Electric Vehicle Enhanced Range, Lifetime And Safety Through INGenious battery management

# D8.16 – White Paper 13

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# LIST OF ABBREVIATIONS AND ACRONYMS

| ACRONYM | DEFINITION |
|---|---|
| AC | Alternating Current |
| API | Application Programming Interface |
| BMS | Battery Management Systems |
| ESC | External Short Circuit |
| EV | Electric Vehicles |
| IoT | Internet of Things |
| ISC | Internal Short Circuit |
| SoC | State of Charge |
| SoH | State of Health |
| SoX | State estimation functions |
| VCU | Vehicle Control Unit |

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# INTRODUCTION

The EVERLASTING project (http://everlasting-project.eu/) will develop innovative technologies to improve the reliability, lifetime and safety of lithium-ion batteries by designing more accurate and standardized battery monitoring and management systems. This allows predicting the battery behaviour in all circumstances and over its full lifetime and enables pro-active and effective management of the battery. This leads to more reliability and safety by preventing issues rather than mitigating them. To raise the awareness of the vital and positive role of Battery Management Systems (BMS), a three-monthly white paper will be written on different BMS topics, aimed at a general technical public. These white papers will be distributed via the EVERLASTING website and through the partners.

This thirteenth issue of the white paper focuses on the topic "Future of BMS".

# 1 WHITE PAPER 13: FUTURE OF BMS

This white paper is intended to address the future of Battery Management Systems. This includes the advances in battery technologies and across various technical aspects of BMS, and their impact on the significance, functionalities and future improvements/modifications of BMS.

# 2 WILL BMS STILL BE NEEDED IN FUTURE?

Even though the continuous advances in battery technologies might make them safer, high-performing and long-lasting, a BMS will still be required for vital tasks namely:

- Monitoring battery pack parameters
- Performance management through battery pack state estimation
- Performing battery pack diagnostics through abuse detection and error data logging
- Interfacing to communicate, e.g. the battery status to the user, error data logging for diagnostics and post analysis purposes
- Safe operation, assuring that the improvements in battery capacity/power/energy are utilized to the maximum possible extent, without sacrificing safety and longevity of battery pack

The advances in battery system technologies and their corresponding impact on the BMS are addressed in Section 3.

# 3 BMS-SPECIFIC CASE STUDY

Most of the market studies on the future of BMS generally concentrate on factors like BMS market value, future market growth, geographic region-specific BMS players and their products. Since EVERLASTING focuses on the technical aspects of BMS, this section briefly discusses the improvements in various technical aspects of Battery Management Systems and their impacts on future BMS.

## 3.1 CELL BALANCING

In general, a battery system is made of series-connected cells and/or parallel-connected cells. Such cells may diverge in their internal resistance and capacity, due to manufacturing tolerances and inhomogeneous ageing, e.g. caused by temperature gradients.

Hence the cells would experience unbalanced charging and discharging, resulting in overcharging of the less aged cells and over-discharging of the more aged cells comparatively, in the battery pack. This leads to incomplete utilization of the pack capacity as shown in Figure 1 and eventually reduced cycle life of the whole battery system. Even worse, this may lead to severe safety issues.

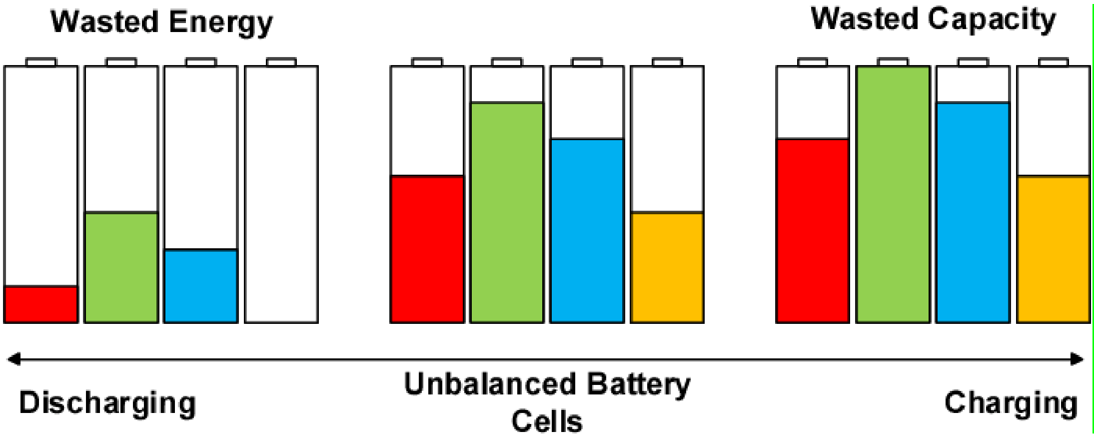


**Figure 1: Loss of capacity and energy due to unbalanced cells in a battery pack [1]**

Battery balancing techniques are employed to solve such imbalanced states of the cells in battery systems. There exist several such balancing methods, generally subdivided into passive and active balancing methods [2]. While each method has its own advantages and drawbacks, the choice is indeed made not only based upon the application requirements and suitability to the system, but also commercial considerations like the cost of the balancing technique and the topology of the cells in the pack.

Improved production techniques minimize the dissimilarity between the manufactured cells, and techniques like sorting shall be used in the initial stages of making a consistent battery pack. Even though, the temperature gradient driven inhomogeneous ageing of cells during operation can be minimized to some extent, it is not completely avoidable, due to the limitations in the cost-benefit ratio of thermal management system, with respect to the reduction in temperature gradient achieved. Hence, sorting the cells based on their capacities and internal resistances to build up a consistent battery pack, reducing the temperature gradients through improved pack design and the usage of balancing techniques, can all together reduce the uneven ageing of cells.

Irrespective of the balancing technique used, the agility of the balancing process highly depends upon the algorithm controlling the balancing process. SoC and voltage-based or combined balancing algorithms are highly influenced by factors like rest time, measurement and estimation accuracies.

Hence, model-based advanced algorithms which are capable of detecting dissimilarities at a very early stage shall be used. Therefore, a further increase in the variance between cells is minimized through intelligent charging and discharging of weaker cells in the pack. Thus, the need for a complex balancing circuit can be reduced in future BMS [3].

## 3.2 SELF-HEATING MANAGEMENT

Operating a battery pack at temperatures lower than their operating temperature range highly reduces its charge and discharge capabilities. It also leads to safety issues like lithium plating and subsequent internal short circuit. Hence, the battery has to be preheated through external (using air, liquid or phase change material) or internal (using AC currents, internal resistive heating, convective heating and mutual pulse) heating methods [4].

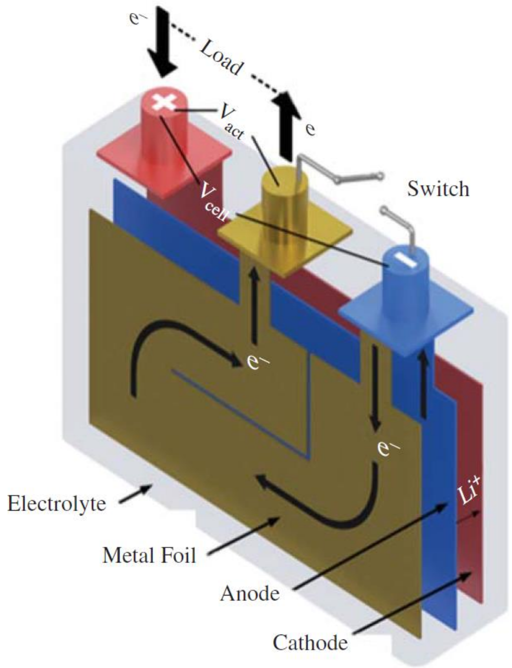


**Figure 2: Schematic of nickel foil-based self-heating [5]**

One such proposed self-heating method uses a nickel foil (50 µm thick) placed inside each cell as shown in Figure 2. An activation switch and temperature sensing circuit is used to perform self-heating through ohmic heating principle. The whole process is controlled by the BMS, depending on the operating conditions and requirements.

Implementation of this method requires the inclusion of a Ni foil inside each cell during the manufacturing process. This methodology proves practical through its adoptability across Lithium-ion battery shapes, sizes and chemistries. It also achieves a temperature rise from -20°C to 0°C in around 20 seconds, with just 3.8% consumption of the cell capacity [6]. With the growing necessity of effective and safe operation of battery applications at low temperatures (highly relevant to geographic regions experiencing very low temperatures during winter), such self-heating mechanisms will play a significant role in future BMS.

## 3.3 Enhanced Safety functionalities

Battery faults can lead to safety issues in EVs. Thermal runaway is always the biggest safety concern for lithium-ion batteries. With the use of thermal management systems, the events of purely temperature-induced thermal runaways can be minimized. The short circuit induced thermal runaways need to be intensely addressed. The short circuit events result in release of a large amount of heat energy within a very short period of time, leading to fires or even explosions.

BMS generally measures battery parameters such as current, voltage and temperature to detect a safety hazard. Nevertheless, monitoring of only these parameters might not be sufficient for detecting short circuit faults.

Moreover, the internal processes leading to an internal short circuit, namely lithium plating, separator corrosion etc. are not instantaneous but built over time. Hence several advanced model-based algorithms have been proposed and are still being improved for earlier detection of an internal short circuit [7] [8] [9]. Dedicated internal short circuit detection parameters are introduced, estimated and continuously monitored throughout the battery life. Any abnormality in the monitored parameters is used to detect the upcoming internal short circuit and subsequent thermal runaway. Avoiding lithium plating by using extended battery models on the BMS also reduces the risk of an ISC.

External short circuit (ESC) faults are equally dangerous as internal short circuits (ISC), capable of triggering high energy exothermic reactions which may spread to neighbouring cells. The ESC is caused by the accidental formation of a low resistance conduction path between the positive and negative battery terminals, due to dislocation/loss of insulation of surrounding conductive components. Similar to ISC detection algorithms, ESC detection model-based algorithms are also widely under development. The abnormalities in the voltage or current measurements shall be used as the triggering factor to initiate the ESC detection algorithms [10]. The development and implementation of ISC and ESC early detection algorithms is crucial for use in future BMS in order to ensure safe operation of battery applications.

## 3.4 Tamper proofing BMS

Hardware and software of the BMS should be designed tamper proof. Making the BMS tamper proof and being able to detect such tampering attempts would improve the safety of the BMS. Further improvements to operational safety include making the BMS sensitive to tampering.

The possible tampering attacks on BMS shall be classified as:

- **Software attacks:** Attacks through software agents like viruses, trojans and worms, due to the vulnerabilities or exposures in the software.

- **Physical attacks:** Physical intrusion at chip, board and system level in order to gain knowledge regarding the layout, components involved etc. for re-constructing or reverse engineering of the attacked Battery Management System.

- **Side-channel attacks:** Observing the properties of a system like fault diagnostics, computation speed, memory allotment, power consumption, electromagnetic radiation etc.

Such attacks shall be prevented through the following measures:

1. Use of a separate secure co-processor and memory modules dedicated for processing and storing all sensitive information respectively.
2. Encryption of all the information communicated by/to such processor and memory.
3. Secure bootstrapping on each system layer, software authentication and security check before execution.
4. Secure packaging of the BMS including seals, enclosures or sensor circuitry to detect and communicate about any physical intrusion.
5. Masking of such sensitive information, inclusion of noise into power measurement data, aggressive electromagnetic shielding etc.

While implementing the above listed measures to make a BMS tamper-resistant, it should also be assured that the confidentiality, integrity and availability (possibility of authorized access) of the system are maintained.

To conclude, the future BMS should be designed tamper-proof from both hardware and software side, if not feasible on all applications, it should at least be able to detect a tampering as soon as possible. Upon such detection, countermeasures like system shut down, emptying of sensitive data memory and recording of such attacks has to be implemented for later inspection [11].

With increasing events and threat of cyber-attacks on IoT-enabled applications, making future BMS tamper-proof will ensure the safety and integrity of the battery-powered application.

## 3.5 Cloud computing

With the development of IoT technology, cloud computing solutions are gradually being applied in BMS. A combined operation of the BMS on-board controller with a cloud-based computing system dramatically improves the performance of the BMS.

There are several architectures proposed for cloud computing enabled BMS. One such architecture is mentioned in [5] and shown in Figure 3. It mainly includes the following layers:

1. **The perceptual layer:** Collects measurement data namely cell voltage, current and temperature and performs basic functions like SoX estimation, safety management, thermal management and charging control.

2. **The net layer:** Responsible for the communication and data transfer with the connected cloud services which might take place through Wi-Fi, cellular system, radio signals etc.

3. **The application layer:** It is the core of cloud computation and performs the main functions namely battery lifecycle usage recording, remaining useful life estimation, battery health analysis, battery model parameter calibration, fault prediction and error data logging.

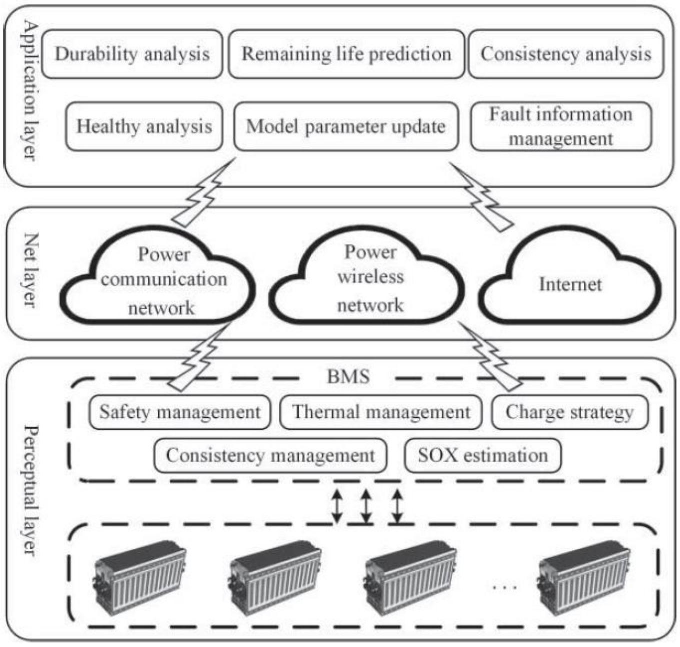


**Figure 3: Architecture of cloud computing for BMS in EVs [5].**

Highly complex algorithms are necessary to perform accurate state estimations, which in turn would demand more computational and memory resources from the BMS. The adaptation of cloud-based solutions for advanced data processing in BMS seems to be a promising methodology for developing a BMS within cost boundaries.

The most vital advantages yielded by cloud-connected BMS are:
1. Intelligent and advanced computationally intensive algorithms, which are difficult to be implemented in an on-board controller, can be implemented.
2. With the complex algorithms running on a powerful remote server, the estimation accuracy, computational speed, multi-tasking capability and data storage capacity can be improved.

The scope of cloud-based solutions or IoT in battery powered applications is not just limited to data processing and storage, but can also be extended further as follows:

- 'Usage-history' recording for residual value and 2nd life usability estimation
- Recommendation for time and extent of charging based on battery state, availability of chargers and electricity prices.
- Mobile app-based monitoring of battery state, balancing status, temperature distribution etc.,
- EV user recommendation on driving range, life and charging optimization, based on traffic, driving dynamics, charging station availability etc.

With such significant advantages and benefits provided by the cloud computing services to the BMS, such technologies are expected to have a huge positive impact in the design architecture, performance and cost of future BMS.

## 3.6 BMS VIRTUALIZATION

The BMS virtualization concept shown in Figure 4, is an adopted form of cloud-based solutions, specific for application in EVs. Here the main controller module of the BMS is replaced by the vehicle control unit (VCU) of the EV. Since VCUs are generally multi-core systems, capable of performing computationally intensive functionalities, BMS virtualization reduces dedicated BMS hardware. This is because only measurement and monitoring BMS modules are required as the controlling functions will be performed by the VCUs itself.

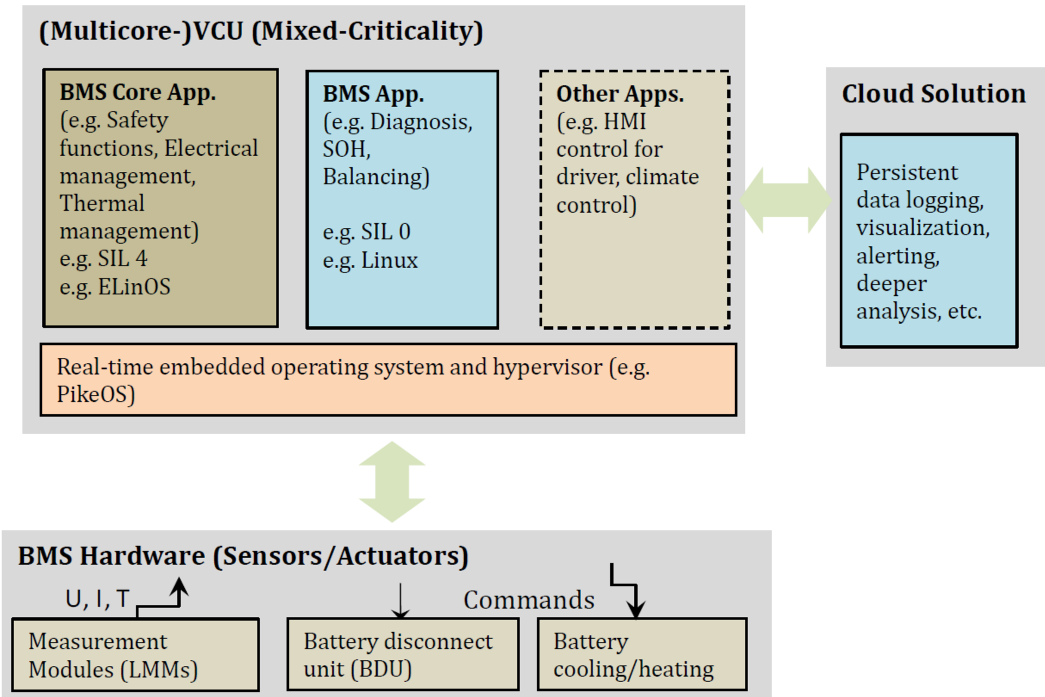


**Figure 4: Possible architecture for BMS virtualization [13]**

In the BMS architecture shown in Figure 4, it can be clearly seen that the BMS hardware is limited to the sensors and actuators. Such a BMS hardware is intended to collect, transmit measurement signals to the VCU, actuate thermal control and battery disconnect function according to the commands received from the VCU. Based on the monitored data received from the BMS hardware, the VCU performs main functionalities like state estimation, fault diagnosis, issues commands to respective sub-systems for performing balancing, thermal management and safety functionalities.

A real-time operating system shall be used to supervise the VCU. A cloud connected feature if included, shall extend the data storage and analysing capabilities of the VCU further.

The vital advantages provided by BMS virtualization include:

- Reduction in the size, cost and complexity of the dedicated BMS hardware
- Integration of advanced model-based algorithm VCU without additional modification in BMS memory or processing hardware
- This virtual BMS can be used as a development tool for training and research purposes (e.g. simulation building block)
- Multitasking of functionalities with varying criticalities and safety level ratings can be achieved through software isolation principle, improving the overall safety of the system

Since the BMS control module (Master) is virtually moved to the VCU, the measurement modules (Slaves) and the battery disconnect unit should be enhanced by equipping them with a dedicated microcontroller to communicate with the virtual machine master module [13]. Considering the benefits offered by such virtualization concept in terms of technical and economical point of view, the possibility of it being implemented in future EV BMS seems high.

## 3.7 Data security

With an enormous amount of data being collected, transferred and processed in embedded control systems, data security issues have become a concern. This fact is backed by the increase in data security related safety flaws in the embedded control systems in automotive and other embedded applications [14]. On an average, the amount of software code lines in a modern new EV can easily exceed the source codes in a (Hubble Space Telescope + a Boeing 787 Dreamliner + Facebook app) all combined [15].

Within such an EV system, several complex critical functionalities have to be performed for which several hundred data variables are collected, transmitted and processed. Considering the BMS as such an embedded system, if any of such critical data received/processed/transmitted by the BMS gets maliciously manipulated or corrupted, it could not only affect the performance, but can also lead to safety issues.

Hence, irrespective of the application, the data transfer within the BMS, with the connected systems as well as with the connected cloud server (if any) should be encrypted, and cyber security measures must be taken to guard the data stored in the server. Such data security measures will gain significance in future BMS.

## 3.8 Open source BMS platform

A BMS is intended to fulfil various application-specific requirements and perform functionalities ranging from safety to performance. In addition, the BMS development time and costs are also the factors to be focused on, since they have a huge impact on product cost and market penetration. The developed BMS design should facilitate the following targets:

1. Modification in the BMS hardware and software due to customer requests or application changes with minimum effort.
2. Compatibility with future technological improvements, as both the BMS hardware and software should facilitate extension/addition of add-ons to make the BMS a future-ready product.

3. A BMS which is understandable and useable by users with various levels of knowledge/experiences in BMS increases its usability. Community-supported open source platforms and references can enrich the user's knowledge on BMS.

Both the BMS hardware and software should be designed in a way that it can be easily adapted for a broad spectrum of applications ranging from mobility to stationary applications. It should also enable the implementation of new functionalities/components to improve the application served. For example, if an isolation monitoring functionality or a sophisticated algorithm has to be implemented, the user can easily apply them through corresponding APIs or drivers. The BMS architecture should also facilitate easy addition of more signal lines and devices.

An open and flexible BMS platform shall be defined as a basic structure upon which each BMS manufacturer can add their hardware and software functionalities to build application specific BMS. Thus, by designing and developing an open-source, flexible and modular BMS platform, both development costs and time can be saved. The reusability and adaptability of a BMS across applications and the capability to integrate new technologies can be improved.

The existence of such a platform will enable participation from a wide community to test and develop features for betterment of BMS-served applications, accelerating its market spread and reducing its cost. Thus, development and existence of such open BMS platforms will be an important phase of future BMS systems [16].

## 3.9 BMS 2$^{ND}$ LIFE MODE

Extending the service life of an end-of-life (EOL) EV battery system through its repurposing in a 2$^{nd}$ life application is a promising way of reducing its overall life cost and environmental impact. For repurposing, the cells in a battery pack are dismantled, tested and reassembled. But the associated BMS from the 1$^{st}$ life EV application may not always be carried over to a 2$^{nd}$ life application. This is mainly because an EV BMS is designed such that it fulfils the design and functionality requirements of an EV application. It has to handle and process several hundred signals and data which are specific to the application it is intended to serve.

Such requirements, functionalities and handled signal/data vary when moving from an EV application to a 2$^{nd}$ life stationary use. Major changes have to be made in areas such as communication protocol and information to be shared by the BMS. Although such adaptations completely depend entirely on the systems present in the 2$^{nd}$ life application and the required functionalities, general guidelines for their adoption into potentially identified 2$^{nd}$ life applications, have to be devised respectively.

If provisions for such adoptions are considered while designing and developing an EV BMS, then repurposing it for a 2$^{nd}$ life application would be comparatively easy and economical. Depending on the 2$^{nd}$ life application, both hardware and software modifications and components shall be provided as add-ons by the EV BMS manufacturer, while repurposing an EV battery pack for a 2$^{nd}$ life application.

The modifications in the BMS software should be made through trained and authorized personnel, while the provisions for integrating additional hardware need to be provided in the EV BMS itself. After implementing the required modifications/additions, the BMS shall be assigned to be operating in a 2$^{nd}$ life mode. The operational limits of the battery pack and the depth of information required, collected, processed and transmitted by the BMS are tailored with relevance to the second-life application. Inclusion of such a 2$^{nd}$ life mode in an EV BMS will have a positive impact on the future BMS.

## 3.10 Impact of Battery Technologies

The battery chemistry specific parameters namely operating window, operating mechanism, state estimation methodology, monitoring and control measures, vary with evolving battery technologies. Future BMS have to undergo significant modifications and updates in order to fit themselves in controlling such battery packs.

Apart from existing Li-ion battery technology, there might be different technologies in the future, below we listed in Table 1, some of the most potential candidates which are currently emerging with significant battery market share. The modifications/updates the BMS have to undergo to efficiently manage such technologies are also stated in correspondence.

**Table 1: Impacts of evolving battery technologies on future BMS**

| Battery technology | Background | (Needed) Updates/impacts in BMS |
|---|---|---|
| **Redox flow batteries** | This battery consists of two liquid electrolytes (catholyte & analyte) in separated tanks. When these electrolytes are pumped through a reaction chamber consisting of an ion-exchange membrane, simultaneous oxidation and reduction takes place resulting in charge transfer.<br><br>Vanadium flow batteries seem to be a promising form of flow batteries for large-scale applications, with a predicted market annual growth of 30% in upcoming years [17] [18]. | SoC estimation algorithms based on the concentration of ions in the catholyte and analyte.<br><br>SoH estimation algorithms based on the degradation of the ion-exchange membrane.<br><br>Additional functionalities for monitoring and control of hydraulics, intended to control the flow rate of catholyte & analyte , opening/closing of valves etc. |
| **Solid-state batteries** | Similar mechanism as that of Li-ion batteries, but with liquid electrolyte replaced by a solid electrolyte (mostly glass, ceramic based) and electrodes replaced by more environmentally friendly, affordable and long lasting compounds (like sodium, sulphur etc).<br><br>Higher energy density and cycle life shall be achieved at a price lesser than comparable Li-ion battery technology [18]. | Sophisticated preheating strategy, since solid state electrolytes conduct efficiently at higher temperatures (at least 10-fold higher than standard room temperature of 25 °C).<br><br>Advanced monitoring and state estimation techniques to understand the degradation mechanisms of the solid-electrolyte and sodium electrodes.<br><br>Temperature uniformity inside the battery needs to be maintained through effective thermal management for efficient operation.<br><br>Specific monitoring techniques to avoid high operating temperature and environmental leakage-related safety hazards (highly reactive sodium and sulphur). |

| | | |
|---|---|---|
| **Battery-capacitor hybrid systems** | Hybrid systems consisting of a battery technology (Lead-acid, Li-ion etc) coupled with a capacitor-based system (Ultra/super capacitor) is gaining more interest due to its technological and economic benefits.<br><br>Such hybrid systems help in achieving both the power and energy densities required by the application, increase the longevity of the battery by avoiding frequent partial cycles and also reduce the cost of the overall system compared to a pure battery-based energy storage system [19]. | Monitoring functionalities for two different energy storage technologies, varying in operating voltage, current and temperature ranges.<br><br>State estimation algorithms for estimating the SoX parameters and degradation of two technologies with varying chemistry, operating mechanism, and degradation.<br><br>Intelligent switching and charging priority allocation between the battery and capacitor, depending upon the nature of the load cycle.<br><br>Separate balancing strategies and hardware for two different technologies. |

# SUMMARY

This white paper has addressed the need of Battery Management Systems, further briefing the advances in terms of cell balancing, self-heating, IoT enabled cloud computing services, and their possible impacts on future BMS. Cloud computing and more powerful VCUs might shift the battery modelling away from the BMS. Therefore, secure communication becomes more critical. Further, the need of implementing data security, tamper-proofing, BMS virtualization concept and BMS 2$^{nd}$ life mode were also explained in short, along with their positive impact on future BMS.

Finally, the potential battery technologies, which are predicted to hold notable market share in the future were also stated and the modification/updates that the existing BMS have to undergo in order to accommodate such battery technologies, were also tabulated. For improving the performance, longevity of the future battery systems and for assurance of their safe operation, the implementation of features/functionalities mentioned in this document, in future BMS is highly recommended.

As a conclusion, it can be understood from the topics discussed in this white paper that the BMS are steadily evolving on various aspects, in concurrence with the advances in battery powered applications and battery system specific technologies, thus making the future BMS more capable and credible.

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