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DNV GL GUIDELINE FOR LARGE MARITIME BATTERY SYSTEMS

Joint project between ZEM, Grenland Energy and DNV-GL
Supported by Transnova

EXECUTIVE SUMMARY

The aim of this guideline is to help ship owners, designers, yards, system- and battery vendors and third parties in the process of feasibility study, outline specification, design, procurement, fabrication, installation, operation and maintenance of large Li-ion based battery systems (i. e. larger than 50 kWh). The guideline is consistent with the DNV rules for battery power.

Electric and hybrid vessels with energy storage in large Li-ion batteries and optimized power control provide significant reductions in fuel consumption and emissions. Such solutions also enable reduced maintenance and improved ship responsiveness, regularity, operational performance and safety in critical situations. However, a maritime battery might be 10 - 100 times (or more) larger than a traditional electric vehicle battery. The high energy content, combined with extreme charging and operational patterns, represents new challenges in relation to safety, reliability and service life.

To avoid accidents and unwanted incidents that may have significant safety and cost implications – and potentially halt the development of these technologies - it is important that the battery related systems are verified and validated according to "best practice".

ZEM (Zero Emission Mobility), Grenland Energy (GE) and DNV GL have worked together in a project to produce this guideline for safe and effective introduction of large maritime battery systems. In addition to addressing safety risks, the project is addressing economic risks such as failure of the business case due to improper selection of the battery system.

The main objective of the joint project has been to improve the systematics, tools and criteria for safe and efficient introduction of Li-ion battery technology. Target applications include hybrid offshore vessels and all-electric ferries and passenger ships. However, the recommendations are also valid for mobile offshore units and most ship types with Li-ion based battery power in all-electric and in hybrid configurations.

DNV's Technology Qualification process, utilised in the project to develop this guideline, has proven to be an effective methodology to identify and address challenges and weaknesses at an early stage in the realization of new technology. The methodology has a risk based approach, focusing on the “vital few” when uncertainty is removed in a systematic way. The main aim of this guideline is to reduce barriers and contribute to faster and safer battery electrification of the maritime sector.

In addition to the guideline, a platform is established for the project participants to perform Failure Mode Effect and Criticality Analyses (FMECA), which can be templated to perform FMECAs for specific designs of maritime battery based systems. Finally, a maritime battery degradation model has been created for service life assessment/ battery optimization analyses.

DISCLAIMER

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1 INTRODUCTION

Increasing complexity and uncertainty and high fuel price and strict regulations will change shipping. Fuel costs, regulations and stakeholder pressure are the key drivers for environmental and energy efficiency technology uptake. This has already resulted in improved ship designs and implementation of measures for reducing fuel consumption. Low sulfur fuel requirements are expected to lead to a 30 – 50 % fuel cost increase the next decade. In some countries and ports there will be local regulations pushing for reduction of local air pollution as well as use of shore electric power.

Battery prices have decreased steadily in parallel with increased energy density and better cycle life. This development is expected to continue due to economies of scale, and from technology evolutions and improvements. It is predicted that high volume Li-ion pack (system) price to automotive manufacturers could drop from current 500 US$/kWh to $200/kWh in 2020 and $160/kWh in 2025 (McKinsey&Co /2/). A large amount of battery research and development is currently on-going on cell, module and system levels. New materials and technologies are explored that could potentially lead to disruptions.

Strict regulations, high fuel price and lower battery prices combined with the Energy Efficiency Design Index (EEDI) requirements and expected additional CO_2 and NOx regulations will lead to the development and use of novel technologies and fuels such as biofuel, hybrid propulsion systems and last but not least, cost effective and safe battery systems.

All-electric ships and hybrid ships with energy storage in large batteries and optimized power control can give significant reductions in fuel costs, maintenance and emissions, in addition to improved ship responsiveness, regularity, operational performance and safety in critical situations. Today hybridization of ships can provide fuel savings of 20 - 30% with a payback time of 2 to 4 years. It can improve performance of diesel fuelled systems as well as LNG fuelled systems, new building or retrofit, and it can work as a storage unit for energy from waste heat recovery, regenerative braking of cranes and renewable energy. It is a necessary component in hydrogen fuel cell systems. Hybrid and pure battery operation works well in conjunction with shore power and low carbon sailing in the port area, and it helps solve local emission problems. Long term it is expected that the charter and second-hand markets will pay increased premiums for fuel efficient ships. Due to an increasingly improved business case, improved technology and new regulations, most vessels will in the future be hybrid or plug-in hybrid.

Several projects have investigated battery electrification of various ship types showing that there is considerable potential to reduce both energy consumption and emissions of CO_2, NO_x and particulate emissions. In addition to all-electric city-, car- and cargo-ferries for “shorter” distances, ideal ship types for battery hybridization typically have large variations in power demands and/or low utilization of the engine for longer periods of time. Ship types of particular interest are ferries, offshore vessels, shuttle tankers, wind farm vessels, passenger boats, fishing boats, tugs and other workboats and special ships with large load variations of the machinery.

DNV Class published requirements for using Lithium batteries on-board vessels in 2012. These requirements are function-based and applicable for all DNV classed vessels having batteries larger than 50 kWh. The requirements are mainly focusing on the safety of the battery and the installation. In addition to the requirements, a class notation named BATTERY POWER was introduced. This notation is mandatory for all DNV classed vessels using batteries as a main source of power for the propulsion of the vessel.

Presently, no international standards exist for such large scale batteries for maritime use. Work is on-going in IEC for establishing standards (e.g. IEC 62619 and IEC 62620). In addition, some standards exist for transportation of batteries, e.g. UN38.3.

2 SCOPE OF GUIDELINE

The aim of this guideline is to help ship owners, designers, yards, system- and battery vendors and third parties in the process of specification, design, procurement, fabrication, installation, operation and maintenance of large Li-ion based battery systems (i. e. larger than 50 kWh).

Figure 2.1 illustrates the ship building process and the responsible party for the different project phases.

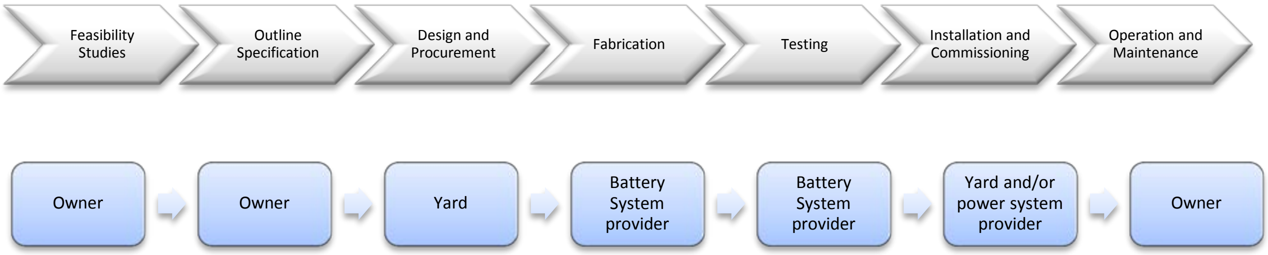

Figure 2.1. The battery system in the ship building process and the responsible party.

This guideline is consistent with the DNV rules for battery power, which shall be used directly for classification purposes. This document is a guideline and not class rules (see Appendix B).

To avoid accidents and unwanted incidents that may have significant safety and cost implications, battery related systems need to be verified and validated according to "best practice". This guideline is such a best practice providing recommendations for safe and effective introduction of large maritime battery systems with focus on potential applications in hybrid and all-electric vessels. In addition to addressing safety risks, the guideline addresses economic risks such as failure of the business case due to improper selection of the battery system. For example, the battery system might be too big and expensive or too small and have too short service life.

The guideline addresses two types of battery solutions:

Battery Power Only
Batteries are the single source of energy on board. Recharging of the batteries is done by external power source only (e.g. shore connection).

Hybrid system with battery and Internal Combustion Engine (ICE)
Batteries are used to complement/optimize onboard power conversion. The batteries are charged by onboard generators. Recharging by shore power connection may be possible (Plugin-Hybrid).

The recommendations are presented separately for the different phases of the ship building process (Chapter 4) and for the maritime battery system (Chapter 5). Relevant definitions and the generic system used as a basis for the system recommendations are described in Chapter 3.

3 DEFINITIONS AND ABBREVIATIONS

3.1 Battery System Definition

The generic battery system applied as basis for the recommendations in this guideline is outlined in the block diagram in Figure 3.1. As shown in Figure 3.1, the main components of the generic battery system are the cells, the hardware needed for making battery modules and sub packs, the required components for thermal management, safety features as contactors and fuses, bus-bars and high voltage cabling, electronics, voltage and temperature sensors and low voltage cabling and connectors. A brief explanation of the terms applied is given under the figure. For further details, reference is made to Appendix A.

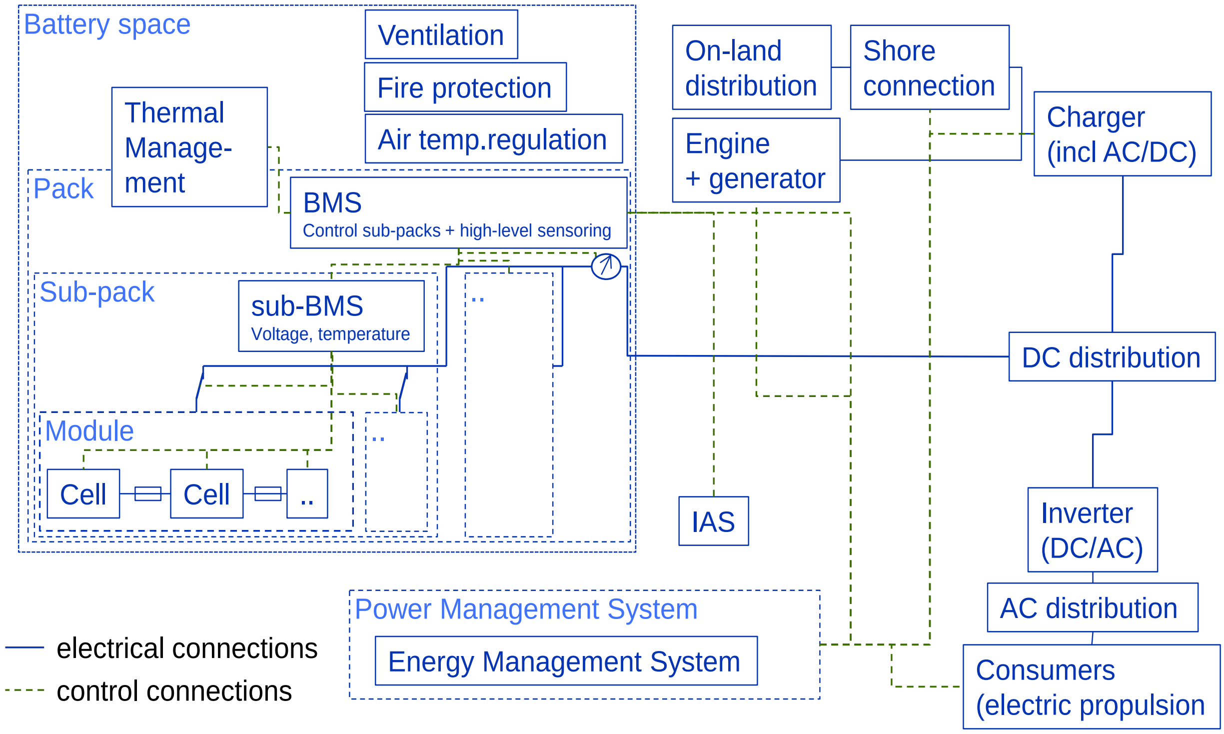

Figure 3.1. Block diagram of a generic system.

Cell	Smallest electro chemical unit
Module	Assembly of cells including some level of electronic control
Sub-Pack	Assembly of 1 or more modules. The smallest unit that can be electrically isolated
String	Smallest unit in a battery system with same voltage level as the battery system (e.g. serial connected cells, modules or sub-packs)
Battery pack	One or more Sub-Packs that can work for the intended purpose as a standalone unit
Battery system	One or more battery packs including all required systems for the intended purpose
Battery space	Physical installation room including walls, floor, ceiling, and all functions and components which contribute to keep the battery system in the defined space at a specified set of environmental conditions (e.g. temperature or moisture level)

3.2 Abbreviations and definitions

A60	Grade for fire proof walls and doors[1].
AC	Alternating Current
BMS	Battery Management System
DC	Direct Current
DUT	Device Under Test
E/E	Electric/Electronic
EMS	Energy Management System
EUC	Equipment Under Control
EV	Electric Vehicle
FMEA	Failure Mode Effects Analysis
FMECA	Failure Mode Effects and Criticality Analysis
H60	Grade for fire proof walls and doors[2].
HVIL	High Voltage Inter Lock
IAS	Integrated Automation System
ICE	Internal Combustion Engine
IP	Ingress Protection
LEL	Lower Explosive Limit, similar to Lower Flammability Limit, LFL
$LiCoO_2$	Cell chemistry: Lithium Cobalt Oxide
$LiFePO_4$	Cell chemistry: Lithium Iron Phosphate
$LiFeO_4F$	Cell chemistry: Lithium Iron Phosphate Fluoride
$LiMnO_2$	Cell chemistry: Lithium Manganese Oxide
LiNMC	Cell chemistry: Lithium Nickel Manganese Cobalt Oxide
LTO	Cell chemistry: Lithium Titanate Oxide
MSDS	Material Safety Data Sheet
PCB	Printed Circuit Board
PE	Protective Earth
PMS	Power Management System
PSDS	Product Safety Data Sheet
RP	Recommended Practice
RT	Routine Test = conformity test made on each individual item during or after production
SDS	Safety Data Sheet
SIL	Safety Integrity Level
SOC	State of Charge in percentage of the rated capacity available for the discharge of the battery (fuel gauge)
SOH	State of Health. Reflects the general condition of the battery and the ability to deliver the specified performance compared to a new battery
SOLAS	Safety Of Life At Sea
SWOT	Strength Weakness Threat Opportunities
TT	Type test = Conformity test made on one or more representative of the production
RT	Routine test
UPS	Uninterruptable Power Supply

[1] A-rating means testing based on a normal ISO standard fire curve (cellulosic fire). The item should maintain specified insulation performance, integrity and load bearing capacity for 60 minutes.
[2] H-rating means testing based on a Hydrocarbon fire curve (i.e. higher temperatures than for A-rated items). The item should maintain specified insulation performance for 60 minutes, and integrity and load bearing capacity for 120 minutes.

4 PROCESS RECOMMENDATIONS

This chapter outlines recommendations as applicable for the different project phases.

The recommendations were developed by carrying out a structured technology qualification process /1/. The approach is described in Appendix A. Qualification documentation must be provided based on assessment of critical functions. Critical aspects need to be taken into consideration throughout all project phases.

4.1 Feasibility Studies

It is recommended to undertake feasibility studies, before deciding to use a maritime battery system.

The purpose of the feasibility study is to evaluate alternative solutions as appropriate for the case considered. Expected operational modes and operational profiles, relevant load cycles, targeted system life etc. need to be considered in the feasibility studies. Evaluation of strengths and weaknesses (e.g. SWOT analyses) of alternative solutions with respect to technical issues, environmental aspects and economy are relevant in this phase. The results of the feasibility studies, which should include a rough sizing of the whole power system with related engines and batteries, will be used to determine whether the project should go ahead to the next phase.

Compared to traditional batteries with water based electrolytes such as lead acid and nickel cadmium batteries, lithium ion batteries have two to eight times as much energy per weight unit. The high energy density as well as the use of a flammable electrolyte makes a safe design more challenging. Lithium based battery systems depend on a well designed and tested electronic control system for safe operations. Appendix E gives an example of technical, economic and environmental analyses. Appendix F compares the CO2 emissions from battery production with the reduced CO_2 emissions during hybrid ship operation, while Appendix G gives an example on how to predict service life.

4.2 Outline and Contract Specification

The outline specification includes the main criteria for the system as given by the ship-owner. These will be project dependent, but typically include regulatory requirements, relevant standards, life time requirements, overall functionality, ship load profiles and power input/output requirements.

Generic	Only Battery Power	Hybrid Battery / ICE System
• Redundancy. • The vessel shall not be less safe than conventional vessels. • A maintenance plan shall be established. • Check additional flag (national) authority requirements.	• At least two completely independent systems shall be installed.	• At least two completely independent systems shall be installed. The battery system may be part of one of these.

Table 1. Examples – regulatory requirements.

Generic	Only Battery Power	Hybrid Battery / ICE System
• DNV Class Rules (including SOLAS). • IEC 61508 may be relevant/useful for BMS. • Other standards relevant for maritime Li-systems.	• Emergency generator can be omitted if flag (national) authorities agree.	• Emergency generator can be omitted if national authorities agree.

Table 2. Examples - relevant standards.

Table 3 illustrates input to system requirements that might be of relevance for the outline specification.

Generic	Only Battery Power	Hybrid Battery / ICE System
• For non-propulsion cases loss of battery power shall not affect critical vessel functions. • Battery lifetime shall be such that the business case is economically reasonable. • Single failure of critical modules, shall not compromise the integrity of the vessel. • The BMS shall communicate critical battery parameters. • The integrity and safety shall not be less than for conventional vessels. • The BMS shall ensure that the battery operates in the safe operating window of the cells. • Important battery parameters shall be logged and stored in a non-volatile memory. • Minimum two independent battery strings per battery system to achieve redundancy to be assessed. • The system shall be maintainable such that defect parts can be substituted safely and effectively. Competence, technical and process requirements shall be specified. • Battery space redundancy and segregation. • Maintenance, access and replacement of parts of the system. • Battery space shall be accessible for spare parts. • Alarms and shutdown functions on several levels (e.g. evacuation mode). • Grounding of batteries: isolated system is recommended. (Isolated positive and negative terminals.) • System shall demonstrate robustness for long term exposure in a marine environment (temperature, moisture, list, trim, roll, etc.). • Battery spaces shall provide protection against external hazards (e.g. fire, mechanical impact). • If the battery system is equipped with a remote logging/diagnostic system, it must be protected sufficiently against intrusion. • Reliability of the complete system must be at least as good as conventional vessels with ICE.	• Useable energy of the battery such that safe return to port is possible with one battery system not working. • SOC and SOH shall be monitored. • Remaining range or time shall be displayed. • Enough charging shall be possible during port stay to keep an acceptable state of charge. • The Battery Space shall comply with machinery space requirements (ref SOLAS), i.e. "Other machinery space".	• "Safe Return to Port" shall be possible. • Battery shall be located in a battery space, of similar requirements as a machinery space. According to SOLAS it has to be placed in a machinery space or adjacent to it if it is a source of main power, i.e. "Other machinery space" or "service space".

Table 3. Example of input to system requirements of relevance for the outline specification.

The outline specification is used by the ship-owner when the yards are invited into the process, even before the bid process is started, and will be part of the basis for this process and price and contract negotiations.

4.3 Battery System Design and Procurement

When the ship building contract is signed, the responsibility and further design work is normally transferred to the yard. The yard prepares procurement packs for the various system components. It is recommended that potential battery providers are consulted at this phase.

Main priorities for a battery system for maritime applications are safety, reliability and sufficient life for the system to be economically feasible. All components in the battery systems must be of good quality to secure a safe and reliable system. The integration and testing of the complete battery system is of similar importance as the quality of its single components. It is recommended that a safety assessment of the battery space is initiated in the design phase.

It is crucial to fully understand the duty cycles of the application as well as understanding the key requirements of the application for battery selection and optimum performance.

4.3.1 Li-ion battery cells

Li-ion based systems require that the voltage, current and temperature of each single cell in the system is monitored at all times. The voltage and current limits are temperature dependent. A proper system design requires that proper action can be taken if cell parameters are outside the manufacturer's recommendation. To decrease system complexity, temperature monitoring can include some predicted values based on measurements for a group of cells. We recommend redundancy in systems when predictive or correlated temperature measurements are used. Cells connected in parallel will have the same voltage and cells connected in series the same current.

There are a large number of manufacturers of different variants of Li-ion cells. Cell chemistries are optimized for different applications. In some applications the main focus is on high energy density and low cost. For other applications a very stable chemistry and long life is the main focus. Other applications can have a focus on power capabilities for charge or discharge or the ability to accept high current pulses for charge and discharge.

There is disparity in product quality between cell manufacturers. Automated production, proper process control, and robust cell design are all crucial elements to ensure good battery cell quality. It is important to base the battery pack on cells with equal properties since the system has to be designed with the weakest cell in mind. Cells with a large variation in properties will mandate overdesign for portions of the battery system and make cell balancing more challenging.

For maritime applications it is important to choose a cell with properties that can provide an optimum combination of safety, life, performance and cost for the application in question. A thorough understanding of all these aspects is required by the team doing the battery system design. To ensure this understanding, independent cell testing or advice from independent third parties who have done neutral testing may be required. See Appendix D for further input on cell testing.

4.3.2 Electrical system

When the cells are assembled into modules, custom supportive materials are added around the cells. The thermal management system, which could be based on either passive cooling or active cooling with air or liquid, is installed and the cells are electrically connected in the specified configuration. The battery cell terminals may either be of a screw type, welded or clamped.

The modules are connected into sub-packs. The sub-packs (or modules if there are no sub-packs) are connected into strings and a number of parallel strings makes the battery pack. A battery system may consist of one or more packs. The electrical connections between the different aggregate levels of the battery system may be connected using cables, bus bars or a combination of these. Low contact impedance for the electrical connections is crucial to avoid over-heating and control the fire risk, as well as maximum efficiency. Several parallel strings will decrease the risk of overheating from increased contact impedance. It can also ease the detection of elevated levels of contact impedance in the electrical connections resulting in increased safety of the system.

4.3.3 Electronic control system

The electronic control system is frequently referred to as the Battery Management System (BMS). Voltage and temperature sensors are usually part of the module. It is recommended to consider some level of redundancy for these fundamental measurements, depending on the safety criticality of the system. The module may also include an electronic circuit board that controls the cells in the module via continuous checks and assessments. A key principle when locating sensors is to make the system in such a way that malfunctioning sensors may be detected. The module level BMS is part of the total battery electronic system. The system may include additional sensor inputs such as current sensors and additional temperature sensors as well as other system specific sensors. It is recommended that each battery string has a separate current sensor in order to detect increased impedance that can lead to overheating. In addition, for systems containing a large number of strings, a group of strings can have a common current sensor. A "Master-BMS" usually controls the assembled battery system and communicates with the external power management system. It is crucial to ensure that the communication between the master BMS and the power management system for the actual application is properly specified for normal operation as well as for situations where a problem has occurred.

If a problem occurs in a battery system it may either be due to components or manufacturing failures. Software faults or inadequacies can also be a major source of problems. For problem solving and fault analyses it is important that all critical components in a battery system can be identified. All software and firmware version numbers and settings must be tracked. All critical components should have their unique number which should be traceable from the manufacturer of the component to final installation in a battery pack. The pack supplier should administer the database identifying the components used for the different modules and packs.

4.4 Fabrication

Fabrication (manufacturing) requirements will vary substantially depending on the technology used. Some common requirements do however exist:

- Product traceability
- Cleanliness requirements
- In-line and end-of-line (EOL) testing
- Operator certification & training requirements
- Health & safety regulations

4.4.1 Product traceability

The safety, performance, life expectancy and reliability of battery systems are potentially very sensitive to a number of factors. Cell level contamination can render a batch of cells vulnerable from a safety point of view. Similarly, other parts or components used in the production or settings used in the production process can give reason for similar concerns. Software controlling safety critical functions and components used for carrying high currents are particularly vulnerable. As are the production settings involving the aforementioned factors. It is therefore very important for the battery systems manufacturer to have a system that can ensure sufficient product traceability to enable preventive actions or recalls in case of systematic faults that can jeopardize adequate safety and performance of the battery system.

4.4.2 Cleanliness requirements

Battery systems are sensitive to contamination with materials that can initiate self-discharge, high impedance, loss of insulation or short-circuits. The cleanliness standards of the manufacturing facilities for each sub-assembly must address the risks associated with the sub-assembly in question. Sufficient internal separation of sub-assembly areas as well as separation of assembly areas, workshop, or packaging areas are usually necessary for both safety and performance reasons.

4.4.3 Sub-assembly and finished product testing

Sufficient testing to ensure that each sub-assembly can be included in the next level of sub-assembly and/or in the finished battery system without posing a safety risk during further testing is necessary. In addition, each sub-assembly should undergo testing, and the testing metrics should correspond to what would be required for the sub-assembly to fulfill its intended function in the system.

4.4.4 Operator certification & training requirements

Construction and assembly of battery systems frequently involve operations that potentially introduce risk to operators. National regulations usually specify the required operator training for different voltage levels. In addition, the battery system manufacturer and power system supplier should have operator certification & training requirements and schedules to ensure necessary operator and product safety as well as product consistency and performance.

4.4.5 Health & safety regulations

For the battery system production facilities, company health and safety regulations need to address both regular industrial and electronics manufacturing hazards and particular hazards related to battery manufacturing. Standard industrial operations such as lifting, risk of crushing, crane operations with associated risks are not treated here. The focus is on the particular hazards related to battery manufacturing.

Production of battery systems can pose several hazards. The main hazards are chemical and electrical. Chemical hazards can occur if electrolyte leaks out of the cells, a thermal event or if a short-circuit leads to overheating internally in the battery or sub-assembly or overheating externally to the battery or sub-assembly. The short-circuit currents can be very substantial and can also lead to serious injuries and loss of life.

A battery manufacturing environment is special in the sense that it will contain sub-assemblies with both high voltage and sensitive electronics. This can pose special challenges for protective gear since conductive materials are preferred to minimize the risk of damage from static electricity, whereas electrically insulating materials are strongly preferred to avoid short circuit risks. To prevent hazards arising from the difference in requirements it is therefore recommended that the manufacturing facilities have different and clearly marked zones for electronics sensitive to static electricity.

4.4.6 Transportation of battery system

In order to ensure safety during transport, nearly all lithium batteries are required to pass section 38.3 of the UN Manual of Tests and Criteria[3] (UN Transportation Testing) which is identical to IEC 62281. Note that this UN regulation is the only mandatory set of regulation for lithium-ion batteries today (12-2013).

Tests 1-8 of this specification are as follows:

T1 – Altitude Simulation (Primary and Secondary Cells and Batteries)
T2 – Thermal Test (Primary and Secondary Cells and Batteries)

[3] Recommendations on the Transport of Dangerous Goods. Manual of Tests and Criteria. 5th Revised Edition, December 2009. Section 38.3 refers to "Lithium Battery Testing Requirements

T3 – Vibration (Primary and Secondary Cells and Batteries)
T4 – Shock (Primary and Secondary Cells and Batteries)
T5 – External Short Circuit (Primary and Secondary Cells and Batteries)
T6 – Impact (Primary and Secondary Cells)
T7 – Overcharge (Secondary Batteries)
T8 – Forced Discharge (Primary and Secondary Cells)

Further the UN rules defines a large battery to have a gross mass of more than 12 kg and a large cell as a cell with a gross mass of more than 500 g. These definitions are important for the number of samples that are required for the testing.

The UN Transport of Dangerous Goods regulations also defines specific requirements for the packaging used when transporting batteries.

4.4.7 Storage before installation

When storing battery cells a certain degree of self-discharge is inevitable. This could be both reversible and irreversible. The higher the storage temperature and the higher the state of charge of the cells, the higher the losses will be due to increased impedance. Most manufacturer ship battery cells and system at around 50% state of charge. It is important that cells and modules are not stored for longer period in hot climate. If the average storage temperature or temperature during transportation is above 30 -35 ºC, degradation due to calendar effects will accelerate. Considerations for storage prior to installation shall also include appropriate temperature and SOC safeguards.

4.5 Battery System Testing by Manufacturer

The following tables show examples for the range of test procedures which can be applied to a battery system for maritime applications by the battery system manufacturer. Some of these tests may be defined in the coming standard IEC62619 and will be applicable for testing. The tests are distinguished between TT (Type Test) and RT (Routine Test). The definitions are as follows:

- Type Test (TT): Conformity test made on one or more items representative of the production.
- Routine Test (RT): Conformity test made on each individual item during or after production.

The tests typically apply to either cell, module, sub pack or the complete battery system (column DUT – device under test).

Test	Comments	DUT	TT/RT
Cell balancing	According to specification	Battery system	RT
SOC validation	Validate the measured SOC	Battery system	RT
Charging behavior	According to specification	Battery system	RT
Discharge behavior	According to specification	Battery system	RT
Capacity check	According to specification	Battery system	RT

Table 4. Battery system performance tests.

Test	Comments	Component	TT/RT
External Short Circuit with no BMS	UN38.3/IEC62281	Module, Sub pack	TT
External short with operable BMS	Could also be performed with a complete string, requires a controller with breakers/relays	Sub pack	TT
Internal Thermal Event	Propagation on pack level. IEC62619 is assumed to cover relevant recommendations: - unchanged module/pack structure (mechanical/electrical) - SOC 100%, all cells balanced - Normal temperature (alternative: max operation temperature) - passive/charging/discharging status - single cell set off on purpose (thermal element or other, cell location to be discussed) - etc.	Sub pack	TT
Overcharge with no BMS	UN38.3/IEC62281	Sub pack	TT
Emergency stop function	-	Battery system	RT
Alarms and shutdowns	-	Battery system	RT
HVIL	-	Battery system	RT
Temperature protection BMS	-	Battery system	RT
Overvoltage protection BMS	-	Battery system	RT
Undervoltage protection BMS	-	Battery system	RT
Sensor failures	-	Battery system	TT
Communication Failure	-	Battery system	RT
Reverse polarity protection	-	Battery system	RT
Nail Test	UL2580	Cell	TT

Table 5. Battery system safety tests.

Test	Comments	Component	TT/RT
Dielectrical strength	High Voltage test	Sub pack	RT
Insulation resistance		Sub pack	RT

Table 6. Battery system electrical tests.

Test	Comments	Component	TT/RT
Vibration	IACS E10 /IEC 60092-504/ UN38.3/IEC62281	Sub pack	TT
Drop	UN38.3/IEC62281	Sub pack	TT
Heat	IACS E10 /IEC 60092-504	Sub pack	TT
Cold	IACS E10 /IEC 60092-504	Sub pack	TT
Corrosion	IACS E10 /IEC 60092-504	Sub pack	TT
Flame retardant	IACS E10 /IEC 60092-504	Sub pack	TT
EMC	IACS E10 /IEC 60092-504	Battery system	TT
IP	IEC 60529	Sub pack	TT

Table 7. Battery system environmental tests.

4.6 Installation and Commissioning

Experience has shown that issues often occur in 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 must be provided by the battery system supplier.

All interfaces must be tested before the installation can be signed out and a proper 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, the supplier of the other power plant components and the yard.

4.7 Operation and Maintenance

The normal use of the batteries should be fully automatic. There should be no need for manual interaction. Table 8 gives recommendations towards a generic operational strategy.

Generic	Only Battery Power	Hybrid Battery / ICE System
• Vessel operation should be as simple and as similar to conventional system as possible, requiring an (automated) energy management system in addition to power management. The BMS keeps battery usage within allowed limits. • Emergency operation procedures necessary (fire, abandonment, etc.).	• Energy management becomes critical. • Charging procedure necessary.	• Energy management becomes critical if battery used as main power source. • Charging procedure if shore power option.

Table 8. Recommendations for operational strategy.

4.7.1 Operation Manual

There should be established a plan (Operational Manual) intended for regular use on board, providing information on:

- Load profiles
- Charging procedure
- Normal operation procedures of the battery system included minimum levels of battery capacity
- Emergency operation procedures of the battery system
- Estimated battery deterioration (ageing) rate curves
- Operating instructions for normal and degraded operating modes
- Details of the user interface
- Transfer of control (if more than one control station, or local control are implemented)
- Test facilities
- Failure detection and identification facilities, automatic and manual
- Data security
- Access restrictions
- Special areas requiring user attention
- Procedures for start-up
- Procedures for restoration of functions
- Procedures for data back-up where applicable

The relevant parts of this plan should also be implemented in the overall ship operation manual.

4.7.2 Maintenance

Overall recommendations for maintenance are outlined in Table 9**.**

Generic	Only Battery Power	Hybrid Battery / ICE System
• Internal diagnostics wherever feasible	• A plan including how and how often the state of charge/health of the batteries is checked/validated shall exist.	• When used as main power: A plan including how and how often the state of charge/health of the batteries is checked/validated shall exist.

Table 9. Overall maintenance strategy.

A plan for systematic maintenance and function testing shall be kept on-board showing in detail how components and systems shall be tested and what shall be observed during the tests. The plan shall include:

- Verification of the SOH (remaining lifetime of the batteries).
- Test of all instrumentation, automation and control systems affecting the battery system.
- Test intervals to reflect the consequences of failure involving a particular system. Functional testing of critical alarms should not exceed 3 month intervals. For non-critical alarms, the longest intervals are normally not to surpass 12 months.
- Acceptance criteria.
- Fault identification and repair.
- List of the supplier's service net.

Different battery systems will have different maintenance needs and maintenance recommendations. This should be included in the maintenance plan. Information about periodically testing should also be included in the vessels unmanned machinery space (E0) manual.

4.8 Documentation Requirements

The following documentation should be part of a battery system delivery:

- Hardware manual: Description of the hardware included with the battery delivery.
- Firmware manual: Description of the firmware included with the battery delivery as well as an overview of which units contain upgradeable firmware.
- Installation manual: Description of requirements as to how the system is to be installed.
- Operation manual: Technical communication document intended to give assistance to people using the battery system. The operation manual should contain a system overview and technical data about the battery system.
- Maintenance manual: Description of regular maintenance, fault identification and repair.
- Material safety data sheet (MSDS) and/or safety data sheet (SDS) and/or product safety data sheet (PSDS): Documentation intended to provide workers and emergency personnel with procedures for handling or working with that substance in a safe manner, and includes information on how to handle the battery system in an emergency situation as well as information on potentially harmful substances.
- Function description: Description of the functionality of the battery system.
- Technical specification: Specification covering the technical details of the battery system such as power and energy capabilities, temperature of operation, system life time etc.
- Parts List (high level bill of materials).

- BUS Communication Protocol: Specification of the communication between the battery system and the rest of the system including communication protocol and available messages with explanation of those. This includes all signals for regular operation as well as all warning and error signals.
- Parameter Settings List including all user visible parameters.
- Dimension Drawing and Layout.
- Internal Wiring Diagram.
- External Wiring Diagram.
- FAT Procedure: A test program for functional and safety tests at the manufacturer's works.
- FAT Report: Mutually signed report documenting that the factory acceptance test is passed.

5 MARITIME BATTERY SYSTEM RECOMMENDATIONS

It is a main goal that the safety and reliability of a vessel with a large lithium battery installation shall be at the same level as a conventional vessel.

It is strongly recommended to evaluate critical failure modes and related safety and economic aspects from the beginning of the concept development. Critical failure modes might, for example, have the potential to cause thermal event propagation between battery cells or modules. It is therefore a need to assess implications for the system as a whole. Short circuiting resulting in thermal run-aways within a cell is an example of a failure mode that should be considered.

Key aspects with possible implications for safety, reliability, life, cost and overall operability of the vessel should include:

- The experience of the battery system supplier.
- Well-designed and well documented battery system with high quality cells.
- Adequate lithium chemistry for the application.
- Temperature control and thermal management of the battery system.
- Sizing of the battery system taking into account the relevant load cycles, charge and discharge patterns.
- Battery space(s) designed to manage ambient temperature, ventilation and safety from internal and external hazards.

Main risks related to formation of flammable gases, thermal events and fire extinguishing need to be considered.

5.1 Battery Space

The battery space is the physical installation room including walls, floor, ceiling, and all functions and components which contribute to keep the battery system in the defined space at a specified set of environmental conditions (e.g. temperature or moisture level).

It is recommended to undertake a safety assessment of the battery space. The safety assessment should include the following steps:

- Identification of all potential hazards with a list of all relevant accident scenarios with potential causes and outcomes, including that Li-Ion battery fires have extinguishing challenges.
- Assessment of risks including evaluation of risk factors.
- Risk control options.
- Actions to be implemented.

It is recommended to initiate the safety assessment in the design phase. Reference is made to the Technology Qualification methodology outlined in Appendix A and the description of functional safety given in Appendix C.

Figure 5.1 below illustrates the battery space definition applied with relevant sub-systems included.

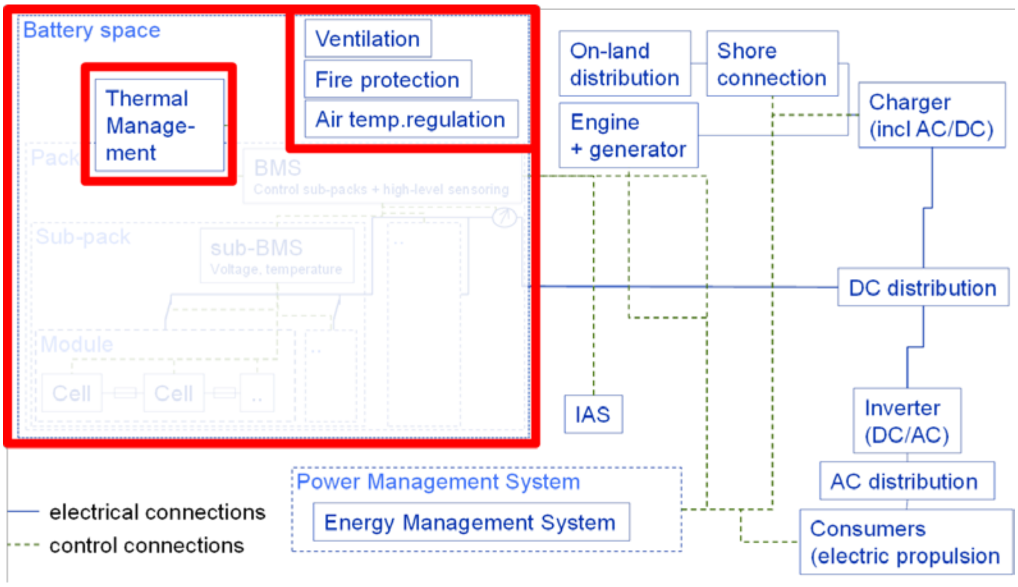

Figure 5.1. Illustration of Battery Space.

5.1.1 Ventilation and accumulation of flammable gases

It is necessary to ensure proper detection of gases that may be emitted from the battery system in the event of a serious fault conditioning, relief and ventilation to prevent the formation of explosive atmospheres. Design therefore needs to consider realistic parameters for the battery system under consideration. This includes flammable gases from decomposition of the electrolyte due to temperature rise in a cell, in addition to hydrogen and other gases that can be created via electrolysis or other processes in case water comes in contact with the battery electrical systems.

Recommendation:

> *The battery system shall not be located without adequate protection from heat, ignition sources, dust, oil pollution or other potential harmful environmental influence to the system and its components. If practical, a battery space should be a dedicated room.*

5.1.2 Fire protection

With respect to rooms adjacent to the battery space, normal good quality fire detection and fire extinguishing should be sufficient in order to prevent a fire spreading from adjacent rooms to the battery space. It is recommended to check the relevant external fire scenarios and whether the segregation from the battery space is sufficient to maintain the required integrity.

With respect to thermal events originating in the battery space, early detection and increased cooling power will help to keep any fire under control.

The following safety strategy with respect to a battery fire is anticipated:

1. Electrical and thermal control through BMS without option for manual override of safety functions.
2. Cell thermal runaway shall be kept confined at lowest possible level, therefore:
   a) The design of a module/sub-pack shall inhibit propagation from cell to cell.
   b) If 2a) cannot be guaranteed, the module/sub-pack outer surface shall not exceed a critical temperature level of approx. 130 °C during a thermal event. No flames shall be visible.

c) If 2b) cannot be guaranteed, the battery space must inhibit propagation between modules/sub-packs as well as surrounding materials catching fire.

3. Fire within several sub-packs must be assumed to be out of control. Vessel evacuation cannot be excluded.

Strategy with respect to fire outside the battery space:

1. Any fire shall not lead to temperature above 70°C within battery modules for more than 30 min.
2. If the cell temperature has exceeded the battery manufacturer's maximum temperature, the battery system needs to be re-certified by the battery supplier before it can be put back into use.
3. Fire classes applied on walls, doors etc. shall protect the battery system, e.g. by A60 fire separation, which indicates the duration the doors and walls must be able to withstand a given type of fire.
4. If possible, decrease SOC to reduce the risk for a thermal event in the battery system.

Recommendations:

The maximum cell temperatures over lifetime shall be monitored. This gives an indication on whether the system can be used further or needs exchange after a critical fault involving high temperatures.

The responsible operators for a battery system shall have sufficient training to be able to decide when and in which cases the fire extinguishing in the battery space shall be deactivated.

5.1.3 Strategy for ventilation and fire protection

It is recommended to develop a strategy for ventilation and fire protection when temperatures above warning levels are detected. Flammable off-gases will be generated from the battery electrolyte solvents if cell temperatures go above certain values. Such hazards need to be considered as a cell can continue to function despite a building off-gas hazard. Adequate ventilation in the enclosed spaces affected can contribute to manage this risk.

The following is an example of a ventilation and fire protection strategy:

1. Reduce or cut battery load.
2. Increase battery cooling as much as possible.
3. Ventilate battery off-gases to outside the ship, as long as there is no fire.
4. If fire breaks out, shut down ventilation and activate fire extinguishing system.

Case by case assessment might be required to assess the risk for propagation of an event from an individual cell to multiple cells, or module(s). Such assessments will provide important input to recommendations for appropriate ventilation and possibly other risk controlling measures. In this setting, the main purpose of (additional) ventilation will be to limit the concentration of flammable gasses and thereby reduce the risk for fire.

For instance, it might be cases where gas emissions from a vented small cell in a large room can be acceptable, while this may be different for gas emissions from a bigger cell or a module where the incident propagates between cells. The size and energy content of cells and modules, local ventilation conditions and (free) volume of the battery space will be case dependent and needs to be assessed on a case to case basis.

Key issues are to quantify the formation of flammable gasses and how the gasses are likely to disperse.

As a general fire extinguishing medium, either water mist or (heavy) foam should be considered. Heavy foam might have advantages, such as:

1. Longer lasting cooling effect since heavy foam might form a “wall” around and between battery sub-packs with a good cooling effect (depending on layout).
2. Potential off-gas which is warmer than air can be ventilated from a high position in the battery space while foam can be injected from the top and spreading slowly downwards.
3. Surrounding foam can bind potentially flammable solid or fluid off-gas products while gases can be ventilated out.

Gas releases are only rarely distributed in even concentrations. A safety margin is therefore recommended. Often a gas detection limit of 20% of LEL is applied to ensure early warning and since local concentrations usually will exceed the average concentrations. There are several different possibilities regarding how the gas volume in relation to LEL should be evaluated:

For modules with very low risk for propagation between cells:

- The gas generation from one cell could be evaluated in relation to the size and conditions for the battery space.

For modules where thermal events are likely to spread throughout the module:

- The gas generation from one module should be evaluated in relation to the size and conditions for the battery space.

For systems where a thermal event spreads between modules or sub-packs:

- This situation is for most cases not acceptable and significant changes to the battery system should be made to prevent such a scenario.

In case the gas formation results in gas concentrations below the detection limit, no additional ventilation or exhaust gas fan system would need to be implemented. If the gas detection limit is likely to be exceeded, further assessment on measures to dilute and extract the gas generated are required. For a single cell, the highest rate of gas emissions from that single cell should be considered.

For systems with propagation, the highest rate of propagation at the highest rate of gas emissions from a single cell should be considered as the dimensioning case.

The general assumption for ventilation systems should be that the gases are highly flammable.

Recommendation:

> *The ventilation system shall be temperature resistant and not impose any ignition risk to the ventilation products. EX certified components according to Zone 2 may be foreseen for exposed parts of the ventilation system. Gas group and temperature class need to be decided based on the battery chemistry.*

5.2 Battery System

The battery system consists of one or more battery packs including all required systems for the intended purpose. This chapter outlines the recommendations made from the FMECA analysis for cells, modules, sub-packs and packs. Figure 5.2 below illustrates the battery system and sub-system definitions applied.

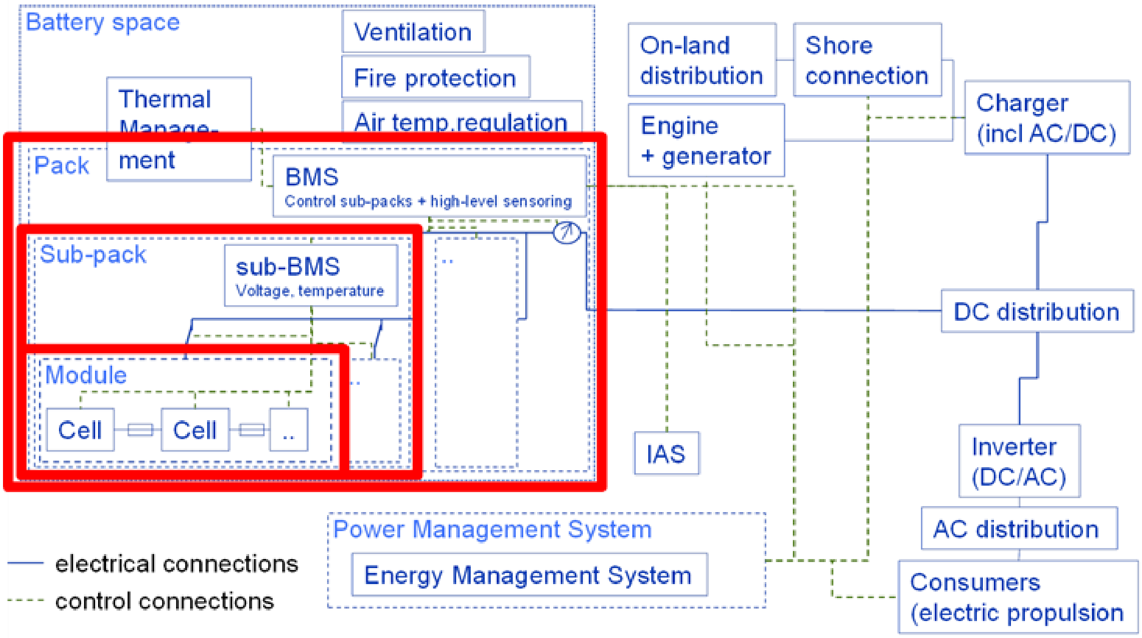

Figure 5.2. Battery System and related sub-systems.

5.2.1 Cells

A cell is the smallest electro chemical unit.

5.2.1.1 Internal short circuit

Internal short-circuits have been a significant cause for thermal events. An internal short-circuit means that an electrically conducting bridge has been formed between the positive and the negative electrodes inside the battery cell. The majority of such internal-short-circuits do not result in a thermal event. A thermal event can happen if the impedance of the internal short-circuit is high enough to create sufficient heat, but low enough to allow sufficient current to pass and that the conductive bridge is strong enough to not break down when current is flowing. In addition, the heating must occur in a location where a high local temperature can induce chain reactions resulting in a cell thermal runaway. Cell level thermal events are usually impossible to foresee. The root causes for such events are usually cell level contamination, often in combination with cell design flaws or damage during service. To minimize the frequency of thermal events a strong quality focus has to be maintained by the cell manufacturer. To minimize the effect of thermal events, the possibility of cell to cell propagation on a battery pack level has to be minimized.

Recommendation:

The manufacturer of a battery system shall monitor the battery cells regarding their self-discharge properties such that potential faults can be detected. A quality regime at the battery system manufacturer shall include rules and documentation with respect to internal short-circuit tolerance of the used cells, e.g. internal production quality documentation and nail test results.

5.2.1.2 High Impedance

To check the AC impedance of individual cells prior to assembly into battery modules, the standard method is to use a Milliohmmeter implementing a 1 kHz AC test signal for precise measurements of extremely low resistances (for instance Agilent 4338B Milliohmmeter). This procedure is usually an inline test to check the supplier quality. It is important to keep in mind that this is an AC impedance test. For the usage of the batteries in a battery pack, the DC impedance is usually more important. The DC impedance will also incorporate capacitive elements originating from electrochemical reactions and diffusion processes. Testing the DC impedance of at least modules prior to commencing usage of the battery system is necessary.

If a cell or cell connection has high impedance it will result in increased heat production during operation. If one cell is exposed to higher temperature, the impedance growth in this cell will be higher than the impedance growth for cells at a lower temperature. This generates a positive feedback effect with the potential to severely affect the life and performance of the battery pack. If the heat production is high enough this can also have severe safety implications since thermal events can be initiated.

The impedance in a cell or a group of cells can be calculated by Ohm's law by dividing the voltage by the current, provided the voltage and current are measured at the same time. Then the impedance of one group of cells can be compared to the impedance of another group of cells.

For batteries with minimum two parallel strings of cells or modules it is important to measure the current in each string because this way the string impedance can also be calculated. Further the string impedances and/or the current going through each string can be individually compared to identify impedance abnormalities.

In all cases the BMS should keep track of the DC impedance of the system and preferably the DC impedance of all cells connected in series in the battery system. This information is important to determine safety performance and battery life.

5.2.1.3 Insulation fault

Pouch cells have a soft exterior surface which needs to maintain its electrical insulation over lifetime. Particles on the surface can damage the outer layer via persistent wear, e.g. under vibration and over time. A pressurized assembly line with filtered air is recommended to mitigate contamination of particles.

Prismatic/cylindrical cells with a solid metal or plastic can are not as sensitive. However, depending on the joining method and other operations during assembly (circuit boards), a clean and dust-free environment is also recommended.

Recommendations:

The manufacturer of a battery system shall install a quality regime that secures, includes or allows:

- *Track and trace system, capable of tracing down to cell or cell batch level.*
- *Where human operations are needed, protective gloves shall be worn.*
- *Consistent use of non-conductive tools during assembly.*
- *Relevant results from in-line testing should be stored at least for the lifetime of the battery.*
- *Temperature and moisture control to avoid condensation if necessary.*

Also refer to description of insulation fault on module level, chapter 5.2.2.5.

5.2.1.4 Electrolyte leakage

Leakage of electrolyte is a possibility, especially from pouch cells. Electrolyte can have a sweet smelling organic solvent odor. Typically the electrolyte contains lithium hexafluorophosphate ($LiPF_6$). The interaction of water or water vapor and exposed lithium hexafluorophosphate may result in generation of hydrogen fluoride (HF) gas and subsequently corrosion products. Contact with battery electrolyte may be irritating to skin, eyes and mucous membranes. Fire will produce irritating, corrosive and/or toxic gases. Fumes may cause dizziness or suffocation.

Solvents within the electrolyte are often variants of ethyl carbonates. Evaporation of these carbonate solvents leads to flammable gases that can create explosion risks when the lower explosion limit (LEL) is reached. In case of electrolyte leakage, proper ventilation is important. Avoiding trapping of the most volatile gases such as hydrogen and methane, is important in order to avoid severe consequences such as fire and/or explosion. Cells leaking electrolyte may produce gases lighter or heavier than air. Volatile and hot gases will rise towards the ceiling of the battery space. It is therefore recommended to have an air intake placed fairly low and a ventilation outlet placed as high as possible in the battery space to avoid trapping of volatile gases. Further the ventilation system should be designed to ensure sufficient air exchange to minimize the risk of any concentration exceeding the lower explosion limit (LEL).

Hydrogen fluoride is extremely corrosive and when formed it will most likely initiate further corrosion in the surroundings. For pouch cell systems, there is a high risk of a corrosion reaction initiating further electrolyte leakage from adjacent cells if electrolyte is allowed to come in contact with the aluminum pouch cell liner on one or more adjacent cells.

Electrolyte leakages are detected via electrical insulation measurements provided that the battery system insulation measurement strategy is designed to detect such leakages. In the case of undetected breaches in cell packaging, leaking and evaporating carbonate solvents can be detected with sensors sensitive to these species. Other detection methods can be increased self-discharge rate, loss of power, increased impedance, detection of organic compound fumes etc.

In case of electrolyte leakage, the battery manufacturers MSDS should indicate methods for cleaning the spill. Pouch cells exposed to electrolyte should be permanently taken out of use as cells may have experienced damage that could be very difficult to detect.

Other cells than pouch cells may also leak electrolyte and proper module design is extremely important in order to prevent such leakage. For cell types where the cell can does not have any polarity, it is important that the can is electrically insulated from the rest of the system.

Typical root causes for electrolyte leakage are cell packaging in electrical contact with battery casing. Pouch cells have several additional potential root causes for electrolyte leakage. Examples of such root causes are improper handling of cell flanges, improper handling of battery cells during manufacture as well as cell pouch liner polarization for instance from poor design in combination with high voltage insulation measurements.

Once one cell starts leaking and the electrolyte from this cell comes into contact with other cells, there is a strong likelihood that the other cells also will experience electrolyte leakage. This is particularly likely for pouch cells where the leaked electrolyte comes into contact with the cell pouch liner. Electrolyte leakage can also cause shorts across cell or module electrical connections, resulting in additional safety risks.

Note that electrolyte leakage in this context has to be distinguished from venting.

5.2.2 Modules

A module is an assembly of cells including some level of electronic control.

5.2.2.1 Battery Management System Control Failure

It is important to:

- Ensure that the High-level BMS can detect critical failures of Sub-BMS and switch off the related module/sub-packs.
- Investigate the criticality of the BMS, ref Appendix C in form of a hazard and risk analysis.
- Provide recommendations on configuration. Include critical alarms and shut down in safety critical situations.

- Make sure that the BMS development and operational processes are commensurate with the BMS level of criticality. IEC 61508 and the DNV Offshore Standard DNV-OS-D203 Integrated Software Dependent Systems are examples of standards where process requirements are differentiated according to the criticality of the function. For safety functions, IEC 61508 is considered to be the one most relevant.
- To increase trust and confidence, the BMS software should preferably be verified and tested by a competent party independent of the software supplier.

5.2.2.2 Short circuits

The following can be considered recommended rules to avoid internal short circuits or to isolate them:

- Basic fusing strategy should follow a cascade, so that an external short circuit causes the main fuse to blow (component easiest to exchange).
- All fuses need to be tested and certified against maximum system voltage to avoid arcing.
- If a module or sub-pack does not have specific fusing capabilities, the supplier needs to demonstrate the safety by an external short circuit test at different voltages and temperatures (see available standards UL/UN transportation, IEC62281/1).
- In order to avoid short circuits, each exchangeable unit (module or sub-pack) must have preventive design measures against accidental shorts (screwdriver etc.) and intrusion of potential conductive particles.

The positive and the negative terminals should not protrude from the module casing. The module casing can include non-conductive, non-removable terminal protection in cases where the terminals are protruding from the module surface.

5.2.2.3 Temperature Sensor failure, Voltage sensor failure

Recommendations for sensor configuration and strategy:

- Voltage sensors to be installed for every cell or parallel cells in a series of connected cells.
- Temperature sensors must be placed in such a way that temperature differences between any cells exceeding 5°C for more than 5 minutes are detected.
- The density of temperature sensors need to be high enough to enable safe battery pack operation, even with one failed sensor per battery module.
- To prevent safety or other critical issues, voltage sensors require some form of redundancy.
- Temperature sensors also need some redundancy with plausibility checks.
- If there is a failure in a voltage sensor, it is possible to further operate the battery pack provided that the cell voltage(s) for each of the cells with failed sensors can be calculated from other measurements (such as module level).
- The accuracy of the voltage measurement needs to take into account safety, energy content estimation and balancing requirements.
- Inadequate design and/or location of battery voltage or temperature sensor wires can pose a fire hazard. Such sensor wires should have a suitable cross section to avoid the possibility of excess heat buildup in case of a short circuit going through the sensor wires. In addition a proper separation of the different sense wires on the BMS is required.

5.2.2.4 Internal open circuit, high impedance

Recommendation:

The electrical architecture of the battery system shall consistently use parallel configurations in order to provide best possible redundancy in case of high impedance or open circuit.

5.2.2.5 Insulation fault

- The insulation resistance should be as a minimum:
    - 1 MΩ for Un < 1 000 V
    - (Un/1 000 + 1) MΩ for Un >= 1 000 V
- Poor insulation can result in premature aging of battery systems and - in extreme circumstances - a safety risk.
- Insulation testing in itself can, under certain conditions with certain pack designs, provoke insulation faults if superimposition of DC voltage is used for insulation measurements as is normal for AC systems.
- For DC systems with high system leakage capacitances, a DC method may not be reliable. Other methods using for instance Non DC signal for measurements are therefore recommended.

5.2.2.6 Loss of cooling

Recommendation:

> *The battery system shall be operable at minimum requested discharge rate (e.g. needed during limp-home mode, steering speed) without external cooling in case the cooling system is needed under normal operation conditions.*

5.2.3 Sub-Packs

A sub-pack is an assembly of one or more modules. This is the smallest unit that can be electrically isolated. Depending on the system architecture, each sub-pack can have internal relays/contactors which can interrupt main power connection.

Recommendations:

> *The sub-pack architecture shall foresee, in case:*
>
> *a) the sub-pack does not contain one or several relays: an exchangeable fuse and a main power connectors with a minimum rating of IP20 in unconnected state (touch proof).*
>
> *b) the sub-packs does contain one or several relays: the main power connectors shall have integrated High Voltage InterLock (HVIL) contact (last make/first break type contact) which opens the relay/relays.*
>
> *Large plastic parts (above 200 g weight) should be material marked, e.g. CE marking.*
>
> *All plastic parts within a battery system should preferably be of low-smoke zero halogen material (e.g. no PVC cable coating). Reference is made also to offshore material standards.*
>
> *Unauthorized access to the internals of battery sub-packs must be inhibited as far as possible.*
>
> *The main components of a battery system (e.g. sub-packs or control units) shall be protected against unauthorized mechanical access (e.g. by tamper-proof screws or crimp seals).*
>
> *All components of the battery system shall be properly marked and reflect their specific danger potential. Relevant operators and personnel shall be trained accordingly.*
>
> *The responsible operator of a battery system shall have a competence requirement scheme for construction, operation and maintenance of the system.*
>
> *The battery sub packs shall have sufficient protection mechanisms against intrusion by software and unwanted calibration access to the battery system.*

The battery sub packs shall include contactors on both + and - sides. The rating of the contactors shall include sufficient margin with respect to the maximum expected current during normal operation.

If the electrical architecture of a sub-pack contains independently controllable parallel strings, each single string shall include independent current measurement.

The battery system shall be able to detect major and potentially dangerous connector high impedance and shall have implemented adequate warnings and/or failure messages for the rest of the system in case such failure is detected. Large impedance differences in parallel strings will cause different current distribution in the strings.

The battery system shall include segregation possibility of its cooling system in case of cooling medium leakage and given the medium is a liquid which imposes potential damage to the system or its environment.

5.2.3.1 IP rating guideline for battery sub-packs

The following guidelines are for battery sub-packs assembled to a battery pack with a maximum voltage less than 1 500 V. Ingress Protection (IP) Rating describes the degree of protection against intrusion, dust, accidental contact and water required by an enclosure. The IP rating is published by the International Electrochemical Commission (IEC).

The logic behind the proposed IP rating table is to take into account potential dangerous wind/weather influence, fire extinguishing, coolant leakage, or condensation:

- The installation location of the battery sub-packs.
- The fire extinguishing installation in the battery space with possible impact on the sub-packs.
- The cooling type and cooling medium used within the sub-packs.

The figures in Table 10 shall be interpreted as the minimum IP rating to ensure product safety. The detailed interpretation of the IP ratings is given in the standard “IEC 60529 Degrees of protection provided by enclosures (IP Code)”. The first digit describes the protection against physical objects provided by the enclosure. E.g. “5” means that dust protection is required, while “2” implies touch proof for a human finger. The second digit describes how well the enclosure protects against water ingress. E.g. “6” implies that the enclosure provides protection against sea spray, while a “2” implies protection against vertically dripping water when the enclosure is tilted at an angle up to 15° from its normal position (less strict). Table 11 gives an explanation of the individual IP ratings given in Table 10.

Each supplier has to conduct an individual requirement specification for the demanded IP grade within the application to ensure product lifetime and avoid quality issues (e.g. corrosion).

Corrosion can be problematic due to exposure to moist air containing salt. A higher IP grade than mentioned in this table should be considered for corrosive environments.

Location	Liquid and potentially conductive substance (including pure water)	Other (e.g. CO2, HALON or powder)
On open deck	IP56/IP22 IP56/IP22	IP56/IP22 IP56/IP22
Mixed installation room, not closed off	IP56/IP22 IP56/IP22	IP44/IP20 IP44/IP22
Dry control room and switchboard rooms, closed off	IP56/IP22 IP56/IP22	IP20/IP20 IP22/IP22

Table 10. Minimum Ingress Protection (IP) rating guideline for sub-packs (further explanation in Table 11).

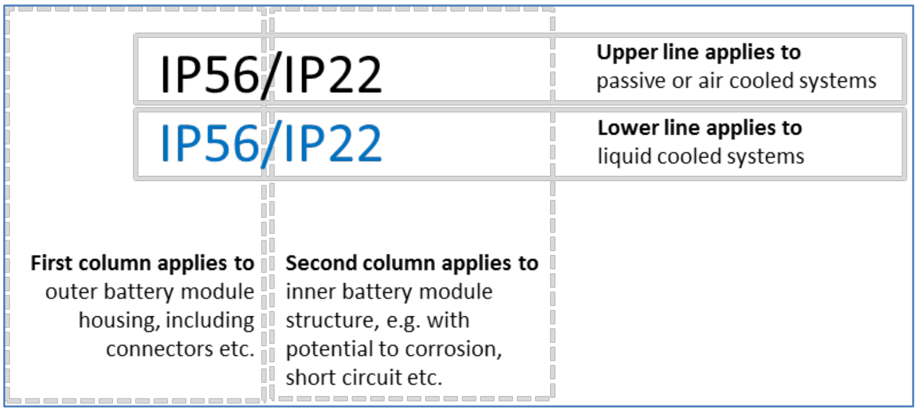

Table 11. Explanation of the IP rating guideline in Table 10 .

5.2.4 Packs

A battery pack consists of one or more sub-packs that can work for the intended purpose as a standalone unit.

5.2.4.1 High level sensor failure

Recommendation:

> *All battery related control systems shall have access to and make use of data from all relevant sensors included in the battery system which are important for critical controls.*

5.2.4.2 Voltage and temperature imbalance

Each Li-ion battery cell in the pack will have its own individual self-discharge rate. The self-discharge rate is determined by the properties and purity of materials used in the cell. The level of contamination in the electrolyte and electrodes is particularly important. The self-discharge rate will depend on temperature and battery cell age. In certain cases the duty cycle experienced by the battery can influence the self-discharge rate. The battery management system may contribute to unequal self-discharge rates between cells or groups of cells.

In order to maximize battery life expectancy and be able to utilize the full capacity of the battery system, a battery balancing system should be included. Large battery packs will have a cell balancing system included in the BMS. This system could be of passive or active type.

The principle behind a passive balancing system is that bleed resistors are used to remove energy from the cells with the highest state of charge. Usually the bleed resistors are activated only at high states of charge. With an active balancing system, energy is transferred from cells with high state of charge to cells with low state.

All cell voltages shall be monitored and the difference in cell voltage should not exceed a specified limit.

- For a fully balanced battery system, all cell voltages are within a specified limit.
- The available energy is limited by the cell with the lowest voltage. In an imbalanced system, this will cause reduced capacity.
- The SOH and SOC should be compensated to account for the capacity loss due to pack imbalance.

When temperature imbalance is considered, it is important to consider that virtually every battery control parameter is temperature dependent. Variation in temperature across the battery pack will therefore influence performance, safety and expected life time. Individual temperature difference should therefore be monitored. Usually the maximum cell to cell temperature difference is specified and it is often recommended that a maximum difference of 5 degrees Celsius should not be exceeded during normal operation.

5.2.4.3 Battery life too short

The key to meet the targeted battery life is a good understanding of the actual load cycle and a battery system optimized for the application. The key elements in such an optimization is a good understanding of the cycle and calendar life of the cells used, the system set up including charge and discharge patterns, the thermal management of the pack and the way the BMS is set up with regards to upper and lower voltage limits, cell balancing and other key parameters.

All batteries degrade as they are used. A good understanding of the degradation for actual application is important for sizing the battery system. If the targeted operational life is 10 years, the expected degradation over this period must be accounted for. Good degradation models are crucial for such a calculation.

An important factor to a long life of the battery system is to keep the cell temperature within the optimal range, usually 20 - 30^0. A good degradation model calculates the cell temperature under different cooling conditions. To achieve an optimal battery size for a given application – load profile, cell type and battery cooling system and energy losses in the system needs to be evaluated.

5.2.4.4 Contactor does not open when required

Recommendation:

> *The battery packs shall include contactors on both + and - sides. The rating of the contactors shall include sufficient margin with respect to the maximum expected current during normal operation.*

5.2.4.5 Contactor does not close when required

Recommendation:

> *If the electrical architecture of a battery system contains independently controllable parallel strings, each single string shall include independent current measurement.*
>
> *The BMS of a battery system shall be able to detect a non-closing relay/contactor.*

5.2.4.6 Reverse polarity protection

It is recommended that battery system safety tests include testing of reverse polarity of control unit supply voltage and mechanical coding of battery terminals.

5.2.4.7 Emergency shutdown

It is recommended that it is possible to disconnect the battery system in an emergency situation. This should be done by implementing an emergency shutdown circuit that disconnects the battery contactor/breaker. This emergency shutdown should be arranged as a separated hardwired circuit. It should be possible to shut down the battery locally and from the bridge.

5.3 Consumers – Electrical Distribution DC

Figure 5.3 below shows the sub-systems included in Consumers.

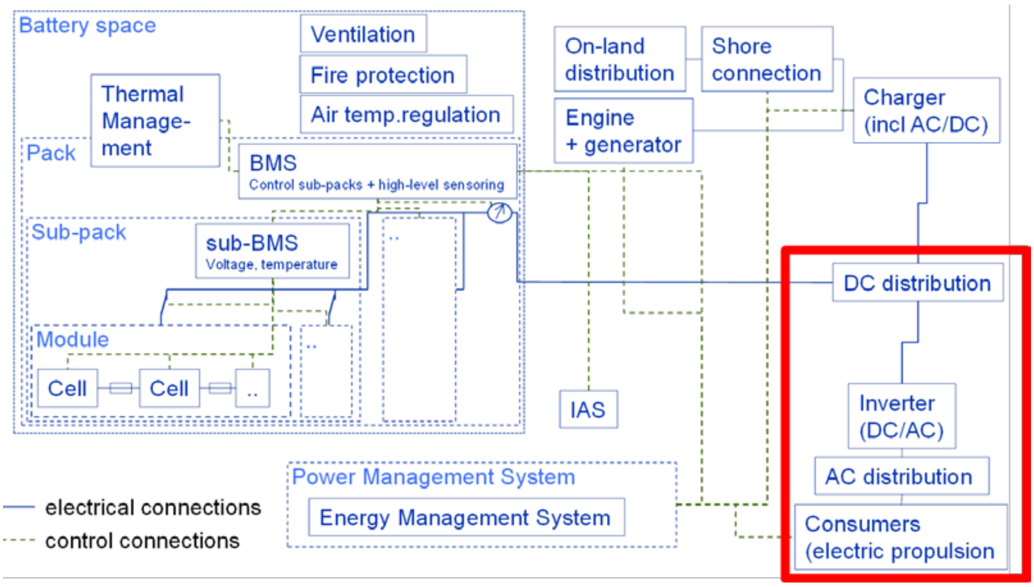

Figure 5.3. Sub-systems for Consumers.

Recommendations:

> *The Redundancy configuration of battery packs shall be such that power blackout of the vessel is prevented. BMS/PMS shall provide alarm when electrical currents are inconsistently high.*
>
> *Testing of breaker selectivity in electrical distribution system shall be performed and documented.*

5.4 Automation – Energy Management System

Figure 5.4 below shows the sub-systems related to automation.

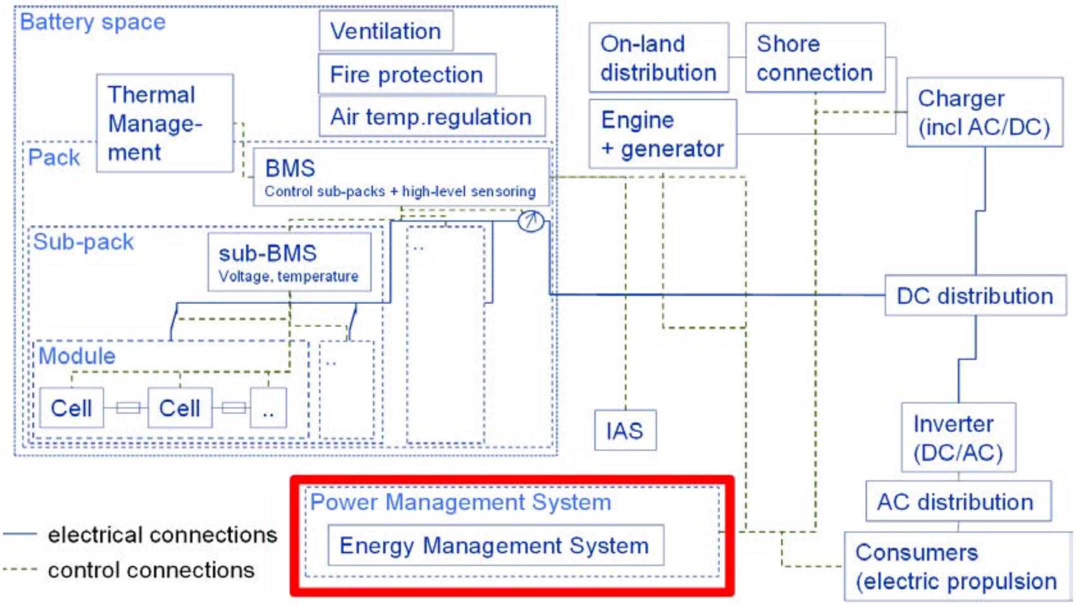

Figure 5.4. Sub-systems related to automation.

5.4.1.1 Estimation of energy fault

Whenever possible, sophisticated systems should be used to make consistency checks and to perform sophisticated, non-critical decisions. These systems should assess the remaining energy and remaining life of the battery system.

- The SOH, normally calculated in the BMS, must be used to calculate available energy and available power.
- For the displayed energy estimation (SOC):
  - Underestimating the energy content in the battery pack is generally safe, but can potentially compromise the business case by leading to shorter battery replacement intervals.
  - Overestimating the energy content is potentially dangerous as it may lead the ship to leave the harbor with too little stored energy in the battery system for a safe crossing.
- The power estimation needs to follow a similar approach.

Calibration/reference point: A fully charged and balanced battery pack where the internal concentration gradients have had time to relax, is at 100% SOC.

To avoid unnecessary questions and to add some safety margins the displayed SOC can be adjusted to be different from the real SOC when the real SOC is above 90% or below 10%. The voltage during operations and charging can be used as a quick check to ensure that the SOC estimate is within reasonable limits. This is particularly true for operations with a non-constant duty cycle.

5.4.1.2 Power Management

Recommendations:

The automation system should be designed in such a way that the battery temperatures are kept within specified limits. This should be done by limiting:

- *Maximum charge and discharge current rates.*
- *Maximum and minimum battery voltages, i.e. over charging and excessive discharge.*

5.5 Power input

Figure 5.5 below shows the sub-systems considered related to power input.

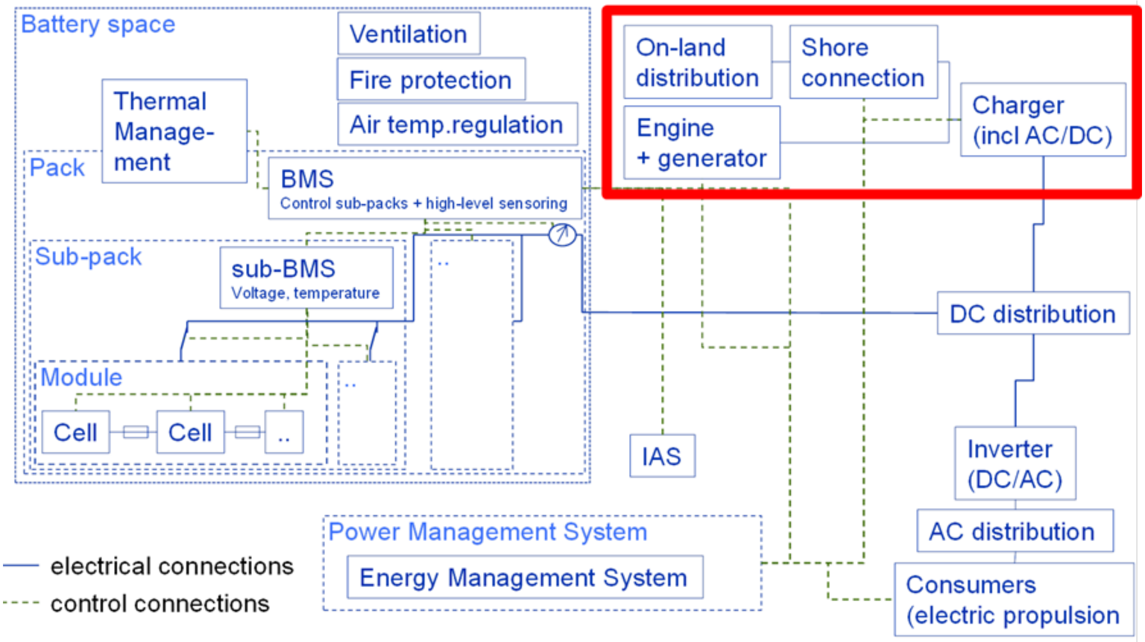

Figure 5.5. Sub-systems considered for power input.

Recommendations:

For applications operating on "battery power only" fast charging feasibility will be critical.

The charging system and other relevant systems shall detect the connection to shore power and activation of propulsion shall be inhibited in this case. Note that some applications will need propulsion power even when connected to shore power, in those cases safety measures must be taken to avoid unintended un-plugging of the charging interface.

There shall be no flammable materials close to shore power connector in order to prevent fire propagation from connector to environment and vessel.

The charging system and shore connection shall include temperature sensors in order to detect high impedance and heating in an early stage.

The mating process of the shore connection shall be preferably automatic. If not, a risk assessment for involved personnel shall be done.

The charger should be designed in such a way that too high charge currents and voltages are avoided.

6 FUTURE OUTLOOK

6.1 Trends

What will happen in the battery business in the years to come? Some quotes from prominent people within the automotive business gives an indication of current views /2/:

- "I do think that cost per kWh at the cell level will decline below $200, in the not-too-distant future." *Elon Musk, CEO Tesla Motors.*
- "Today there are prototypes out there with 400 Wh/kg, the industry is in a period of rapid transformation*." Gary Smyth, GM Director of Global Research and Development.*
- "In the next 3-4 years there will be more progress in battery development than the previous 100 years*." Ian Robertson, BMW Board Member.*
- "Through mass production, we will soon lower production costs to a quarter of what they were in 2009." *President Makoto Yoda, GS Yuasa Corp (Mitsubishi Motors Corp battery supplier).*

As clearly stated in these quotes, there are on-going and potentially transformative developments in the battery sector. On short and medium sight, significant increase in cycle life, energy density and lower cost are expected. Predictions given by McKinsey&Co, /2/, indicate that complete battery packs of automotive quality (which in quality is comparable to what is required for a marine battery pack), will drop in price from current 500 US$/kWh to 200 US$/kWh in 2020 and 160 US$/kWh in 2025.

The cost decrease will partly be due to increased manufacturing volumes, cost decreases in the supply chain and improved yield. On the technology aspects, significant improvements in energy density, which will also lead to lower cost per kWh, are expected. Additional cost reductions may accompany the entry of battery technologies into new markets. There will be significant improvements in C-rates/power density, safety and cycle life.

On longer term, future technologies like Li-Air, Li-Sulfur and other similar chemistries will be available.

Improvements in electrode materials will boost power capabilities which are important for hybrid applications. Together with improved cycle life, power batteries can be made much smaller and thus cheaper than today's solutions. Such development will expand the market for marine battery systems significantly. The trend is supposed to go towards more specialized solutions.

Saying all this, there are differences between automotive and shipping, where installations for ships are commonly tailor made and produced in lower volumes.

6.2 Recommendations for R&D and further work

Several areas need further research or investigations:

- Thermal management, ventilation of the battery space and fire detection and extinguishing systems. It is not possible for a battery supplier to guarantee that short circuiting within a cell cannot lead to a thermal event. To avoid significant consequences of a thermal runaway within a cell, the battery system must be made such that a thermal event in one cell will not propagate to an extent where it cannot be controlled.
- Repair, replacement and maintenance. As more experience and knowledge is gained this should be included in relevant manuals and recommendations.
- Competence requirements. Required competence and training for operators should be investigated considering EN 50110 "Operation of electrical installations" /4/ and vessel types.
- Establish a baseline for warranty requirements for different vessel types and different operational profiles.

- Improved models for battery degradation. Only limited experience from ships with large batteries is available. More logging of duty cycles and monitoring of battery degradation is important to understand the real life of such systems in maritime applications. Such data will be used to calibrate battery degradation models and provide input to optimization of the battery system with regards to cell chemistries, sizing, cooling systems, optimal pack management, and battery management systems.

7 CONTRIBUTORS

The project team developing this guideline consisted of:

Name	Affiliation	Role in Project
Narve Mjøs	DNV-GL	Project manager
Sverre Eriksen	DNV-GL	Class approval & rules
Gerd Petra Haugom	DNV-GL	Maritime advisory, safety, fire & explosions
Siegfried Eisinger	DNV-GL	Technical facilitator, systems & software expert
Davion Hill	DNV Research & Innovation	Battery expert
Benjamin Gully	DNV Research & Innovation	Battery expert
Eirik Ovrum	DNV Research & Innovation	Battery expert, link to Fellowship project
Roman Stoiber	Grenland Energy	Battery expert – Systems
Lars Ole Valøen	Grenland Energy	Battery expert – Cells & System
Egil Mollestad	ZEM	Battery expert

Table 12. Project team developing the guideline.

In addition, the guideline has been subject to an external review process, where the institutions listed below have contributed.

The contributors are gratefully acknowledged:

ABB	-	Jan-Fredrik Hansen, Frank Wendt, Børre Gundersen, Stig Leira
Corvus	-	Brian Baker
DNV GL	-	Petra Boer de-Meulman, Joachim Zipfel
Earl Energy	-	Doug Moorehead
FFI	-	Øistein Hasvold, Torleif Lian, Sissel Forseth, Nils-J. Storkersen
Fjellstrand	-	Jan-Fredrik Paulsen
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Siemens AS	-	Kenneth Presttun Tjong
Sjøfartsdirektoratet	-	Lasse Karlsen
Solstad Shipping AS	-	Hans Ole Bergtun

8 REFERENCES

/1/ Qualification of Large Maritime Battery Systems, Project Internal Working Document, rev. AI, 25th Oct 2013.

/2/ McKinsey&Co (2013), "Will batteries become cheaper", Zero Conference. 5th-6th Nov 2013.

/3/ DNV Recommended Practice DNV-RP-A203, Technology Qualification", revision of July 2013. Source: http://exchange.dnv.com/publishing/Codes/download.asp?url=2013-07/rp-a203.pdf.

/4/ EN 50110 "Operation of electrical installations".

APPENDIX A. PROJECT METHODOLOGY

The Generic System Assessed

A generic approach, widely applied by DNV in several industries to qualify technological solutions for new applications, was applied during this project to develop this guideline. It was applied on the system outline/block diagram shown in Figure A1 below. Table A1 gives an overview of the main components and sub-systems.

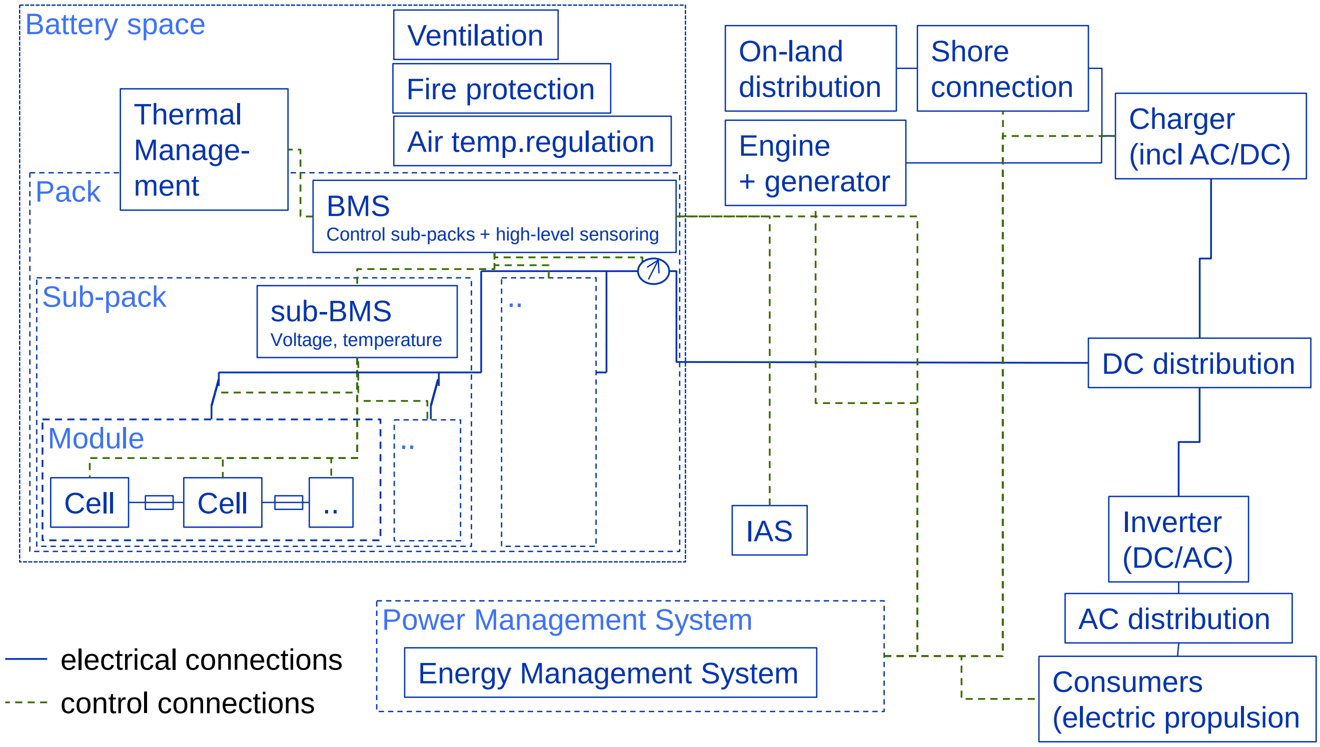


Figure A.1. Block diagram of the generic system assessed.

Generic	Only Battery Power	Hybrid Battery / ICE System
• Battery pack(s) • Battery Management System (BMS) • Electrical interconnections inside battery system • Energy/Power Management System (EMS/PMS) • Power Electronics (charger, converters) • Electrical distribution system on vessel • Thermal management system • Battery space(s) • Ventilation system for battery space • Fire protection system for battery spaces • Electric propulsion system	• Shore connection • On-land distribution • Charger	• Engine + Generator • Shore connection • On-land distribution • Charger

Table A.1. Overview of relevant main components and sub-systems for a generic marine battery system.

It is necessary to distinguish the different operational modes both of the vessel system(s) and the battery system. Table A2 gives an overview of the operational modes considered.

Examples of critical vessel operations are dynamic positioning, low speed navigation through narrow or shallow waterways, harbor operations, or in general all operations with special requirements on redundancy and immediate energy availability.

Battery system	Vessel system(s)
• Contactors open/closed/checking • Isolation testing shut down/monitoring/startup • BMS shutdown/monitoring/balancing • Battery passive • Battery charging • Battery discharging	• Starting up • Full electric critical/non-critical operations • Hybrid electric critical/non-critical operations • Systems shut down • Installation and service • Moored – Discharge • Moored – Charge • Moored – Passive • Laid up

Table A.2. Overview of the operational modes for the vessel system(s) and battery system.

The following table gives an overview over important parameters for battery system characterization:

Generic	Only Battery Power	Hybrid Battery / ICE System
• State of charge • Voltage range • Chemistry type • Temperature range • Power requirements • Energy storage capacity • DC distribution voltage • Recommended and maximum charge and discharge rate • Expected lifetime (in dependence on other parameters) • Battery system physical size and weight • Thermal management system type and capacity • Implemented diagnostics and diagnostic data	• Shore connection characteristics • Short circuit capacity of the batteries (to ensure trip of right breaker)	• Shore connection characteristics (if relevant) • Short-circuit capacity of the batteries if providing power to main functions. • Size of diesel engine

Table A.3. Overview of important data for battery system characterization.

Technology Qualification Methodology

The generic methodology process, used to develop this guideline, is described in the DNV document "Recommended Practice DNV-RP-A203, Technology Qualification", revision of July 2013. The document can be found on the following link:

Recommended Practice DNV-RP-A203, Technology Qualification

The DNV Recommended Practice (RP) for Technology Qualification is a procedure that covers the need for a systematic approach to the qualification of new technology. The main purpose of applying the technology qualification methodology is to ensure that a technology is compatible with an application, and that it functions within specific limits, and with an acceptable level of confidence. The main steps in the Technology Qualification Process as outlined in the DNV-RP are illustrated in Figure A2 below. The main steps in the process are described in the text overleaf. The three first steps outline the risk and safety assessment part of the process.

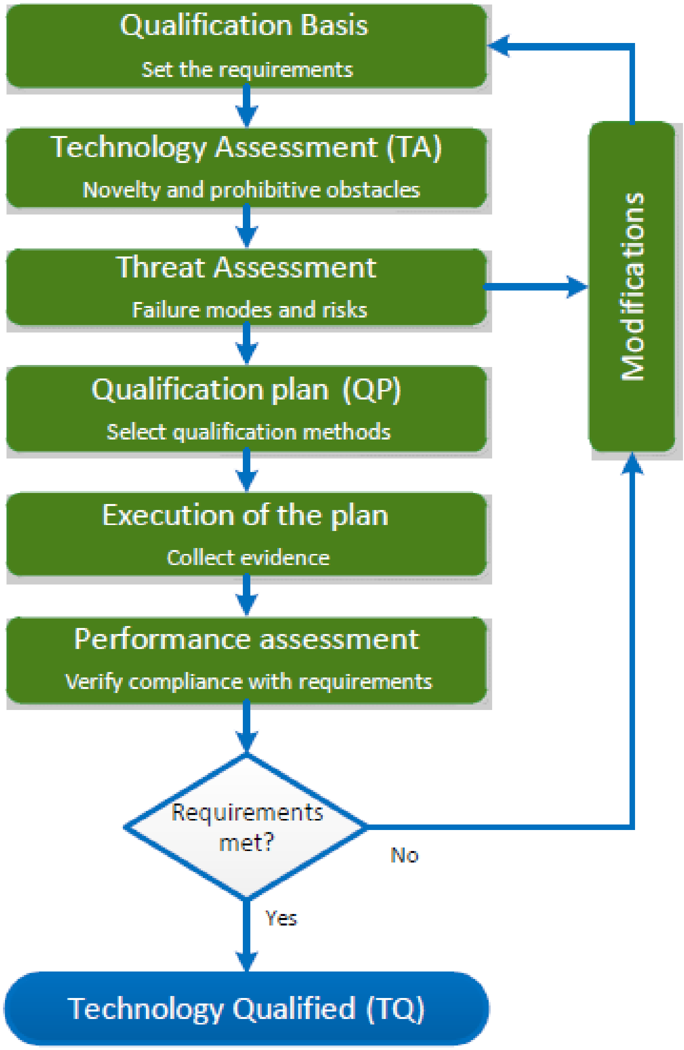


Figure A.2. Steps in the basic Technology Qualification Process.

Qualification Basis: The purpose of the Qualification Basis is to provide a common set of criteria against which all qualification activities and decisions will be assessed. This step describes what parts of the battery related systems with their environment and usage patterns to be qualified (System boundaries, ambient temperature, charging pattern and operation pattern). Functional, reliability and safety requirements are established.

Technology Assessments: The battery related systems are divided into sub-systems and components. Technology maturity is assessed in relation to the environment and usage pattern such that the qualification can be focused on elements where the uncertainty and consequences are largest. The Technology Qualification risk is rated both with respect to the technology itself and the maritime application.

Threat Assessments: Failure modes, effect and criticality analyses are performed (FMECA). Stakeholders decide on risk parameters to be assessed, i.e. safety and economy. For novel elements, stakeholders identify relevant failure modes with cause, and rank the associated risks with likelihood of occurrence. Then consequences are assessed with local effect and global effect. The hazard analysis for the battery management system was conducted based on IEC61508 “Functional Safety of Electrical/Electronic/ Programmable Electronic Safety-related Systems”.

Qualification plan: Plan how to address the important failure modes. This includes technical analysis, laboratory testing, collection of data, experience and knowledge, or to establish user requirements in order to avoid possible problems. In this case all laboratory testing was done on the battery cell level while the theoretical studies described above were done at the system level.

Execution of the plan: In this data collection phase above qualification activities in the plan are performed. In this work we used both internal and external laboratories. DNV and ZEM’s battery degradation model is further developed to analyze the reliability of the battery over its useful life. Because the maritime environment is a new application, the effect of usage and charging patterns are assessed.

Performance Assessment: Finally, a capability assessment is performed to confirm to what degree the qualification basis is met. This is done by verifying that the qualification activities have taken place in a proper manner, that the acceptance requirements have been met, and by updating the risk matrix when one has taken into account the collected data from the exploration, analyses and testing.

The development is an iterative process of development towards greater detail after each iteration. This work is done with experts in relevant technical disciplines.

Battery Space and related failure modes

Figure A3 shows the sub-systems in the Battery Space, and table A.3 shows the failure modes identified and assessed.

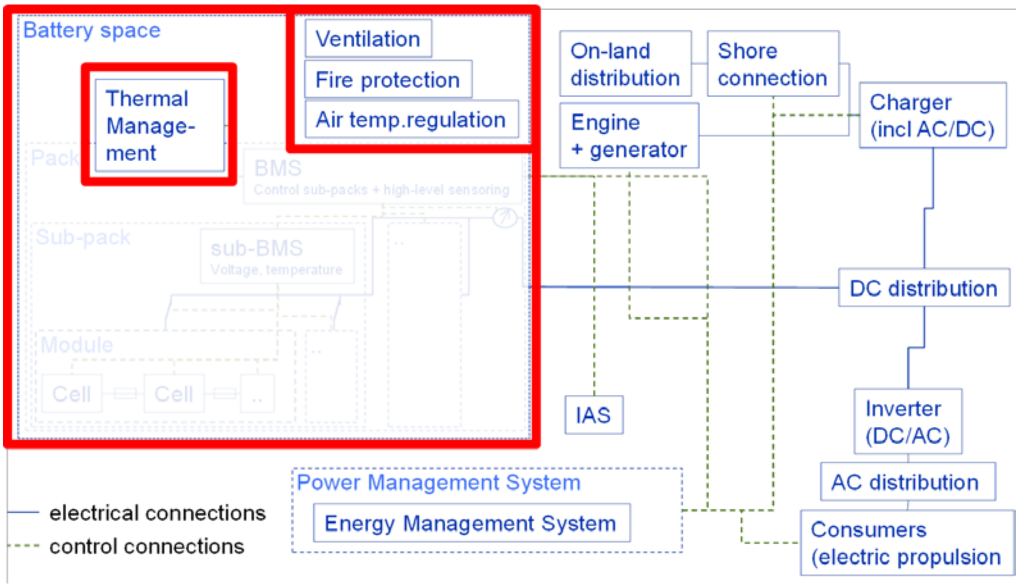


Figure A.3. Subsystems in "Battery Space".

Component	Objective	Failure modes
Air temperature regulation	Control temperature in Battery Space. Passive or active air removal/replacement.	Too high / too low temperature in space.
Ventilation	Remove possible gases from battery faults. Possible detection of gases and active air removal. Connection to duct into safe area.	Air pollution in space - Accumulation of flammable gases
Fire protection	In case of battery fire or fire in battery space, keep temperature as low as possible and try to extinguish fire. Standard fire detection. Type of fire protection may be dependent on battery chemistry and will be discussed later.	Fire detected late or not at all
		Unintended activation
		Unsuccessful fire extinguishing
Thermal management	Control temperature within modules by measuring cell temperature, providing adequate cooling medium and inform BMS on temperature (such that module can be switched off if too warm).	Sensor failure cooling medium failure Control failure

Table A.4. Failure modes in "Battery Space".

Battery System and related failure modes

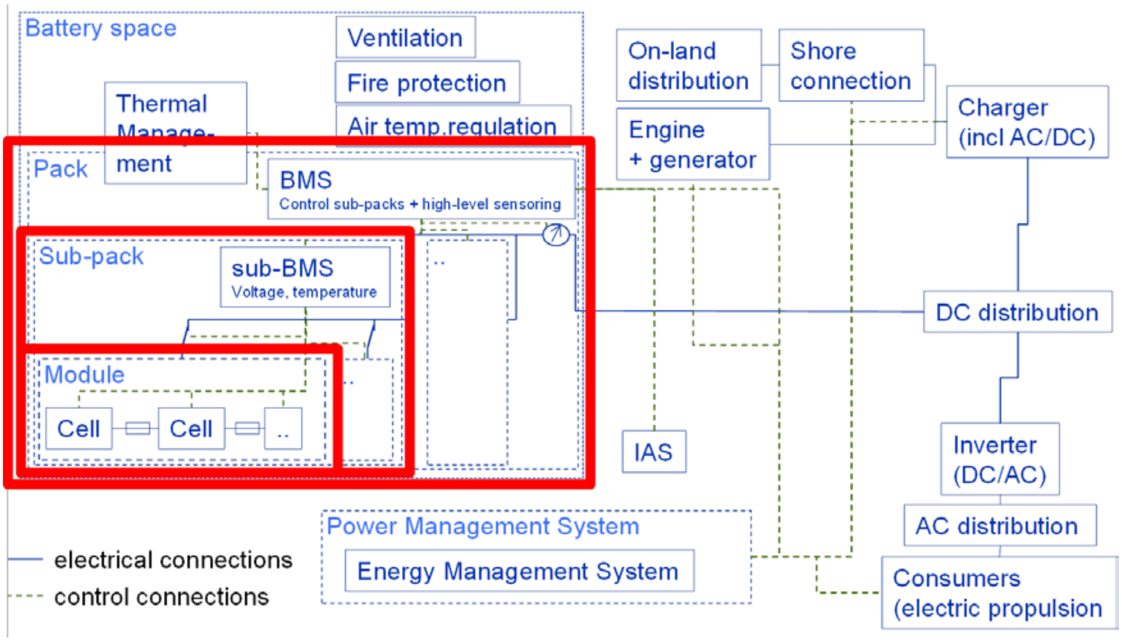


Figure A.4 Subsystems in "Battery System".

Component	Failure modes
Cells	Internal short circuit
	High Impedance
	Insulation fault
	Electrolyte leakage
Modules	Temperature Sensor failure
	Voltage sensor failure
	Control failure
	Internal short circuit
	Internal open circuit
	High Impedance
	Insulation fault
	Cooling system leakage
	Loss of cooling
Sub-Packs	Contactor does not open when required
	Contactor does not close when required
	Current sensor measurement error
	Connector high impedance
	Leakage of cooling connector
	Sub-pack enclosure leakage/damage
	Mishandling of battery system.
Packs	Contactor does not open when required
	Contactor does not close when required
	High level sensoring failure
	Internal pack imbalance
	Temperature imbalance within pack
	Battery life too short
	Energy losses too high

Table A.5. Failure modes in "Battery System".

Consumers and related failure modes

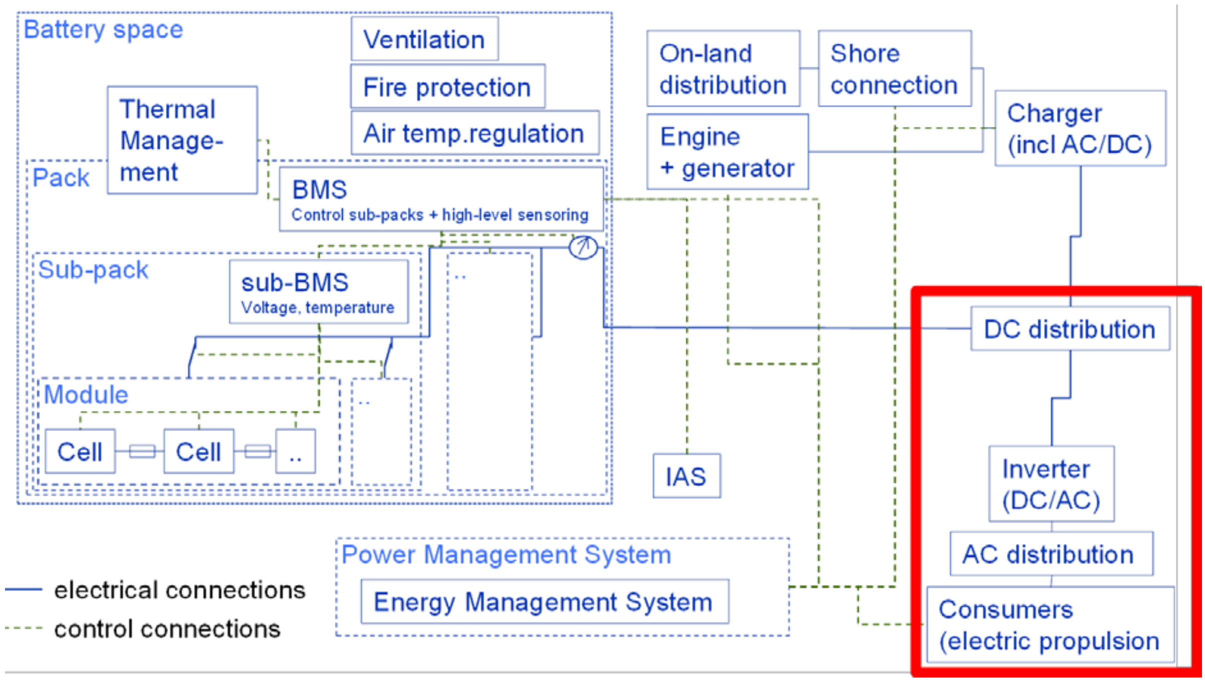


Figure A.5. Subsystems in "Consumers".

Component	Description	Failure modes
DC Distribution	DC distribution network from battery packs to consumers or inverter. Includes Insulation supervision. Protection against local short circuits. Selectivity between breakers. Disconnect battery pack breaker for isolation purposes.	Circuit breaker does not open when desired
		Circuit breaker opens when not desired
Inverter (DC/AC)	Provide AC power to vessel consumers (e.g. propulsion).	*(not relevant - proven technology)*
AC Distribution	Distributes electrical energy in AC network.	*(not relevant - proven technology)*
AC Consumers	Consumes AC electricity, e.g. motors, pumps, hotel load etc.	*(not relevant - proven technology)*

Table A.6. Failure modes in "Consumers".

Automation and related failure modes

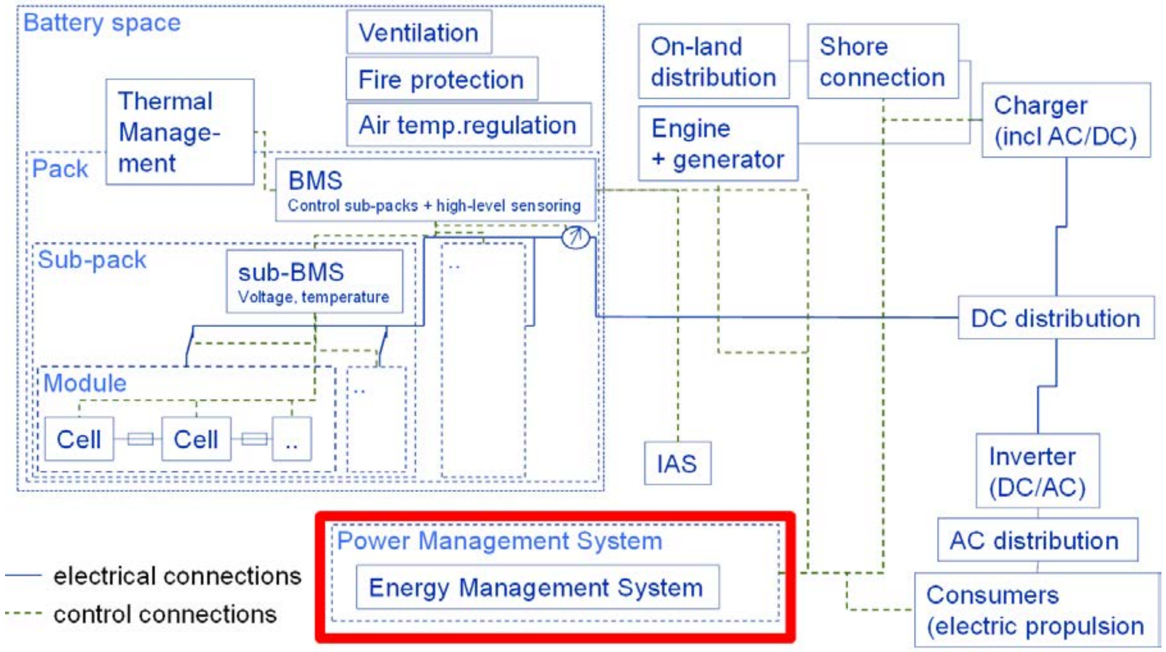


Figure A.6. Subsystems in "Automation".

Component	Description	Failure modes
Power Management System	Power distribution between internal energy sources and consumers. Battery added as additional power source and consumer.	Control failure
Energy Management System	Measurement and presentation of remaining energy in batteries. Normally a function within PMS.	Estimation of energy wrong Presentation failure

Table A.7. Failure modes in "Automation".

Power Input and related failure modes

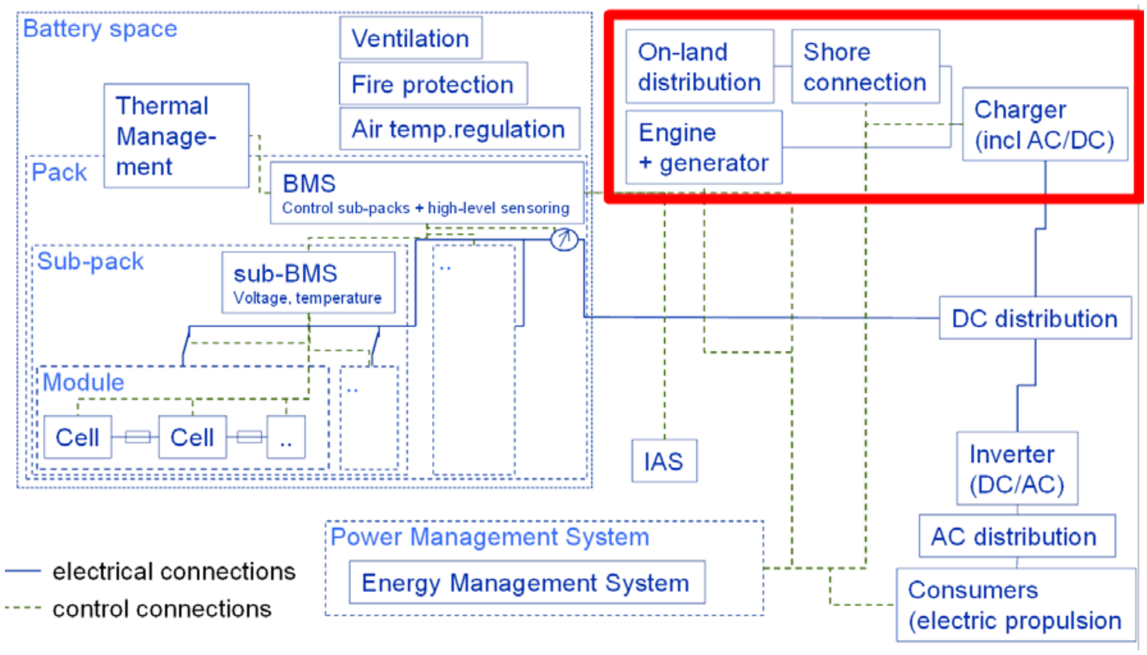


Figure A.7. Subsystems in "Power Input".

Component	Description	Failure modes
Engine + Generator		*(not relevant - proven technology)*
On-Land Distribution		*(not relevant - proven technology)*
Fast Shore Connection	Transfer electrical energy from shore network to vessel. May be AC or DC. Fast connection possibility often necessary. Maritime environment.	No Power High Impedance Short circuit. Creep currents Incompatible power supply
Charger (incl. AC/DC)	Transfer electrical energy from AC source (200-690 V) to battery DC. Deliver voltage and current according to charging requirements, controlled by BMS.	*(not relevant - proven technology)*

Table A.8. Failure modes in "Power Input".

Competence Requirements

The following outline competence requirements for evaluating new battery projects:

- Electrochemistry
- Power electronics
- BMS systems
- Software
- Vessel safety and classification
- Vessel operation
- Vessel design
- Battery system expertise
- System integration
- Functional Safety
- DC electric systems
- Onshore power distribution

APPENDIX B. CLASSIFICATION

BATTERY RULES

Background:

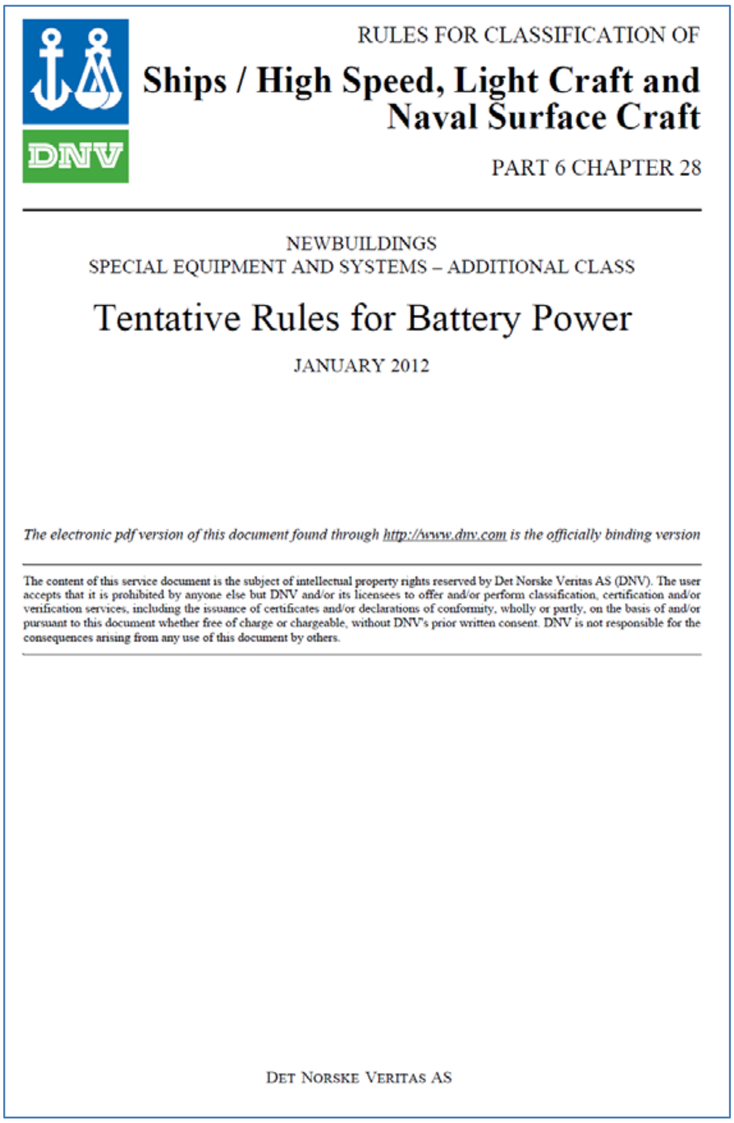
Due to the new battery technology, where it is possible to use batteries as a part of the propulsion energy for vessels it is possible to make hybrid battery solutions and "pure" battery driven vessels DNV introduced class rules for battery powered systems. The rules have been official from 1. January 2012.

The requirements cover:
- Safeties of the battery installation with special focus on lithium batteries.
- Battery systems used for propulsion
- Requirements for certification of the batteries.

Class notation
A new notation "BATTERY POWER" for vessels where batteries are used for propulsion is established by DNV.

Class rules
The rules can be found on the following link:

DNV Rules for Battery Power



RULES FOR CLASSIFICATION OF

Ships / High Speed, Light Craft and Naval Surface Craft

PART 6 CHAPTER 28

NEWBUILDINGS
SPECIAL EQUIPMENT AND SYSTEMS – ADDITIONAL CLASS

Tentative Rules for Battery Power

JANUARY 2012

The electronic pdf version of this document found through http://www.dnv.com is the officially binding version

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CERTIFICATION

For a DNV classed vessel it is required that the batteries shall be certified for each vessel. Requirements for the certification are given in the Battery Power class rules. In addition to this, DNV offer a service for Type Approval of battery systems. This type approval will on a generic level verify that the battery system fulfill the requirements in the DNV class rules including applicable type tests (safety and environmental tests). The type approval does not replace the "case by case" certification, but will limit the scope of the "case by case" certification.

APPENDIX C.   FUNCTIONAL SAFETY

The term “Functional Safety” describes the safety related aspects of electronic equipment within a system. Functional safety measures can be realized by hardware (e.g. a watchdog unit) or software (e.g. a monitoring function) and depend on both the criticality level identified for the specific hazard and the nature of the feature involved in the safety function.

The basic steps to address functional safety in a system are:

1. Identify potential hazards (e.g. through hazard studies)
2. Assess the risks and compare with given criteria
3. Assess the required risk reduction
4. Allocate risk reduction to technologies
5. Assess the Safety Integrity Level (SIL) for chosen risk reduction measures
6. Design, implement and validate risk reduction measures

To identify and implement measures to reduce the risk of a hazardous situation to an acceptable level, a hazard can be reduced by either reducing its consequence or its likelihood. This is illustrated in Figure C.1:

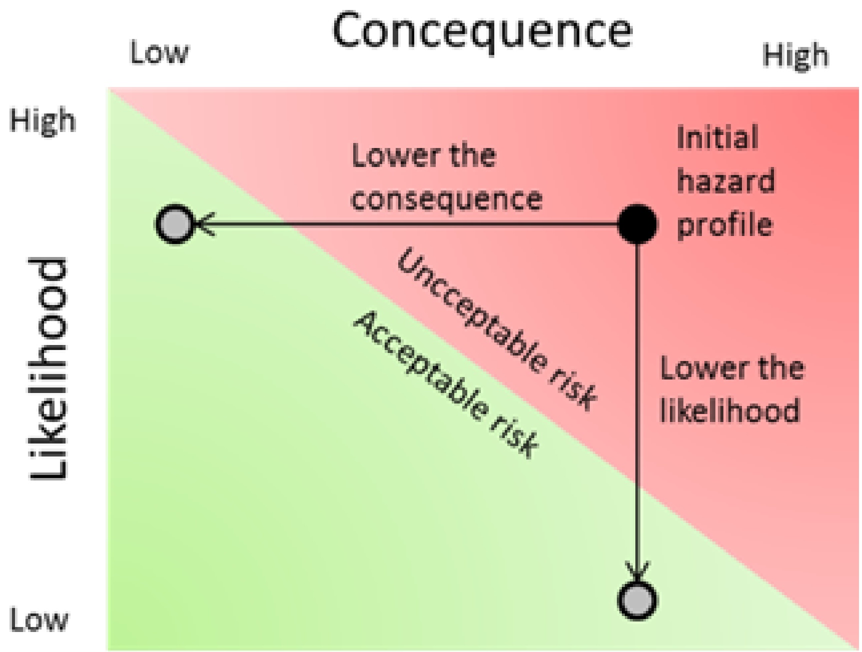

Figure C.1. Risk diagram.

There are numerous standards addressing functional safety which provide industry specific frameworks, such as:

- IEC 61508 (Functional safety of electrical/electronic/programmable electronic safety related systems)
- ANSI/ISA S84 (Functional safety of safety instrumented systems for the process industry sector)
- IEC 61511 (Safety instrumented systems for the process industry sector)
- IEC 62061 (Safety of machinery)
- ISO 26262 (Automotive adaptation of IEC 61508)

All of these standards use a similar approach to evaluate and classify hazards, according to a "Safety Integrity Level" (SIL), which is represented by a number (e.g. IEC61508 SIL1 = least critical, SIL4 = most critical).

The following example, which is illustrated in the diagram below, represents one case in the hazard analysis conducted during this project:

Hazard: Charger overvoltage or overcurrent (during charging with full battery in hybrid application)

Worst case consequence: Thermal event with full propagation

Consequence: Casualties assumed during evacuation in general and due to fire.

Frequency: Hybrid vessels are in operation most of the time, assumed crew is on board 100% of operation time. Charging always can take place in a hybrid application.

Possibility of avoidance: Skilled personnel onboard and controlling the equipment. Multiple detection measures assumed to be installed in battery space and battery system. Thermal event due to overcharge does not lead to sudden fire or explosion.

Probability of avoidance: Not all overcharge events lead to a thermal event. Different chemistries react more or less sensitive on overcharging. W2 is assuming a chemistry very prone to damage through overcharge. Parameter could be reduced to W1 if tolerance against overcharge can be proven on cell level.

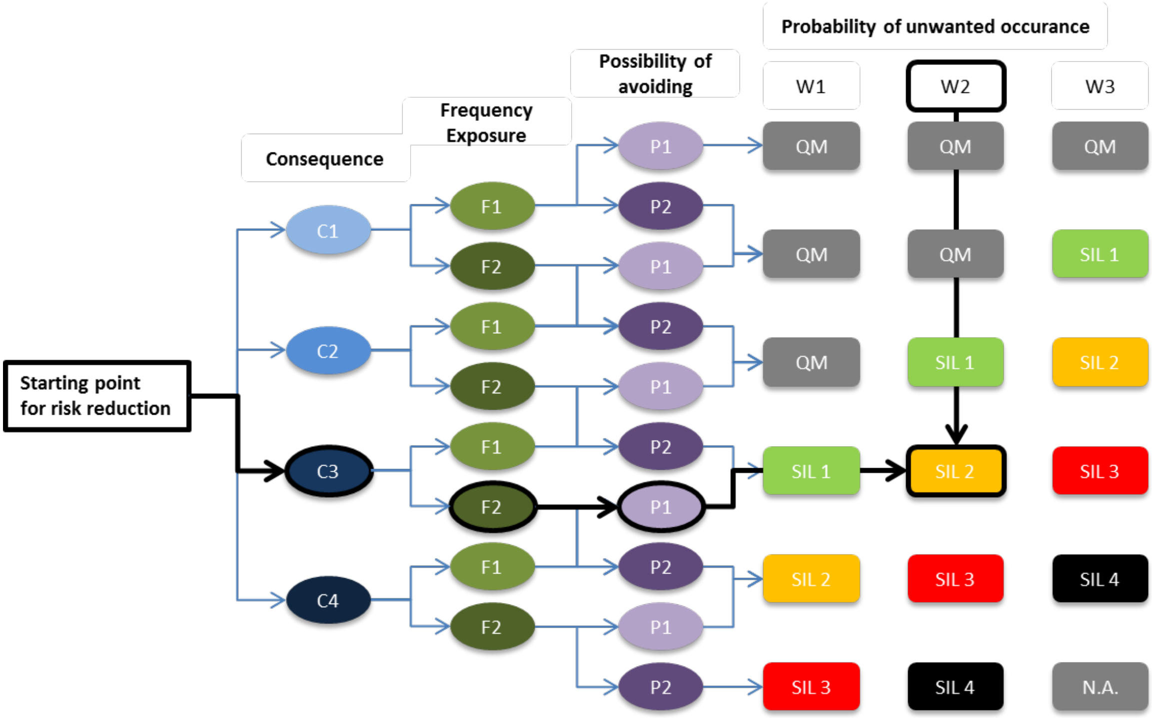

Figure C.2. Hazard analysis example.

APPENDIX D. CELL TESTING FOR MARITIME APPLICATIONS

Investigation of battery suitability should minimize the testing required to create a dataset that can be used to assess and determine the risks that will threaten battery performance in its intended application.

The maritime market represents a new battery application that may involve conditions or intended uses that provide exceptions to traditional automotive practices, which have informed much of battery testing procedures to date. The purpose of risk based testing is not necessarily to characterize the battery in detail, but to assess the effect of environment or duty cycle on lifetime and throughput and assign risks to that performance.

DNV recommend a minimum 5 tests to create a map of cumulative battery output, with the possibility of repeating the tests at higher and lower temperatures as well as higher and lower C-rates. This map is intended to encompass a range of possible lifetimes and capture relevant technical risk factors that may affect battery life. These conditions are the minimal conditions to obtain adequate information suitable to make predictions or recommendations about battery life in a given application.

This testing desires to capture the effect of the main battery degradation parameters: temperature, average depth of discharge (DOD), charge and discharge rates (C-rates), and compounding effects of these parameters, in addition to consequential effects of unique duty cycles and heat generation.

Five testing methods were identified:

1. The manufacturer specification test (MS), which is the optimal baseline performance of the battery
2. A voltage sensitivity test (VS), which investigates the performance of the battery when cycling occurs near or beyond upper or lower voltage limits
3. A current sensitivity test (CS), which investigates the effect of fast charging or pulse discharging
4. A high average state of charge (HAS) test, which investigates the battery lifetime when cycling occurs near its upper voltage limit on average
5. A low average state of charge test (LAS), which investigates the battery lifetime when cycling occurs near its lower voltage limit on average

Measurement parameters for these tests shall include at a minimum: voltage, current, and ambient temperature. Preferred additional data may include: cell resistance and cell temperature. The following statistics can then be obtained:

- Percentage of time during cycling that the battery resides per each voltage range and its effect on overall capacity
- Maximization of battery life as a function of battery residence time in each voltage range
- Effects of temperature
- Dominant performance metrics
- Calculated metrics such as average state of charge (SOC), active cell heating, and C-rates
- Effect of these parameters over a range of possible lifetimes or energy throughput, and a risk ranking of these impacts

This section refers to the draft DNV Recommended Practice titled “Cell Level Risk Based Evaluation of Batteries for Maritime, Energy Storage, and Other Applications” (Rev. 3, OCTOBER 2013).
Cell Level Risk Based Evaluations of Batteries for Maritime

APPENDIX E. TECHNICAL, ECONOMIC, ENVIRONMENTAL ANALYSES EXAMPLE

For hybrid ships, a key finding from the technical-economic analysis is that the most important factor for profitability of a hybrid installation is the capital costs of the battery itself. Therefore it is essential to minimize the size, in kWh, of the battery, and to do this properly one must perform a detailed analysis of the operation of the hybrid ship.

DNV Research & Innovation participated in the Research council of Norway funded project Low Carbon Shipping, performing simulations of lithium-ion batteries and hybrid ship operation. The DNV internal report 2012-1565 “Modelling lithium-ion batteries for hybrid crane operation in a real ship application” described our effort to quantify the benefits of using hybrid power with batteries for energy storage on ships, for the special case of crane operations. The results were made public, see DNV Research Blog. The report gives an overview of the field of modeling of lithium-ion batteries and presents DNVs battery model. Our battery model was calibrated to data from Corvus, the battery manufacturer for both the FellowSHIP III project and Norway’s first battery ferry on the Lavik-Oppedal route.

Detailed information about the operation of the ship is needed to accurately quantify the benefits of a hybrid ship compared to a conventional ship. The Low Carbon Shipping project cooperated with the ship owner Grieg Star from Bergen, Norway, and therefore it was possible to model the crane operation of one of their ship classes.

Crane operations are especially suited for hybrid power production, because cranes can be run by electric motors that use regenerative braking. The case study presented a Grieg Star open hatch vessel with four cranes driven by electric motors, capable of regenerative braking. We modeled diesel generator sets, the cranes and the ship hotel load in order to simulate the power production of the ship, with a conventional and a hybrid power management system.

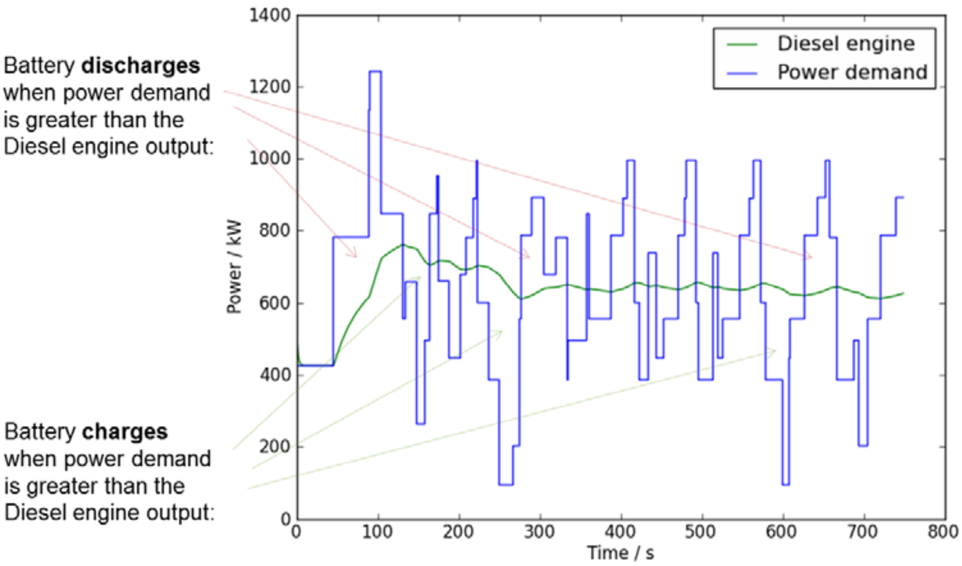

Figure E.1. The simulated power demand of the crane operation of a hybrid ship. The blue line is the ship’s power demand and the conventional genset power, while the green line is the hybrid genset power.

From the complete economic model we could estimate the battery package size and the annual fuel savings for the hybrid system, compared to the conventional system. Our economic analysis took into account the installation and fuel costs of both the conventional and hybrid systems. Due to the benefits of hybrid power production, as well as the gains from regenerative braking of the cranes, we find that hybrid operation of cranes is highly profitable. The installation costs of the two system alternatives are almost equal, with a payback time of less than a year for the hybrid system. The hybrid system additionally saves $110,000 per year from crane operations on the ship alone. The annual savings of the hybrid solution amount to a third of the battery costs, but since we install fewer diesel gensets, the payback time is less than one year.

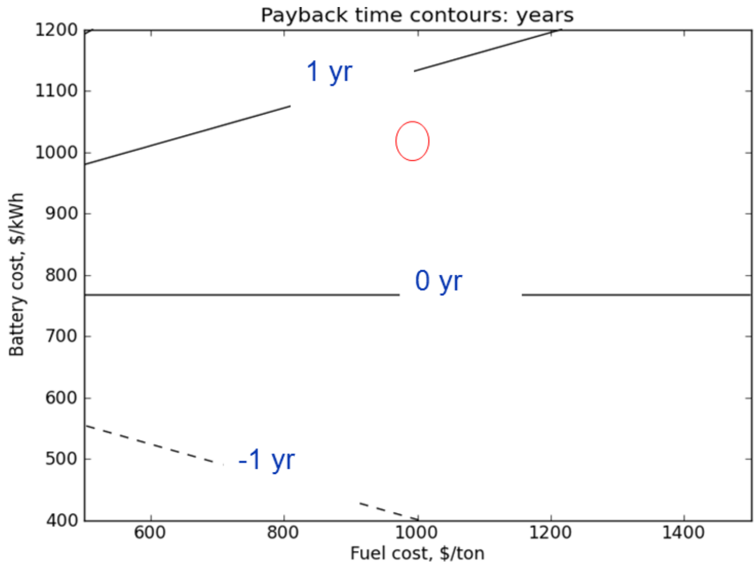

Figure E.2. This is a contour plot of the payback time of the battery installation, with the lines as constant payback times for different fuel costs and battery prices.

This section refers to DNV Report 2012-1565, title “Modelling lithium-ion batteries for hybrid crane operation in a real ship application”.

APPENDIX F. ENVIRONMENTAL ASSESSMENT

Environmental analysis of battery production for hybrid ships

Battery production is energy intensive and therefore there has been several studies investigating the life cycle CO2 equivalent emissions of hybrid and battery cars. In Ellingsen et al.[4] a thorough analysis was done on the CO2-eq. emissions during the production of a 26.6 kWh NMC li-ion battery pack, approximately the size of the battery pack for the Nissan Leaf. The study concluded that the emissions during battery production were between 172-487 kg CO2-eq./ kWh.

To investigate the benefit of a battery in reducing the emissions of climate gases, we need to compare the emissions during production of the battery to the reduced emissions during the lifetime of the battery. In DNV Research & Innovation we have looked at three different hybrid ships: the crane operation of a hybrid ship in the previous appendix; early estimates of savings from the Viking Lady in the FellowSHIP project; and the world's first hybrid tug, Carolyn Dorothy.

As an example calculation we look at the hypothetical hybrid ship doing crane operations. The ship needs a battery of ~300 kWh and saves about ~90 tons of fuel per year. Using the highest value for CO2-eq. emissions of battery production, one emits 300 kWh * 480 kg CO2-eq. ~ 150 tons CO2-eq. The battery saves 90 tons of fuel per year, amounting to reduced emissions of about 270 tons of CO2-eq. This means that the CO2 payback time is about half a year for the battery.

If the battery lifetime is ten years, which is a design question, then the battery will reduce the ship's emissions by 2700 tons CO2 during its life, see figure below

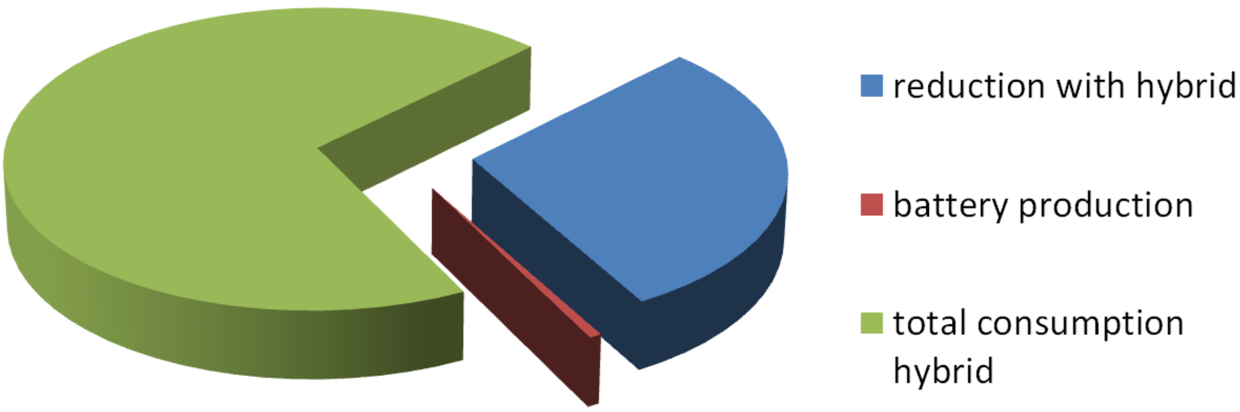

Figure F.1. Over a lifetime of ten years, the production emissions of the battery are insignificant compared to the savings during operation.

For hybrid ships, the CO2 emissions from producing batteries are insignificant compared to the savings during operation.

With some conservative estimates for the three ships we have looked at, a battery lifetime of ten years, and mid-range emissions of 240 kg CO2-eq./kWh for production of the battery, we get a total saving over the battery life of 8 tons of CO2-eq. per kWh produced. (This is ten times more than a typical electric car saving in CO2 emissions compared with gasoline, i. e. it is more effective to hybridize commercial vessels with more or less continuous operation than private cars with normal use.)

Production	0.24 tons
Savings	8 tons

[4] L. Ellingsen, "Life cycle assessment of a lithium-ion battery vehicle pack", Journal of Industrial Ecology, DOI:10.1111/jiec.12072.

APPENDIX G. SERVICE LIFE ASSESSMENT EXAMPLE

The following scenario is outlined to use battery life prediction tools (such as DNV's Battery XT) to estimate the impact of temperature and cycling on battery lifetime, and to use this data to assess the risk of the battery meeting its intended specifications for the duration of its service life.

A screenshot of Battery XT is shown in Figure G.1 below.

This tool or any other tool designed for this purpose should have the following capability:

1. Accept a range of duty cycle characteristics
2. Accumulate the effect of temperature and duty cycle on the total lifetime
3. Account for both calendar and cycling components of battery capacity fade
4. Provide inputs battery sizing and a reference state of charge to be used for computing initial and final battery states for the duty cycle

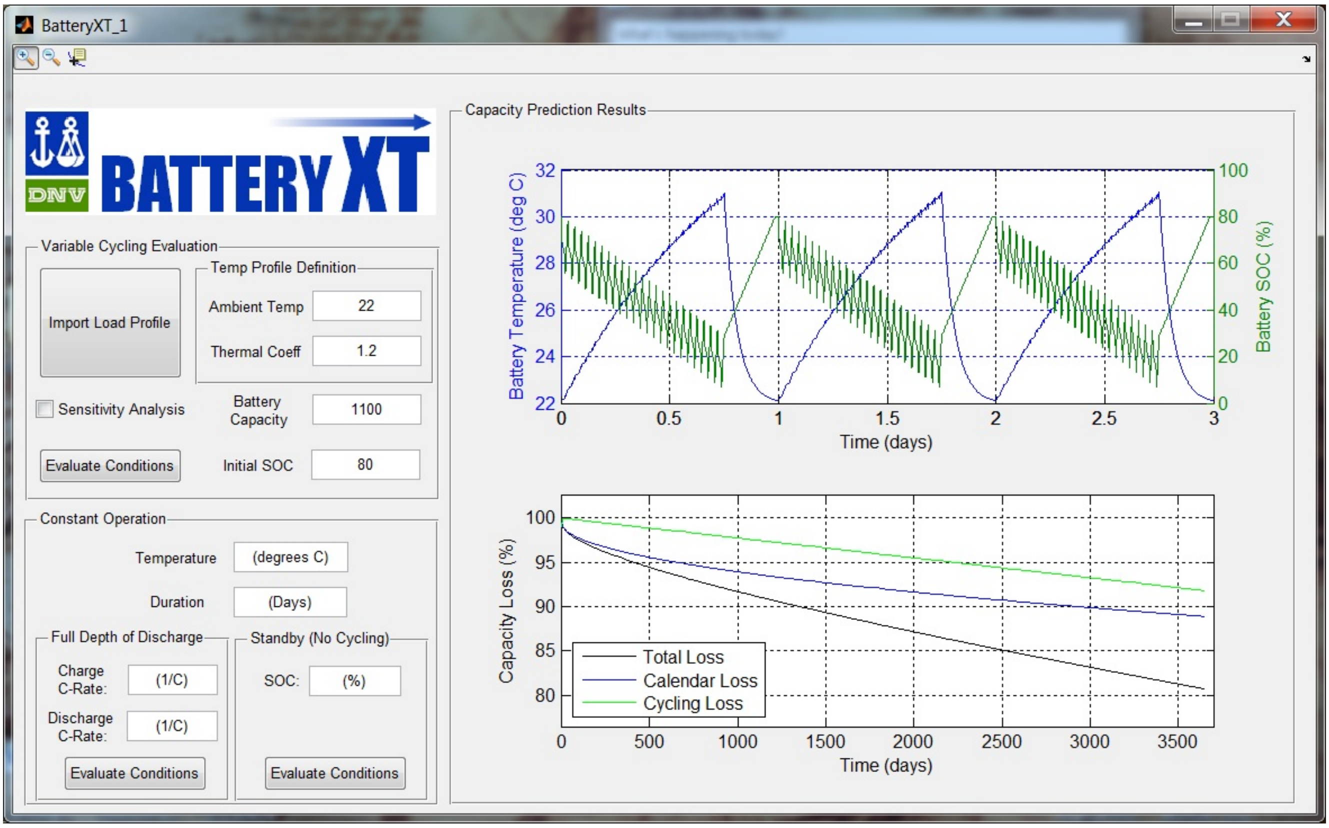

Figure G.1. Screenshot of Battery XT.

To illustrate the functionality of the software, the following scenario can be envisioned:

A ship builder designing an electric tour boat will operate roughly 100 days per year during the warmer months. The builder intends to build two vessels, one of which will have most of its activity in the summer months of a Norwegian fjord (average battery room ambient temp = 20 °C) and the second which will operate near Athens, Greece, with an average temperature of 32 °C. For days when the boat is active, it will deplete to 80% capacity and then recharge. For simplicity assume electricity rates are $0.12/kWh (0.7 NOK) in Norway and $0.20/kWh (1.2 NOK) in Athens. Assume the equivalent bunker fuel vessel would consume 1 000 gallons (4 000 L) of fuel for the equivalent trip. Assume a conventional vessel would cost $700k (3 MNOK). Assume the electric vessel consumes 1 MWh per trip.

Issues of interest:

- Is the battery appropriately sized?
- What is the difference in lifetime between the Athens battery and the Norwegian battery?

- If the battery boat has a capital cost of $2.5M USD (6MNOK) and fuel prices are 13 NOK/L ($8.60/gal) in Norway and 8 NOK/L ($5.30/gal) in Athens, what is the ROI for the vessel in each region?
- Is either vessel at risk of not being able to complete its mission in the future?
- If the operator wishes a 3 year ROI in both cases, will it be met?
- Will the battery complete its intended 10 year service life?

In the investigation, the Battery XT tool is used to estimate the battery capacity at future times by examining the effect of temperature. The predictions for both the Norwegian and Athenian conditions are shown in Figure G.2 below. It can be seen that the warmer temperatures for the Athenian vessel could implicate too much capacity loss by year 6-7.

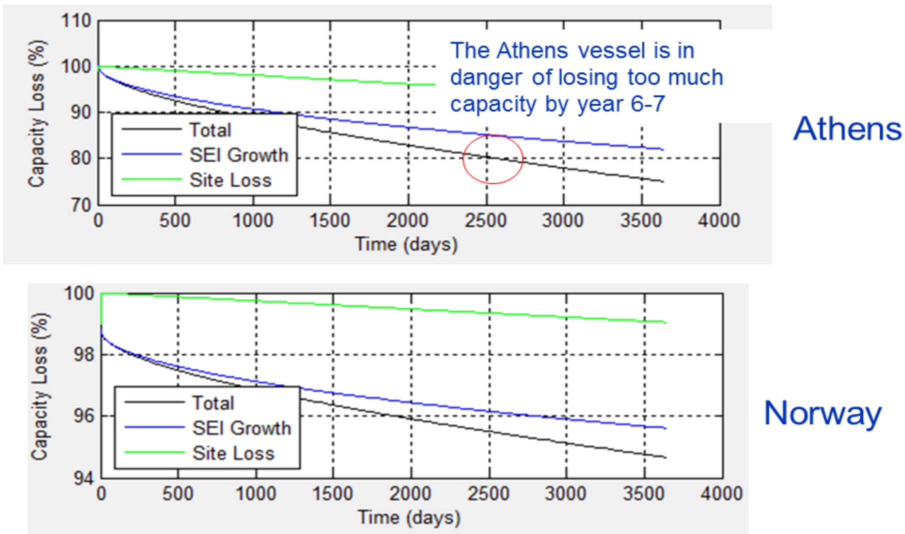

Figure G.2. Predictions of battery capacity by the Battery XT tool to examine the effect of temperature for two different cases, Athens and Norway.

To estimate the financial trade off of design criteria, these capacity estimations can be used to determine the return on investment (ROI) or payback for the vessel. The conventional vessel would have an estimated capital cost of $700 000 USD and an $860 000 USD/y fuel consumption cost. The Athens vessel would have the same capital cost with a $530 000 USD/y fuel consumption cost. The electric vessel would cost $2.5M USD but would cost $12 000 USD/y to operate in Norway versus $20 000 USD/y in Athens. Looking at the simple payback (non-discounted), one can see that the Norwegian vessel meets the 3 year payback criteria but the Athenian vessel would take longer.

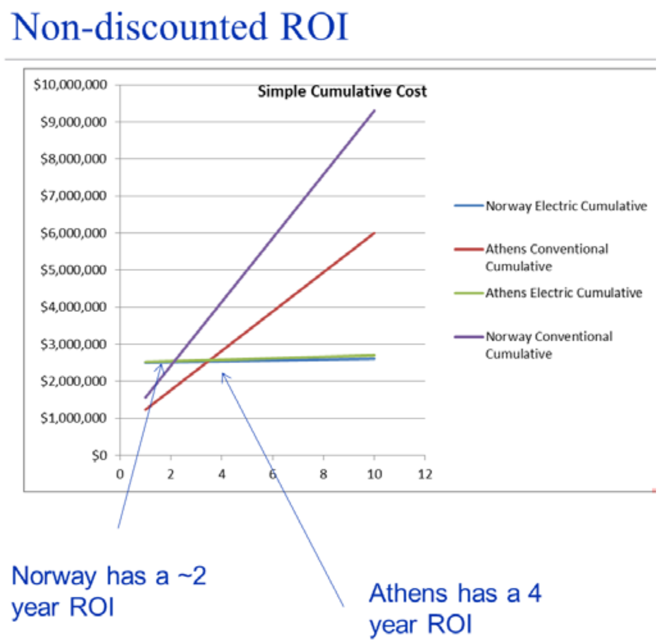

Figure G.3. Non-discounted ROI.

The answers to the above questions are then:

- Is the battery appropriately sized?
  - *For the Norwegian vessel: YES. For the Athenian vessel: NO.*
- What is the difference in lifetime between the Athens battery and the Norwegian battery?
  - *The Athenian battery is as much as 20 % more degraded during the same lifetime.*
- If the battery boat has a capital cost of $2.5 M USD (6 MNOK) and fuel prices are 13 NOK/L ($8.60/gal) in Norway and 8 NOK/L ($5.30/gal) in Athens, what is the ROI for the vessel in each region?
  - *The Norwegian vessel pays back in less than three years while the Athenian vessel pays back in nearly 4 years.*
- Is either vessel at risk of not being able to complete its mission in the future?
  - *The Athenian vessel may reach 80 % capacity by year 6-7.*
- If the operator wishes a 3 year ROI in both cases, will it be met?
  - *The Norwegian vessel pays back in less than three years while the Athenian vessel pays back in nearly 4 years.*
- Will the battery complete its intended 10 year service life?
  - *For the Norwegian vessel: YES. For the Athenian vessel: NO.*

The service life assessment tool can be used to answer additional questions. For example, one can estimate the necessary capital cost for the vessel in order to make a 3 year payback in the Athens environment. This may be useful for a ship owner if multiple bids are accumulated on the ship build. One could also evaluate the effect of adding cost (such as a cooling system) to determine if the payback or service life is improved. In this case, if an $800 000 USD cooling system is added to the Athenian vessel in order to keep the temperature at a constant 28 ^{o}C, the battery will not degrade below 80 % capacity during the 10 year service life, but the payback time is extended further into the future. Alternatively, the battery can be slightly oversized and in this case, this turns out to be the more cost effective solution, prolonging battery life (yet still not meeting the 3 year ROI) at a lower cost than adding a cooling system.

APPENDIX H. BATTERY RELATED SERVICES

DNV GL

DNV GL is the world's largest ship and offshore classification society and a recognized advisor for the maritime industry; a world-leading independent provider of risk management, technical advisory and technical assurance services to the upstream oil & gas industry; a world-leading provider of testing, certification and advisory services to companies in the electrical power value chain; a world-leading provider of software for managing risk and improving asset performance in the energy, process and maritime industry; and one of the leading certification bodies in the world.

DNV GL was the first classification society worldwide issuing rules for battery power.

DNV GL provides the following battery related services:

- Independent analyses, verification and validation
- Technical, economic and environmental performance analyses
- Battery service life assessment/ battery optimization analyses
- Qualification of battery related systems
- Requirement specification assessment and design review
- Ship power and energy system advisory services
- Risk analyses, such as FMECA
- Independent Software Verification & Validation
- Test planning/management/execution
- Independent QA, verification and validation
- Ship classification
- Training – Introduction to Maritime Battery Systems

DNV GL Maritime Battery Services

ZEM AS

ZEM AS, headquartered at the Veritas Center in Høvik, is a technology focused consultancy company that emerged from a World Economic Forum Initiative on Zero Emission Mobility in 2008. Engaged today in multimillion R&D and advisory activities in 5 countries, ZEM brings more than 15 years of experience with lithium ion battery systems to help facilitate the electrification and hybridization of the marine industry.

Analytical Services

Lithium Ion batteries have complex operational behaviors and degradation patterns which need to be assessed in order to understand how they might perform in any given application. ZEM Analytic Services uses a set of technical tools that simulate battery behavior and aging, based on different load cycles. ZEM's battery models capture the battery's complexity and make it possible to draw actionable conclusions, and provide simple answers to critical business questions...

- What is the best type of battery for my application?
- How many kWh's should my battery be?
- How long will the battery be able to perform the load cycle I intend for it?
- Do I need special cooling for my battery system?
- What is the real cost of my battery system given the above?

Critical to all these questions is how much a battery's capacity will degrade over time, given the conditions it is subjected to. ZEM simulates different battery types, sizes, cooling systems and load cycles to provide answers.

ZEM's methodology and modules leverage 15 years of experience with lithium ion batteries and thousands of hours of tests and real world experience in integrating batteries. ZEM's mathematical models are comprised of a number of inter-dependent modules that can work together to provide the relevant results. Two critical elements are the electro-thermal modules and the aging modules.

Electro Thermal Modules

To determine the suitability of a battery for any application, ZEM's battery models calculate degradation effects based on the detailed electrochemical properties of each battery type.

Aging Modules

Higher currents increase resistance which generates more heat. At higher temperatures, a battery will degrade more and its capacity decreases. This aging effect is captured by the aging modules. The algorithms used to calculate the degradation of the batteries, and the increase of resistance, are based on actual battery test results.

With its aging models, ZEM predicts battery degradation under any given load profile.

For more information about ZEM battery related services, see www.zemenergy.com or email us at contact@zemenergy.com.

Grenland Energy AS

Grenland Energy is a supplier of Li-Ion battery technology solutions for maritime and specialty applications and combines 35 years background from both cell suppliers and the automotive OEM and supplier industry.

A Li-Ion battery is a complex system, consisting of electrochemical cells, electronic circuits, safety critical software, electric components and rigid mechanical constructions. This complexity requires a multidisciplinary team with sufficient experience in all relevant areas. Our approach to handle this complexity combines development and testing into an integrated process, inherited from the automotive industry.

Our Products

Products from Grenland Energy are designed with highest quality components and rigid safety requirements, all contributing to stop a potential thermal event already at cell level. Quality, reliability and robustness are important in demanding maritime environments – the reason why we made it our top priority.

- Modular and extendable battery solutions with fully redundant systems control architecture and flexible customer interface, for:
    - High energy applications, such as electric ferries, passenger boats etc.
    - High power demanding applications, e.g. peak shaving, hybrid vessels, offshore power backup
- Customer specific battery solutions in all sizes
- Data logging and remote access/monitoring systems

Our Services

The safe introduction of Li-Ion battery technology is of vital common interest for both the maritime industry and battery suppliers and many questions need answers during this process. Examples for related services, provided by Grenland Energy to e.g. ship owners, yards and designers:

- Identifying the relevant battery requirements in maritime applications can be a challenge. From analyzing operational profiles and customer requirements, we can assist with the specification of battery systems, taking into account different energy-to-power ratios and cell life models for various cell chemistries and formats.
- Demanding operations and load cycles have a crucial impact on the chosen system and its lifetime which can with smallest uncertainty be determined by cycling tests. We offer battery related testing services (module and pack cycling) and simulation of customer specific operational profiles on real battery systems.
- Large systems can impose significant hazards to environment, life and economics. We can provide independent assessments of functional safety and systems for safety critical applications.

For more information, contact us at post@grenlandenergy.com or visit our website www.grenlandenergy.com.

ABOUT DNV GL

Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil and gas, and energy industries. We also provide certification services to customers across a wide range of industries. Combining leading technical and operational expertise, risk methodology and in-depth industry knowledge, we empower our customers' decisions and actions with trust and confidence. We continuously invest in research and collaborative innovation to provide customers and society with operational and technological foresight. With our origins stretching back to 1864, our reach today is global. Operating in more than 100 countries, our 16,000 professionals are dedicated to helping customers make the world safer, smarter and greener.

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