Selecting and validating Li-Ion Battery Energy Storage Systems for Surface Combatants with DC Power Distribution

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Synopsis

Increasingly, Surface Combatants built use Electrical Direct Current, DC, Power Distribution technology, and feature distributed power generation and energy storage. DC Power Distribution supplies power for mission, propulsion, and hotel loads, while meeting the survivability requirements of naval applications.

Retaining a certain amount of energy storage in those systems is critical to support the highly dynamic loads and system reconfiguration requirements, and the Direct Current DC Power Distribution does this all while performing at significantly higher fuel efficiencies than conventionally powered vessels. Furthermore, energy storage technology selection is a holistic process, and safety characteristics of Li-ion batteries are a major concern for Navies.

This paper first establishes the various needs for DC power distribution systems based on the power requirements of current surface combatants and future margin. Then, it derives the energy storage characteristics, such as power, energy, cycle life, size and weight for these vessels. The paper then guides through the process that establishes criteria and evaluates the different aspects of the available technologies to be suited. Safety aspects will be described from battery chemistry to cooling methods to FIFI and battery room demands. The selection process presents energy storage technology suitable for NATO combatants. This technology is now being used for several Combatants within NATO Europe.

Keywords: Energy storage; Li-Ion; Navy; Battery Safety; LTO; F126 Frigates.

1. Introduction

Shipboard power systems evolved from the conventional diesel mechanical (DM) propulsion system that is complemented with a diesel electrical (DE) auxiliary power system, to the Integrated AC Power System (AC-IPS) that shares the diesel electrical power plant with propulsion and auxiliary loads, to the Integrated DC Power and Energy (DC-IPES) system that integrates energy storage [1].

The need for energy storage onboard marine vessels with electrical power distribution is well established and has been implemented on a growing numbers of different vessel types across the past decade. The driving factors for energy storage depends on the vessel type, but in general these are 1) increasing fuel efficiency for environmental reason and mission duration; 2) Improving the power system performance dealing with dynamic loads; and 3) enhancing the power system reliability.

Li-Ion batteries have been in use by the commercial shipping industry for more than a decade. More recently, Naval Submarines have started to embrace the benefits; however, some of the surface fleets have been hesitant to install such systems specifically due to concerns on their safety and survivability impact on the overall platform.

This paper aims to show the differences in the various Li-Ion chemistries and that these designs have significantly diverse safety characteristics and performance; and that specific types of Li-Ion batteries are safe to work in a Naval surface environment.

Lars Y Karlsson received his M.Sc in Electrical Engineering from Chalmers University in 2008 and have since then have various roles in ABB from Electrical Design, Commissioning and Engineering Management. Currently he works with ABB Marine & Ports as Navy solutions manager entirely dedicated to design and develop powersystems for Navies.

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2. Why BESS on a Combatant

The first and most important question is what purpose the Energy storage will have onboard the combatant. While there are ambitions for full Zero Emission Operations such as green port entry and for silent modes such as for anti-submarine warfare (ASW) operations, these functions require a large energy type of BESS. However, reasonably sized energy type BESS systems would currently still have limited endurance, considering the powers needed onboard a large or even medium sized combatant. While battery energy densities will improve and increase endurance in the future, for currently built combatants in Europe, the intent has been to dimension the powerplants to support following functions:

- Increasing efficiency and dynamic response on the powerplant
- Increasing QPS (Quality Power Systems) with blackout prevention to load centers in the unlikely event of a diesel genset being out of service
- Futureproofing powerplant for pulsed loads and mission systems
- Acting as redundant power supply when vessel is on Shore connection

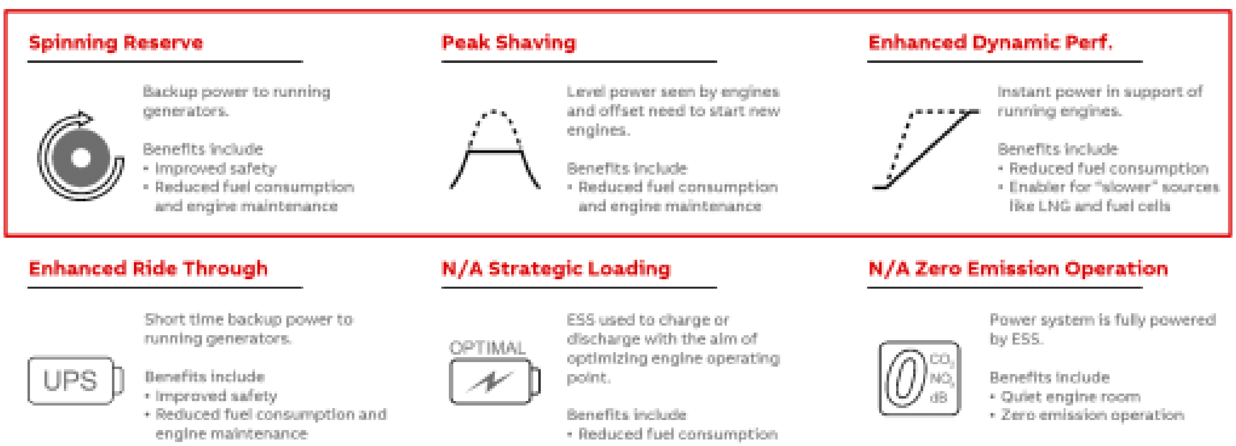

Figure 1 - shows an overview of the BESS functions in a DC power system, with the focused functions discussed above highlighted

Overall, the tactical benefits of using DC power and electrical propulsion with energy storage systems ESS result in improved dynamic performance and optimal uptime on sensors and mission systems. The focus BESS functions mentioned indicate that a High-Power and High-Cycle Life battery is preferable.

3. Integration of BESS to The Power System

Naval combatant powerplant systems are built with forward (FWD) and rear (AFT) electrical redundancy, typically in a two or four split arrangement. In this design the BESS is incorporated in each of these splits as can be seen in Figure 2 which is a notional two split power system. Each of these autonomous subsystems include two generators, one battery, one Off-Grid Converter (OGC) to produce the 440 VAC STANAG1008 voltage, and a propulsion converter.

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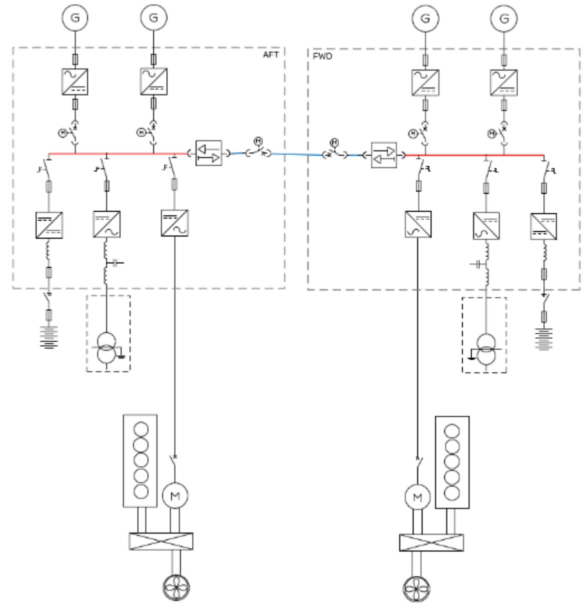

Figure 2 - Notional CODELAD two split DC-IPES showing power generation, energy storage, auxiliary power, propulsion load and the solid state breaker

As discussed in [3], all subsystems should be connected in normal operation, i.e. the solid-state DC breaker closed, and just disconnected for maintenance or as required by fault and ship damage situations. This provides for the optimal vessel fuel efficiency, as just the minimal amount of gensets need to be online to cover the overall vessel power needs. On discretion of the vessel commander the system can run in the disconnect mode, or in any other configuration, during e.g. combat. The shown propulsion arrangement is CODELAD, the propulsion motor could be full power take in/out (PTI/PTO) as desired. Load sharing is done by droop control, and a power and energy management system (PEMS), a very capable redundant, distributed control system coordinates all control functions for all operating modes as required.

The batteries are connected to the DC system with DC-DC converters. While these DC-DC converters take space, and have losses, this arrangement is preferred, as the batteries can be connected to the system and operate regardless of the individual battery State of Charge (SOC). This becomes obvious when e.g. connecting/energizing a subsystem, and the system DC voltage of each subsystem needs to match before closing the solid-state breaker.

It should be noted, that in some application that depend on very large energy stored onboard the vessel, e.g. an all battery-operated ferry or submarine, the batteries are connected directly to the DC link, and thus all batteries need to be on the same voltage, i.e. SOC. This eliminates the losses, and thus increases the round trip energy efficiency, but the system DC link voltage will fluctuate, and inefficiencies come by increased margins of the DC link connected power converters.

Figure 3 shows a detail of one "damage zone" for further discussion. Note, no propulsion load is present, since propulsion is part of another subsystem. Assigning the different loads and other assets to several connected subsystems is an optimization process that considers survivability, space at the specific damage zone, and many other factors, all proprietary and cannot be discussed here. However, the DC distribution technology allows for all such variations in the most flexible way.

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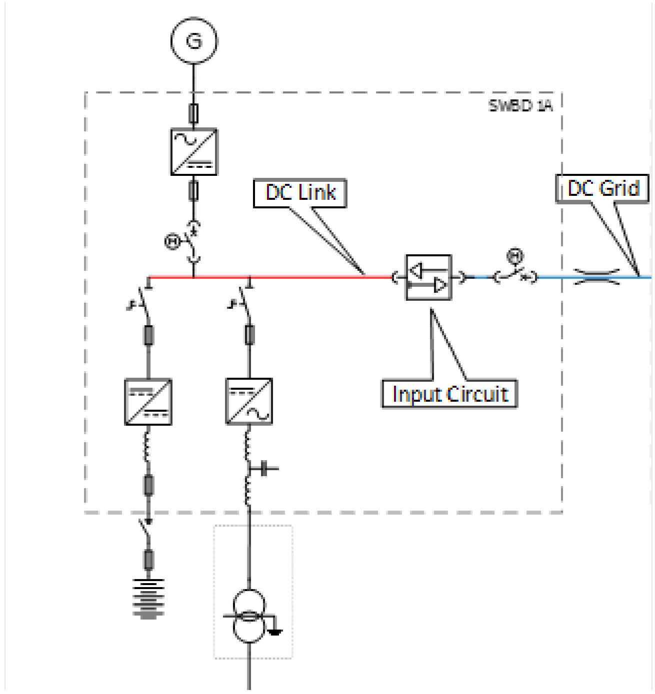

Figure 3 – Notional SLD detail for a combatant damage zone BESS integration. Note complete e.g. four split configurations and SLD can be commercially sensitive and thus is not presented

4. BESS SIZING

As an example, a typical generator size for a CODLAD/CODLAG Frigate is 2-3 MW. The battery could then be set to the full power of one generator to provide the full spinning reserve battery function. However, due to the hybrid design the BESS does not need to be dimensioned for the full power loss of the generator. In fact, in case of a generator loss the electrical propulsion power would be instantly shed by the drives control and PEMS in a fault ride through scenario. This assures the hotel load and vital mission system maintain power and prevent a blackout. So, for such scenario the battery power required notionally could be 1,25 MW per FWD/AFT split. This is shown in the visual representation of the system wide battery usage in Figure 4. Therefore, the dimensioning criteria for this exercise is 1,25 MW FWD or AFT for the time needed to startup one genset (with one failed attempt) until a new genset is online or changeover from FWD/AFT load center has occurred., i.e. notionally energy required for spinning reserve is 1.25 MW for 2 x ~30 s

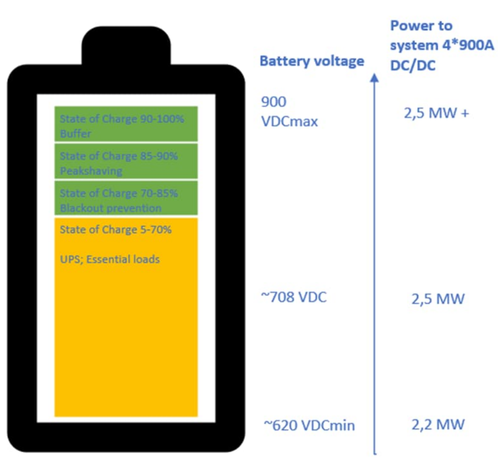

Figure 4 – Example for visual representation of Battery usage, Battery voltage and available power to the system (total for vessel).

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The total energy of the BESS system on the vessel could be as low as 250 kWh. The final selected installed energy could consider future growth and other margins. Figure 4 also indicates some other interesting facts, such as minimal and maximal SOC are limited for battery life and operational margins, and the UPS function supporting essential loads for several hours in certain blackout situation allocates the most energy installed (yellow section).

5. BESS design selection criteria

Since 2017, ABB Coast Guard & Navy have conducted extensive research, testing and simulations covering numerous leading OEMs and cell types to find a suitable technology. This analysis was led by our embedded marine Battery Experts within our Corporate Research function. In order to conduct this evaluation, a high level selection criteria was made as depicted in Figure 5:

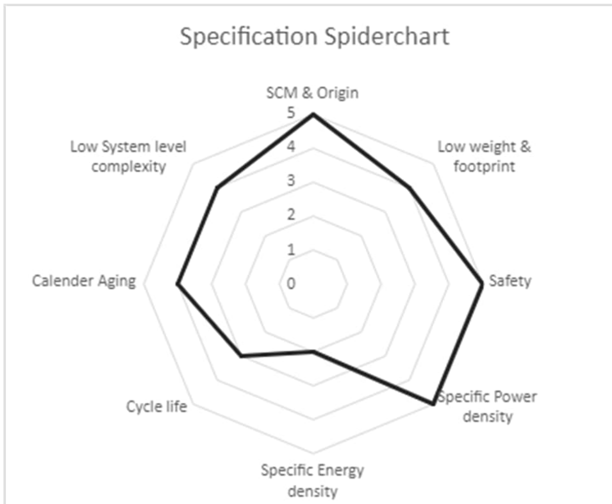

Figure 5 – Main criteria and importance (1-5) for BESS design

Since Supply Chain Management SCM & Origin is sensitive for a NATO Combatant, a large portion of the Marine BESS market was ruled out in the study at an early stage. In addition, some OEMs are hesitant to work with the defense industry and MIL standards.

Future promising technologies were also part of the study however ruled out due to low technical readiness level TRL numbers.

For the stated specification and other requirements for the BESS Application on combatants above, below in Figure 6 are estimated results for the shortlist of three major Li-Ion chemistries with mature TRL levels:

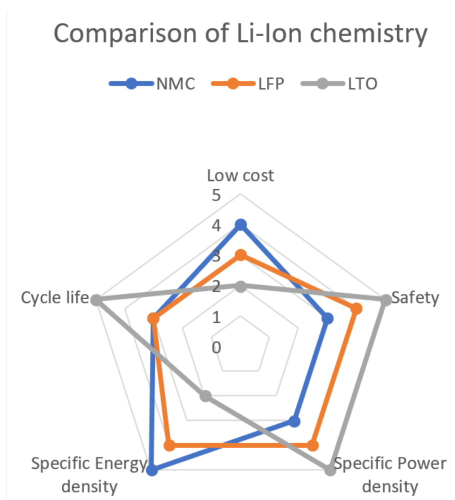

Figure 6 – Shortlist of three different Li-Ion chemistries and assessment of main characteristics.

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Table 1 lists additional information on the three Li-Ion chemistries considered.

Chemistry	Anode	Cathode	Typical C-rate (System)	Cycle life typically
NMC	Graphite	NMC	3	6000+
LFP	Graphite	LFP	10-15	6000+
LTO	LTO	NMC	10-15	30 000+

Table 1 – Characteristics of the three Li-Ion chemistries

As a reference, Lead-Acid batteries typically have a cycle life of ~500 – 2,000cycles.

The extensive battery evaluation study led to recommending LTO in this application being the frontrunner over NMC and LFP due to the combined benefits of high cycle life, high C-rates and high Safety characteristics. The downside of LTO is higher cost and lower specific Energy density as shown in Figure 6.

To explain the superior cycle life of LTO: LTO is a “zero-strain” material, meaning it undergoes minimal volume change (<1%) during lithium ion insertion/extraction. This stability contributes to excellent cycling stability, allowing for over 30,000 cycles.

Not shown in Table 1 is the operating temperature. According to [4] LTO has an increased operating temperature range of -30C to 75C whereas LFP and NMC have a -20C to 60C range. This is due to the absence of a carbon anode in LTO, which does not form an SEI layer, and thus TR onset temperature of the LTO cell is higher, see further below.

In total the BESS weight due to the lifecycle and C-rates for LTO can be below 5 tons total for a BESS systems capable of delivering 2,5 MW+ consisting of approx. 4+4 strings and250 kWh vessel total.

Moving forward in this paper LTO BESS will be described in more detail.

6. Thermal runaway (TR)

Li-Ion batteries can develop a thermal runaway that exponentially generates heat over time. This can be initiated by external forces or internal failures such as internal/external short circuit, overcharge/over-discharge, and overcurrent.

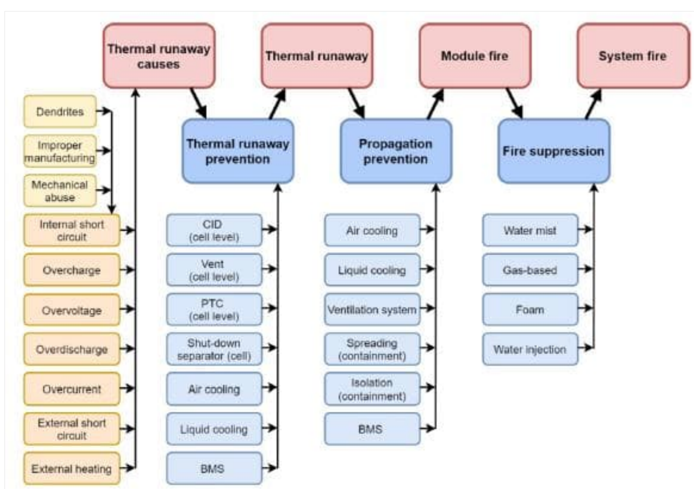

Figure 7– Causes and prevention methods of TR [4]

If a battery is operated and stored within the limits recommended by the manufacturer, the failure rate is estimated to only be 1 in 40 million [4]. An overview is presented, and the main causes and methods of TR prevention is shown in Figure 7.

As the Cycle Life and weight of LTO in this application is superior the below depicts the safety aspects of LTO chemistry.

6.1 Causes of Thermal Runaway

LTO cells can go into thermal runaway but requires much more abuse to do so. In case of severe abuse, a cell may vent flammable electrolyte fumes and explosive gases. Adequate ventilation is therefore required by class. The higher degree of robustness originates from:

- No SEI (Solid Electrolyte Interphase) layer
  →no exothermic SEI decomposition
  → pushes TR onset temperature higher
  → therefore more robust to thermal abuse

6.2 Internal short circuit

Limited by design as shown in Figure 8, dendrites formation in LTO anode will not occur as a risk for internal short-circuit because an SEI layer is not formed.

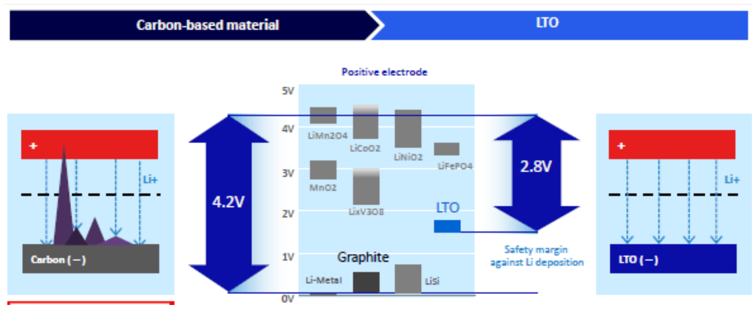

Figure 8 – How LTO compares with Graphite/Carbon Anode

There is a huge electrochemical margin to Li-metal plating, potentially more resistant to overcharging, and no risk for dendrite formation and internal short circuit.

LTO phase transformation at high current densities prevent fast discharge and thermal runaway TR in case of internal short (due to i.e. nail penetration). For the mechanical abuse tests with 0.50 Caliber (12,7 mm) penetration and crushing tests shows no explosion or fire.

Figure 9 - Overcharge/Overdischarge/Overcurrent/Overvoltage/external short circuit

Due to DC/DC converters maximum current limitation, the overcharge and overvoltage fault is limited by design. In addition, the battery management system (BMS) monitors voltage and current as well as temperatures initiating a trip of the affected battery string. In addition, System OEM designs selectivity with fuses and selectivity to protect cabling and DC switchboard and ensure personnel safety.

6.3 External heating

Due to the 180C onset temperature of LTO and tests for external fires, this risk is reduced compared to other chemistries, however, it cannot be dismissed. Exothermic reaction can still be triggered in cathode if cell temperature

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goes above 180C. If cells are heated above ~180C, cathode and electrolyte will decompose exothermally (but without contribution from the LTO anode) or if extensively overcharged to >200% SOC (4.8V/cell). On the other hand, the qualitive hotspot testing using gas burner indicates 700-800℃ for fifty minutes until one cell goes into TR without propagation to other cells or modules.

Figure 10 – Picture of external heat test

If the external temperatures can reach those levels with the A60 barrier, then there are other severe issues onboard the platform not originating from the BESS.

6.4 Thermal runaway prevention & propagation

Class tests for nail penetration show that the LTO in addition to the physical abuse requires overvoltage to get the affected cell into TR. This one cell is proven not to propagate to other cells eliminating the needs for current interrupting device (CID), Vent, positive temperature coefficient (PTC), Cell to Cell isolation (Shut-down separator (cell)), or active Cooling.

The battery system manufacturer needs to prove that the system is by its own accord, or has sufficient safety measurements built in, to be deemed safe to use onboard a ship. One of these tests is the Propagation test. DNVGL is using IEC62619 modified to one of two design options.

1.The battery system is designed for no propagation between cells within a module.

2.The battery system is designed for no propagation between modules - with or without an extinguishing agent.

The performed tests aim to fulfil design option 1, thus no propagation between cells within a module. the designed.

The battery system manufacturer has also proved that the LTO module has sufficient safety measurements built in, to be able to pass three propagation tests according to the DNVGL standard based on IEC 62619. No propagation took place in the battery module when the battery trigger cell was overcharged to less than or equal to 4.1 V, which corresponds to 152% of overcharge of the battery cell voltage.

6.5 Battery management system BMS

Needless to state the BMS plays a vital role in the safety of the BESS, and needs to be immune to electromagnetic disturbance and proven in use. It is recommended that the BMS always stays on active to make early detection of any abnormalities. Fault safe monitoring and redundant measurements (Cell/Module voltage and temperatures) are required.

6.6 Fire Suppression

Due to the CBRN (Chemical, Biological, Radiological and Nuclear) design with overpressure onboard combatants, this makes the design of some of the commercial firefighting FIFI systems such as NOVEC or CO_2, that is also toxic to the crew, not favorable onboard vessels [7]. Typically, the shipyard designs with a water mist system that is further discussed below.

Water Injection or immersive cooling is a promising technology for BESS with higher energy content and lower onset temperature for TR

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6.7 *Gas generation during TR*

A thermal runaway event will lead to the release of gases that are measured during testing. These contain a mixture of H2, CO2 and CO, CH4, C2H4 and C2H6, and including the highly toxic hydrogen fluoride HF. As the LTO modules are tested not to propagate, the gas released for one cell is very limited, for the LTO example < 100 l per cell .

6.8 *Water or Air cooling*

Water cooling is a fairly common design in Marine BESS that gives thermal benefits for an energy dense profile that have high RMS C-rates. However, water-cooling can lead to safety aspects, see [6] for a summary of a battery event on a Norwegian vessel in 2019.

The use profile depicted in the combatant simulation for system wide heat rejection, resulted in the average cell temperatures listed in Table 2 for the two BESS functions, spinning reserve and peak-shaving.

This means that in this application there is no need for active water-cooling. Air cooling eliminates the need for managing condensation that could occur with water cooled battery systems and it is safe even in case of failure of the cooling system. Air-cooling in this application lowers the system complexity, improves the system reliability and is easier to comply with Shock and Vibration according to MIL mechanical standards.

Function	C-rate & Power	Systemwide heat rejection	Average Cell temperature
Continuous Peakshaving	1C RMS ~30 kW per string	~2,5 kW	~20->26°C
Spinning re-serve/Blackout prevention	12C Pulse one minute, 310 kW	<1kW	~20->23°C

Table 2 – Heat dissipation simulation results

Nevertheless, it should be noted that a in a different application active water-cooling may be preferred.

6.9 *Summary FIFI cell originated TR*

For the LTO case several abusive tests show that if one cell is forced to go into TR this is undramatic with no fire or explosion. The affected string will be disconnected and in the same time the gas-sensor detects and opens the off-gas ducting and start to ventilate the <100 l gases overboard. Battery Room ventilation is activated. See Figure 11 for a notional diagram of an air cooled LTO battery ventilation system.

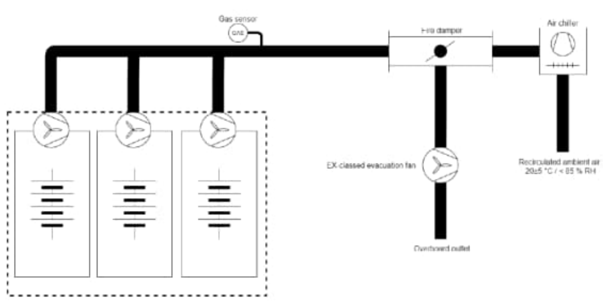

Figure 11 – Notional picture on aircooled LTO Strings with combined gasevacuation and cooling duct. Note that the separate Battery Room ventilation is not indicated in figure.

6.10 *Summary FIFI external fire*

In a confirmed fire onboard a combatant the ventilation will be turned OFF, as there could be the need to evacuate personnel. The purpose to turn ventilation off in the affected zone is to keep the smoke propagation confined. The Battery room should be a sub-citadel with kept ventilation to evacuate any potential gas during abnormal events.

Cooling of an adjacent fire will be performed either by using Hi-Fog systems or manually by the Battle Damage Repair Team (BDR) using hoses. Purpose of the external cooling is to make sure the LTO cells are not heated up.

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If the external fire is spreading, then the Power drain of the BESS can be evaluated. Alternatively, if the BESS is the only power source onboard, then battle-override can void temperature alarms from BMS and a temporary seawater powered fan can be used to cool the batteries to increase survivability.

Flooding of the battery room should be the very last resort as flooding with Seawater will create electrolysis and thus H2 and O2 generation. Room ventilation must be kept running. Qualitive drench tests in saltwater tests have been performed that generated corrosion however otherwise undramatic, no fire nor explosion.

Figure 12 – Output of qualitive drench test in saltwater

6.11 Summary FIFI events

As summary Table 3 provides basic input to the Killcards for the Damage Control System:

Stage	**Thermal Runaway**	**Cooling of adjacent room fire**	**FIFI in battery Room**
Description	One cell vents gases ~<100 liters	To limit or make sure cells are not heated up >180 C	Adjacent fire have spread to battery room
Battery Room air handling	BESS Gas evacuation ON Battery Room Ventilation ON	Watermist ON BESS cooling ON Room Ventilation ON	Hi-Fog, Sprinkler, Seawater Room Ventilation ON
Impact	Only the affected string is disconnected by BMS	None unless BMS detects abnormal temps; Evaluate battle override to keep vital systems running. Evaluate increasing power drain if situation get worse to reduce stored energy	BESS inoperable
Comment	Undramatic in the case of LTO cells, no fire	Depending on the specification of the BESS and the fire state onboard	This should be the very last resort as flooding with Seawater will create electrolysis and thus H2 and O2 generation

Table 3 – Simplified layout of FIFI events onboard a combatant with an LTO BESS

7. Further Validation & Testing

Needless to say that after the extensive internal testing our end users have commenced on significant performance tests of their own. [8]

8. Conclusions, future work

This paper indicates the operational benefits of hybrid Combatants with ESS integrated through a DC power distribution architecture:

- Distributed DC power generation and energy storage technology allows for robust designs with superior survivability
- Increase efficiency and Dynamic response on Powerplant

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- Increase QPS with blackout prevention to load centers in the unlikely event of diesel generator is out of service
- Futureproof powerplant for Pulsed loads and mission systems
- Act as redundant power supply when vessel is on Shore Connection

The ESS can be realized with a remarkable small footprint and weight using High Power LTO technology. The most important for safety in the design is the cell chemistry used and the BMS. The superior safety aspects of LTO is well suited for use on Naval Combatants. For the cooling on this Combatant ESS LTO application, the introduction of water-cooling would merely generate an additional risk and no additional benefits. Due to the safety aspects of LTO the greatest concern for TR is adjacent fires that can heat up the module. European Navies have started to embrace and build Frigates with Li-Ion LTO ESS to embrace the operational benefits while still managing the safety aspects.

DC power distribution systems, with battery energy storage and power generation, all distributed across the vessel, have been applied in numerous ships in the commercial industry in the past decade. The flexibility in building architectures to meet the specific vessel application, and very significant fuel efficiency gains have been well established.

Further work is required for guidance on ESS design on warships for further applications such as Containerized Energy storage for Zero emission/silent operations with a high Energy cell. In addition, guidance for charging of drones onboard vessels is also required.

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