Roadmap Theme 3 – Energy Storage

Background

State-of-the-art energy storage components for electric vehicles (EVs) are Lithium-ion batteries (LIBs) and proton exchange membrane fuel cell (PEMFC) systems. On the market there are a number of different EV-brands using batteries of different size, form factor and chemistry, both in hybrid and fully electric applications. The fuel cell systems are not as developed, but an upcoming market, not least regarding heavy duty vehicles and ferries.

Theme 3 is mainly focusing on the energy storage system (ESS) for different transport applications, however the interface for refuelling is included. Charging and refuelling possibilities and the availability of electricity / hydrogen are key enablers for energy storage systems in electric vehicles. Meaning that interaction with other themes that are looking more at infrastructure and interactions with the electricity grid for both hydrogen refuelling stations and fast charging is important. Figure 1 illustrates the relation between the five different thematic areas contained withing the SEC.

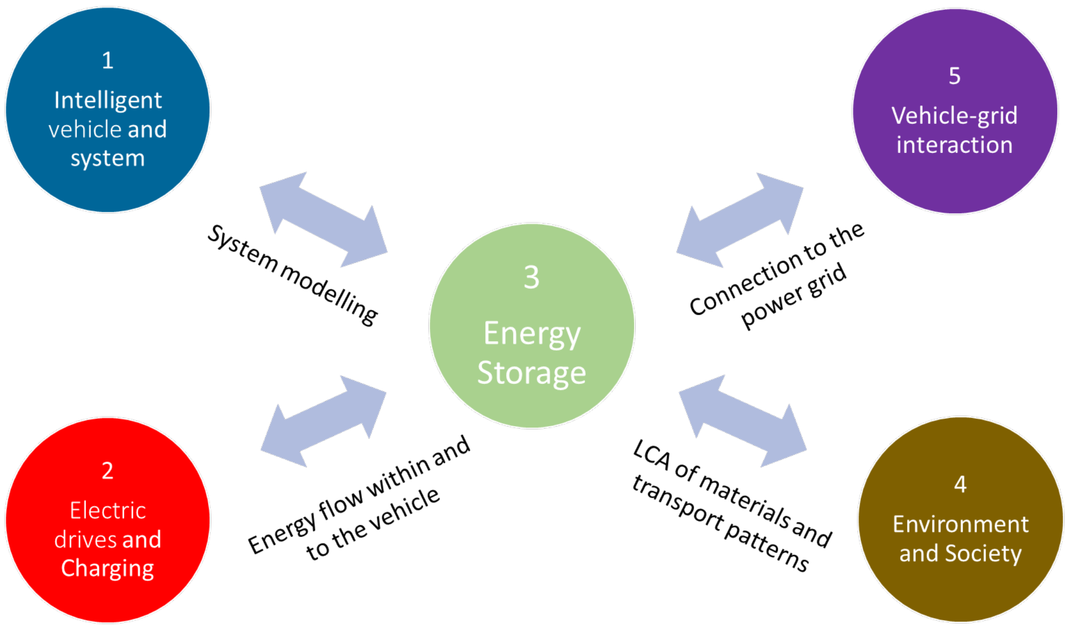

Figure 1: Illustration of the interrelation between the different schematic areas of the SEC.

Introduction

The ESS is the most critical component in a hybrid-, battery-, or fuel cell EV. It defines many of the technical limitations of the powertrain, adds weight and volume, and contributes to additional costs of the system. Hence, a successful development of an energy efficient, cost-effective and sustainable system relies on a good understanding of the possibilities and limitations of the energy storage component: the battery or fuel cell (including the hydrogen tank). Deeper knowledge about the interrelations between chemistry, electrochemistry, mechanics and usage is therefore important in all stages and levels of system development. Thus, this energy storage thematic area has the primary function of deepening the understanding of battery and fuel cell packs, cells, materials, and performance limiting processes, and help make this knowledge useful for the development of EV systems.

Scope and boundaries

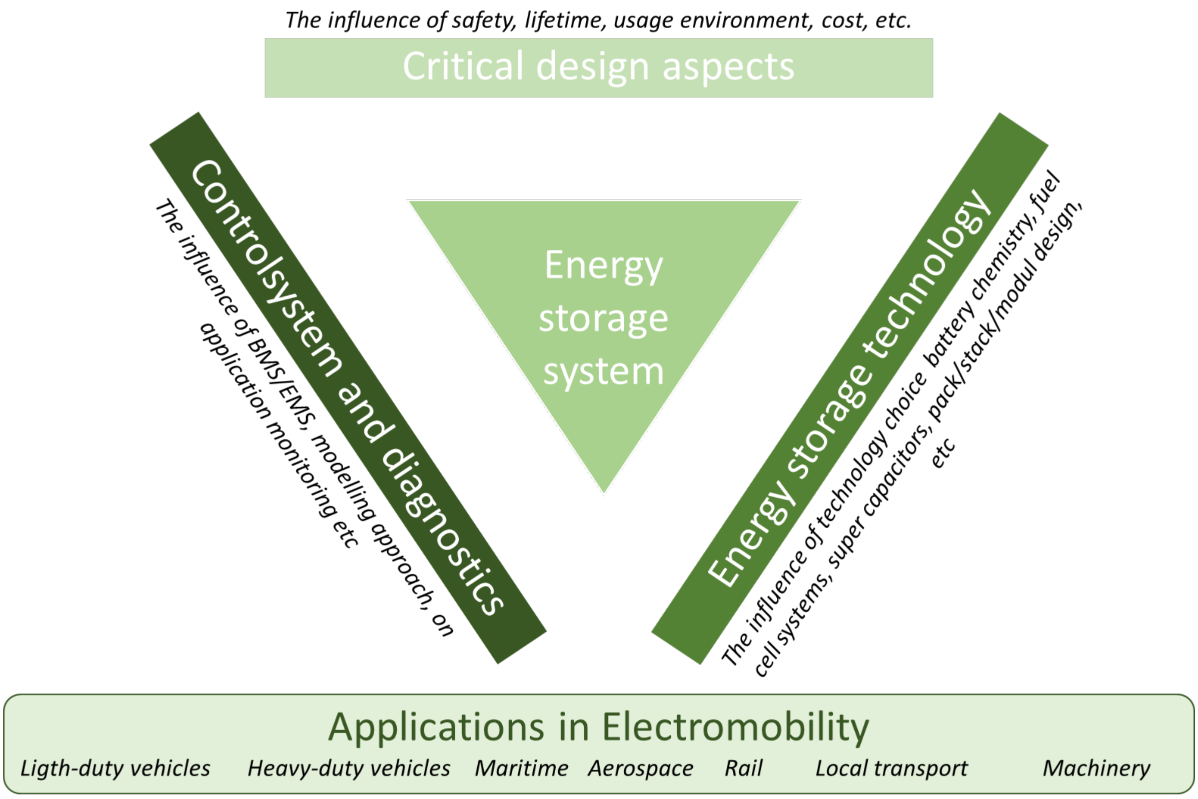

Figure 2: Thematic area 3 works with the energy storage system as a central component. The relation to its boundary conditions as well as applications are illustrated.

The thematic area focuses largely on electrical energy storage (EES) using LIB and FC technology, but also with outlook into other vehicle relevant and conversion systems for vehicles, not least other emerging high power/high energy density batteries and fuel cells. We work in fields ranging from electrochemistry, material science and physics, to system engineering. In figure 2 the energy storage systems interrelation with the monitoring and diagnostics, design aspects, choice of technology as well as applications are schematically provided. For batteries we span the content from small cylindrical cells and coin cells to larger pouch and prismatic cells. A shared theme of the research is the direct link to energy storage usage in the vehicle, applied to all levels from electrode/electrolyte surface reactions to EVs pack/stack behaviour. A major topic is the degradation and aging of the battery/fuel cell, linked to relevant usage patterns and operating conditions. One objective here, contributing to the system development of the EV, is improved predictability and optimized usage of the ESS. Method development in alignment with the research topics are also pursued, targeting on-board diagnostics and state-ofhealth monitoring, as well as off-board end-of-life prediction, including on-board state-of-safety monitoring and early warnings of critical events.

A large part of the transport needs on roads can likely be electrified based on batteries, but there could be applications where the energy density of the batteries or the charging infrastructure is insufficient. Energy conversion of hydrogen in fuel cells here offers other possibilities in the form of higher energy density and rapid refuelling of hydrogen gas. The fuel cell technology has not reached the same maturity level as batteries and is facing challenges related to key issues such as cost, service life, fuel cell system optimisation, hydrogen storage on board the vehicle, and hydrogen infrastructure. As with batteries, deeper knowledge is important at all levels of development in order to successfully integrate fuel cells systems in vehicles.

Besides batteries and fuel cells, there are also other possibilities for intermediate energy storage on board vehicles, like flywheels, super-capacitors or pneumatic systems. However, the current state-of-the-art, the family of LIBs, is considered the only alternative in the short-term due to its superior combination of cost, energy, power, safety and general predictability. In somewhat longer time-frame, sodium-ion (SIB), solid-state Li-metal or Na-metal batteries and hydrogen fuel cells systems are emerging as relevant complements or competitor storage technologies. While other storage technologies and other battery and fuel cell chemistries are not considered mature enough for most EV demands, other than in a much longer time perspective, major breakthroughs in this development may change this picture and openness must therefore be maintained.

Battery research currently relies on one hand on the development of improved batteries and battery components, and on the other on the understanding of the fundamental processes occurring in batteries and their interrelation with battery usage behaviour. The scope of SEC is focused on the latter, which is associated to the use of batteries in vehicles and how this controls parameters such as ageing, safety and performance limitations. This scope is, however, strongly related to the materials and overall chemistry of the battery cell, and the vital understanding of battery usage in EVs therefore needs to be strongly coupled to the cell components.

Current Trends and Needs

There is currently plenty of research on battery cells, with regards to energy and power density as well as lifetime and safety, both in Sweden and internationally. Much attention is put into new and better battery chemistries, i.e. improved electrolytes, electrode materials and other (inactive) cell components. However, while there exists a general trend of rapid progress in materials and storage systems, and their functionality in different types of battery cells, no revolutionary new materials are expected to be introduced in the batteries used for EV applications in the very near future. Current cell material technology still improves largely based on incremental optimization of already existing materials, concepts and manufacturing methods, and by up-sizing of cells. It will likely be possible to continue increase the energy density for the next ten years or so, but depending on the target application, improvement of other attributes such as power, life, or safety may triumph energy density. Thus, competitiveness may require prioritizing differently than simply maximizing the battery energy and driving range.

The consistency of the LIB chemistries forms a basis, where enough data is generated from similar cells to constitute "state-of-the-art" cells, where specific behaviour patterns can be distinguished, compared and modelled, and thereby provide the foundation for a more thorough understanding. Nevertheless, novel components (composite anodes, Ni-rich cathodes, new electrolytes, binders, separators, etc.) are being introduced into the LIB cell chemistry in a rapid pace, which puts certain needs on understanding their behaviour during both short-term and long-term use in EV systems. The potential introduction of solid-state systems will pose a range of challenges in this area.

Insights regarding lifetime and aging issues are also gained by a growing bulk of battery lifetime data for different battery charge/discharge cycles, e.g. fast-charging applications and from EV-field data. Ageing mechanisms of LIBs are also becoming better understood, and corresponding models are being developed. Experience from these kinds of studies will likely improve the lifetime of the battery system by avoiding detrimental physical and electrochemical operational regimes. In this context, it is also vital to consider the effect of ageing on larger systems than cells, and understand how different cell formats or module construction influence cell behaviour and ageing taking into account the interplay between electrochemistry, materials chemistry, mechanical load, temperature, etc. Furthermore, with a more extensive use of EV batteries being envisioned for use as EES in the grid, there is an increased need to understand how these "V2X" phenomena affect battery ageing. The need to understand V2X phenomena could mention the business models that will require realistic input on cost/capacity from the battery system, which seems to be more of a bottle-neck than the signal type.

Moreover, increased utilization of different cell chemistries within the same EV battery module or pack is likely to be more extensively applied, either due to of the combination of cells with different performance merits (energy optimized, power optimized, low cost, etc.), or due to remanufacturing and repair. Balancing, ageing, control and safety aspects of such battery systems require further exploration. Including the battery swapping technique with development of standardisation of size and interface, including new business models.

Industrialisation of the above-mentioned material chemistries opens up for studies into different form factors of the battery cells. Different form factors will influence the packability of the cells in the transport applications and thereby affect the energy density efficiency of the system. A higher energy density may result in a slightly compromised safety and this trade-off is constantly considered during research and development. Currently there is a lot of focus on development of cylindrical or prismatic (blade) cells, however, in the future other engineering solutions such as solid state and structural batteries may come into play.

The rapid advancement of battery models and associated software is an important trend, as well as it's correlation to improved battery management (not least through smarter Battery Management Systems (BMS)) and battery diagnostic tools. There is a clear need for such development, in order to mitigate or predict ageing, performance and thermal behaviour, and to improve the safety aspect. Questions of performance prediction, safe-operation-area, and design of cells and packs are also connected to mechanical and electrical engineering of the battery.

With larger volumes of batteries being produced, cost and sustainability aspects are becoming increasingly important. For EVs, the room for compromising the electrochemical performance is, however, small. Development towards LIBs with less Co-rich alternatives is currently seen, although the largest sustainability impact might occur through prolonged lifetime and improved recycling. Increased attention towards improving or substituting additional battery and fuel cell components, which are problematic in a cost and sustainability context, can be foreseen.

There is a need for stronger interplay between cell manufacturers and the automotive industry. This will make it possible to engineer improved EV batteries, tailor the BMS properly, and – primarily – understand novel implementations and improvements in LIBs, so that battery management and vehicle use can be optimized, and implementation time minimized. A trend in the area is that the responsibility for the full battery system, including assembling of cells into modules, and the BMS is shifting from the cell manufacturers to the OEMs, and an increased vertical integration of the battery value chain into the vehicle industry, either in the form of joint ventures with cell producers or with cell production being built up by the OEMs themselves. This will require broader battery competence in the automotive industry. Recent initiation of LIB cell production in Sweden may in the long term also affect the interplay between OEMs and cell manufacturers. Cell production in Sweden could open up for interaction between OEMs and material development at an earlier state of cell production.

In parallel with batteries, interest for hydrogen is also flourishing. In the hydrogen strategy for a climate-neutral Europe communicated by the European Commission, hydrogen has been identified as a key contributor in the mitigation of climate change. The strategy is to make green hydrogen along with electricity the main energy vectors that enables a zero-emission Europe. It then becomes important to obtain synergetic intersectoral effects by integration of hydrogen into the existing systems for energy and transport. Thus, it is quite evident that hydrogen based on renewable electricity will be available at a competitive cost also for transportation purposes. A natural consequence of this is that the interest in electrification of the transport sector with the help of hydrogen-powered fuel cells has increased dramatically during the past years. Commercial production of fuel cell vehicles has increased significantly during the last decade. Today there are commercial suppliers in Japan, Korea, China, the EU and USA at the forefront of this development. Manufacturing volumes are still low but steadily increasing, and the initial focus has been on light- to medium-duty vehicles, the largest volumes are in small forklifts, passenger cars and buses for public transport. In recent years, two companies have started series production of trucks internationally, and several actors on the European market have announced the goal to have series production by 2030. There is also very strong initiative for more refuelling stations in Sweden and internationally which will increase the focus on new vehicles. When needed to carry larger amounts of energy on board a vehicle, systems based on fuel cells have higher energy density than pure battery systems, and thus offer an interesting alternative for long-distance transport with short downtime. There is also an exciting development of the use of fuel cells for trains, in the maritime sector and for aerospace applications. In the latter two sectors there are currently strong trends on developing fuel cell modules with higher power per module and an overall more efficient system. There is also an increasing interest in using liquid hydrogen as energy storage, and this introduces new challenges and has gained a new momentum in the research arena.

Fuel cells will always be combined with batteries on board vehicles, and the use of fuel cells will not reduce the need for good battery knowledge. However, new interesting questions arise how to best combine these two technologies for energy storage and energy conversion depending on application. One trend is a focus on adopting batteries and fuel cells for larger systems than passenger cars: utility machinery, heavy transport, maritime and aerospace applications. This will increase the need for power- and energy optimization of the energy storage unit and significant development of the energy management system (EMS). This will also require adaptation of the whole system, while also safety aspects are becoming critical for these generally upscaled packs. The research in this area is still not as mature, and more efforts are needed.

For the fuel cell systems one aspect that currently also demands attention is the development of automated production lines and how this will influence the stacks. Production lines will be essential to have a large-scale role out of the systems on the mass market and decrease cost of the drivelines. There is further a lot of focus on research on the safety of the drivelines and how they should be engineered to be safe in case of collision.

The research needed to meet the above gaps could be divided into two main areas:

- The batteries and fuel cells available today are far from optimal from an automotive perspective, and improvements concerning energy- and power density, lifetime, cost, safety and sustainability must be achieved in order to reach long-term goals. This will require optimizing the material properties and cell designs of the present Li-ion and fuel cell technologies. Solutions involving post Li-ion technologies must also be explored in this long-term pursuit.

- Our mastery, as users and system integrators of the currently available LIBs and fuel cells, is far from sufficient. Better characterisation techniques and engineering tools that can be used to understand and predict battery and fuel cell behaviour and safety performance, that can also be adopted by the industry, would be immensely valuable. It is not foreseeable that this can be obtained without a profound knowledge about all limiting processes, from system perspective down to molecular level of the cell components.

Strategic areas

The field of battery research and development is highly competitive globally. This results in a massive flow of information, impossible for any single actor to fully grasp. Therefore, the selection and interpretation of vital information will likely be much easier for a cohort of active researchers with different background and focus. Thus, an important long-term objective of this thematic area is to maintain sufficient competence at the universities and institutes to extract information about global trends, and to follow the status of future technologies, but also to actively assess new technology by pursuing own research on emerging battery chemistries and materials, or improved operandi and in situ analysis methods.

The theme aims to be a forum for discussion between researchers in academia and industry and bridge the communication gap between academic research and vehicle development, encompassing several cell formats and sizes of cells, modules and packs, and interfaces between them. Shared testing facilities with up-scalable testing environments provide an important base for lifting ideas from lab to higher TRLs. The understanding of battery ageing and battery operation is a vital area for interplay between academia and industry, as is the circularity of the battery and the effect of possible strategies for reuse, remanufacturing and refurbishment. The gradual introduction of batteries in vehicles and the whole transport sector is expected to continue. The pool of joint experiences and methods for evaluating vehicle energy storage within the Theme could possibly be utilized to facilitate the industry to set up and evaluate databases of vehicle energy storage field data.

The research needs stated above present an enormous challenge, and SEC cannot be expected to cover all areas of the field. Breakthroughs in battery technology might happen in a long-term perspective. However, near-future EVs are most likely to use battery technology available today, although the cell chemistry is shifting each battery generation by the manufacturers. Thus, SEC activities should consider a better understanding of present technologies, where state-of-the-art products constitute key objects of general interest for method development as well as joint benchmarking activities. In addition, upcoming technologies and future needs should also be explored. In this context, SEC should work to spread results between thematic areas and between partners. Additionally, SEC should also play an essential role in initiating new projects. For this, both academia and industry need to communicate issues arising in their field of research and/or development.

- Testing and diagnosis is currently a focus area for SEC. Characterisation techniques and engineering tools that can be used to understand and predict battery/fuel cell behaviour, and that radically reduce the need for expensive and time-consuming testing by the industry are obtainable in a long-term perspective. The challenges and research need to achieve this are immense and for SEC to make a difference in this field sufficient resources must be made available inside SEC.

- Modelling is currently a focus area for SEC. Not least implementation of ageing mechanisms in current LIB and fuel cell modelling is of necessity to aid and support testing and to better correlate this with field data. Multi-scale modelling, with interfaces towards material modelling and the use of Artificial Intelligence, are areas expected to make a large impact on the field in upcoming years, which are also prioritized by SEC. Moreover, the correlation of cell modelling with diagnostic tools, such as impedance and sensor systems, and also coupled to BMS and/or EMS development, constitute a strategic priority.

- The energy storage system is a focus area for SEC. Understanding the interrelation between the use of the vehicle / load demand, and the implication on energy storage system design is crucial. Especially since the components used in the power transfer chain are all possible system limiting devices that can influence both charging / refuelling as well as using the vehicles. This includes battery swapping techniques as well as infrastructure interactions.

- System control and safety is currently a focus area for SEC. A long-term objective is to build knowledge that makes it possible to maximize the use of the battery and fuel cell system in a vehicle, also large-scale systems, without violating safety or the specified lifetime of the system. Safety testing and safety prediction are also crucial. A specific field that attracts more attention is the possibility to rapidly charge a battery without violating safety or affecting aging. Cutting edge knowledge could be developed within the SEC network. More safe battery chemistries (e.g. solid state) should also be explored as well as safety limitations for hydrogen tanks.

- System design aspect is currently a focus area for SEC. For the energy storage system this focuses on surrounding systems and design aspects that ensures optimal thermal, mechanical and electrical working environments. For batteries an example is the temperature management system during the discharge/charge cycles, or the mechanical design for safety/optimal use. For fuel cells it will include the Balance-of-plant (BoP), i.e. all other system components except the stack. The BoP contribute to a large part of the overall weight, volume and cost of a fuel cell system and is a field with large potential for improvements. Combining competences from several fields can lead to large improvement on system level.

Projects and activities do not need to be isolated to a single focus group. Single projects can, where suitable, preferentially feed multiple focus groups with data of interest. A further expectation of the thematic activity is to educate personnel highly trained in this field. The availability of well-trained students with different backgrounds is a necessary prerequisite for further development of Swedish automotive, machinery, maritime and aerospace industry. This requires activities spread among universities and research groups, and coordination of these activities.

Forecast

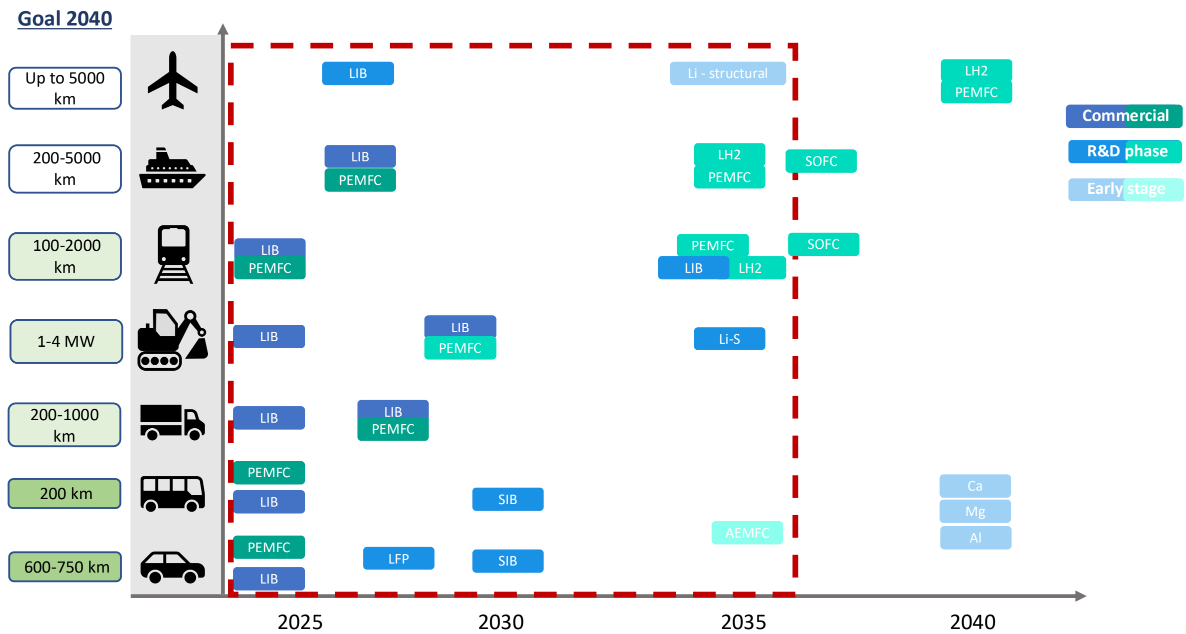

Figure 3: A schematic forecast of the 5-, 10- and 15-year research and implementation perspective. The colours that refer to the different technologies as Commercial, R&D or Early represent the status today, while the placement on the y- and x-axis shows when the first commercial applications are expected, and which type of application will use the technique. Furthest to the left there is also an expected goal for 2040 and the green colour represent how close we are to this goal today.

Figure 3 illustrates a schematic presentation of a technology forecast of theme 3. To be on the market within the electromobility area, not only the energy storage system has to be developed, but the controls, thermal management, and interaction with the rest of the vehicle has to be in place as wells as the interaction with the refuelling / charging infrastructure.

In a 5-year perspective

Many of the short-term improvements to the energy storage systems in mobility will be incremental and based on current state of the art. A few major steps can also be forecasted for, and these will the depend on which driveline system is discussed, purely battery, or a battery fuel cell hybrid.

For pure LiB systems a new Li-ion chemistry, such as high-voltage cathodes, also targeting Co-free chemistries, will likely be implemented. These comprise Ni-rich layered oxides and Mn/Ni-based spinel materials. A renaissance for Fe-based cathodes (LFP), also targeting EVs, can be foreseen in Europe and the US, despite the lower energy density, since lower cost battery packs are possible. High-capacity anodes (Si composites with graphite) are likely being implemented to a larger degree for EVs, but where prelithiation of Si and advanced tailoring of the electrode structure will be necessary. Hybrid battery systems are introduced, where less stable but more energy dense cell chemistries are combined with cells of higher stability, which are utilized for the main part of the energy throughput. Sodium-ion is an alternative low-cost chemistry, and batteries comprising a mix of Li-ion and Na-ion cells are proposed to compensate for the comparatively low energy density of Na-ion cell chemistries.

Other than electrode materials the traditional electrolyte systems are going to continue to dominate LiBs. Still, development of novel electrolyte additives and more safe electrolyte systems are likely being implemented to enable e.g. higher voltage cut-offs. Also, water-processable chemistries – primarily realized by the replacement of the currently dominating PVDF binder system – can be expected to generate novel cell chemistries, which in turn affect performance and ageing. This will also be correlated to design of battery cells for re-use and recycling. Solid-state electrolytes (ceramic, polymer, composite and quasi-solid state) will continue to be a highly sought-after target and emerge in certain applications.

While the development of new chemistries is not the focus of SEC knowing which new cells are coming will influence the ESS design in the application and the center will need to start to understand how to integrate packs and so on. An improved use of online diagnostic tools, especially impedance and ultrasound, and in conjunction with better ageing models, can lead to longer battery lifetime, and thereby superior sustainability.

For fuel cell systems the development focus in the short-term is expected to focus on integration of the existing proton exchange membrane fuel cell (PEMFC) stacks in energy storage systems on applications. This will involve a strong focus on BoP components, energy management systems, power electronics and so on. Work on EMS and power electronics will imply the need for a strong interaction between Theme 3, 1 and 2 regarding the ESS. The planned build out of nationwide network of hydrogen refuelling stations along the road network will indicate that rolling applications will be first. There are also announced plans for some demonstrators using hydrogen in the maritime and off-road segments in Sweden and internationally there are plans for fuel cell driven airplane demos.

For stack development a clear trend will be development of larger fuel cell stacks which will change how the system design looks especially for applications with power needs above 100kW. There will be a start to focus on new membrane chemistries to reach higher operating temperatures and lower content of fluoropolymers. The higher operating temperatures would allow for more efficient system design. Furthermore, the first production lines are expected to have been developed for PEMFC and increase role out and the need for smart diagnostics to ensure stack quality. With production lines there is also a focus on new bipolar plate materials especially for heavy-duty applications with higher demands on the stack. At the same time production technology moves to thinner and thinner membranes and plates to make the volume of stacks smaller and have a better form factor.

In a 10-year perspective

In electromobility it is possible that there will be more discussions on mixed energy storage systems over the next 10-15 years. There are some segments where application will use a plug-in hybrid design with a combination of both fuel cells and batteries. Also, hybrid systems with batteries/supercapacitors can be interesting for numerous EV applications.

For battery it is expected that solid-state systems, utilizing metallic anodes, can potentially now become competitive and implemented in a range of EV applications. Na-based systems will likely have developed to be more competitive with Li-ion, also for some EV systems where energy density is not the major concern. Si-anodes with controlled/mitigated volume changes have probably been introduced on the market, as well as anode-free cells. The development of low temperature sulphur-based chemistries (e.g., Li-S) can be foreseen to have developed into competitive niche EV applications. Advanced surface engineering of batteries is likely to have a profound effect on battery ageing. Self-healing materials in batteries can be expected to have entered the market, for improved energy density (through use of alternative electrodes) and improved safety. Improved design of current collector and electrode structure, to minimize resistance and improve active material utilization, have been implemented.

Next-generation fuel cell systems are likely to have reached the EV market where novel proton conducting polymers may enable higher operating temperatures. There will most likely also have been a shift to hydrocarbon membranes in several applications which will reduce the amount of non-environmentally friendly fluoropolymers. It is also expected that some applications will start using other fuel cell chemistries such as solid-oxide fuel cells (SOFC) and anion exchange membrane fuel cells (AEMFC). Larger volumes of pressurised and cryogenic hydrogen will be available at competitive prices thanks to development of electrolysis and liquefaction techniques. Novel type of sensoric systems will improve battery and fuel cell diagnostics.

Electrification of air transport will be a sector that grows more in this time perspective.

In a 15-year perspective

At this point we believe that many electromobility applications will look at large variations of hybridization and intake of energy through both charging and filling. It is believed that there will be more of an acceptance that a mixture of solutions will be needed, and that hybridization is common. There may also exist hydrogen solutions where the electricity is produced in a turbine and the combined with batteries. This will also mean that more standards will emerge where handling H2 and batteries in the same application and/or environment will be defined. This is a safety question that will be raised in how the technologies co-exist.

For batteries multivalent battery chemistries (Al-, Mg-, Ca-based) are expected to be competitors to Li/Na-counterpart at this stage. Solid state-Na-metal batteries could be widespread, something that would make the electrification less of an equality issue. A renaissance for complex yet exceptionally high energy-dense systems based on oxygen (air), in particular Li-O2 and Na-O2 batteries, cannot be excluded in this time frame, as well as other, today immature, chemistries, such as organic cell chemistries.

For fuel cells more competitive costs of systems are expected thanks to both novel electrode design and materials where less and less platinum is used. The AEMFC and SOFC are also expected to have become competitive at this point. On the overall larger systems are expected to be common in for example maritime or aerospace applications and with more versatile hydrogen storage systems.

For hydrogen storage on the vehicles there will probably be more alternatives and especially liquid hydrogen is expected to have become more competitive. There may also especially for maritime be more solutions with methanol- reformer-fuel cell.

At this point the industry as well as the society will likely have a high focus on circularity, with mature recycling systems adapted to different chemistries. We will probably see more integrated value chains and incentives that force the industry to actively design batteries for long duration and, at the end of 1^{st} life, for easy disassembling. Mature and accurate diagnostic tools have been developed, which can possibly even allow for single cell replacements.