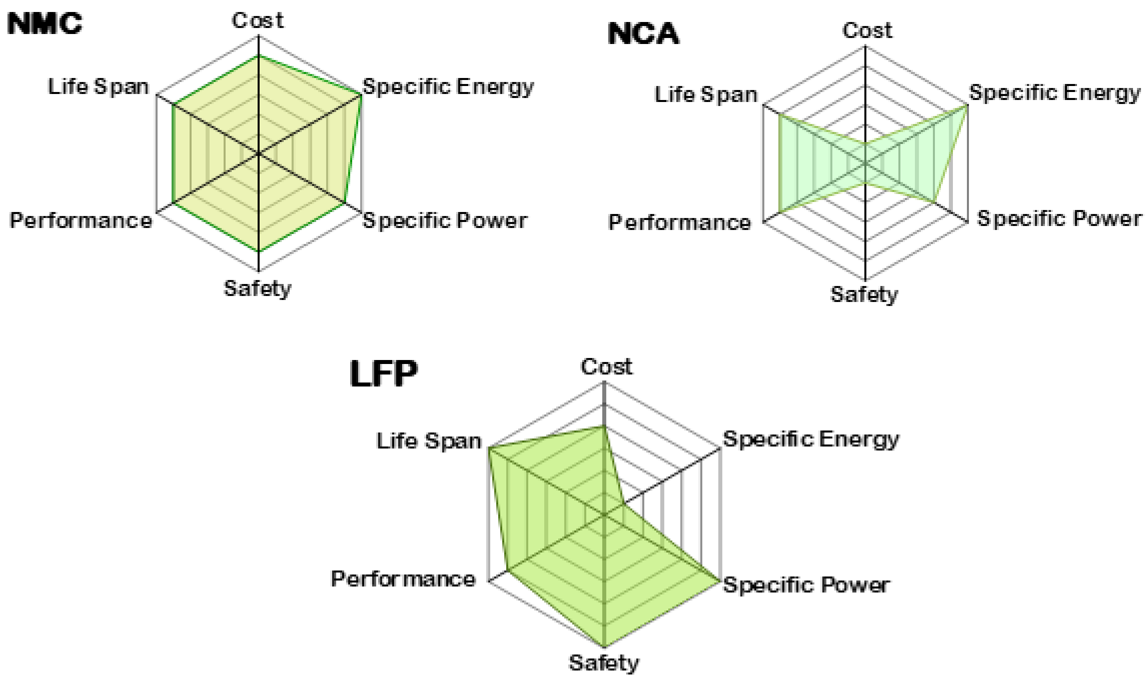

Figure 26: Characteristics of the Li-ion cathodes (NMC, NCA, and LFP) used today and expected to be used shortly in Li-ion batteries for EVs

6.1.2.1 NMC and NCA cathodes

Lithium Nickel Manganese Cobalt oxide, NMC ($LiNi_xMn_yCo_zO_2$ with x+y+z = 1) cathodes exhibit a plateau (working) voltage between 4.3 and 3.7 V for an experimental capacity of approximately 150 mAh.g^{-1} (cut off 2.0 V) and the lithium Nickel Cobalt Aluminium oxide, NCA ($LiNi_xCo_yAl_zO_2$ with x+y+z = 1) cathodes exhibit a plateau voltage between 4.3 and 3.5 V for a capacity of approximately 175 mAh.g^{-1} (cut off 2.0 V).

Nickel is known for its high specific energy but poor stability; manganese forms a spinel structure achieving low internal resistance to the lithium conduction but offers low specific energy. Combining the metals enhances each other's strengths. Cobalt stabilizes the nickel regarding oxygen, a high-energy active material[61]. The cobalt, therefore, avoids oxygen releases stabilizing the crystal structure.

Previously it was mentioned that LIBs dominate the global market, and the cathode exhibits some of the most determinant characteristics of batteries used in commercially available electric vehicles. Furthermore, all passenger vehicles sold on the European market use batteries with cathodes containing Cobalt. Tesla and Panasonic have developed battery cells with NCA as the cathode and all models sold by Tesla on the European market have batteries based on this system. On the other hand, the vast majority of car manufacturers incorporate batteries with Nickel-Manganese-Cobalt oxide as the cathode type, with a clear tendency for the NMC622 ratio ($LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$)[62] as highlighted in the first ALBATTS Desk research report. LG Chem, one of the world leaders in the number of NMC batteries sold[63], shows a clear strategy for reducing cobalt content that consists of developing new cathodes with more favourable ratios (reducing the Cobalt content while maintaining or enhancing the performance). The company is focusing on developing NMC712 ($LiNi_{0.7}Mn_{0.1}Co_{0.2}O_2$), NMC811 ($LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$), and NCA chemistries for the next generation of electric vehicles[64] (see **Figure 25**).

Finally, Northvolt summarizes in one sentence all the cathodes strategies for Cobalt containing cathodes:

> *"All the development around NMC 811 has been to keep the high energy density while maintaining the stability and cycle life"*[65].

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[61]Battery University. (2020, March 4). *BU-205: Types of Lithium-ion*. https://batteryuniversity.com/article/bu-205-types-of-lithium-ion (assessed on 04-07-2021).
[62]Salgado, R. M., Danzi, F., Oliveira, J. E., El-Azab, A., Camanho, P. P., & Braga, M. H. (2021). The Latest Trends in Electric Vehicles Batteries. *Molecules*, 26(11), 3188. https://doi.org/10.3390/molecules26113188
[63]A. *Tesla's Reluctant Commitment to Cobalt a Warning to Others-Andy Home*. 2020. Available online: https://www.reuters.com/article/us-tesla-cobalt-ahome-idUSKBN23U20Q (accessed on 02/07/2021)
[64]Phadatare, M.; Patil, R.; Blomquist, N.; Forsberg, S.; Örtegren, J.; Hummelgård, M.; Meshram, J.; Hernández, G.; Brandell, D.; Leifer, K.; et al. *Silicon-Nanographite Aerogel-Based Anodes for High Performance Lithium Ion Batteries*. Sci. Rep. 2019, 9, 14621.
[65]*Northvolt is building a future for greener batteries*. (2019). Chemical & Engineering News. https://cen.acs.org/energy/energy-storage-/Northvolt-building-future-greener-batteries/97/i48 (accessed on 21/07/2021)

6.1.2.2 Lithium-Iron-Phosphate (LFP)

Lithium Iron Phosphate (LFP), $LiFePO_4$, exhibits a lower plateau voltage when compared to NMC; LFP cathodes display a flat plateau voltage of approximately 3.3 V for a capacity that is approximately 160-170 $mAh.g^{-1}$ (cut off 2.0 V).

Lithium Iron Phosphate batteries exhibit several advantages that enable their application, despite their lower specific energy, in mobile motorhomes[66] and vehicles with low range and performance requirements[67], such as garbage trucks and electric road sweepers. LFP battery cells provide high cycle life and reduced risk of thermal runaway[68], have no toxic components, low internal resistance, and high-load handling capability[69]. They also display high specific power (see **Figure 26**).

CATL is the main responsible company for developing this type of cathode, supplying several car manufacturers from China - its native country. In 2015, LFP batteries were the most popular for plug-in hybrid electric vehicles (PHEVs) and EVs[70], but over the last five years, NMC surpassed this type of cathode, both in market share and research interest.

With the new factories, being built in Austin, Texas, USA, and Germany and the societal pressures to avoid the use of Cobalt, LFP may become a prominent cathode again shortly.

Figure 27 shows the goals that remain to achieve while highlighting the present battery features already accomplished.

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[66] Fan, X.; Liu, B.; Liu, J.; Ding, J.; Han, X.; Deng, Y.; Lv, X.; Xie, Y.; Chen, B.; Hu, W.; et al. *Battery Technologies for Grid-Level Large-Scale Electrical Energy Storage*. Trans. Tianjin Univ. 2020, 26, 92–103

[67] Gong, C.; Xue, Z.; Wen, S.; Ye, Y.; Xie, X. *Advanced carbon materials/olivine $LiFePO_4$ composites cathode for lithium ion batteries*. J. Power Sources 2016, 318, 93–112.

[68] Zhang, W.J. *Structure and performance of LiFePO4 cathode materials: A review*. J. Power Sources 2011, 196, 2962–2970.

[69] Armand, M.; Axmann, P.; Bresser, D.; Copley, M.; Edström, K.; Ekberg, C.; Guyomard, D.; Lestriez, B.; Novák, P.; Petranikova, M.; et al. *Lithium-ion batteries – Current state of the art and anticipated developments*. J. Power Sources 2020, 479, 228708.

[70] Mohamed, N.; Allam, N.K. *Recent advances in the design of cathode materials for Li-ion batteries*. RSC Adv. 2020, 10, 21662–21685.

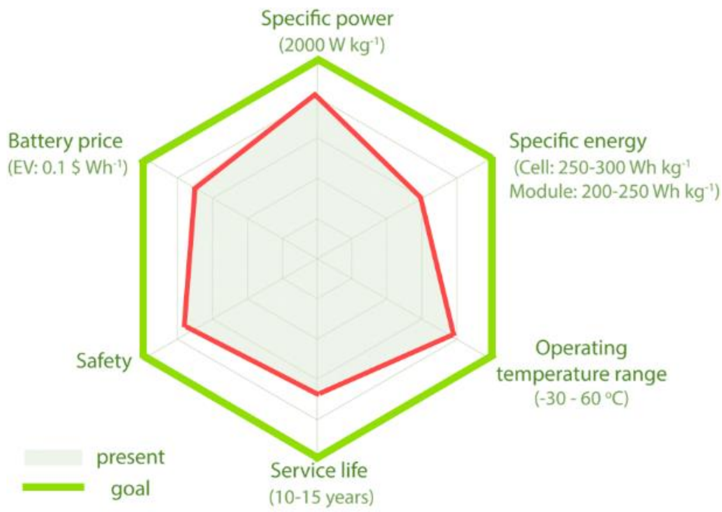

Figure 27: Characteristics of the Li-ion batteries for EVs. The shaded area represents accomplished improvements in the present (2020) Li-ion batteries. Adapted from[71]

6.1.3 Electrolytes for all battery types

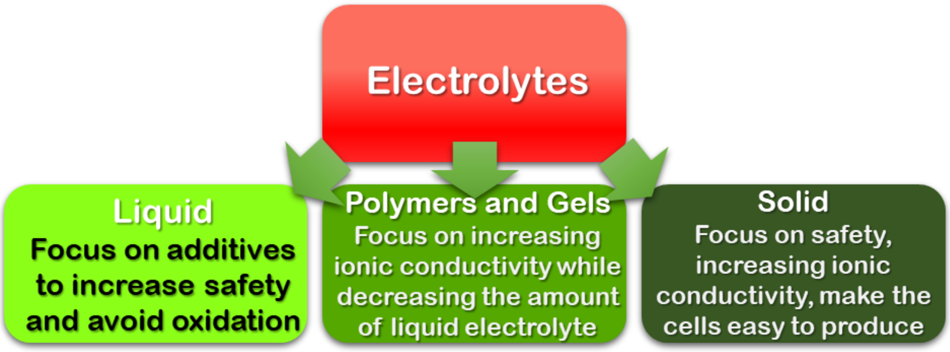

Figure 28: Electrolytes' latest trends towards the future

6.1.3.1 Liquid electrolytes additives for LIBs

Electrode decay and thermal runaway of LIBs remain potential threats because of the flammability of the organic electrolyte solutions used (**Figure 28** and **Figure 29**). Therefore, developing electrolytes and electrolyte additives that protect batteries while maintaining or enhancing their efficiency is an important field of battery research.

[71]Adapted from: Tamirat, A. G.; Guan, X.; Liu, J.; Luo, J.; Xia Y. *Redox mediators as charge agents for changing electrochemical reactions*, : Chem. Soc. Rev., 2020, 49, 7454-7478.

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Alliance for Batteries Technology, Training and Skills - ALBATTS - Project number 612675-EPP-1-2019-1-SE-EPPKA2-SSA-B. The European Commission's support for the production of this publication under the Grant Agreement № 2019-612675 does not constitute an endorsement of the contents, which reflects the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

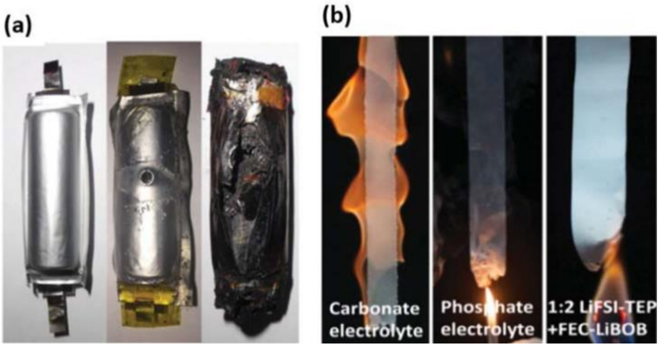

Figure 29: a) Blank cell before nail penetration test for 18,650 cell using 1:2 LiFSI-TEP(Triethyl phosphate) + FEC-LiBOB electrolyte (middle) and commercial carbonate electrolyte (1.0 M $LiPF_6$/EC:DEC:EMC, v/v/v = 1/1/1); b) Flame tests of (1.0 M $LiPF_6$/EC:DEC:EMC, v/v/v = 1/1/1) electrolyte, 1:2 LiFSI-TEP electrolyte, and 1:2 LiFSI-TEP + FEC-LiBOB electrolyte[72]

A problem associated with most of the common electrolytes used in Li-ion cells is the window of electrochemical stability of the electrolyte (e.g., 1.0 M $LiPF_6$ EC/DEC = 50/50 (v/v) in which $LiPF_6$ is the salt and ethylene carbonate/diethyl carbonate are the solvents). For example, the latter liquid electrolyte has a 4.3 V window of stability, meaning that it is not suitable to be used with the graphite anode and the NMC cathode, which is charged to 4.3-4.5 V. Above 4.3 V, the electrolyte starts being reduced by the electrons conducted from the negative electrode, forming an SEI layer as explained previously. This SEI layer is a Li-rich insulator that reduces the capacity of the cathode because it is Li consuming, therefore reducing the capacity of the cell.

Most additives are designed to form a protective film on the electrode surfaces, preventing parasitic solvent reduction or oxidation[73].

Several strategies were pursued to tackle this problem, one being solid polymers. Most of these polymers still contain flammable solvents though, as shown in **Figure 30**.

[72]Zeng, Z.; Murugesan, V.; Han, K.S.; Jiang, X.; Cao, Y.; Xiao, L. *Non-flammable electrolytes with high salt-to-solvent ratios for Li-ion and Li-metal batteries*. Nat. Energy 2018, 3.
[73]Chawla, N.; Bharti, N.; Singh, S. *Recent Advances in Non-Flammable Electrolytes for Safer Lithium-Ion Batteries*. Batteries 2019, 5, 19. https://doi.org/10.3390/batteries5010019

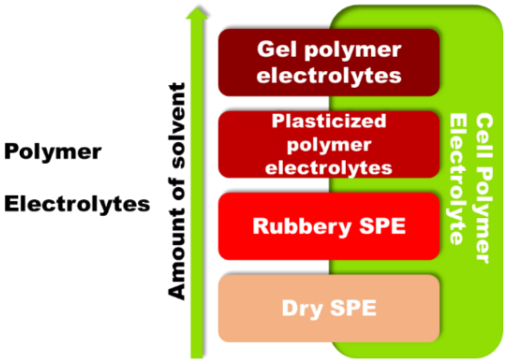

Figure 30: The amount of solvent (usually flammable) used within polymer electrolytes. Adapted from[74]

Another strategy to overcome this safety problem while increasing the capacity of the battery cells is to use all-solid-state electrolytes, which is going to be discussed next.

6.1.3.2 Solid electrolytes

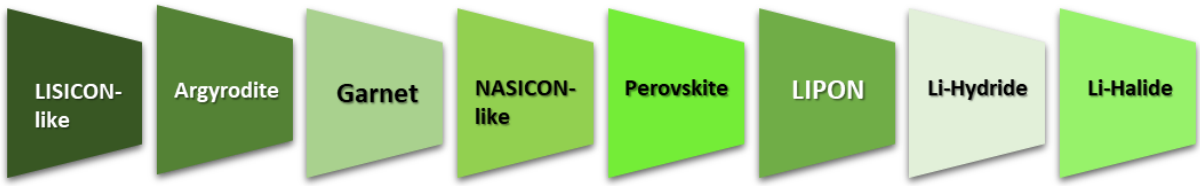

Figure 31: Types of solid electrolytes. Adapted from.[74]

The performance of the traditional Li battery is limited by its flammable liquid electrolyte as pointed out previously. In this context, the ongoing solid-state battery efforts to replace the traditional Li-ion battery, in particular due to the safety issues, is plagued by four main bottlenecks:

(1) slow kinetics of ion diffusion in solid-state electrolytes, and the transport of ions across the solid-solid interfaces which requires heating the solid electrolyte batteries above room temperature, usually to a minimum temperature of 50°C;

(2) chemical instabilities at the Li metal-solid electrolyte and high voltage cathode-solid electrolyte interfaces;

(3) local mechanical and structural instabilities in solid-state electrolytes that fail to resist lithium dendrites (whiskers) and compromise safety;

[74]IDTechEx. *IDTechEx: Market Research, Scouting and Events on Emerging Technologies*. https://www.idtechex.com/ (assessed on 04-07-2021).

(4) the necessity of renewing the existing Li-ion assembly lines and equipment, which is an additional impediment for the fast commercialization of all currently available all-solid-state solutions.

In the case of EV applications, the high cost of ceramic ion conductors, low power and energy densities, safety, and low cycle-life must be addressed.

On the other hand, while the liquid electrolyte soaks the electrodes, allowing a 3D diffusion of the Li-ions, with a solid electrolyte the processes are much more 1D, which seems to make it more difficult to fabricate efficient battery cells. Conversely, the latter challenge can bring innovative solutions based on other kinds of processes such as the electrostatic (e.g., as in a capacitor), instead of just the traditional electrochemical storage mechanism (e.g., as in a battery).

A solid electrolyte allows a battery cell to be functionalized with alkali metals, such as Lithium exhibiting a much higher capacity (theoretical 3860 $mAh.g^{-1}$) enabling the use of cathodes such as sulfur with a theoretical capacity of 1672 $mA.g^{-1}$ leading to the cells' higher specific energy, as discussed ahead in this document.

In **Figure 31**, the solid electrolytes families being studied and developed are shown, and in **Figure 32** the strategy that can be pursued towards developing an all-solid-state battery.

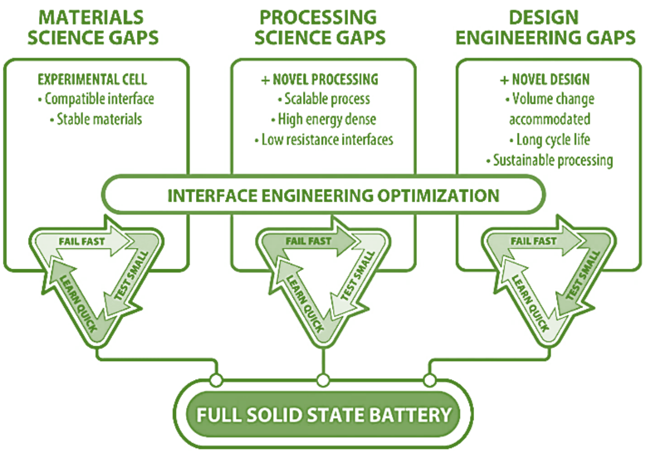

Figure 32: Schematic summarizing the critical gaps for the realization of competitive solid-state batteries[75].

[75]Albertus, P; et al. *Challenges for and Pathways toward Li-Metal-Based All-Solid-State Batteries*. ACS Energy Letters 2021 6 (4), 1399-1404 https://doi.org/10.1021/acsenergylett.1c00445

6.2 LITHIUM-SULFUR BATTERIES

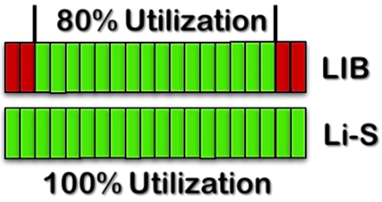

Figure 33: Utilization of battery cells. Adapted from[76]

The Lithium-sulfur (Li-S) chemistry is considered to have a less environmental impact when compared to other technologies such as the Li-ion. The Li-S cell utilizes sulfur in place of heavy metals such as cobalt, which have a significant environmental impact as referred to in a previous ALBATTS desk research report, whereas sulfur may have its origin in recycled material, a by-product of the oil industry.

Lithium-sulfur batteries (Li-S) are being developed since the 1960s, but because their plateau voltage varies from 2.5 to 1.7 V against Li/Li^+ and the theoretical capacity of S_8 is 1620 $mAh.g^{-1}$, only an anode such as Lithium with a theoretical capacity of 3860 $mAh.g^{-1}$, can compensate the lower plateau voltage to compare favourably with the specific energies of the Li-ion batteries with a traditional cathode such as NMC (150 $mAh.g^{-1}$; nominal voltage 4.0 V). To achieve the specific energy of 600 $Wh.kg^{-1}$ (active cathode), such as that obtained in Li-ion cells with NMC (just taking into account the cathode active material), the sulfur capacity must be at least 286 $mAh.g^{-1}$, indicating the advantage of using Lithium.

Li-S cells have a 100% available Depth-of-Discharge (DoD). This compares with Li-ion batteries which are only used across 80% (or less) of their available discharge range. The latter indicates that Li-S cells may use all their stored energy – full discharge.

The Lithium-sulfur battery cells have a long shelf-life, with no charging required when left for an extended period. Li-ion batteries require a recharge every 3-6 months to prevent failure and often cause significant warranty issues.

The challenge with lithium-sulfur battery cells is the limited cycle life of 40–50 charges/discharges as sulfur is lost during cycling by shuttling away from the cathode to the anode polysulfides that react with the lithium anode ($S_8 \rightarrow Li_2S_8 \rightarrow Li_2S_6 \rightarrow Li_2S_4 \rightarrow Li_2S_3 \rightarrow Li_2S_2$

[76] *Oxis Energy - Next Generation Battery Technology - Li2S*. (2021, May 21). Oxis Energy. https://oxisenergy.com/ (assessed on 04-07-2021).

→ Li_2S). Laboratory experiments reported improvements by achieving 200 or more cycles. Other problems are poor conductivity and poor stability at higher temperatures. Trials with graphene are being implemented to increase the performance of the sulfur in the cathode, with promising results[77].

The all-solid-state strategy can be used in Li-S batteries with great advantages that pass by minimizing shuttling. A tandem all-solid-state electrolyte may have to be used to avoid reactions on the anode side.

6.3 SODIUM-ION BATTERIES

In June 2021, CATL announced they are launching a sodium-ion battery (NIB)[78]. However, in 2015 a start-up from CEA and the CNRS, TIAMAT (France)[79], announced the prototype of the sodium-ion "18650" battery, a standard format used in portable computers. Others followed such as Faradion[80], HiNa Battery Technology[81], Altris AB[82], Natron Energy[83], and Broadbit[84].

The development of the sodium-ion battery took place side-by-side with that of the lithium-ion battery in the 1970s and early 1980s[85,86]. In the 1990s, LIB had demonstrated greater commercial promise, causing interest in sodium-ion batteries to decline. In the early 2010s, NIB's resurgence in R&D was driven largely by the increasing demand for and cost of lithium-ion battery raw materials.

Presently, scientists across the globe, including the US, China, Japan, the UK, and Israel, are working on this technology—which today is considered one of the most serious alternatives to lithium-ion batteries[73]. Because lithium is not a naturally abundant element, it is predicted to surge in price as demand for new and large-scale uses grows. This will have an impact on reserves as well. According to estimations, global Li consumption in 2008 was almost 21 280

[77] Battery University. (2020b, March 4). *BU-212: Future Batteries*. https://batteryuniversity.com/article/bu-212-future-batteries (assessed on 04-07-2021).

[78] Wang, B. (2021, June 13). *CATL Will Start Mass Producing Sodium Ion Batteries*. NextBigFuture.Com. https://www.nextbigfuture.com/2021/06/catl-will-start-mass-producing-sodium-ion-batteries.html (accessed on 15/07/2021)

[79] *A Battery Revolution in Motion*. (2015). CNRS News. https://news.cnrs.fr/articles/a-battery-revolution-in-motion (accessed on 15/07/2021)

[80] *Home*. (2020, December 8). Faradion. https://www.faradion.co.uk/ (accessed on 18/07/2021)

[81] T. (2021, August 7). *HiNa Battery Technology*. Companies | Tracxn. https://tracxn.com/d/companies/hinabattery.com (accessed on 18/07/2021)

[82] Altris - *We enable the next generation of batteries | Altris is a Swedish company that has discovered a new way to produce a sodium based cathode material using only renewable materials. This groundbreaking discovery enables a new generation of batteries that are not only friendly to the environment but also cheaper to produce than the competitors*. Altris. https://www.altris.se/ (accessed on 18/07/2021)

[83] Natron Energy. (2021, June 10). *Home*. Natron. https://natron.energy/ (accessed on 18/07/2021)

[84] *Broadbit Batteries | Green Battery Technology*. (2020). Broadbit Batteries. http://www.broadbit.com/ (accessed on 25/07/2021)

[85] Yabuuchi, N.; Kubota, K.; Dahbi, M.; Komaba, S. *Research Development on Sodium-Ion Batteries*. Chemical Reviews. 114(23) (2014) 11636–11682. doi:10.1021/cr500192f

[86] Sun, Y.-K.; Myung, S.-T.; Hwang, J.-Y. *Sodium-ion batteries: present and future*. Chemical Society Reviews. 46(12) (2017) 3529–3614. doi:10.1039/C6CS00776G.

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tons; so, current mineable resources might last for up to 65 years at an average growth rate[87,88] making the implementation of the EVs, grid, computers, wearables, IoT, and other applications difficult and very costly.

Sodium, the fourth most prevalent element on the planet, appears to have an infinite supply.[89] With 23 billion tons of soda ash in the United States alone, sodium-containing precursors are plentiful. The abundance of resources and lower cost of trona (about $135–165 per ton), from which sodium carbonate is made, compared to lithium carbonate (around $5000 per ton in 2010), give a compelling argument for the development of NIBs as LIB alternatives.[90, 91].

Like lithium-ion cathodes, sodium-ion cathodes also store sodium via an intercalation reaction mechanism. Owing to their high operating potentials and high capacities, cathodes based on sodium transition metal oxides have received the greatest attention. From a yearning to keep costs low, significant research has been geared towards avoiding or reducing costly elements such as Co, Cr, Ni, or V in the oxides. $Na_{1-x}FeO_2$ and derivatives, for example, can be charged to 4.5 V and show an energy density that varies from 70 to 140 $mAh.g^{-1}$.

As in Li-ion batteries, carbon in its non-graphitic (hard carbon), graphitic and graphene doped are the most common anodes used in Na-ion batteries.

On the drawbacks side, the sodium Na^+-ion is bigger than the lithium Li^+-ion ionic radius leading to a more difficult insertion of sodium ions in NIB than in LIB, decreasing the capacity of the cell as well as the cycle life.

6.4 STRUCTURAL BATTERIES

Contrary to all the previously discussed battery architectures, structural battery cells do not verify an architectural concept for a cell and are not defined by a type of electrodes or electrolyte. Nevertheless, due to safety reasons as these batteries have to withhold mechanical loads, it is expected that these batteries will tend to be all-solid-state. In fact, structural batteries are defined as devices that can carry a mechanical load while storing electrical energy. They can be constituted by two types of batteries, the laminated, in which a battery is placed between structural elements (usually a carbon fiber shell), and the 3D-fiber

[87] Pan, H.; Hu, Y.-S.; Chen, *Room-temperature stationary sodium-ion batteries for large-scale electric energy storageL*. Energy Environ. Sci., 2013, 6, 2338–2360
[88] Zhu, C.-X.; Li, H. *Thermodynamic analysis on energy densities of batteries, Energy Environ*. Sci., 2011, 4, 2614–2624.
[89] de la Llave, E.; et al. *Comparison between Na-Ion and Li-Ion Cells: Understanding the Critical Role of the Cathodes Stability and the Anodes Pretreatment on the Cells Behavior*. ACS Appl. Mater. Interfaces, 2016, 8, 1867–1875.
[90] Slater, M.D.; Kim, D.; Lee, E.; Johnson, C.S. *Sodium-Ion Batteries*, Adv. Funct. Mater., 2013, 23, 947–958.
[91] Reddy, T. B.; Linden, D. Linden's *Handbook of Batteries*. McGraw-Hill, 2010.

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structural battery in which the carbon fibers are used in the electrochemical process. In the latter, a graphite or hard carbon fibers structural anode is lithiated and delithiated. The cathode structural element is composed of a cathode active material (e.g. $LiFePO_4$) bonded to carbon structural fibers.

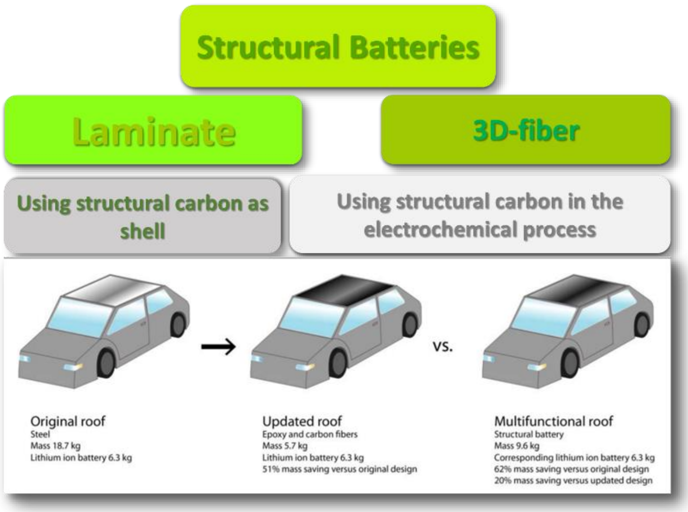

Figure 34: Types of structural batteries and comparison between traditional and structural applications. Adapted from[92]

As previously highlighted, Lithium-ion based batteries have shown an unparalleled combination of high energy and power density, quick charge, and long cycle life that made this technology the choice for electric vehicles, portable electronic devices, and many other applications[93].

A great opportunity to achieve all these goals at the same time is offered by the use of multifunctional systems and materials such as structural batteries[94,95,96,97]. As described by Thomas et al.[98], multifunctional systems and materials correspond to all the structural configurations and materials that can fulfil more than one primary function simultaneously.

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[92]The bottom figure adapted from: Johannisson, W.; Zenkert, D.; Lindbergh, G. *Model of a structural battery and its potential for system level mass savings*, Multifunct. Mater. 2 (2019) 035002.
[93]Danzi, F.; Salgado, R.M.; Oliveira, J.E.; Arteiro, A.; Camanho, P.P.; Braga, M.H. *Structural Batteries: A Review*. Molecules 2021, 26, 2203. https://doi.org/10.3390/molecules26082203
[94]Ferreira, A.D.B.; Nóvoa, P.R.; Marques, A.T. *Multifunctional Material Systems: A state-of-the-art review*. Compos. Struct. 2016, 151, 3–35.
[95]González, C.; Vilatela, J.; Molina-Aldareguía, J.; Lopes, C.; Llorca, J. *Structural composites for multifunctional applications: Current challenges and future trends*. Prog. Mater. Sci. 2017, 89, 194–251.
[96]Yang, H. *A Review of Structural Batteries Implementations and Applications*. In Proceedings of the 2020 IEEE Transportation Electrification Conference & Expo (ITEC), Chicago, IL, USA, 23–26 June 2020; pp. 223–228.
[97]Asp, L.E.; Greenhalgh, E.S. *Multifunctional Structural Battery and Supercapacitor Composites*. In Multifunctionality of Polymer Composites; Elsevier: Amsterdam, The Netherlands, 2015; pp. 619–661.
[98]Thomas, J.; Qidwai, S.; Pogue,W.; Pham, G. *Multifunctional structure-battery composites for marine systems*. J. Compos. Mater. 2012, 47, 5–26.

The idea of manufacturing structural composite batteries capable of storing electric energy and, at the same time, carrying mechanical loads is one of the most appealing applications of multifunctionality as shown in **Figure 34**.

The embedded cell idea (laminated) emerged from the necessity of optimizing the volume, more than the weight, of a composite structure by embedding electrical power elements without compromising their mechanical performance. The bonding process does not result in a remarkable overall improvement because the battery elements, as they are, are bearing no-load, hence their mass is not contributing at all to the structural performance of the final product.

The other concept of monolithic multifunctional materials, instead, comes from the consideration that high-performance composites and modern lithium-ion batteries have several features in common as explained previously:

(1) the fact that carbon fibers, commonly used in high-performance composites for their high specific stiffness and strength, also exhibit significant electrochemical properties such as good electrical conductivity and high lithium-ion intercalation, namely, the graphite carbon allotrope;

(2) In a second development, the layered configuration that characterizes both modern composites and state-of-the-art lithium-ion batteries can be exploited for a synergistic design;

(3) Moreover, the well-known wide range of composite processing techniques enables great freedom in the design of innovative configurations suitable for structural batteries.

Unfortunately, as in all the other technological progress, the development and the manufacturing of this new class of materials pose new challenges to the researchers.

Regarding the embedding alternative, the main drawback comes from the maximum operating temperature of the power elements, which is usually < 60°C. This limit is far below the typical curing temperatures of high-performance composites and adhesives, commonly above 100°C. For this reason, a co-curing of the batteries in high-performance laminates in compliance with the material curing cycle is unfeasible.

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Notwithstanding the remarkable results already achieved by the previously presented approaches, several issues must be overcome:

(1) the use of the liquid flammable electrolyte even if in resin or polymer electrolytes (see **Figure 29**), which is critical for application in structural elements that may be exposed to high mechanical load and structural failure (see **Figure 35**);

(2) the application of the multifunctional element to a limited temperature range as discussed previously;

(3) the use of carbon fibres/graphite as anodes enduring lithiation/delithiation leading to a quick degradation reducing cycle life;

(4) the necessity for a complex battery management system limiting its applications;

(5) the cost.

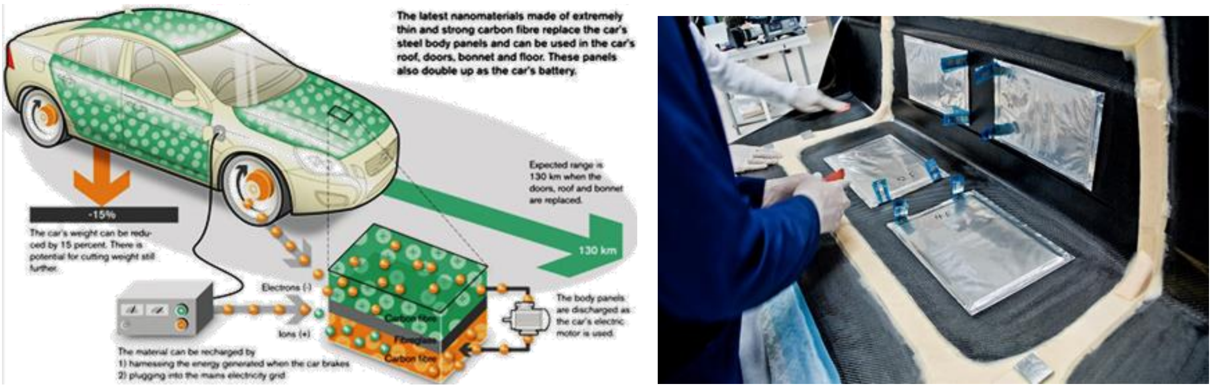

Figure 35: Structural batteries in electric vehicles substituting traditional batteries with structural supercapacitors: future vision and trial example (laminate structural battery)[99]

Structural batteries may assume preponderant importance if a suitable cell architecture and safe, cheap solid electrolytes that can withstand higher temperatures such as 80-125°C and low temperatures down to -40°C are used. They may have different shapes such as "coaxial" beams that allow for reinforcement of the structure while potentiating the electrostatic properties of the structural battery.

These batteries were already targeted in Tesla's Battery Day to achieve "negative mass" in EVs and by Volvo car group that was funded by the EU to develop these batteries in consortium with R&D institutions and companies.

In a very recent patent filed by Tesla[100], it is highlighted:

[99]Volvo Car Group makes conventional batteries a thing of the past. (2013). www.media.volvocars.com (accessed on 06/07/2021)
[100]Alvarez, S. (2021, May 27). *Tesla structural battery pack patent hints at clever contingencies for crashes, cell failures*. TESLARATI. https://www.teslarati.com/tesla-structural-battery-pack-patent-crashes-cell-failures/ (accessed on 22/07/2021)

"Illustratively, an integrated, unitary battery pack may be formed and used as part of the structural support for a vehicle frame. For example, the battery pack may include a bottom layer that is formed from a honeycomb or ridged surface which is mechanically linked to cells [cylindrical, almost the size of a soda can] within the battery pack. The bottom layer is designed so that it can absorb and distribute impact energy from below, mitigating potential damage sensitive battery materials or breach of the sealed battery pack enclosure."

Moreover, CATL, one of Tesla´s suppliers, as of late declared working with this technology, looking to incorporate the battery cells directly into an electric vehicle's chassis.[101]

6.5 SUPERCAPACITORS AND ULTRACAPACITORS

Supercapacitors (SC), comprise a family of electrochemical capacitors. The supercapacitor, sometimes called ultracapacitor, is a generic term for electric double-layer capacitors (EDLC), pseudocapacitors, and hybrid capacitors. They do not have a conventional dielectric solid. The capacitance value of an electrochemical capacitor is dependent on the two storage interfacial capacitors, both of which contribute to the total capacitance of the capacitor (as shown in **Figure 3** in the case of the batteries). Depending on the value of the dielectric constant, type of dielectric, and geometry, the capacitance may depend on the solid dielectric.

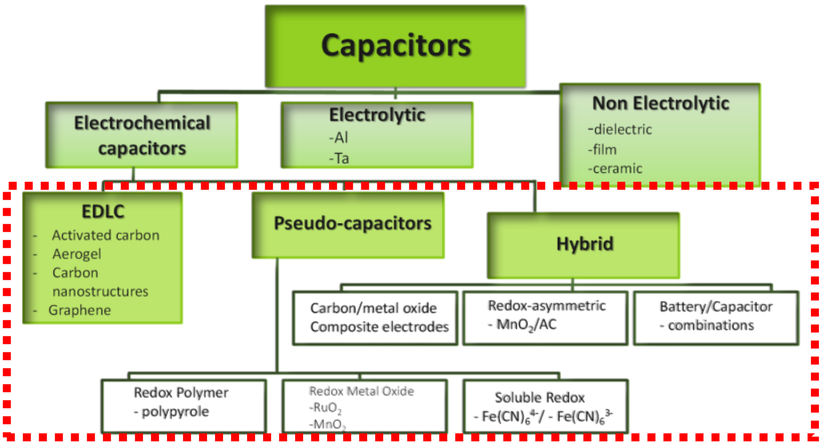

Figure 36: Different types of Capacitors. Note: AC stands for Activated Carbon here.

[101]*Battery Maker CATL is Working to Integrate Electric Vehicle Batteries into the Vehicle's Chassis.* (2021). FutureCar.Com. https://www.futurecar.com/4091/Battery-Maker-CATL-is-Working-to-Integrate-Electric-Vehicle-Batteries-into-the-Vehicles-Chassis (accessed on 27/08/2021)

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Capacitors are distributed in three types, electrochemical, electrolytic, and non-electrolytic (see **Figure 36**). The latter electrolytic capacitor is constituted by a metallic anode that forms an insulating oxide layer upon anodization. This oxide layer acts as the dielectric of the capacitor. A solid or liquid/gel electrolyte covers the surface of this oxide layer, functioning as the cathode. The non-electrolytic capacitor, conversely, is non-polarized (can be connected either way in a circuit); frequently non-electrolytic capacitors are paper capacitors in which the paper is the dielectric material. The paper separates flat thin strips of metal foil conductors.

Electrochemical capacitors or supercapacitors (SCs) can be EDLCs, pseudocapacitors, or hybrids[102]. EDLCs form electrical double-layer capacitors (EDLCs) at the interface's negative electrode/electrolyte and electrolyte/positive electrode to align the electrochemical potentials as described above at the beginning of the Technology chapter.

If Faradaic electrochemical reactions take place at the surface of the electrodes, these capacitors are denominated pseudo-capacitors. Furthermore, if one of the electrodes is a battery electrode, the SC is a hybrid capacitor. The discharge of a capacitor is linear, with a constant slope. A hybrid capacitor shows a battery-like plateau corresponding to a two-phase equilibrium attained during discharge on the battery-like electrode.

Supercapacitors or ultracapacitors are one of the typical non-conventional energy storage devices and are based on similar working principles to those of batteries focused on (**6.1**). Supercapacitors are suitable energy storage devices when available power is more imperative than energy (**Table 7** and **Figure 37**). Frequently, SC and batteries or fuel cells are associated to develop a wide range of solutions.

[102] Simon, P., and Gogotsi, Y. (2008). *Materials for electrochemical capacitors*. Nat. Mater. 7, 845–854. doi:10.1038/nmat2297

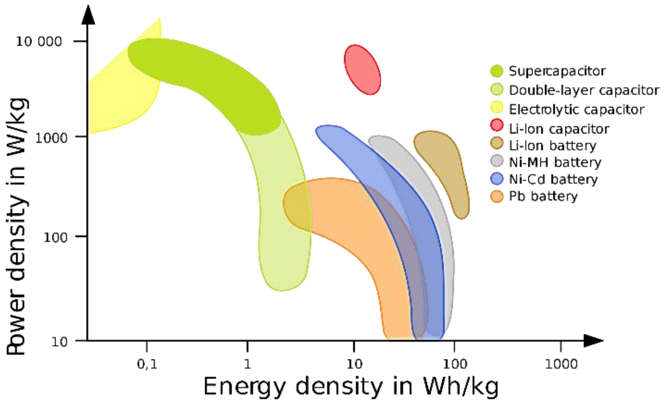

Figure 37: Structural batteries in electric vehicles substituting traditional batteries with structural supercapacitors: future vision and trial example (laminate structural battery)[103].

Internal combustion engines, fuel cells, and batteries are all good options for a low-power continuous source. However, because they discharge and recharge slowly, they are unable to properly handle peak power demands or recuperate energy in today's applications. Supercapacitors or ultracapacitors, however, deliver quick bursts of energy during peak power demands, then quickly store energy, and capture excess power that is otherwise lost[104]. Because they discharge and recharge quickly and can charge batteries, they are an excellent complement to an energy storage source in today's applications. In the development of applied and fundamental elements of SCs, significant progress has been made.

[103] *Shaddim talks*. (2013). https://commons.wikimedia.org/wiki/File:Energiespeicher3.svg (accessed on 06/07/2021).
[104] *Maxwell Ultracapacitors: Enabling Energy's Future*. Maxwell Technologies. https://www.maxwell.com/products/ultracapacitors (accessed on 06/07/2021)

Table 7: Supercapacitor characteristics comparison vs. capacitors and batteries[105]

Parameter	Supercapacitors	Capacitors	Batteries
Energy Storage	Watt second of energy	Watt second of energy	Watt hours of energy
Charge Method	Voltage across terminals (for example, from a battery)	Voltage across terminals (for example, from a battery)	Current and voltage
Power delivered	Rapid discharge, linear or exponential voltage decay	Rapid discharge, linear or exponential voltage decay	Constant voltage over a long time
Charge/Discharge Time	Milliseconds to seconds	Picoseconds to milliseconds	1 hour to 10 hours
Form Factor	Small	Small to large	Large
Weight	1 g to 2 g	1 g to 10 kg	1 g to >10 kg
Energy Density (Wh/kg)	1 to 5	0.01 to 0.05	8 to 600
Power Density (W/kg)	High, >4000	High, >5000	Low, 100 to 3000
Operating Voltage	2.3 V to 2.75 V/cell	6V to 800 V	1.2 V to 4.2 V/cell
Lifetime	>100k cycles	>100k cycles	150 to 1500 cycles
Operating Temperature (°C)	-40 to +85	-20 to +100	-20 to +65

All types of carbons from activated carbon to graphene, manganese, and other oxide electrode materials as well as polymers have been well studied as electrodes for SCs.

In summary, capacitors and supercapacitors may deliver higher power density and withstand many thousands of cycles. Conversely, they show much lower energy density.

6.6 FUEL CELLS

With the advancement of green energy harvesting solutions, the synthesis of hydrogen from the hydrolysis of the water became viable, giving rise to another commercial way to store energy for highly specific energy applications, the fuel cells. There are different kinds of fuel cells working at different temperatures. For mobility and grid, the interest is focused on those that can perform below 80°C, such as Proton Exchange Membrane (PEM) shown in **Figure 38**.

[105] *Design center*. EeNews Power. https://www.eenewspower.com/design-center/keep-powering-your-system-when-primary-supply-intermittent/page/0/2 (accessed on 06/07/2021).

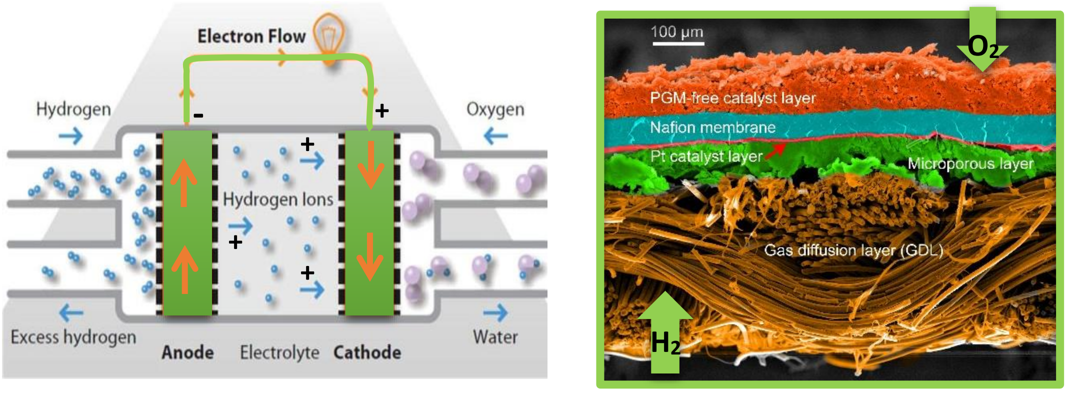

Figure 38: Schematics representing how a fuel cell works. Adapted from (left)[106]. SEM micrograph of a PEMFC MEA (Proton-exchange membrane fuel cells) cross-section with a non-precious metal catalyst cathode and Pt/C anode. False colours were applied for clarity. Adapted from (right)[107]. Note: PGM – Platinum group metals.

Fuel cells are especially important for heavy-duty vehicles such as buses as they have a higher energy density than batteries (see **Figure 38** and **Table 7**).

In **Figure 39** and **Figure 40** a comparison is made between Li-ion batteries technologies and hydrogen fuel cells used in EVs, seen from the perspective of the Canadian Hydrogen and Fuel Cell Association.

Figure 39: Comparison between batteries and fuel cells for EVs use[108]

[106] *Hydrogen fuel cell.* igem.org.uk and https://www.carsguide.com.au/oversteer/tech-through-time-hydrogen-fuel-cell-59905 (accessed July, 11th 2021)

[107] Yin, X.; Lin, L.; Chung, H.T.; Komini Babu, S.; Martinez, U.; Purdy, G. M.; Zelenay, P. Effects of MEA Fabrication and Ionomer Composition on Fuel Cell Performance of PGM-Free ORR Catalyst, ECS Transactions. 77 (11): 1273–1281.

[108] *6 Ways Hydrogen and Fuel Cells Can Help Transition to Clean Energy.* (2020, April 15). CHFCA. http://www.chfca.ca/fuel-cells-hydrogen/6-ways-hydrogen-and-fuel-cells-can-help-transition-to-clean-energy/ (accessed on 11/07/2021)

What stands out is that the technologies do not differ much, but batteries are used if power densities are needed. Fuel cells are part of the solution towards the electrification of society provided a green hydrogen strategy is implemented.

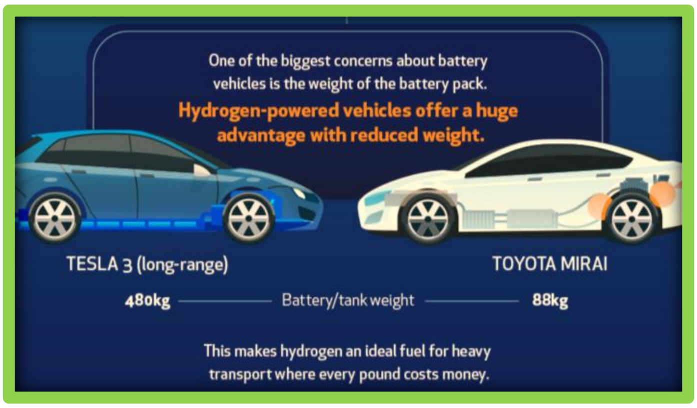

Figure 40: Comparison between the weight of batteries and fuel cells for EVs use.[108]

It is noteworthy that the working principles of batteries, capacitors, and even fuel cells are similar. Fuel cells are constituted by an anode, an electrolyte, and a cathode[109]. While discharging, the cell takes the hydrogen (H_2) on the anode where the molecule is dissociated into two H^+-ions freeing one electron for each hydrogen atom. The electrons circulate from the anode to the cathode through the external circuit. The H^+ ions diffuse through the electrolyte to the cathode where the oxygen molecules are dissociated into O^{2-} by catalytic action and reduction of the incoming electrons and react with two H^+ ions to form water molecules.

An important part of the research and development on fuel cells is related to the catalyst used to dissociate the H_2 and O_2. The idea is to replace Platinum, the most used catalyst, which is expensive and rare, with Nickel and Iron alloys or catalyst architectures such as core-shell nanoparticles.

Other studies are focused on replacing Nafion[110], which is used as a separator membrane (placed between anode and cathode) in Proton Exchange Membrane (PEM) fuel cells and is an expensive proprietary product but still very much in use. Nafion has received a considerable amount of attention as a proton conductor because of its excellent thermal and mechanical stability.

[109] Dwivedi, S; *Solid oxide fuel cell: Materials for anode, cathode and electrolyte, Int*. J. Hydrogen Energy 45 (2020) 2398 -24013
[110]A DuPont (https://www.dupont.com/) product

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A typical fuel cell shows a voltage of 0.6 to 0.7 V at a full rated load. The voltage decreases as current increases, due to several factors:

(1) Activation loss;

(2) Voltage drop due to the internal resistance of the cell's components and interconnections (Ohmic loss);

(3) Mass transport loss (depletion of reactants at catalyst sites under high loads, causing rapid loss of voltage)[111].

To deliver the desired energy, the fuel cells can be associated in series to yield higher voltage (using a similar strategy as used with batteries and capacitors), and in parallel to allow a higher current to be supplied. The latter association is called a fuel cell stack. The cell surface area can also be increased, to allow higher current in each cell.

6.6.1 Metal-air batteries

Currently, metal-air batteries are also designated fuel cells as they obey similar principles to those ruling fuel cells. Metal-air batteries such as lithium-air[112], have higher energy density than aluminum-air (see **Figure 41**); however, aluminum is attractive as the most stable metal[113] and it is being developed in the EU by Albufera[114]. Zinc-air[115], Magnesium-air[116,117], and Sodium-air[118] are also promising alternatives as their specific energy is high.

[111] Larminie, James (1 May 2003). *Fuel Cell Systems Explained, Second Edition*. SAE International. ISBN 978-0-7680-1259-0.

[112] Liu, T.; Vivek, J.P.; Zhao, E.W.; Lei, J.; Garcia-Araez, N.; Grey, C.P. *Current Challenges and Routes Forward for Nonaqueous Lithium–Air Batteries*. Chem. Rev. 2020, 120, 14, 6558–6625

[113] Brown, Richard (3 February 2020). *"Al-air: a better battery for EVs?"*. Automotive Logistics (accessed on 11/07/2021)

[114] Al-air and Al SSE https://albufera-energystorage.com/tecnologia/ (accessed on 25/07/2021)

[115] Zhang, Y.; *et al Recent Progress on Flexible Zn-Air Batteries*. Energy Storage Materials, 35, 2021, 538-549

[116] Zhang, T.; Tao, Z.; Chen, J. *Magnesium–air batteries: from principle to application*. Mater. Horiz., 2014, 1, 196

[117] Vaghefinazari, B.; Höche, D.; Lamaka, S.V.; Snihirova, D.; Zheludkevich, M.L. *Tailoring the Mg-air primary battery performance using strong complexing agents as electrolyte additives.* J. of Power Sources, 453, 2020, 227880

[118] Bi, X. et al; *From Sodium–Oxygen to Sodium–Air Battery: Enabled by Sodium Peroxide Dihydrate.* Nano Lett. 2020, 20, 6, 4681–4686

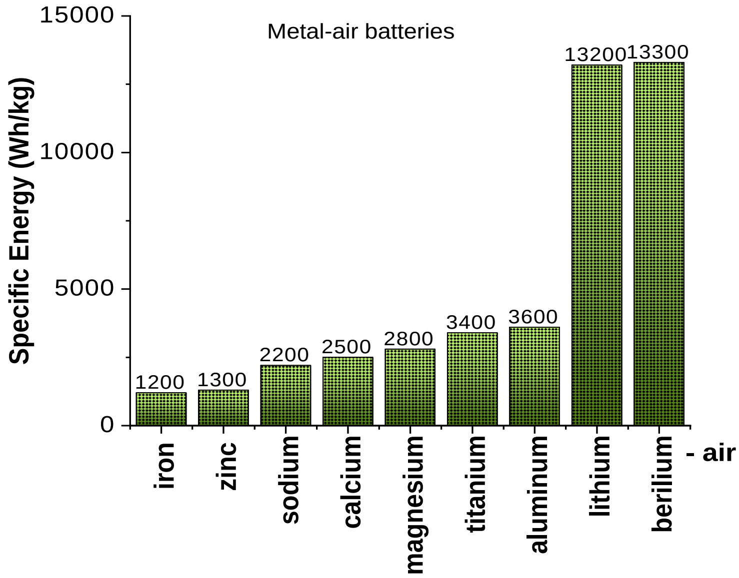

Figure 41: Theoretical specific energy of metal-air batteries

Most of the commercial metal-air cells are primary cells (e.g. Zn-air[119,120]) but numerous research studies are being followed showing that, depending on the cathodes and catalysts, it is possible to fabricate secondary cells.

Lithium-air batteries possess specific energy that is theoretically comparable to gasoline[121] and is, therefore, very attractive; but problems leading to a very high internal resistance and a very short cycle life made the research investment in this technology lose its vitality in recent years. However, new approaches have been developed to address the chemistry's many problems, such as the use of solid catalysts, redox mediators, solvating additives for oxygen reaction intermediates, gas separation membranes, and so on.

[119]Thompson, H. (2021, January 5). *Zinc-air batteries are typically single-use*. A new design could change that. Science News. https://www.sciencenews.org/article/zinc-air-batteries-single-use-new-design-rechargeable (accessed on 14/07/2021)
[120]Sun, W.; et al. *A rechargeable zinc-air battery based on zinc peroxide chemistry.* Science, 2021, 371(6524) 46-51
[121]Zhu, A.L.; et al. *Zinc regeneration in rechargeable zinc-air fuel cells—A review*. Journal of Energy Storage 8 (2016) 35–50

7 Job Roles and Skills

Information on the required job roles, skills/competencies, and knowledge within the research and development domain were gathered via the job advertisement analysis where the occurrence of skills concepts is analysed in a form of a competence matrix.

Altogether 31 job position advertisements + additional industry inputs were analysed, and consequent skills/competencies and other requirements were categorised into 5 main categories according to the classification provided by sectoral intelligence methodology:

(1) soft competencies – a combination of people skills, social skills, communication skills, character or personality traits, attitudes, career attributes, social intelligence, and emotional intelligence quotients, among others, that enable people to interact with their environment, work well with others, perform well, and achieve their goals with complementary hard or sector-specific/transversal skills; **(2) academic competences** – basic and complex skills that are the primary focus of academic institution to provide knowledge for further development in student's career; **(3) general transversal competences** – general ability or expertise which may be used in a variety of roles or occupations; **(4) cross-sectoral specific competencies** – specific ability or expertise that can be used across multiple sectors or domains in more concrete context; **(5) sector-specific competencies** – are particular or specialised skills necessary to perform particular jobs in specific sectors.

Results for each category are depicted by a 100% stacked bar where the percentage represents the distribution of selected skills within the set – some competencies were omitted due to the low occurrence.

7.1 ANALYSED JOB ADVERTISEMENTS AND AREAS OF EXPERTISE

Analysed job advertisements represent an occupational profile or a set of job roles depending on the scope and detail of the description provided within the advert. Mainly the research positions require competencies concerning **battery engineering** (mechanical, electrical, material, thermal simulation, or chemical) or **cell design** (specific cell components – anode, cathode electrolyte, or separators) and **development**. Other positions require competencies concerning **software development/modelling as well as production, maintenance,** or **testing of the batteries.**

7.1.1 Soft Competencies

Soft competencies comprise 10 selected skills and knowledge concepts as seen in **Figure 42**.

The most commonly occurring soft competencies are teamwork, communication, and problem solving/troubleshooting, and adaptation.

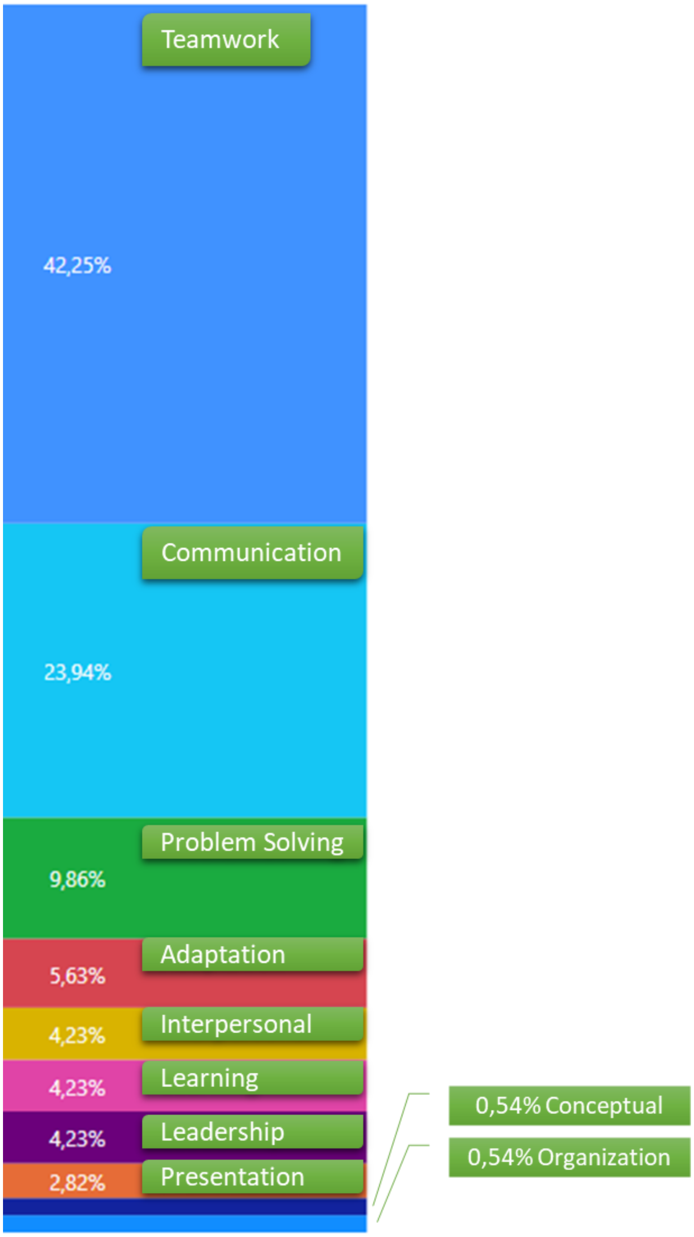

Figure 42: Research and Development – Soft Competencies

7.1.2 Academic Competences

Academic competences comprise 12 selected skills and knowledge concepts as seen in **Figure 43**. The most commonly occurring academic competences are chemistry, material science, and electrochemistry.

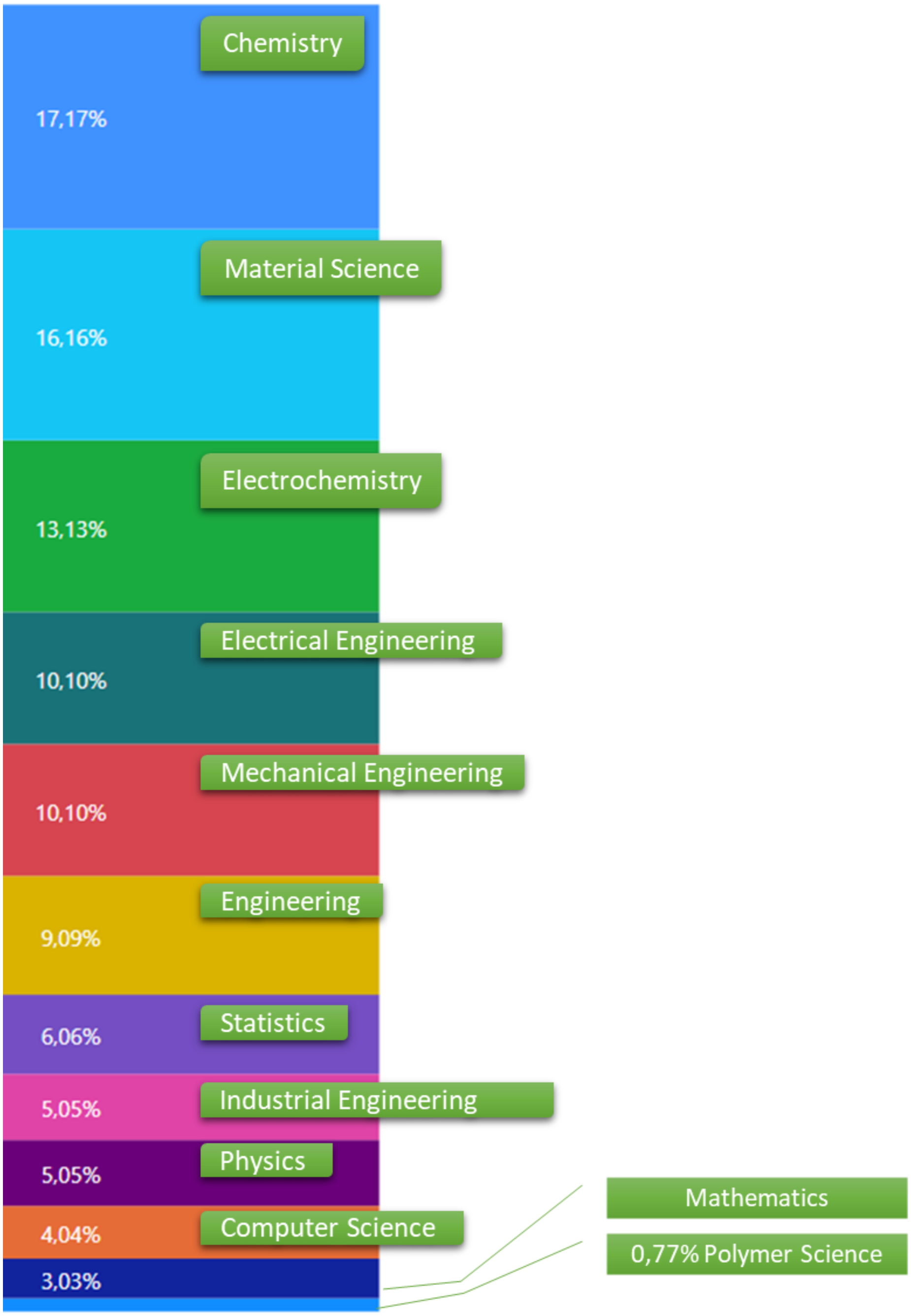

Figure 43: Research and Development – Academic Competences

7.1.3 General Transversal Competences

General transversal competences comprise 11 selected skills and knowledge concepts as seen in **Figure 44**. The most commonly occurring academic competences are negotiation with stakeholders or customers, reporting, and documentation.

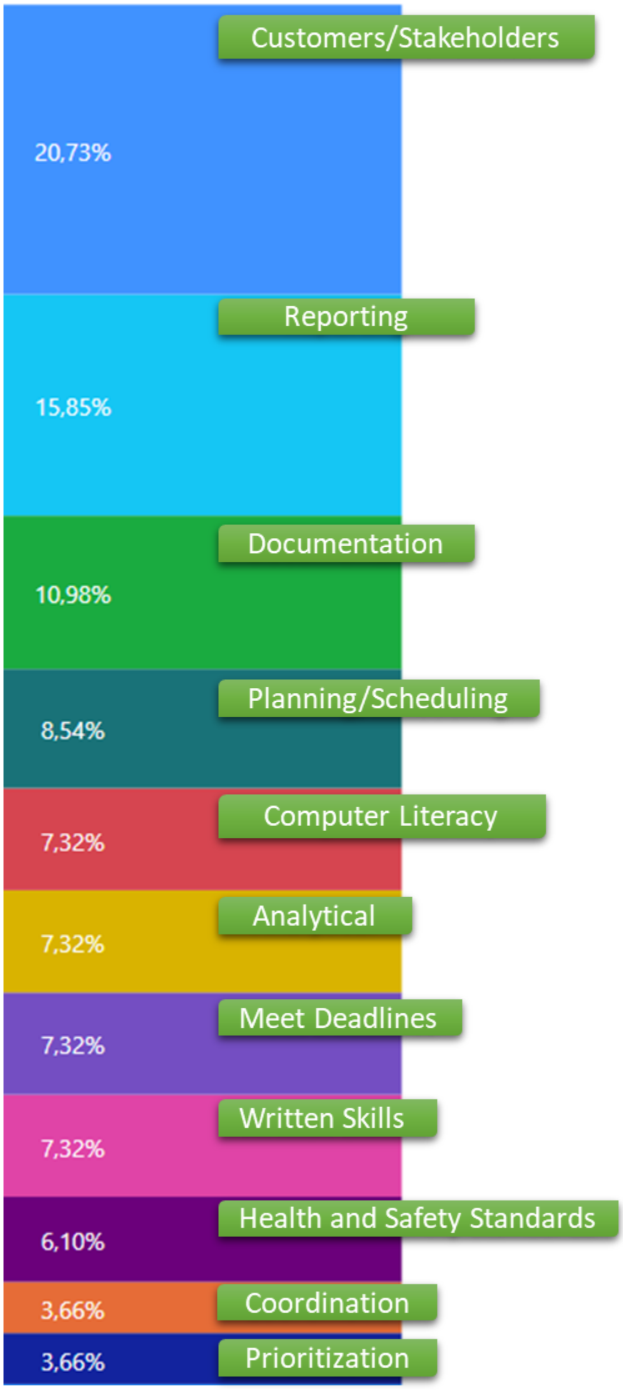

Figure 44: Research and Development – Academic Competences

7.1.4 Cross-sectoral Specific Competencies

Cross-sectoral specific competencies comprise 16 selected skills and 14 selected knowledge concepts as seen in **Figure 45** and **Figure 46** respectively. The most commonly occurring competencies are **(1) skills** – product testing, test data analysis, product design as well as prototype development (context of battery or cell development mainly); **(2) knowledge –** analysis methods, production processes, data analysis, and science, as well as manufacturing methods and engineering.

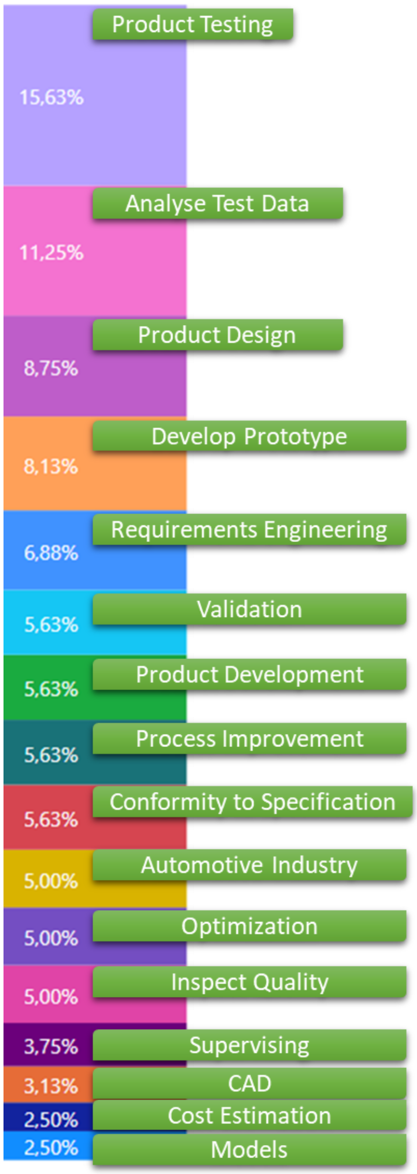

Figure 45: Research and Development – Cross-sector Specific Skills

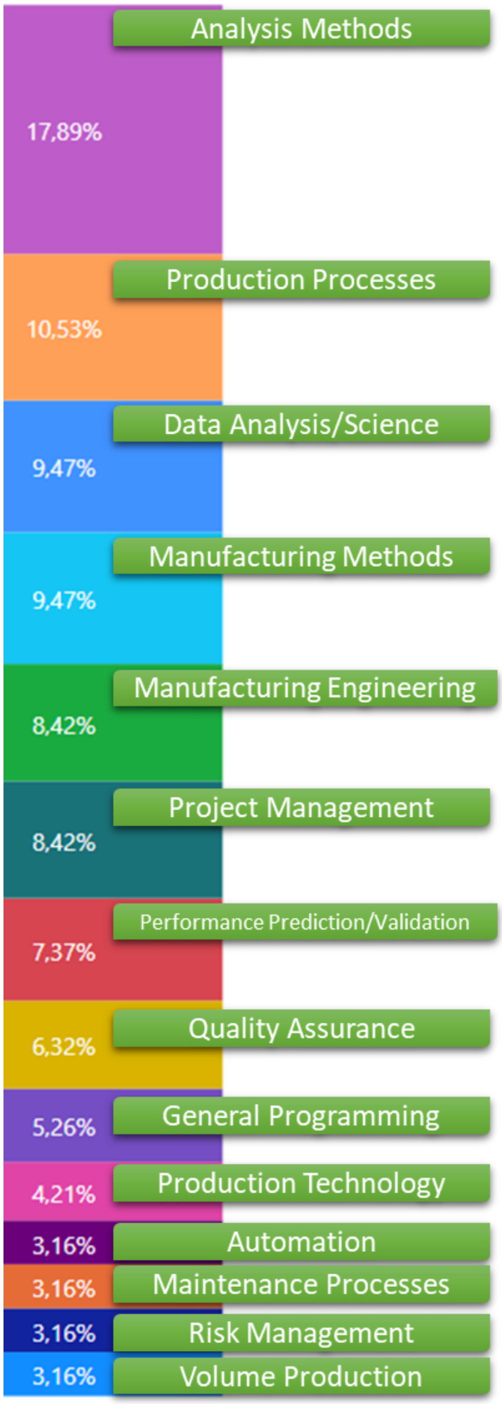

Figure 46: Research and development – Cross-sector specific knowledge

7.1.5 Sector Specific Competencies

Sector specific competencies comprise 11 selected skills and 13 selected knowledge concepts as seen in **Figure 47** and **Figure 48** respectively. The most commonly occurring competencies are **(1) skills** – characterization techniques, cell evaluation, and validation, electrolyte development, or thermal management; **(2) knowledge –** cell design, battery components, lithium-ion battery chemistry, battery design, and battery material.

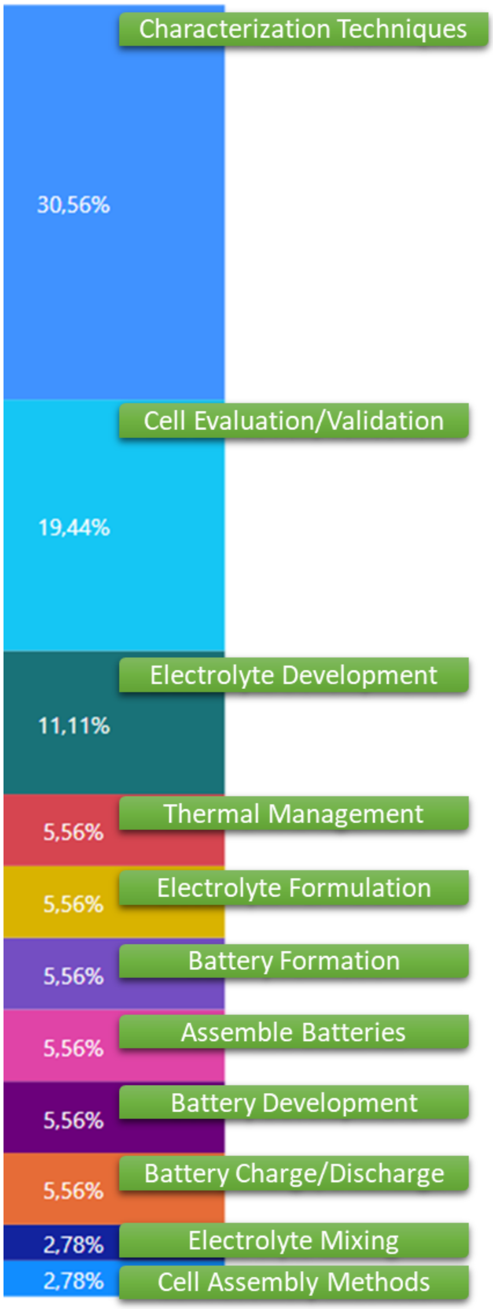

Figure 47: Research and development - Sector specific skills

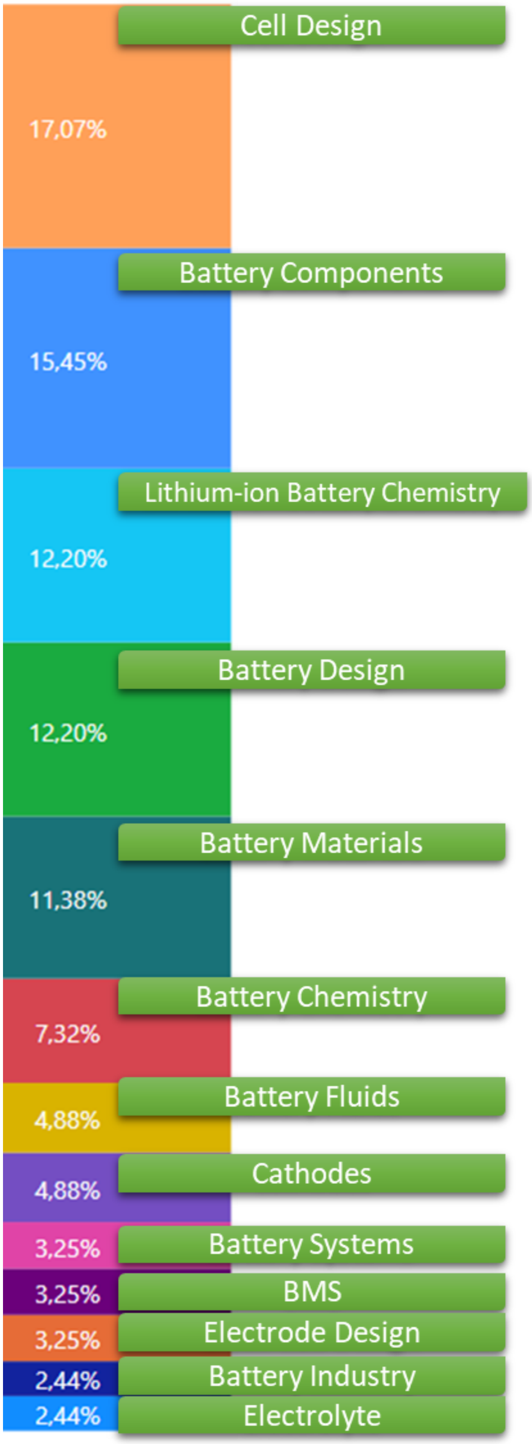

Figure 48. Research and development - Sector specific knowledge

8 Education

On the EQF 7 (master level) and EQF 8 (Ph.D. education level), there are many universities already active with education on battery chain content and skills. There are, in addition, many EU- and nationally funded education-related projects and research centre structures.[122,123]

There are critical questions, however, as: Will the education volume be sufficient for the future? Are the curricula used optimally for the available and future expert jobs? How could academia and industry cooperate better for a competitive battery value chain in Europe? What can be done about the uneven access to relevant and specialised education offerings over member states? How can education offerings be enhanced and speeded up?

The report *Future Expert Needs in the Battery sector*[124] (below called *Experts Needs*) from Fraunhofer on behalf of EIT Raw Materials was based on an online expert workshop on October 14th, 2020, where many European industry stakeholders were represented; besides some EU projects, as ALBATTS. This report, published in March 2021, is also connected to Batteries Europe's *Position paper on Education and Skills* (below called *Position paper*), which was developed during the same period but published later.[125] ALBATTS has been involved as a discussion partner in both report processes.

The *Expert Needs* report spans over and discusses all competency needs in the Energy Storage value chain, focusing on the academic level, besides the professional and vocational level. The period is from today towards 2030 and beyond. This is done in three categories which also connect as a simplified value chain:

- Materials industries (raw materials, active materials to components)
- Production industries (process/ equipment, cells/ modules/ packs)
- System integrators (direct applications, 2nd life applications, etc.)

Expert Needs finds that there are some education needs that they have in common:

- Systemic cross-discipline battery knowledge

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[122]PhD level projects as the European Training Networks (ETN) las Polystorage, Marie Skłodowska-Curie Actions, COFUND projects as Destiny, other H2020 projects, Alistore-ERI co-shared Ph.D. programme etc.

[123]Msc level multi-university programs or initiatives as the Erasmus Mundus joint master (MESC), the EIT Innoenergy master programmes on Energy storage, etc. For more, see the ALBATTS Deliverable D6:1.

[124]Thielmann, A., Neef, C. Hettesheimer, T., Ahlbrecht, K. & Ebert, S (2021) Future Expert Needs in the Battery Sector. EIT Rawmaterials & Fraunhofer.https://eitrawmaterials.eu/wp-content/uploads/2021/03/EIT-RawMaterials-Fraunhofer-Report-Battery-Expert-Needs-March-2021.pdf (accessed on 14/08/2021)

[125]Dominko, R., Maleka, D. & Thielmann, A. (2021) TF Education and Skills Position Papers. BatteriesEurope. This paper represents the combined view of the Thematic Working Groups of Batteries Europe. https://ec.europa.eu/energy/sites/default/files/documents/education_and_skills_task_force_position_paper.pdf (accessed on 14/08/2021)

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- Digitalisation and a digital mindset
- Soft skills.

There is also a significant need for up- and reskilling experts in all three categories now working in other industries. They can have valuable expertise to apply to the battery sector, but they must also learn about batteries.

Both reports emphasise that European academic education and training on an expert level is generally of very high quality. Many of the needed experts are already educated, even if their education in electrochemistry, process engineering, or material science could be more battery-adapted when we know the future expert needs more in detail. Moreover, Europe has the advantage that there are many national and European funding resources available for R&D.

When it comes to volumes of available experts and education sizes, the *Position paper* emphasises that suitable education almost throughout all the groups is very undersized, while the *Expert Needs* report is more cautious and differentiated regarding evaluations and predictions.

Materials industries comprise raw materials, active battery materials, and components needed for battery production. The *Expert Needs* mentions three critical categories:

- *Electrochemists* (PhDs, mainly, with a deep understanding of electrochemical processes around electrode manufacturing),
- *Inorganic material scientists* (with deep knowledge of inorganic syntheses), and
- *R&D experts on emerging battery materials trends* and disruptive technologies.

The need for *process engineers* and various *experts in recycling* is also mentioned as crucial. Another critical lack of experts is in *upper management*, leaders with detailed knowledge of the battery sector. Asian companies in the energy storage value chain have a lot of them, as they often have been operating for 2-3 decades. There is another urgent situation in the European value chain as many massive production units (gigafactories and similar) are starting during the next few years. The *Expert Needs* report recommends the industry be aware of this and try to educate academics in management rather than sending managers from other sectors to courses in electrochemistry or similar.

The *Expert Needs* estimates that the present education volume of electrochemists is sufficient but should not be allowed to diminish. The report also emphasises that it is essential to work actively with the attractiveness of electrochemistry studies for younger students.

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For the digitalisation knowledge and skills needed, the *Expert Needs* report wants engineering experts in the materials sector to learn IT, rather than use general IT people and teach them batteries. Concerning the need for soft skills, it is hard to solve just by a course or two. Instead, it is crucial "to qualify and sensibilise people" (p. 18) so they can communicate well across disciplines and cultures and be able to solve problems together.

Production industries - in "production", the equipment manufacturers should also be included. The *Experts Needs* report calls for *project managers with experience in handling complex and large project*s, *experts in new or disruptive manufacturing technologies*, *skilled process engineers*, and the need to mobilise specialised "entirely new staff" from similar industries which move into the battery production sector and need upskilling.

There is, in addition, a need for *logistics experts* working in qualified teams for large-scale production in a battery plant. The traceability of materials throughout the production is essential, and the ASRS (automated storage and retrieval systems) needs specialised engineers.

System integrators, system engineers, or application experts are sometimes experienced electrical or electrochemical engineers or engineers coming from the ICE industry. According to the *Expert Needs* report, there will be competition along the value chain for these integrators, especially as short-time problem solvers. Nothing is mentioned about how to educate new system integrators, nor about systems integrators as entrepreneurs.

Recommendations:

Both reports issue many ideas and recommendations to both industry and academia on the education of experts on the master and Ph.D. levels. Some of the most important are listed below. They are mixed and integrated between the reports (there is in general alignment with one another but with different points of emphasis):

- A closer communication between academia and industry to identify the concrete needs
- Interdisciplinary programmes and initiatives should be offered in cooperation between academia and industry
- Curricula should be adapted for existing relevant education of future battery experts for the three main expert engineering groups: electrochemists, production, applications
- More specialised and differentiated online courses are needed, not only general ones on batteries, energy storage, and EVs

- More reskilling solutions for experts from the ICE industry
- Better upskilling solutions inhouse in the industry when new staff is hired
- Supply of preparation courses preceding onboarding training in the industry
- More internships for transfer academia to industry and the other way around
- More platforms for exchange between academia and industry (R&D centres, pilot lines, etc.)
- More cooperation on attractiveness for the sector and work with the attractiveness of battery production hotspots for more effortless mobility
- Mobility should be more encouraged, also by member states and EU
- Access to training and practice infrastructure (pilot plants, labs, simulations) should be funded and increased for both recruitment target groups and SMEs
- The industry should supply Train-the-trainer / teach the teacher programmes
- More information to the public about the sector from all stakeholders
- More use of ICTs to enhance the education process
- More courses on, for example, hands-on battery manufacturing, tailor-made circular battery economy, AI, Industry 4.0, battery safety and security, and so on.
- Setting up of educational testbeds
- European standardised course or programme curricula to speed up offerings in member countries
- More use of standardised master programmes for several universities in collaboration to increase EU-wide access to education

Ph.D. and master level education are not the main focus of the ALBATTS project. Instead, ALBATTS is the only present actor in the EU project context on vocational and professional education on EQF 4 (adult education) and 5 (Professional technician education level). In the informal Battery Edu network, ALBATTS cooperates with other initiatives, as the Battery 2030+[126] project family focuses on the research agenda, the LiPlanet project[127], Fraunhofer Batterien Allianz[128], EIT Innoenergy[129], BatteriesEurope[130], EBA250 Academy[131] , and others. The development of curricula for general European use is a specialty for a work package within the Battery2030 – which we will also consult for vocational and professional level curricula. The LiPlanet project focuses on research and training on pilot lines and with simulations, etc., ALABATTS cooperates with them. The EBA250 Academy is a close partner in the vocational

[126] *Battery 2030*. (2021). Battery 2030. https://battery2030.eu/https://battery2030.eu/ (accessed on 14/08/2021)
[127] *LiPlanet.* (2020). LiPLANET | Network of Research Pilot Lines for Lithium Battery Cells. https://www.liplanet.eu/ (accessed on 14/08/2021)
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sector, as they have a European Commission-initiated task of setting up a network of battery education suppliers all around Europe. In this task, ALBATTS fits nicely in. For questions about vocational and professional education trends, see ALBATTS Work Package 4 deliverable D4.4 concerning Battery production.

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