Road map Theme 3

Introduction

The energy storage component is the most critical component in a hybrid electric, battery electric, or fuel cell electric vehicle (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. 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

The thematic area focuses largely on energy storage using lithium-ion battery technology, but also with outlook into other vehicle relevant energy storage 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 control engineering, centred on the EV battery. We span the content from small cylindrical cells to large pouch and prismatic cells. A shared theme of the research is the direct link to battery usage in the vehicle, applied to all levels from electrode/electrolyte surface reactions to EV pack behaviour. A major topic is the degradation and aging of the battery, 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 battery. Method development in alignment with the research topics are also pursued, targeting on-board diagnostics and state-of-health monitoring, as well as off-board end-of-life prediction.

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 refueling 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 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 Li-ion batteries, 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 timeframe, solid-state Li-metal batteries and hydrogen fuel cells 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 use. The scope of SEC is focused on the latter, which is associated to the use of batteries in vehicles and how this controls ageing, safety, performance limitations, etc. 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 components of the cell.

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 in the Li-ion battery chemistry 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 provides 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 Li-ion battery 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 with regards to lifetime and aging issues is also gained by a growing bulk of battery lifetime data for different battery charge/discharge cycles, e.g. fast-charging applications and from field data from EV batteries. Ageing mechanisms of Li-ion batteries 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. The rapid advancement of better battery models and associated software, of battery ageing, and correlation with battery management (not least through improved Battery Management Systems (BMS)) can be foreseen to merge in upcoming years, also correlated with improved battery diagnostic tools. There is a clear need for such a development, in order to mitigate ageing and for improved safety. 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 the larger volumes of batteries produced, cost and sustainability aspects are becoming increasingly focused. For EVs, the room for compromises with electrochemical performance is, however, small. A development towards Li-ion batteries with less Co-rich alternatives is currently being seen, although the largest sustainability impact might occur through prolonged lifetime and improved recycling. A development of improving or substituting also other 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 Li-ion batteries, so that battery management and vehicle use can be optimized. 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. This will require broader battery competence in the automotive industry. Recent initiation of Li-ion battery cell production in Sweden may in the long term also affect the interplay between OEMS and cell manufacturing. Cell production in Sweden could open up for interaction between OEMS and material development at an earlier state of cell production.

Commercial production of fuel cell vehicles has only a few years on its neck, and Japanese and Korean manufacturers are at the forefront of this development. Manufacturing volumes of passenger cars are still modest but steadily increasing. In recent years, the interest in fuel cells for commercial vehicles has grown for both buses and trucks. 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 marine sector and for aviation. 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.

Yet one trend is a focus on adopting batteries and fuel cells for larger systems than passenger cars: utility machinery, heavy transport, marine applications, flights... This will increase the need for power- and energy optimization of the energy storage unit. This will require adaption 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.

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

- The batteries available today are far from ultimate from an automotive perspective, and large improvements concerning energy- and power density, lifetime, cost and safety must be achieved in order to reach long-term commercial goals. This will require large improvements of material properties and cell designs of the present Li-ion technology. Solutions involving post Li-ion technologies and fuel cells must also be explored in this long-term pursuit.
- Our mastery, as users and system integrators, of the currently available Li-ion batteries is far from sufficient. Better characterisation techniques and engineering tools that can be used to understand and predict battery behaviour, and that can 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 processed in the battery, from system perspective down to molecular level in the individual cells.

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 to extract information about global trends, and to follow the status of future technologies, but also to actively asses 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. 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. 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 from battery generation to 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 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 needs 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 Li-ion battery modelling is of necessity, to aid and support testing and better correlate with field data. Multi-scale modelling with interfaces towards material modelling and the use of Artificial Intelligence are areas which are expected to make a large impact on the field in

upcoming years, and prioritized for SEC. Moreover, the correlation of cell modelling with diagnostic tools such as impedance and sensoric systems, and with BMS development constitute a strategic priority.

- 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 system in vehicles, 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. Cutting edge knowledge could be developed within the SEC network. More safe battery chemistries (e.g. solid state) should also be explored.
- Fuel cells is currently a focus area for SEC. EVs based on fuel cells (in combination with batteries) are still in an early state of commercialisation. Challenges range from components in the fuel cell to system design and operation. Catalysts, electrodes and membranes with improved performance and lifetime, as well as improved cell and stack design will result in better stacks. Balance-of-plant, e.g. all other system components except the stack, is contributing 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. Questions linked to the hydrogen infrastructure, an important prerequisite for large scale introduction of fuel cell vehicles, could be handed together with other Themes.

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 industry. This requires activities spread among universities and research groups, and coordination of these activities.

Forecast

In a 5-year perspective

While incremental improvements are foreseen, a few major steps can also be forecasted for the Li-ion chemistry. 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, also targeting EVs, can also be foreseen, 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.

While traditional electrolyte systems are going to dominate, 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. An improved use of online diagnostic tools, especially impedance and also in conjunction with better ageing models, can lead to longer battery lifetime, and thereby superior sustainability. We will see an emerging use of fuel cell concepts for EVs and infrastructure for hydrogen. A clear trend will be rapid electrification of heavy-duty vehicles, work machinery and marine applications.

In a 10-year perspective
Solid-state systems 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. Hybrid systems with batteries/supercaps can be foreseen to be interesting for numerous EV applications. The development of low temperature sulfur-based chemistries (e.g., Li-S) can be foreseen to have developed into competitive niche EV applications. Next-generation fuel cell systems are likely to have reached the EV market. 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. Novel type of sensoric systems will improve battery diagnostics. Electrification of air transport is growing.

In a 15-year perspective
Multivalent battery chemistries (Al-, Mg-, Ca-based) are expected to be competitors to Li/Na-counterpart. A renaissance for complex yet exceptionally high energy-density systems based on oxygen (air), in particular Li-O2 and Na-O2 batteries, cannot be excluded in this time frame. More competitive prices on fuel cell systems and vastly improved hydrogen infrastructure will likely cause a wide-spread use of fuel cell vehicles throughout society.