Safe Energy Storage Systems for Hybrid Electric Marine Vessels

C. Watts[*a], J. Marco[b], P. Faithfull[c]
[a]*Babcock Defence Systems Technology Ltd, Leicester LE3 1UF, UK*
[b]*Warwick Manufacturing Group (WMG), University of Warwick, Coventry CV4 7AL, UK*
[c]*Potenza Technology Ltd, Coventry CV4 8AW, UK*

*Corresponding author. Email: chris.watts@babcockinternational.com

Synopsis

In recent years, with the fuel consumption of marine vessels accounting for an increasing portion of total global fuel usage, there has been significant effort in improving emissions within the shipping industry. Improving the energy efficiency of vessels is therefore necessary for saving fuel as well as underpinning a future reduction in greenhouse gas emissions. This demand has led to an increase in hybrid-electric and full-electric propulsion technologies capable of interfacing multiple power sources, including batteries, with ever more sophisticated energy management systems.

The focus of this paper is to consider the safety implications of battery systems on board marine vessels and how they integrate with energy management and distribution systems. Experience has been drawn from an automotive perspective, where advances in battery technology and integration have been significant over the last decade, with a great deal of this knowledge potentially being applicable to the marine sector.

The safety issues surrounding Lithium-ion battery technology are well documented, with several high-profile cases involving failures resulting in dangerous situations. Inevitably, this has led to reluctance in the adoption of Lithium battery technology across numerous sectors. This is particularly relevant to the marine sector, where future demand for clean, efficient power is driving the industry towards more energy and power dense storage technologies, while maintaining a high level of safety within frequently harsh environments.

In order to meet these demands, a holistic approach to marine power provision must be adopted, where energy storage is incorporated early in the design process in order to protect and prolong battery life. Key considerations are inherently safe chemistries with robust management systems built around them and effective control of the installation environment, employing cooling and monitoring systems where appropriate.

Keywords: marine vessel, propulsion, hybrid, full-electric, energy storage, battery safety, technology transfer

1 Introduction - Marine vessel energy management systems

Energy management systems (EMS) are high on the agenda across many sectors for further development. The ideal system would increase efficiency, reduce environmental impact and drive down cost; in both production and operation. There is also an increasing demand within the marine sector to implement sufficient energy storage into these systems to improve the efficiency by storing surplus energy in times of low load and bolster the supply during a peak load period – improving system resilience. Furthermore, from a defence perspective, advancements in pulse power technologies (rail guns, electromagnetic launchers, high power radar etc.) requiring large amounts of power will need devices capable of high capacity and rapid charge/discharge capabilities to supplement them [1]. Hence there is a business opportunity to deliver robust and inherently safe solutions to address future demand.

At sea, the vessels deployed on operations are in themselves mobile, condensed versions of the national power grid; this is an area where the whole system can be reinvented by a modern energy system implementing cutting edge energy storage and smart grid technology to improve vessel efficiency and capabilities.

The maritime sector, both military and commercial, is a huge potential market for new energy innovations as the requirements of the modern ship are very different to those of its predecessors. The need for increased functionality, higher levels of automation, longer at-sea life, EU directive compliance and reduced through life

Authors' Biographies

Dr. Chris Watts is Technology Acquisition Lead at Babcock Defence Systems Technology. He is a Chartered Engineer and member of the IET. He obtained his PhD from the University of Leicester in the field of brushless motors and drives. He is currently working within R&D to expand the company product portfolio into new markets.

Dr. James Marco is a Reader in Vehicle Electrification and Energy Storage at WMG, University of Warwick. He is a Chartered Engineer and member of the IET. His research interests include the application of systems engineering, real-time control, and physical systems modelling for low carbon technologies in the transport and energy storage sectors.

Dr. Paul Faithfull is the founder and Managing Director of Potenza Technology Ltd. He has many years' experience working in the automotive sector, particularly in the field of hybrid and electric vehicles. He has worked on the development of vehicle control systems, including electronics, software and safety analysis.

cost can be addressed through the development of an adaptable energy system implementing the latest energy storage and distribution technologies.

Across the automotive sector, recent developments in energy storage technology are increasingly being applied in electric vehicles (EVs). This ranges from mild hybrids, incorporating internal combustion engines with electric motors, to fully electric plug-in battery powered vehicles. There is scope for similar usage in marine vessels, with several potential benefits:

- Reduced capital cost on electrical generation equipment.
- Improved fuel economy from operating engines in their most efficient power / torque regime.
- Reduced environmental emissions, associated with improved energy efficiency.
- Greater flexibility and robustness from a fully integrated power system.

The introduction of novel energy storage and management systems provides an attractive solution when coupled with modern trends of marine propulsion and power distribution. The development of hybrid and full-electric propulsion, incorporating both direct and indirect drive systems enables greater flexibility, not only in the design of vessels, but also in their operability. This in turn affects through life cost and environmental impact. The move towards DC distribution facilitates this further, with improved technologies becoming available to overcome the hurdles that have prevented DC adoption over AC distribution in the past [2].

2 Potential technology transfer from the automotive sector

A recent 2015 report by KPMG [3] highlights the potential for electrified vehicles to be between 11-15% of new vehicle sales within the EU and China by 2025. Within the US, the market may comprise 16-20% of vehicles over the next 10 years. These predictions are comparable to those cited in [4]. The article collates a number of studies and concludes that, by 2025, there will be in excess of 11 million EV sales worldwide, with approximately 6 million in North America (20% of new vehicle sales). While a number of sources predict rapid sales growth, there are variations in the predicted technology-mix that will underpin this. In particular, the relative sales of hybrid electric vehicles (HEVs) that typically employ a smaller battery system (e.g. Toyota Prius Plug-in Hybrid Electric Vehicles (PHEV), with a 4.4 kWh battery), compared to an EV (e.g. the Nissan Leaf or the BMW i3), which require larger batteries in the order of 24 kWh and 22 kWh respectively. Table 1 presents the battery specification for the battery systems employed within a subset of commercially available EVs. Further, Figure 1 presents an overlay of different energy and power requirements for a range of vehicle types including EVs and HEVs (including plug-in, mild hybrids and full hybrids).

Table 1: Battery Pack Specification for a sample of commercial EVs

Model	Battery pack energy (KWh)	Electric power (kW)	Maximum C-rate [hr^{-1}]	Nominal battery pack Voltage (V)
Tesla Model S	85	310	3.6	355
Nissan Leaf	24.0	80	3.3	360

A consensus does not yet exist as to the optimal design of battery cell, in terms of both chemistry and form-factor, for use within automotive applications. There is significant research characterizing the different chemistries, including: Lithium Cobalt Oxide ($LiCoO_2$), Lithium Iron Phosphate ($LiFeP0_4$), Lithium Nickel Cobalt Manganese (NCM - $LiNi_xCo_yMn_xO_Z$) and Lithium Titanate Oxide (LTO - $LI_4Ti_5O_{12}$). These chemistries are discussed further in Sections 3 and 4. Table 2 summaries the pertinent performance characteristics for a range of Lithium battery technologies. The integration challenge associated with designing a complete energy storage system (ESS) using either pouch cells or cylindrical 18650 cells is reported within [5-7]. In [5] and [6] the authors highlight how cell-to-cell variations and non-uniformity within the cell further complicates ESS integration. Whereas within [7] the authors discuss the instrumentation and on-line monitoring requirements that underpin the battery control software.

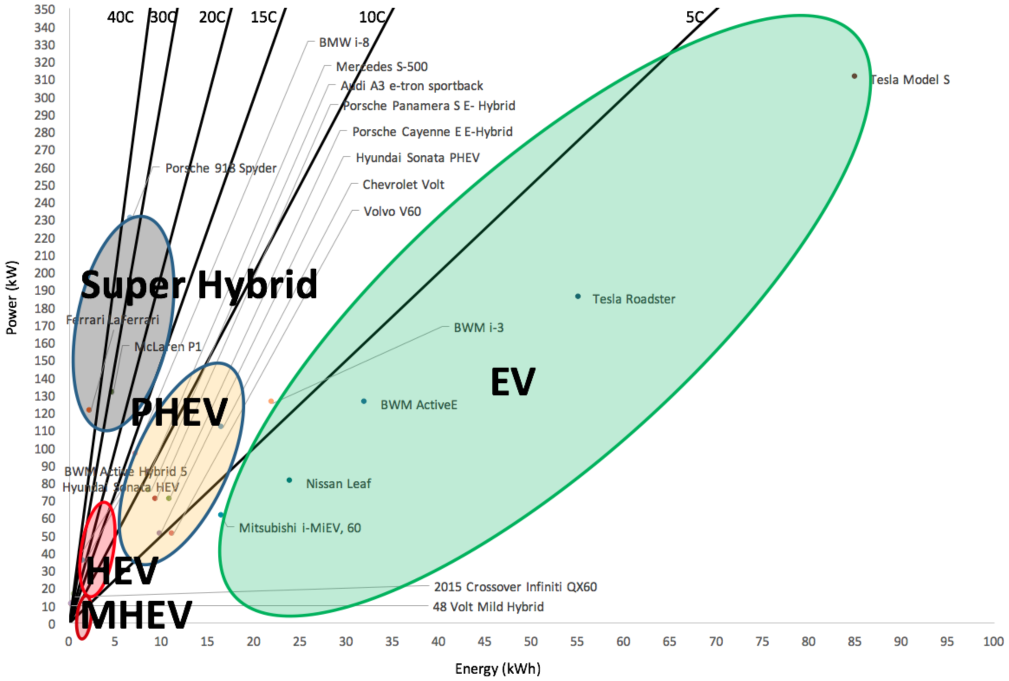

Figure 1: Overview of electrified vehicle market and energy storage power and energy requirements

Table 2: A summary of Lithium battery technologies under investigation by the automotive industry

Cathode chemistry with exception of $Li_4Ti_5O_{12}$	Cell specific energy density [Wh.kg^{-1}]	Cell energy density, [Wh.l^{-1}]	Cycle life (durability), 100% DoD	Estimated price [US$/Wh]	Power C-rate [hr^{-1}]	Onset of thermal runaway (safety) [°C]	Nominal cell voltage [V]	Upper and lower operating temperature limits [°C]
$LiCoO_2$	170-185	450-490	500	0.31-0.46	1 C cont.	150	3.6	-20 to 60
$LiFePO_4$ (EV/PHEV)	90-125	130-300	2000	0.3-0.6	5 C cont. 10 C pulse	270	3.2	-20 to 60
$LiFePO_4$ (HEV)	80-108	200-240	>1000	0.4-1.0	30 C cont. 50 C pulse	270	3.2	-20 to 60
$LiMn_2O_4$	90-110	280	>1000	0.45-0.55	3-5 C cont.	255	3.8	-20 to 50
$LiNi_xCo_yMn_zO_2$ (EV/PHEV)	155-190	330-400	1500	0.5-0.9	1 C cont. 5 C pulse	215	3.7	-20 to 60
$LiNi_xCo_yMn_zO_2$ (HEV)	150	270-290	1500	0.5-0.9	20 C cont. 40 C pulse	215	3.7	-20 to 60
$Li_4Ti_5O_{12}$	65-100	118-200	12,000	1-1.7	10 C cont. 20 C pulse	Not susceptible	2.5	-50 to 75
$LiNi_{0.8}Co_{0.15}Al_{x0.05}O_2$	233	630	500	0.23-0.61	1 C cont. 5 C pulse	150	3.6	-20 to 60

It is beyond the scope of this paper to discuss, in detail, the engineering challenges associated with the ESS; further information can be found within [7, 8]. To illustrate the complexity within a real-world automotive system, Table 3 presents an overview of the contents of the battery pack within the commercially available Nissan Leaf EV. The Nissan Leaf has a reported range of 109 miles over the New European Drive Cycle (NEDC). The complete battery assembly weighs 293 kg and contains 48 battery modules, each containing 4 Li-ion pouch cells. An active cooling system is not included within the battery, but it does contain an electrical heating element to warm the Li-ion cells. The 48 modules within the battery are grouped together into 3 primary sub-assembles called module stacks, each containing a number of electrical interfaces and mechanical fasteners. The battery pack is held together and attached to the vehicle chassis using 20 mechanical bolts. Within the battery, at the module stack and module levels, a variety of different joining methods are employed, including mechanical screws and bolts, totalling 376 fasteners.

Table 3: Overview of the Nissan Leaf battery system

Nissan Leaf Battery System Overview									
Module Stack 1		Module Stack 2		Module Stack 3		Mechanical Subsystems		Mechanical Subsystems	
Item	Quantity	Item	Quantity	Item	Quantity	Item	Quantity	Item	Quantity
Modules	12	Modules	12	Modules	24	Compression Test Plug	1	BMS	1
Enclosures	24	Enclosures	24	Enclosures	48	Enclosures	2	BMS Mounting Bracket	1
Inner Cell Bundles	12	Inner Cell Bundles	12	Inner Cell Bundles	24	Cross-member Support	3	BMS Casing	2
Insulation sheets	24	Insulation sheets	24	Insulation sheets	48	Wiring Harness Brackets	4	Enclosures (Top/Bottom)	2
Metal Inserts	48	Metal Inserts	48	Metal Inserts	96	Seal	1	Bus Bar	4
Spaces	24	Spaces	24	Spaces	48			Current Sensor	1
Terminal Protection	12	Terminal Protection	12	Terminal Protection	24			Wiring Harness	1
Front Brackets	12	Front Brackets	12	Front Brackets	32			Relay Bracket	1
Rear Brackets	4	Rear Brackets	4	Rear Brackets	16			High Voltage Bus Bar	4
Bus Bar Assembly	1	Bus Bar Assembly	1	Bus Bar Assembly	1			Wiring Support	2
Base Plate	1	Base Plate	1	Base Plate	1			Plug	1
Front and Rear Plate Assembly	2	Front and Rear Plate Assembly	2	Brackets	4			Fuse	1
				Sub-pack Restraining Bolts	4			Relays	3
								Temperature Sensors	3
								Spacer	1
								Resistor	1

Moving forward, the automotive industry is embarking on a comprehensive programme of collaborative research and development, working in partnership with a number of UK academic institutions and stakeholders from across the energy storage supply chain. The Advanced Propulsion Centre (APC) has developed a research roadmap that defines the primary challenges across the different Technology Readiness Levels (TRLs) that they have proposed to the UK government and it is this that will underpin much of the investment and research strategy, as the UK seeks to decarbonize and electrify much of the transport sector. The matrix of research challenges is presented in Figure 2.

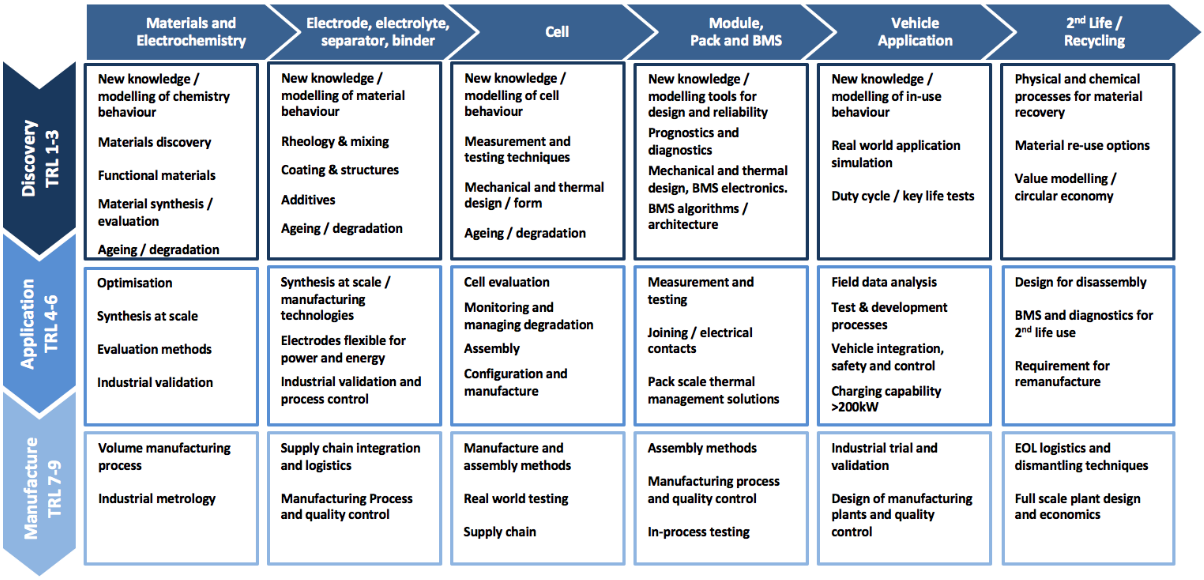

Figure 2: Research challenges across the TRL spectrum for the induction of energy storage within the transport sector

3 Established battery chemistries

This section provides some background on the most common battery technologies available on the market and widely used across many sectors today.

3.1 Lead-acid

Lead-acid batteries are a very mature technology, being the standard choice for automotive SLI (Starting Lighting Ignition) with internal combustion engines. They also have an extensive maritime heritage, from small pleasure craft through to submarines. Lead-acid batteries prefer to be maintained at 100% state of charge, but special versions are designed for deep discharge cycling.

In comparison to Lead-acid alternatives, Li-ion is expensive; for this reason the Lead-acid market has not been majorly affected. Where space and weight are not such a primary concern, Lead-acid batteries are still excelling due to their low cost to energy density ratio, which is compared in Table 4.

The affordability of Lead-acid batteries has allowed them to retain their place in the market and for the predicted future. Recent reports analysing the market suggest that Li-ion and Lead-acid batteries are set to dominate the battery market in the next 10 years [9].

Table 4: Battery chemistry comparison

Battery type	Cost ($/Wh)	Wh/kg	Joules/kg	Wh/litre
Lead-acid	$0.17	41	146,000	100
Alkaline long-life	$0.19	110	400,000	320
Carbon-zinc	$0.31	36	130,000	92
NiMH	$0.99	95	340,000	300
NiCad	$1.50	39	140,000	140
Lithium-ion	$0.47	128	460,000	230

Lead-acid batteries have a proven and established recycling supply chain, benefit from low maintenance requirements and are capable of high discharge rates. However, improper charging can lead to thermal runaway and risk of explosion due to the emission of hydrogen and oxygen, which can be of significant concern in poorly ventilated enclosed spaces. Other safety concerns arise from the environmentally unfriendly nature of both the electrolyte and Lead which can be extremely toxic with long term health impacts.

Advancements such as TPPL and AGM (Thin Plate Pure Lead and Absorbed Glass Mat) technology have breathed new life into the platform, offering higher energy densities while reducing weight. In the same battery family are Lead-carbon batteries, their aim being to have the high energy density of a battery with the high power output of a supercapacitor. By adding carbon to the negative plate of the electrode, the issue of sulfation found in Lead-acid is removed; this in turn improves charging/discharging performance and prolongs the battery’s life. Lifetime and the need for regular replacement when compared to Li-ion will also be the major issue for Lead-acid technology in large capacity installations.

3.2 Lithium-ion

Lithium is the current dominant battery technology for small-scale power supplies in consumer goods (phones, laptops etc.) and across the modern electric vehicle market. This is due to its superior energy density and it’s cornering of the market, both in terms of investor backing and the current structure of the supply chain which is geared to the manufacturing and distribution of Li-ion batteries. Announcements such as the Tesla Gigafactory, which will drive up production and drive down cost, only serve to further cement Lithium based cells in the market for the coming decade.

Where size and weight are a factor, Lithium-ion batteries are dominating the energy storage industry which is largely due to low self-discharge, low maintenance and their superior energy density over previously dominant Nickel based chemistries (NiCad and NiMH) and Lead-acid. This density allows them to be scaled down to smaller physical sizes while still offering the capacity to power our modern-day electronics i.e.

smartphones. When size/weight is not such a constraint, Li-ion batteries have brought about a revolution in the form of viable electric cars which are a major global market trend [10].
The main Lithium technologies currently on the market are:

- Lithium Cobalt Oxide (LCO)
- Lithium Iron Phosphate (LiFePO)
- Lithium Manganese Oxide (LMO)
- Lithium Nickel Manganese Cobalt Oxide (NMC)

Although Lithium Cobalt Oxide offers greater energy density than the other types, they present increased safety risks, especially when damaged. The other technologies, despite lower energy density, offer longer life and improved safety, with Lithium Iron Phosphate currently favoured for off grid, marine, and vehicle applications.

Lithium technology does have its limitations, the risk of thermal runaway in modern Li-ion cells has resulted in specific regulations it must abide by for transportation due to risk of fire and explosion under certain circumstances [11]. To mitigate this, protective circuitry is required alongside robust battery management systems, which contributes to their relatively high cost.

After the high-profile battery failure issues on Boeing's 787 Dreamliner, the fleet of 50 was grounded while engineers worked to redesign the battery unit to improve safety [12]. The following improvements were made:

- Improved electrical insulation
- Spacers used to improve thermal and electrical isolation
- Battery Monitoring Unit employed to tighten the allowed voltage range
- Drain holes added to the frame to allow potential moisture to escape
- Each cell wrapped in electrically isolating tape

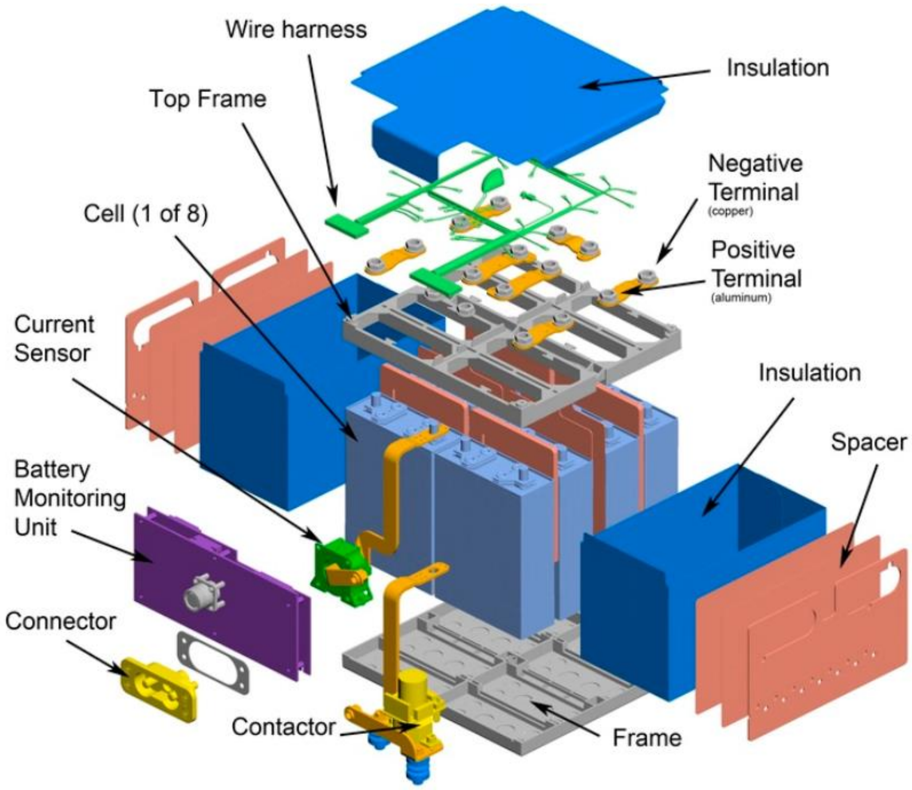

Figure 3: Boeing's improved battery unit [12]

These features combined are assumed to help prevent potential failures leading to unsafe events and reduce the impact of any issues that do occur. The adjustments demonstrate how limitations in the inherent safety of battery chemistries can be compensated for to enable their integration into robust energy management systems.

4 Developing battery chemistries

Although Lithium-ion is currently the dominant chemistry across a number of sectors, including marine hybrid technology, the desired performance characteristics of future power systems will clearly surpass the limits of its capabilities. Even with projected improvements in Li-ion capacity, the inherent shortfall in the technology means that novel chemistries will need to be developed. In the short term, Li-ion will remain the market leader, but this is set to change, with key drivers being capacity (in terms of both energy and power density) and safety.

4.1 Advanced Lithium technology

4.1.1 Lithium-titanate

The chemistry characteristics of Lithium-titanate technology offers increased operational safety and higher levels of abuse tolerance than existing Lithium-ion technologies.

The advantages of these batteries are that they can be charged very quickly, have a longer life, higher power density, wider operating temperatures, and greater stability under electrical and mechanical stress (i.e. the cells cannot catch fire) when compared to other Lithium-ion technology. A disadvantage is that they have lower specific energy than other Lithium-ion cells.

4.1.2 Lithium-sulphur

Lithium-sulphur cells were under development well before Lithium-ion technology was introduced. They are cheaper than Li-ion due to their use of sulphur and are inherently safe due to their chemistry.

Lithium-sulphur cells have a higher energy density (5 times) than Lithium-ion, making them a very promising future alternative. Technical challenges include self-discharge, coulombic efficiency, and rate performance. They are still relatively prototypic, but are now starting to become available on the market in small volumes.

4.2 Sodium-ion

Although currently at a low technology readiness level (TRL), Sodium-ion batteries are a promising competitor for the dominant Lithium-ion chemistry within many sectors, including grid storage and marine; offering many of the same characteristics. Their advantage is that they are up to ten times cheaper to produce due to the abundance of Sodium salts in comparison to Lithium salts. They can be drained to zero charge, which allows for safer shipping and storage. The major factor preventing this technology from taking off is the slow charge/discharge rate, though recent research has been successful in improving this. This slow charging rate, though limiting for dynamic systems, wouldn’t prove a problem in applications such as grid balancing. Hence, despite Sodium-ion lacking the inherent power density required for pulse power applications, as the technology advances and becomes widely available on the market, its attributes indicate significant potential for the marine sector in general.

4.3 Solid-state

Solid-state batteries are unique in that they have no liquid electrolyte; this means no leaks, no risk of fire and an increased storage life. The batteries have no need for any cooling system or supporting material which makes up more than half the weight of a Lithium-ion package. Their ability to be scaled down to very small sizes, along with the low weight, makes them perfect for portable electronics and remote powering. Also, with zero risk of fire, they circumvent the transport regulations which hinder liquid-electrolyte batteries i.e. airlines banning Lithium-ion batteries from cargo hold. The limiting factor for this technology is the low power-density, with the difficulty of getting high currents across solid interfaces. This must be improved if it is to be used in modern systems with high power demands. They are also currently at a low TRL, meaning that it will be some time before they are readily available on the market.

4.4 Metal-air (Aluminium, Lithium, Zinc etc.)

Metal-air batteries are promising for the future due to potentially high energy-density, long lifespan, cheap operation and recyclability.

These batteries produce energy through the reaction of metal oxidising with air. The air is taken from the ambient environment through an electrode which can ‘breathe’ the air into the battery with water being used as the electrolyte. These batteries claim to achieve higher energy densities than that of Li-ion but are at a very low

TRL. Lithium-air batteries, for example, have the potential to reach energy densities up to 10 times higher than current Li-ion cells, but at their present TRL suffer from poor cycle life and charge rate. However, many of the reported improvements fail to take into account the additional balance-of-plant required to make the battery function properly.

4.5 Supercapacitors

Supercapacitors are a commercially available technology with a high TRL. Due to their high charge and discharge rates, they can meet peak demands when they arise and then quickly store energy and excess power that would otherwise be lost. They are almost tailor made to meet the pulse power demands that occur on a marine vessel with power densities up to 10 times that of batteries. Future pulsed power requirements are likely to increase for naval applications with development of electromagnetic launch (e.g. aircraft, torpedo), directed energy weapons (lasers) and high power radar.

Supercapacitors can be charged in seconds, perform well at low temperatures, have virtually unlimited cycle life. Due to their low internal resistance, they do not heat up as much as batteries and are not susceptible to explosion when short circuited. This simplifies the charging process and reduces the number of safety considerations. However, they have a tendency to self-discharge, compared to batteries. They also have a linear discharge voltage meaning that the full energy spectrum of the device cannot be fully exploited. If used continually or in long bursts, they require thermal management, although their attributes make them generally unsuitable for use in this manner and so, if implemented correctly, this should not be an issue.

Hybrid Lithium-ion capacitors are also being developed, with intermediate power and energy values [13]. The electrolyte is the same as Lithium-ion cells and so suffers from the same flammability issues. The electrodes are typically a mixture of high surface area active carbon and partially lithiated graphite; the former provides the power and the latter the energy.

5 Safety standards and challenges

Automotive standards for high voltage batteries (classified as above 60V DC in [14]) are evolving rapidly, with notable moves in the Chinese regulations around electric vehicles. The primary standard is UNECE Regulation No. 100 [14] which defines mechanical safety mechanisms (finger proof connectors for example), levels of isolation required and tests to be undertaken on packs which include reaction to potential failure stimuli e.g. external fire and over-charge. For software and hardware design at a BMS level, the ISO26262 standard [15], derived from IEC61508 defines the process for identifying hazards, and establishing the development process to ensure robustness and rigour. This is not a requirement (in the same manner of vehicle homologation) in order to place a product on the market, but rather a defence case in proving best practice has been applied in the event of litigation.

Within the marine sector the regulations come from certification bodies, rather than from national or UN regulations. Thus a ship can undertake to meet the requirements of a certification body e.g. Lloyd's [16], DNV GL [17], or ABS [18] by meeting a different set of requirements. At present there are a number of guidelines, which follow a different ethos to automotive of: "detect and contain" rather than reliance wholly on prevention. Within automotive, the low failure rate (leading to thermal event) is acceptable as thermal events tend to lead to occupants exiting a vehicle and the loss of a relatively low cost vehicle. For large marine vessels, the cost of the vessel, combined with the number of occupants who could potentially sustain harm, and ultimately a different commercial model will result in a different approach to tackling harm. It could be that marine applications lead automotive in the future with respect to safety mechanisms as piece-cost is less inhibiting.

Packaging of battery modules has an influence in automotive, as there is limited space and weight restrictions. For example, there is simply no room for fire suppression systems such as a fire extinguisher, whereas in a marine environment, weight and space are less restricted meaning the use of water or foam to deal with fires is possible. However, it should be noted that if thermal runaway is initiated in a cell within a packaged battery module, there is little that can be done to avoid internal damage and the knock-on effect to other cells leading to fire and explosion. Therefore, prevention of this state in the first place is a critical aspect of safety.

The approach to high levels of electric vehicle battery safety is discussed in detail in [19] where many layers of various safety techniques are used to create a holistically safe system. Figure 4 shows the safety onion from [19] with examples of diverse safety actions used to ensure a low probability for fault, and to minimize the consequences of a fault. In principle, there are three main safety levels: cell, battery system and vehicle level.

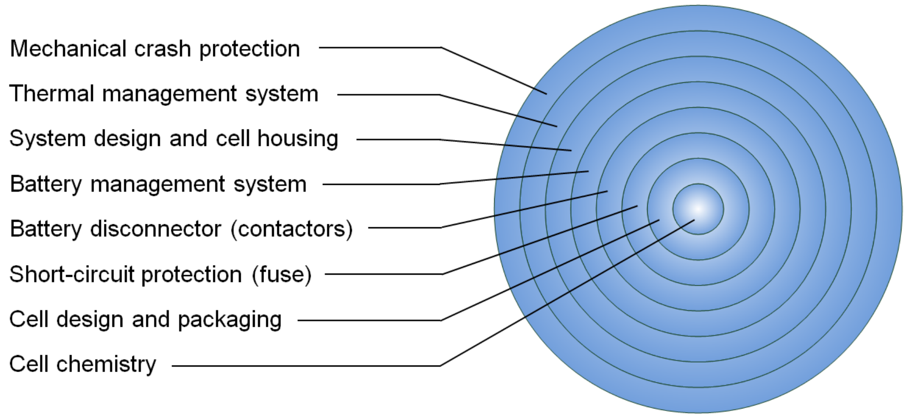

Figure 4: The safety onion showing examples, layer by layer, of different safety actions that can be used to establish a safe battery system in electric vehicles [19]

The above approach of layered safety can be adopted for the marine environment and is indeed encouraged by the rules, regulations and guidance currently published [16-18]. These publications suggest a holistic approach, where the main safety levels are cell, management system and environment. In general, the key design principles can be identified as:

- Consideration of hazards – mechanical, chemical (cell type), electrical, fire, environmental
- Location of battery space and configuration
- Environmental control – temperature and humidity, cooling and ventilation, hazardous area designation
- Fire safety – detection, protection, suppression
- Management system – battery management (BMS), monitoring, communications, interfaces, software
- Testing – at cell and system level, environmental, interfaces, alarms, safety functions
- Operation and maintenance – human factors, through-life management

There is an emphasis on testing, particularly in [17] at cell, system and environment levels to ensure safety is fully proven before installation in a vessel. Compliance is referenced to external standards in the form of IEC and UN for acceptability, although the approval of specific battery chemistries is on a case-by-case approach, acknowledging a rapidly developing market.

6 Conclusions

6.1 A holistic approach to safety drawing on an automotive approach

Developing safe hybrid propulsion systems incorporating energy storage for a marine environment can draw significantly on the automotive approach. Development of robust control systems will be key to maximising performance while ensuring safety.

HIL (Hardware-in-the-loop) testing has been employed extensively for automotive systems and this technique can be adopted effectively to consider marine micro-grid power systems.

There are a number of attributes to developing safe energy storage systems on board marine vessels that are common in the automotive sector. Shock and vibration are prominent considerations for both applications, as are cooling methodologies and fire suppression. Battery characterisation, including thermal cycling and abuse testing can highlight issues with specific technologies and indicate the levels of mitigation required in systems and sub-systems to address them. Some technologies are inherently safer than others, with cell chemistry being the basis of thermal stability coupled with effective cell design and packaging. A good understanding of this through characterisation is therefore crucial in the design of safe systems and in this way costs can be reduced by only applying necessary mitigation strategies.

Legislation and guidance is still relatively immature for the marine environment, with the likes of Lloyds, DNV GL and ABS starting to publish and further develop specific documents on energy storage systems, working on a case-by-case approach as technology evolves.

6.2 *Further work*

The Innovate UK funded Marine Energy Management Project is underway to develop an Agile Power Management System (APMS). The project will create algorithms for the optimal management of marine energy systems, considering the performance and safe implementation of energy storage. HIL testing is being used to develop the algorithms specifically for marine usage scenarios, drawing on the expertise of the partners from an automotive approach.

In parallel with this, the project will also investigate a number of battery chemistries and supercapacitors for use in the marine environment. This test range will encompass both well-established and relatively novel technologies, which are just starting to become available on the market. The energy storage devices will be characterised by testing under a range of temperature and charge conditions to determine performance capabilities and safety considerations.

The APMS project aims to take significant steps forward in developing marine energy management systems, safely incorporating energy storage, by adapting a holistic approach via technology transfer from the automotive sector.

7 Acknowledgements

This research is supported by Innovate UK through Project Number: 102437 in collaboration with Babcock Defence Systems Technology Ltd; WMG Centre High Value Manufacturing (HVM) and Potenza Technology Ltd.

8 References

1. Lloyd’s Register, QinetiQ and University of Southampton, Global Marine Technology Trends 2030 p113, August 2015.
2. A S Allan, MEng, MIET and C G Jones, MEng, PhD, MIET; Frazer-Nash Consultancy Ltd., UK. Modelling and simulation of direct current electrical architectures and key enabling technologies.
3. Becker D. KPMG’s Global Automotive Executive Survey 2015.
4. Ramoni MO, Zhang HC. End-of-life (EOL) issues and options for electric vehicle batteries. Clean Technol Environ Policy 2013;15:881–91. doi:10.1007/s10098-013-0588-4.
5. Lu L, Han X, Li J, Hua J, Ouyang M. A review on the key issues for Lithium-ion battery management in electric vehicles. J Power Sources 2013;226:272–88. doi:http://dx.doi.org/10.1016/j.jpowsour.2012.10.060.
6. Santhanagopalan S, White RE. Quantifying Cell-to-Cell Variations in Lithium-ion Batteries. Int J Electrochem 2012;2012:1–10. doi:10.1155/2012/395838.
7. Waag W, Fleischer C, Sauer DU. Critical review of the methods for monitoring of Lithium-ion batteries in electric and hybrid vehicles. J Power Sources 2014;258:321–39. doi:10.1016/j.jpowsour.2014.02.064.
8. Hannan M a., Azidin F a., Mohamed a. Hybrid electric vehicles and their challenges: A review. Renew Sustain Energy Rev 2014;29:135–50. doi:10.1016/j.rser.2013.08.097.
9. F. Gonzales, IdTechEx Report: Advanced and Post Lithium-ion Batteries 2016-2026: Technologies, Markets, Forecasts.
10. International Energy Agency, Global EV Outlook 2017.
11. International Air Transport Association, Lithium Battery Shipping Guidelines 2017
12. Aviation Week, Boeing reveals 787 Battery Fix Details, March 2013 http://aviationweek.com/awin/boeing-reveals-787-battery-fix-details
13. V. Khomenko, E. Raymundo-Piñero & F. Béguin, High energy density graphite/AC capacitor in organic electrolyte. J. Power Sources 177 (2008) p. 643.
14. UNECE Regulation No. 100 - Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train, August 2013.
15. ISO 26262 Road Vehicles – Functional Safety, November 2011.
16. Lloyd’s Register Guidance Note - Battery Installations - Key hazards to consider and Lloyd’s Register’s approach to approval, January 2016
17. DNV GL, Class Programme, Type Approval, DNVGL-CP-0418 Lithium Batteries, Dec 2015.
18. ABS, Guide For - Use of Lithium batteries in the marine and offshore industries, May 2017
19. Fredrik Larsson, Petra Andersson and Bengt-Erik Mellander, Lithium-ion Battery Aspects on Fires in Electrified Vehicles on the Basis of Experimental Abuse Tests.

9 Bibliography

1. Foster M, Isely P, Standridge CR, Hasan M. Feasibility assessment of remanufacturing, repurposing , and recycling of end of vehicle application Lithium-ion batteries 2014;7:698–715.
2. BSI. BS8877-1:Design for manufacture, assembly, disassembly and end-of-life processing (MADE) - Part 1. Br Stand Inst 2006.
3. Ahmadi L, Yip A, Fowler M, Young SB, Fraser R a. Environmental feasibility of re-use of electric vehicle batteries. Sustain Energy Technol Assessments 2014;6:64–74. doi:10.1016/j.seta.2014.01.006.
4. Fang HC, Ong SK, Nee a. YC. Product Remanufacturability Assessment based on Design Information. Procedia CIRP 2014;15:195–200. doi:10.1016/j.procir.2014.06.050.
5. MCA: Marine Guidance Note MGN 550 (M+F) - Electrical Installations - Guidance for Safe Design, Installation and Operation of Lithium-ion Batteries
6. IEC 62619:2017 Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary Lithium cells and batteries, for use in industrial applications
7. IEC 62620:2014 Secondary cells and batteries containing alkaline or other non-acid electrolytes - Secondary Lithium cells and batteries for use in industrial applications
8. IMO: International Maritime Dangerous Goods (IMDG), Dangerous Goods List, Substance Details – UN 3481, Lithium-ion Batteries Contained in Equipment (including Lithium-ion polymer batteries), 1/2/2013
9. NAVSEA TM-S9310-AW-SAF-010: US Navy Technical Manual for Batteries, Navy Lithium Safety Program Responsibilities and Procedures
10. NAVSEA SG270-BV-SAF-010: High-Energy Storage System Safety Manual
11. UL 1642: Standard for Safety of Lithium Batteries
12. UL 2054: Standard for Household and Commercial Batteries