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Hybrid Power Plants Going Green: Risk Assessment of Electrical Energy Storage Systems and their Impact on Dynamic Positioning Vessels and their Power Plants

Abstract

Over the last 10 years, the price of lithium-ion (Li-ion) batteries has reduced by 90%. To reach the climate goals from the 2015 Paris Agreement, the growth in this industry over the next 20 years is projected to be around 50 times bigger than today, not only including electric cars but also including energy storage systems (ESS) in wind farms and solar panel farms. Every household already has an average of 35 Li-ion batteries (in phones, laptops, cars, etc.) with around 300 different types of Li-ion batteries available (reference 19). While this paper will not explore all the different types of Li-ion batteries, there are many reference papers and rules that study and outline these in more detail.

This paper will focus on the risks and benefits of using these new developments for new “Green Operations” onboard dynamic positioning vessels. It will also examine the drive-off risk due to smaller blackout recovery time capabilities depending on the designs and the number of batteries. Onboard drill-ships, there are two options for energy storage: the DC grid for the drilling drives and each thruster drive.

This paper will also review in detail some Lessons Learned by others using ESSs and relevant Classification Rules and other industry standards.

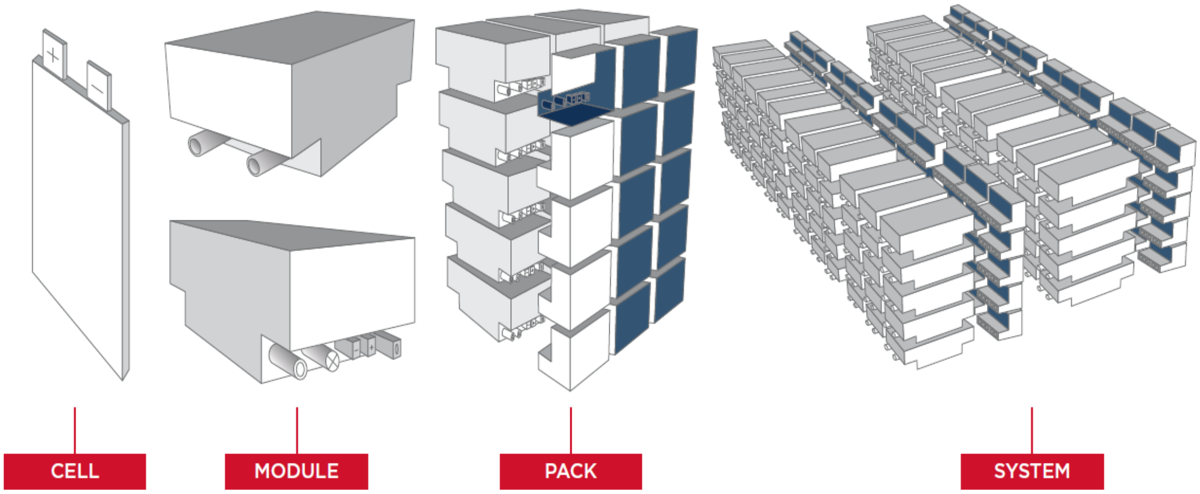
Focus of This Paper

This paper highlights the design benefits and risks involved with significant power storage requirements onboard dynamic positioning (DP) vessels, with an emphasis on lithium-ion (Li-ion) battery systems and the worst-case scenarios for the onboard installations on DP vessels. Considering all studies and experiences, we focus on the firefighting capabilities onboard DP vessels, the design of specific spaces on these types of installations, and requirements for specialized firefighting training for the crew for handling specific situations like long-term cooling of chemical fires (potentially 9–10 days). Looking at a few installations, we can conclude that the following issues need more attention:

1. Distances (separation) between large battery banks and arrays when thermal runaway occurs (high risk for chain event). This risk can be reduced by testing during type approval. Many battery modules are resisting propagation due to single-cell thermal events.
2. Long-term cooling and capacities of relevant firefighting equipment and systems to mitigate possibility of reignition. Systems with a medium from bottles like CO_2, halon, and NOVEC can have a risk that when the bottles are empty, the fire can start again. Most gaseous media have very little cooling capacity. Rules are making progress on this issue. We also look at the battery rooms’ equipment and firefighting strategy.
3. Insufficient ventilation for high amounts of toxic and explosive gas. An approach to ventilation different from conventional firefighting practice may be required due to toxic gases. Usual marine practice may be to close all dampers and shut down fans/ventilation, but for Li-ion installations, this may increase the likelihood of a concentration of toxic and explosive gases rather than clear them. This is a risk assessment issue.
4. Apart from making the power plants hybrid, we see a lot developments using fewer main engines in closed-bus operations, more energy-effective software and energy storage, and efforts to lower the emissions using selective catalytic reduction (SCR) systems (cleaning exhaust gases).

Abbreviations

ACH	air changes per hour
AEGL	acute exposure guideline level
BESS	battery energy storage system
BMS	battery management system, or battery-monitoring system
CAES	compressed-air energy storage
CFD	computational fluid dynamics
DCE	duty cycle eccentricity
DP	dynamic positioning
EES	electrical energy storage system (also EESS)
EOL	end of life
ESS	energy storage system
FAT	factory acceptance test
FDS	functional design specification
FMEA	failure mode and effect analysis
IDLH	immediately dangerous to life or health
GHG	green house gasses
JDP	joint development project
KERS	kinetic energy recovery system
LCO	lithium cobalt oxide
LEL	lower explosion limit
LFP	lithium ferro phosphate (iron phosphate)
Li-ion	lithium-ion
LMO	lithium manganese oxide
LTO	lithium titanate oxide
NFPA	National Fire Protection Association (USA)
NMC	nickel manganese cobalt oxide
NCA	lithium nickel cobalt aluminum
NOx	nitrogen oxide
OEL	occupational exposure limit
PAC	protective action criteria
RISE	research Institutes of Sweden
SCR	selective catalytic reduction
SOC	state of charge
SOE	state of energy
SOH	state of health
SOx	sulfur oxide



Li-Ion Safety Concerns

The following is excerpted from the online article “Lithium-Ion Safety Concerns” (reference 32):

> When Sony introduced the first lithium-ion battery in 1991, they knew of the potential safety risks [fire and explosive]. A recall of the previously released rechargeable metallic lithium battery was a bleak reminder of the discipline one must exercise when dealing with this high energy-dense battery system.
>
> Pioneering work for the lithium battery began in 1912, but it was not until the early 1970's when the first non-rechargeable lithium batteries became commercially available. Attempts to develop rechargeable lithium batteries followed in the eighties. These early models were based on metallic lithium and offered very high energy density. However, inherent instabilities of lithium metal, especially during charging, put a damper on the development. The cell had the potential of a thermal run-away. The temperature would quickly rise to the melting point of the metallic lithium and cause a violent reaction. A large quantity of rechargeable lithium batteries had to be recalled in 1991 after the pack in a cellular phone released hot gases and inflicted burns to a man's face.
>
> Because of the inherent instability of lithium metal, research shifted to a non-metallic lithium battery using lithium ions. Although slightly lower in energy density, the lithium-ion system is safe, providing certain precautions are met when charging and discharging. Today, lithium-ion is one of the most successful and safe battery chemistries available. Two billion cells are produced every year.
>
> Lithium-ion cells with cobalt cathodes hold twice the energy of a nickel-based battery and four-times that of lead acid. Lithium-ion is a low maintenance system, an advantage that most other chemistries cannot claim. . . . The battery does not require scheduled cycling to prolong its life. Nor does lithium-ion have the sulfation problem of lead acid that occurs when the battery is stored without periodic topping charge. Lithium-ion has a low self-discharge and is not very “environmentally friendly” so disposal via recycling needs to be better arranged for various countries.

> Long battery runtimes have always been the wish of many consumers. Battery manufacturers responded by packing more active material into a cell and making the electrodes and separator thinner. This enabled a doubling of energy density since lithium-ion was introduced in 1991.
>
> The high energy density comes at a price. Manufacturing methods become more critical the denser the cells become. With a separator thickness of only 20-25µm, any small intrusion of metallic dust particles can have devastating consequences. Appropriate measures will be needed to achieve the mandated safety standard set forth by UL 1642. Whereas a nail penetration test could be tolerated on the older 18650 cell with a capacity of 1.35Ah, today's high-density 2.4Ah cell would become a bomb [certainly an uncontrolled release of flammable electrolyte and potentially explosive gases] when performing the same test. UL 1642 does not require nail penetration. Lithium-ion batteries are nearing their theoretical energy density limit and battery manufacturers are beginning to focus on improving manufacturing methods and increasing safety.

At present we can define six groups of Li-ion batteries with different chemical content:

1. LFP is lithium ferro phosphate (used in ships).
2. LMO is lithium manganese oxide.
3. LTO is lithium titanate oxide (occasionally used in ships).
4. LCO is lithium cobalt oxide.
5. NCA is lithium nickel cobalt aluminum.
6. NMC is lithium nickel manganese cobalt oxide (used in ships).

Li-Ion Battery Thermal Runaway

A “thermal runaway” can start from >80°C depending on the type of cell. The temperature can go far beyond >660°C and will start with one cell and develop fast in a chain reaction with the danger of explosion. The following items will all affect “thermal runaway” severity:

1. State of charge (most volatile at 100% charged)
2. Overpower (high current)
3. High temperature (>80°C)
4. Cell chemistry
5. Construction of cell
6. Architecture of battery packet (module)
7. Isolation cells by distance, cooling, or fire resistance material
8. Close distance between the cells
9. Cell rupture valve / module valve

The following items can lead to a “thermal runaway” (in individual cells):

1. External heating
2. Mechanical damage
3. Overcharging
4. Deep discharge
5. Fast charging
6. External short circuit

7. Leak in cooling system causing short circuit
8. Production fault (low quality control)
9. Fault in battery management system (BMS) or BMS not installed
10. Defect charger process or no original charger
11. Chemical process issues

Note: See, for example, *Lloyd's Register Type Approval System Test Specification Number 5*. A single-cell propagation test requires a module design that inhibits the spread of a thermal event.

Space Separation—Electrical Energy Storage System

Below are recommendations from page 27 of the National Fire Protection Association (NFPA) *Sprinkler Protection Guidance for Lithium-Ion Based Energy Storage Systems*, dated June 2019 (46 pages) (land-based requirement). The distance below is based on a test with a system with 125 kWh electrical capacity for NMC with 83.6 kWh.

> For the tested LFP system:
>
> - Without fire protection, the minimum space separation [required] from any part of the ESS [energy storage system] is 1.2 m (4 ft) from non-combustible objects and 1.8 m (6 ft) from combustible objects.
> - With [an installed] sprinkler protection, the minimum space separation from any part of the ESS [can be reduced to] 0.9 m (3 ft) from non-combustible objects and to 1.5 m (5 ft) from combustible objects. The sprinkler system water supply should be designed for a minimum 230 m² (2,500 ft²) demand area and a duration of at least 90 minutes.
>
> For the tested LNO/LMO [NMC] system:
>
> - Without fire protection, the minimum space separation from any part of the ESS is 2.4 m (8 ft) from non-combustible objects and 4.0 m (13 ft) from combustible objects.
> - With sprinkler protection, the minimum space separation from any part of the ESS is 1.8 m (6 ft) from non-combustible objects and 2.7 m (9 ft) from combustible objects. The sprinkler system water supply should be designed for the total room area where the ESS is located, and the water supply should be calculated as 45 minutes times the number of adjacent racks.

Note: Beware direct comparison with land-based applications as freshwater supply onboard will be limited by storage capacity, and saltwater, while in infinite supply, can be assumed to damage the battery installation beyond use. Saltwater also has better discharge.

Firefighting Li-Ion Battery Thermal Runaway

Many Li-ion battery fires are self-oxygenating and thus very challenging to extinguish. Cell size, the number of cells on fire, and access to the fire are generally very important in terms of how difficult it is to extinguish the fire. Heat removal and extraction is a key requirement of the extinguishing system to minimize damage. This is the reason for the class requirements. Battery fires may persist for extended periods, so ample quantities of water should be ensured to be available for a period of 9–10 days. If the extinguishing system has been identified as a requirement for prevention of thermal runaway propagation, it should be implemented in the same manner as tested.

Note: These are uncontrolled exothermic chemical reactions and not conventional fires. In some circumstances, they will continue to react under water. This is important because assumptions around conventional firefighting based on a fire triangle are not applicable, except to deal with consequential fires caused by the high temperatures to which adjacent materials may be exposed. Earlier comments on water supply and the like apply to this section.

Pre-thermal runaway warning: Fire propagation protection and the current interruptive device are two of the most important safeguards to be installed in a lithium-type battery system.

Note: Isolating the batteries does not remove the charge, and thus it does not remove the hazard posed.Battery Room

To fight a fire in a battery room, ask the following questions:

- Can you read outside the room (next to the door) the temperature inside the room?
- Can you look inside the room through a little window or CCTV camera?
- Can you discharge other units (healthy ones) in the same room before it gets too hot?
- Can you ventilate all toxic gases before you enter the room?
- How much saltwater can you get into the room with a sprinkler for cooling?
- Is a gas detector installed in the room?
- Does the bridge have battery monitoring?

Twenty-three Incidents in South Korea with Electrical Energy Storage System Units (Lessons Learned)

The following is excerpted from "South Korea Identifies Top 4 Causes for ESS Fires" (reference 33):

South Korea announced the conclusions from their fire investigation committee regarding the root cause for the 23 energy storage system fires that have occurred since August of 2017. The lithium-ion battery fires resulted in system losses valued at over $32M USD. In January, the government requested to stop operation of existing systems which resulted the shutdown of 522 ESS units – approximately 35% of the budding market. The Ministry of Industry formed an investigation committee of academics, research institutions, laboratories and ESS industry experts to investigate the causes of the fires. Their report was released on Tuesday, June 11, 2019 and included four causes for the fires:

1. **Insufficient battery protection systems against electric shock**

Systems were not able to properly protect against electrical hazards due to ground faults or short circuits. When large electrical surges were imposed on the battery system the fuse [or breaker] was not able to quickly interrupt the current which led to catastrophic failure of the contactors. The short circuit current allowed the failures cascade to the bus bar which resulted in fires inside the ESS. This failure mode was confirmed by the committee during their fire accident investigation.

2. **Inadequate management of operating environment**

Of the 23 fire incidents that occurred, 18 were installed in the mountains or coastal areas. It was concluded that these environments resulted in harsh conditions including large temperature swings, high humidity and elevated levels of dust and particulates which ultimately led to failure modes resulting in fires. The elevated humidity levels and large temperature swings resulted in condensation, and resulting residue after drying, within the battery system. This effect was determined to degrade the electrical insulation inside the battery modules between the cells and module ground which resulted in short circuits and subsequent fires. This cause was believed to be made worse by modules fans designed to air-cool the battery modules.

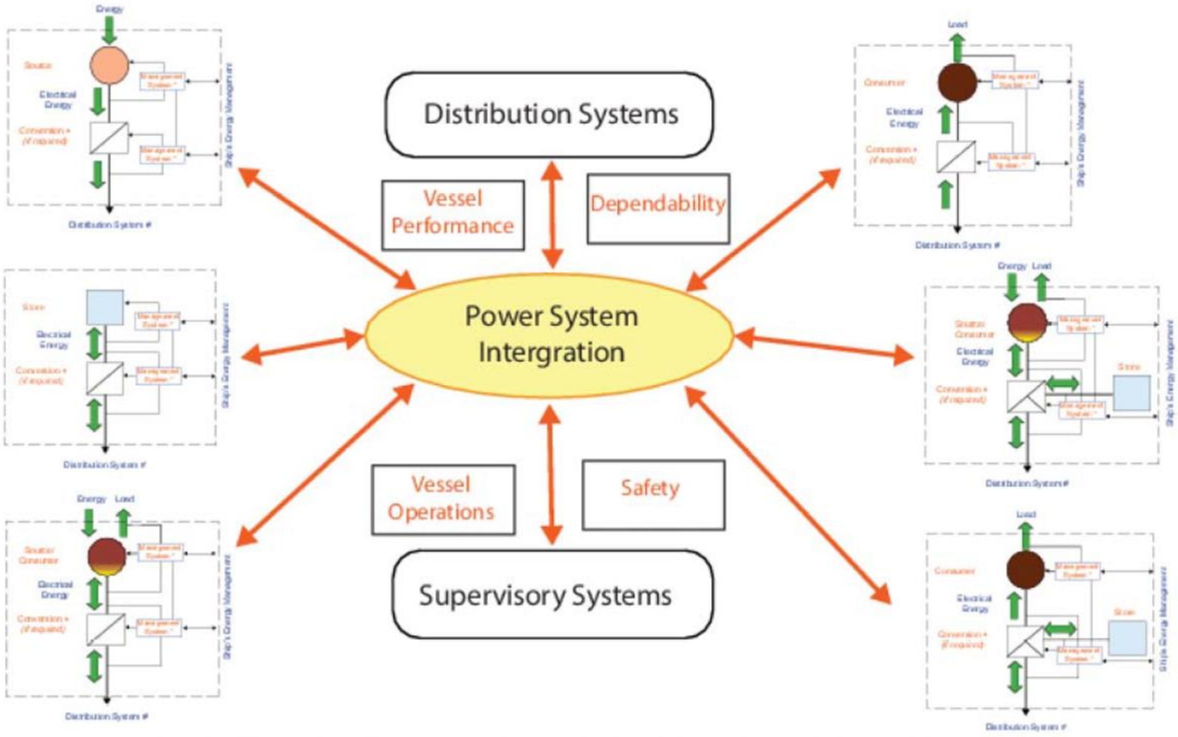
3. Faulty Installations

It was determined that human error during installations can also lead to system faults resulting in ESS fires. Not many details were provided by the investigation committee, but cases such as faulty wiring or mechanical damage to the batteries during installation were [cited].

4. ESS System Integration

The integrated protection and management systems [associated with the ESS] were found to be insufficient. . . . It was confirmed by the committee that gaps in the integration of the battery management system (BMS), energy management system (EMS), and power management system (PMS) can result in conditions that lead to fire. Integration issues included inadequate information sharing between systems, system operating sequence, and checking for abnormalities of the batteries after PCS maintenance or troubleshooting.

The committee also identified defects in battery cells including cutting defects and poor coating of the electrode materials. However, testing over 180 charge and discharge cycles did not result in fires, so the cell defects were not listed among the root causes for the system fires.



* "Supervisory Systems" may Include Intergrated Automation Systems (IAS), Power/Energy Management Systems (PMS/EMS), Dynamic Positioning (DP) Control Systens, Health/Condition Monitoring Systems.... etc.

Tests during Commissioning and Acceptance

How can we make sure that the best electrical energy storage system (EES) for a specific vessel type has been installed? Has the best BMS for safe operations been selected? Do we have the best BMS to warn us of a thermal runaway? Do we have the best fixed firefighting system in place to fight this fire for the complete duration, estimated as 9–10 days for a worst-case scenario? Have firefighting teams had sufficient training to fight these specific types of fires? Do they have toxic gas training?

Class rules can give some guidance and recommendations on A full and comprehensive factory acceptance test of the ESS prior to transportation and installation onboard the vessel would be a prerequisite for demonstration of functionality, performance, and safety features and capabilities.
Some sample useful references are the following:

- Page 60 of DNVGL-RP-0043, table 7-1 (overview), with 25 different tests and 11 standards
- IEC 62133-2 for cell tests and certification
- *LR Rules*, part 6, chapter 2, sections 12 and 24, "Hybrid Electrical Power Systems," January 2020. When the EES is part of the overall hybrid power system, it is an *LR Rules* requirement to perform a failure mode and effect analysis (FMEA) on the overall hybrid power system.
- *Lloyd's Register Type Approval System Test Specification Number 5: Type Testing for Lithium Battery Systems*, March 2019
- Page 41 of *DNV GL Handbook for Maritime and Offshore Battery Systems*, 2016

Installation and Commissioning

The following is excerpted from *DNV GL Handbook for Maritime and Offshore Battery Systems*, 2016, page 41:

> Experience has shown that failures/unwanted issues often occur at the interface between systems. The interfaces between the battery system and the other ship systems therefore need special focus.
>
> The Battery Management System communicates with the ships Power Management System and key battery information is displayed at the ships bridge. The BMS must have an override function to prevent the Power Management System to perform tasks outside its safe boundaries.
>
> Proper installation documentation [or procedures] must be provided by the battery system supplier.
>
> All interfaces must be tested before the installation can be signed out and a proper [specific] test and commissioning plan must be made for the testing to be done at the yard before final sign out. This task should not be underestimated and needs a close cooperation between the battery system supplier [i.e. original equipment manufacturer (OEM)], the supplier [OEM] of the other power plant components and the yard. Functional testing of the safety features of the battery space (ventilation, gas detection, fire detection) must also be performed.

Benefits for a DP Vessel Using a Battery Power System Package

1. Reduced fuel consumption between 12% and 20% depending on operations (using a battery energy storage system [BESS] as a spinning reserve to reduce the number of running generators in this context)
2. Reduced CO_2 emissions in the range of 15% to 25% depending on design (see above)
3. Faster blackout recovery or only partial blackout (depending on design), with thrusters kept running up to 7–8 minutes depending on the battery package
4. More stable power grid and fewer surge peaks on the grid (11 kV) (called "peak shaving hybrid" design)
5. Creation of a more stable grid on DP drill-ships with active heave drawworks with the addition of a kinetic energy recovery system (KERS) in combination with EES
6. Together with closed-bus operations, reduction of fuel consumption up to 33%
7. In combination with Energy Emission Efficiency software (SMC)
8. Lower nitrogen oxide (NOx) emissions by cleaning exhaust gases using SCR up to 90%

SCR Package

The following is excerpted from "What is SCR?" (reference 34):

> Selective Catalytic Reduction (SCR) is an advanced active emissions control technology system that injects a liquid-reductant agent through a special catalyst into the exhaust stream of a diesel engine. The reductant source is usually automotive-grade urea, otherwise known as Diesel Exhaust Fluid (DEF). The DEF sets off a chemical reaction that converts nitrogen oxides into nitrogen, water and tiny amounts of carbon dioxide (CO2), natural components of the air we breathe, which is then expelled through the vehicle tailpipe.
>
> SCR technology is designed to permit nitrogen oxide (NOx) reduction reactions to take place in an oxidizing atmosphere. It is called "selective" because it reduces levels of NOx using ammonia as a reductant within a catalyst system. The chemical reaction is known as "reduction" where the DEF is the reducing agent that reacts with NOx to convert the pollutants into nitrogen, water and tiny amounts of CO2. The DEF can be rapidly broken down to produce the oxidizing ammonia in the exhaust stream. SCR technology alone can achieve NOx reductions up to 90 percent.

KERS

The KERS (mechanical flywheel) in combination with EES will have a very good impact on the stability and fuel reduction for drill-ships and semi subs with active heave drawworks. This type of system has also been used in Formula 1 race cars since 2009, in the beginning with 60 kW and later with 120 kW extra engine power. The weight of the unit is 35 kg. The system can generate power during the braking of the car to charge the battery system and in addition can use the generator temporarily as a motor to generate extra power for about 6 seconds. On drilling ships with drawworks (normal and active heave), we can use this system to create a more stable grid as the drawworks is often responsible for high peaks on the 11 kV grid. Fuel consumption can be reduced by up to 80% (see also NOV website).

Compressed-Air Energy Storage

Compressed-air energy storage is a system used for many years onboard drill-ships and semisubmersibles for active heave systems. The marine riser tensioner system and the crown-mounted compensator have many cubic meter bottles with high-pressure air between 200 and 300 bar. The tensioners are filled with hydraulic fluid, and behind is the high-pressure air to operate the tensioners. We will not use this system in this paper because it is not used together with BESS.

Closed-Busbar Configuration

Closed-busbar operations are also part of the upgrades working towards fuel reduction in combination with EES on DP 2 and 3 vessels. Depending on the 11 kV breaker protection, it is not always possible. When the power plant is allowed and tested to run in closed-busbar configuration during DP operations by class, one of the considerations is whether the protection software is fast enough to open tiebreakers in case of a major failure on the main busbar. Blackout recovery with the capabilities of the EES can be very fast depending on how long they can operate the variable-frequency drives of the thrusters. When they can cover between 2 and 3 minutes, the DP vessel will not lose position during blackout. For closed-busbar operations, there are other parameters, and it is more complex to achieve, depending on the tiebreaker type and software. Many power plants can run in closed-bus bar configuration (technical) but are not allowed when they run in DP 3 operations because of worst-case failure.

Hybrid Power

The energy use onboard a rig is characterized by high peak loads during certain operations. By installing energy storage by use of batteries, basic energy requirements can be met by fewer engines operating at higher intensity, supplemented by battery power—which is both more efficient and reduces CO_2 and NOx emissions. The ESS also allows for recovery of braking energy, which adds to energy savings and further reduces emissions.

Solid-State Battery Development

The latest development in the battery industry is the solid-state battery. This will be a safer concept because they do not have thermal runaway. By 2025, all Li-ion batteries will be replaced by this development. They have more capacity per battery weight and no thermal runaway. All big carmakers are investing in the development of this new type of battery.

Conclusions

- **Monitoring pre-thermal runaway warning**

Implementation and use of a suitable BMS will make this the ESS safer in operations and will enable the crew to take precautions and preventive actions before a thermal runaway occurs.

- **Fixed firefighting equipment**

The most effective fire suppression systems are direct injection with foam, high-pressure water mist, and normal sprinklers. These three have the most effective cooling performance over long-term duration (see DNV GL study *Technical Reference for Li-Ion Battery Explosion Risk and Fire Suppression*, published in November 2019, done by the Maritime Battery Safety Joint Development Project). One comment on these studies is that the longest time of all tests during these studies was 50 minutes. Most heat and gases are produced in this timeframe, but from experience it is clear that when firefighting is stopped or even the ventilation is stopped, the chemical fire can still continue for about 9–10 days.

- **Lessons Learned from fires with electric vehicles**

During the fire, the battery cells can explode and be propelled up to 50 meters away. Damaged batteries and cells can cause self-ignition at a later date, even after successful fire extinguishing. After the fire, most fire teams put the electric vehicle in a water tank; practice has shown that the battery pack can discharge and can take 9–10 days. Saltwater helps discharge faster than freshwater, and this is conducted outdoors because of the ongoing release of toxic and explosive gases.

- **Ventilation of toxic and explosive gases**

With tests of a 14 kWh battery packet, concentrations from 11,700 ppm of deadly gases have been measured. A 100-gram battery mass can produce 5,000 m^3 of toxic air (see DNV GL study *Technical Reference for Li-Ion Battery Explosion Risk and Fire Suppression*, published in November 2019 by the Maritime Battery Safety Joint Development Project, chapter 15, pages 132–170, “Explosion Analysis and Assessment”).
The highest air changes per hour (ACH) during the tests were conducted at 30 ACH for a “big” room of 25 m^3. As an example, we have seen already a room of about 390 m^3 filled with battery packs with a weight in batteries of up to 26 metric tons.
Note: Discuss gas ducting and space ventilation strategies here, as well as how they link to active fire protection choices (hint: it is undesirable for ventilation to remain on when gaseous extinguishing media are being used, but it is desirable for ventilation to remain on should a thermal event continue beyond the initial release). Different risk mitigations depend on the scale of battery installations (*LR Rules* consider <20 kWh as lower risk).

- **Limitations of traditional fire safety measures**

A study from Research Institutes of Sweden (RISE) expresses doubts that rules can cover all the issues and risks involved with high amounts of battery mass in one space onboard a vessel (*Safe Introduction of Battery Propulsion at Sea*, 2017, chapters 7 and 8). Now in 2021, there are not many changes with regard to this matter. In section 7.4 of DNV-GL-RP-0043 (pages 70–74), safety requirements are most detailed rules (guidance) for all ships. When all batteries are in one space on a DP ship, there is no redundancy in case of a significant fire.

- **Recommendation**

The best recommendation is during the purchase of a big EES, also arrange in the contract the disposal of the Li-ion batteries when they do not produce enough anymore (after the end of life).

- **Hybrid DP vessels and jack-ups**

The following DP vessels have been built or will be built with hybrid power plants:

1. *Transocean Spitsbergen*, 5.6 MW battery pack (AKA/GE), upgrade
2. *Deepwater Poseidon*, capacitor pack (AKA/GE), new build
3. *Deepwater Titan*, 8.4 MW capacitor pack (AKA/GE), new build
4. *Deepwater Atlas*, 8.4 MW capacitor pack (AKA/GE), new build
5. *West Mira*, 6 MW battery pack (Siemens), upgrade (4 × 1.5 MW)
6. *Nordic Spring*, 4.8 MW battery pack (Kongsberg), new build
7. *Deepsea Nordkapp*, semisubmersible 2019, upgrade in near future
8. *Maersk Intrepid*, hybrid upgrade 2020, part of low-emissions upgrades
9. *Maersk Integrator*, hybrid upgrade in near future, part of low-emissions upgrades

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34. Diesel Technology Forum, “What is SCR?,” accessed 21 May 2021, https://www.dieselforum.org/about-clean-diesel/what-is-scr.

Note: Most of the above documents are available on the internet.

FMEA

One of the recommendations is to have a separate FMEA made for this complex issue that will focus on all the areas discussed in the paper above. The following are a few more issues to consider:

- DP operation in both normal and reasonably foreseeable abnormal conditions—particularly the time that particular faults may take to develop compared to the time to safely terminate a DP operation. Consider different scenarios like the BMS detecting abnormalities in a module compared to a fire in the battery space. What information is passed to the DP control system consequence analyzer from the BMS/PMS/EMS and how should it act?

- The role of a human in complex systems and consequently the training and procedural approaches that may be necessary to address gaps like firefighting on lithium battery systems
- Extinguishing systems and safe storage of combustible material from the battery rooms (EES) in operational manuals and part of crew familiarization training. Safety zones should be identified around battery rooms (similar to hazardous-area zones).
- The cause and effect of ventilation failure resulting in a possible overheating situation
- The effect on the FMEA of fire from a neighboring space
- Study about worst-case failure / configuration / capability plot
- The full lifecycle including disposal

Websites

https://www.nov.com/success-stories/preserving-lost-energy
https://www.dnvgl.com/expert-story/maritime-impact/Building-battery-confidence-Project-unites-stakeholders-around-battery-fire-facts.html
https://www.sdir.no/en/news/news-from-the-nma/supporting-preliminary-report-after-battery-incident/
https://en.wikipedia.org/wiki/Solid-state_battery

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